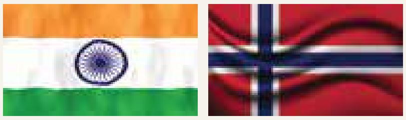


AN INDO-NORWEGIAN KNOWLEDGE PARTNERSHIP ON GREEN HYDROGEN
TOWARDS BUILDING AN INTERNATIONAL HYDROGEN ALLIANCE

TOWARDS SUSTAINABLE FUTURE

GREEN HYDROGEN | BIOFUEL | RENEWABLES

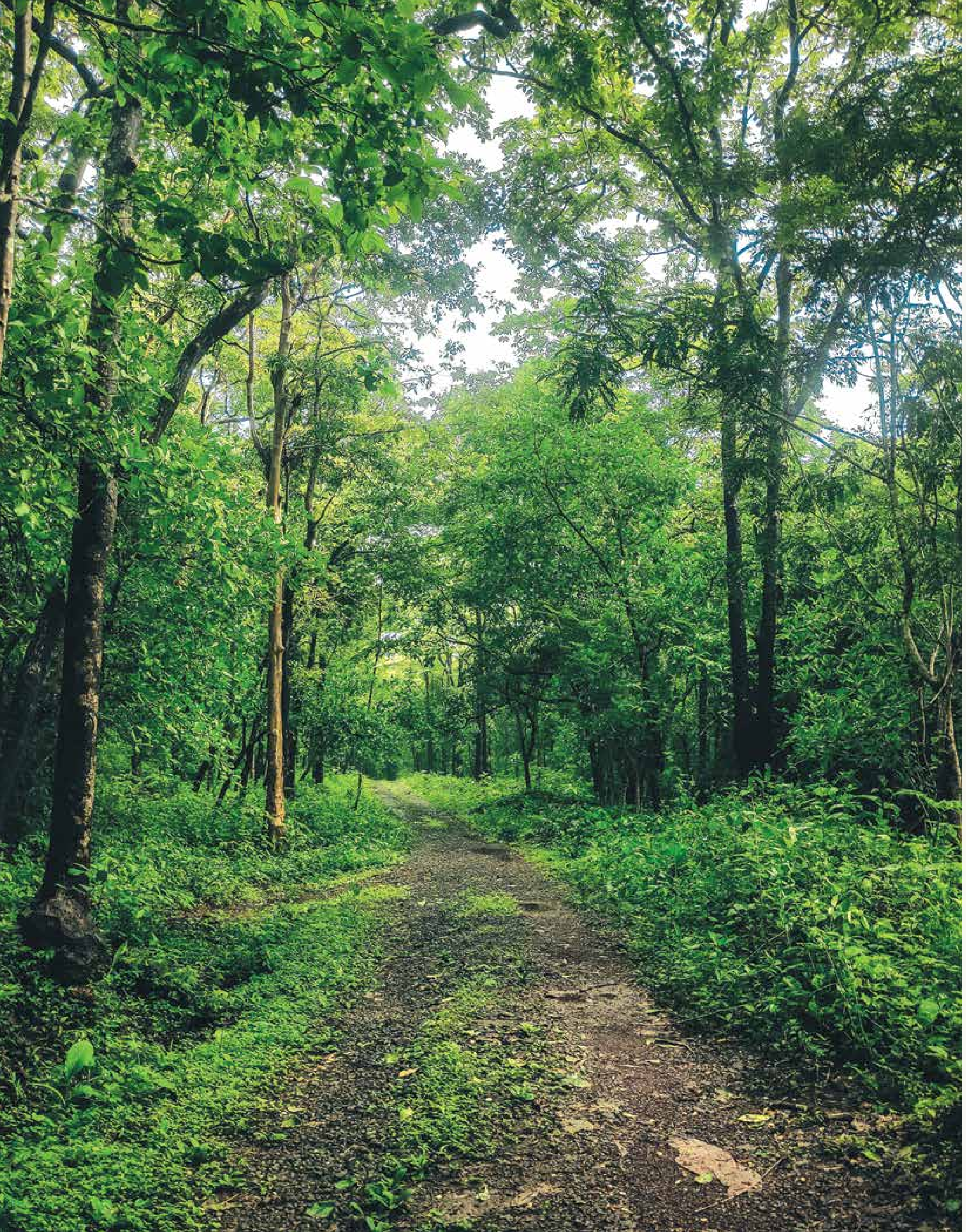
LIFESTYLE FOR ENVIRONMENT (LIFE)

LiFE
Lifestyle for
Environment

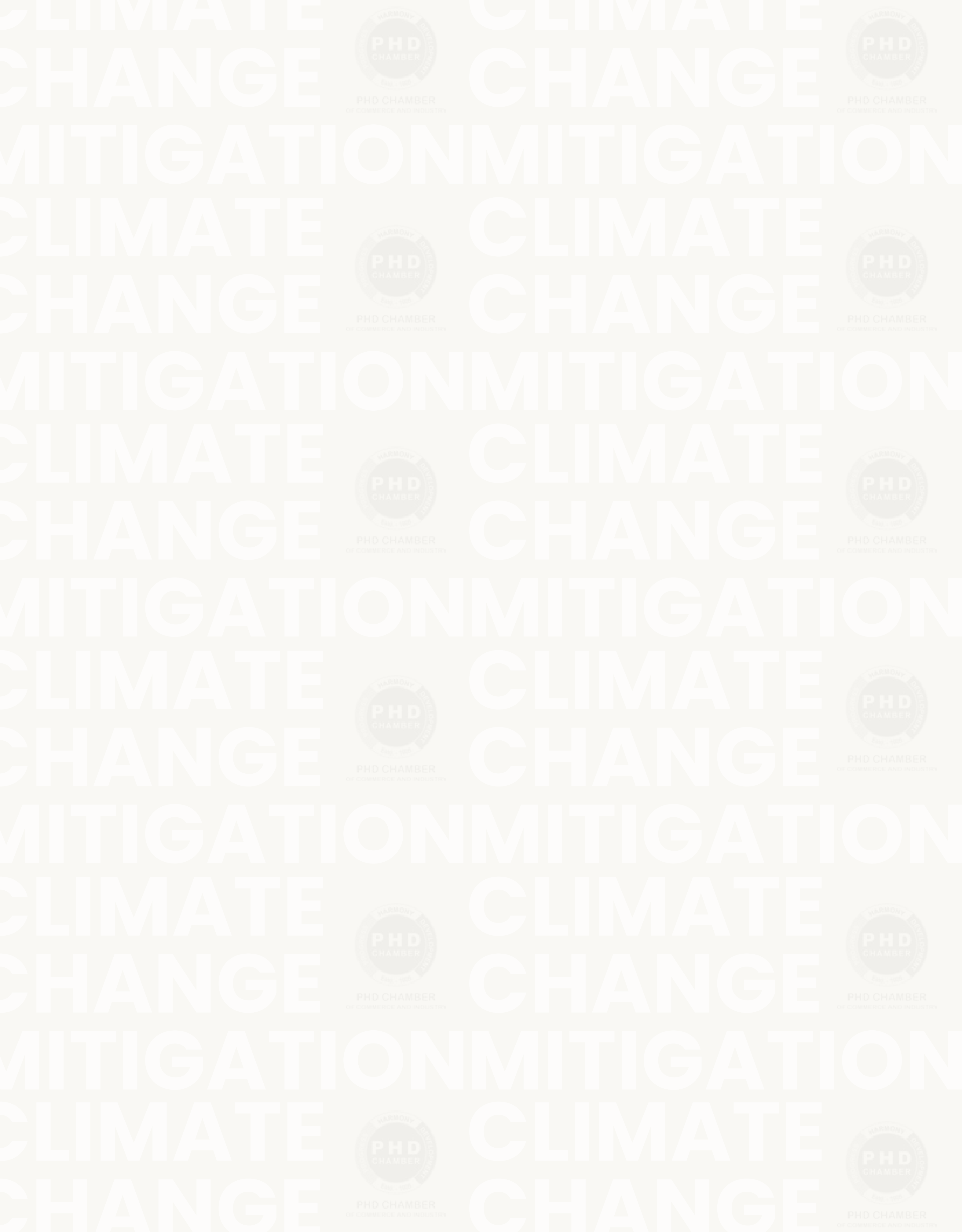
PHD CHAMBER
OF COMMERCE AND INDUSTRY

- **Dr J P Gupta**
- **Dr Karen Landmark**
- **Dr Sarala Balachandran**

Only through PEACE we can Thrive Collectively Purpose, People, Profit & Planet



TOWARDS SUSTAINABLE FUTURE



TOWARDS SUSTAINABLE FUTURE

GREEN HYDROGEN | BIOFUEL | RENEWABLES

DR J P GUPTA
DR KAREN LANDMARK
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PHD CHAMBER
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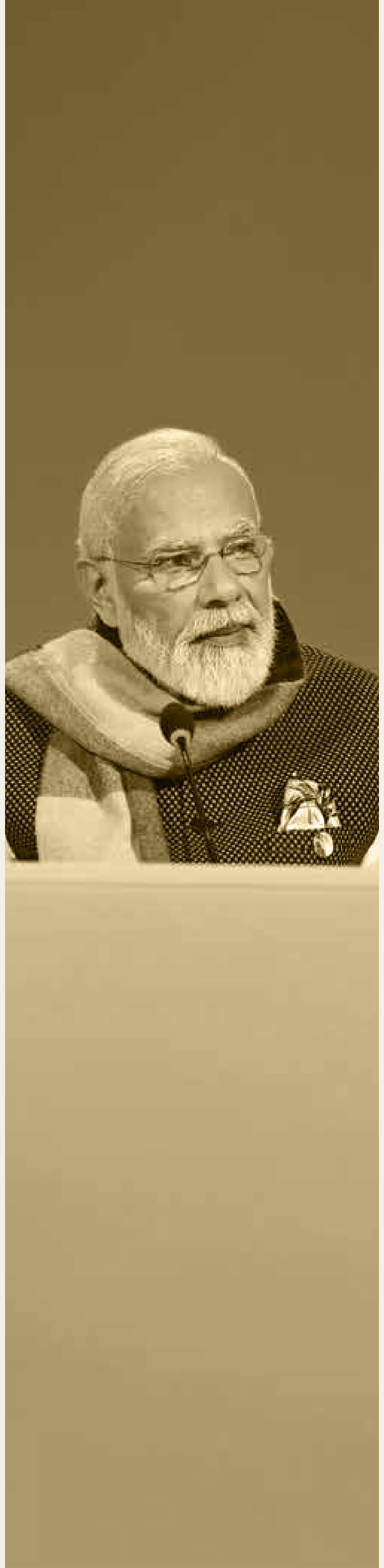


DEDICATION

With genuine gratitude and warm regards,
the authors dedicate this Knowledge Book
Towards Sustainable Future: Green Hydrogen, Biofuel, Renewables
to the

Hon'ble Prime Minister of India
Shri Narendra Modi

Salvation from climate change cannot be achieved by getting rid of fossil fuels alone. A new approach has been shown by Shri Narendra Modi to tackle climate change i.e. LiFE, Change in the Lifestyle for Environment – based on Ancient Wisdom.

His visionary thought and proactive steps for AtmaNirbhar Bharat (self-reliant India) concerning the energy roadmap for the country by launching the National Hydrogen Energy Mission in December 2020 have immensely motivated the authors to write this book.

The presented Knowledge Book not only has the potential to establish India and Norway as the leading centres for hydrogen energy but also suggests a novel approach towards sustainable consumption-oriented development.

Contents

Preface

DR J P GUPTA

Chairman, Environment
Committee
PHD Chamber of Commerce
and Industry
Managing Director
Greenstat Hydrogen India
Private Limited

Climate change is a huge crisis, seriously endangering humanity because we're using too much fossil fuel like crude oil, natural gas, and coal. Additionally, rampant deforestation exacerbates the problem. Renowned U.S. scientist Prof. James Gustave Speth aptly identified selfishness, greed, and apathy as the root causes of the top environmental problems. The seriousness of this crisis means we have to find alternatives to fossil fuels and move to energy sources that don't produce carbon emissions. Our very survival depends on it.

This book aims to provide an informative and insightful approach to climate change mitigation by proposing a new pathway known as the Fusion of Ancient Wisdom with Green Energy. Ancient wisdom emphasises the interconnectedness of the world, viewing it as one global family with the earth as a unified country and all individuals as its citizens. This perspective acknowledges that the environment knows no boundaries. Achieving acceptance of this worldview can be facilitated through spiritual and cultural transformation.

Our Hon'ble Prime Minister emphasises the importance of making lifestyle changes that support the environment and promote sustainable development. This new pathway involves embracing sustainable consumption, adopting a circular economy, and placing spirituality at its core. By recognising our natural environment as our spiritual environment, we can foster a sense of inner peace and reduce restlessness. Materialistic pursuits, driven by a lack of spiritual knowledge, often lead to a narrow definition of success centred around wealth, pleasure, possessions, and status. However, by adopting a spiritual way of life, individuals can forge a deeper connection with nature and cultivate a more caring attitude toward the environment.

As the current president of the G20 nations, India has a unique opportunity to convey a significant message and spearhead a global movement. Our message stems from the belief of India's 1.4

billion citizens who view the world as a single family—a message of peace and togetherness. The movement, initiated by our Hon'ble Prime Minister, aims to mobilise collective action and inspire individuals worldwide to embrace simple, eco-friendly practices in their daily lives for the betterment of the environment. We seek to create a lifestyle for the environment where sustainable choices become the norm.

Our mission is for India to become a year-round producer of renewable energy at the lowest possible cost, leveraging our abundant research and development resources and IT professionals to establish ourselves as a global hub for renewable energy production. Achieving this objective requires collaborative partnerships that promote accelerated growth and innovation.

In conclusion, the objective of this book is to present the collective knowledge and insights of both scientists and spiritual masters who have joined forces to convey this valuable information.

The vision of our esteemed prime minister highlights the fusion of ancient wisdom with renewable energy as the sole solution to safeguard our natural surroundings and address the climate change crisis. The movement we are launching today calls for active participation from all individuals as we collectively adopt simple, eco-friendly practices in our daily routines for the benefit of the environment. By embracing a lifestyle that harmonises with nature, we can strive towards a sustainable and resilient future for generations to come.

Acknowledgements

I would like to express my heartfelt gratitude to Mr. Saket Dalmia, President PHD Chamber of Commerce & Industry, Mr. Saurabh Sanyal, Secretary-General, PHD Chamber of Commerce & Industry, and other team members of PHD Chamber for their support in producing the Knowledge Book on Climate Change Mitigation. Dr S. P. Sharma, Chief Economist and Deputy Secretary General, PHDCCI, contributed a chapter on government policies on green hydrogen, and he deserves acknowledgement for his continuous support.

I would like to make a special mention of the contributions made by the team members from Norway, led by Mr. Sturle Pedersen, Chairman, Greenstat Hydrogen India Pvt. Ltd., for their valuable support in this book's production. Dr. Charly Berthod, Project Manager, Greenstat Energy AS, Dr. Knut Linnerud, Senior Business Developer, International, Greenstat Asia, and Ms. Oda Marie Ellefsen, R&D Coordinator/Project Manager Hydrogen, Asia, contributed significantly by authoring important chapters in the book.

Dr. Karen Landmark, Green Strategy Officer/Chair of the Board, Greenstat Asia, has contributed a chapter on regenerative leadership, and I am grateful for her constant support, guidance and inspiration.

I am grateful to all the authors who took time out of their busy schedules to contribute highly technical content, information and knowledge to the book. I would like to extend a special thanks to Mr. Amarnath, Additional Secretary, Department of Administrative Reforms and Public Grievances, Ministry of Personnel, Public Grievances and Pensions, Government of India, for writing a policy paper on How India could Attain Net Zero Much Earlier than Stipulated While Achieving Energy Security.

Dr. Sarala Balachandran, Chief Scientist at CSIR, deserves a special mention for accepting the responsibility of editor of the book and working tirelessly to coordinate with authors to complete it in record time, and I am grateful of her efforts.

I would also like to thank my wife, Dr. Purnima Gupta, and my late brother-in-law Mr. Chander Mohan Mittal, for their support and inspiration throughout the book's writing process. Although I am deeply saddened by Mr. Mittal's passing, his divine blessings helped me persevere. He had a fulfilling life, but there was still much more ahead of him. We should celebrate the legacy he left behind and continue it. I have faith that he is with me even now.

Finally, I express my gratitude to all the staff members, professionals, and PHD Chamber of Commerce & Industry staff who worked diligently to complete this Knowledge Book. Their efforts merit recognition and heartfelt thanks from me.

Dr J P Gupta
Editor and Author

Foreword

ERIC SOLHEIM
Former Minister, Climate and the Environment, Norway

When Swami Vivekananda delivered his speech at the World Parliament of Religions in 1893, he received a thunderous applause from the western dignitaries in attendance. His words provided them with much to ponder upon:

> *'I am proud to belong to a religion which has taught the world both tolerance and universal acceptance,' he said. 'We believe not only in universal toleration, but we accept all religions as true.'*

Even 130 years after Swami Vivekananda's powerful speech, his message continues to inspire India and the world. This year, as India holds the G20 presidency under the leadership of Prime Minister Modi, there is an opportunity to lead a global discussion on spirituality, lifestyle and climate change, which is perfectly aligned with Swami Vivekananda's ideals. This volume is a valuable addition to the ongoing global conversation on these important topics.

The G20 slogan of India is in harmony with Swami Vivekananda's teachings, indicating the direction we should take as a global community:

> *One earth, One family, One future.*

To discover motivation to protect the environment, one can turn to the profound knowledge of ancient Indians who regarded nature as divine, as evidenced in the Vedas and other texts. They respected nature so highly that they even depicted deities as half-human and half-animal, such as Ganesh and Hanuman. While some may mock the concept of "holy cows" in popular culture and among intellectuals, it is a representation of the notion that animals have sacred worth. This concept urges us to treat the animal kingdom with reverence and not exploit animals for short-term pleasure.

In India, vegetarianism is a mainstream lifestyle choice rather

than an alternative idea propagated by left-wing groups, as seen in the Western world. Not only is vegetarian food considered healthy, it also reflects a deep respect for nature. This provides a positive starting point for our discussions on lifestyle changes that can benefit the environment. This idea is rooted in the core values of Hinduism and other belief systems, making it a positive agenda for change that can enhance the well-being of both humans and Mother Earth.

Far too often, the call for lifestyle changes devolves into a practice of pointing fingers at others. The affluent telling the poor to better their behaviour and intellectuals scolding the working class. Everyone demands that others should adopt the same ideal lifestyle that they do, resulting in disrespect for the idea of lifestyle changes. However, lifestyle changes are not just about individual morals but rather societal transformations.

Fortunately, a constructive plan exists for implementing such lifestyle changes.

If we demonstrate greater reverence for nature and adopt a more modest approach in our interactions with the earth, it will reciprocate with benevolence. The earth grants us the freedom to indulge our fondness for the natural world and our inclination to draw nearer to animals, trees, flowers, mountains, deserts and rice fields.

By transitioning to environmentally friendly ways of living, our cities can become more hospitable for the people. By utilising public transportation and switching to electric vehicles, we can reduce pollution and noise, conserve space for parks and urban forests, and create liveable cities. We no longer have to waste many hours every week trapped in traffic, and our lives can become more joyful. Hyderabad was recently designated as the World Green City of 2022, and the capital of Telangana is one of the fastest-growing cities in India due to its residents' appreciation for an eco-friendly urban lifestyle. Shenzhen is China's greenest city, featuring excellent electric transportation and green corridors, and also boasts the country's highest real estate prices because people love living there.

The positive lifestyle agenda also focuses on health. With less pollution, better products, and living closer to nature, our health will improve. When India became independent, life expectancy was around 30 years. Today, 75 years of Indian independence have brought it to 68, it will soon pass 70. Serum Institute in Pune has installed capacity to produce vaccines for all 8 billion humans in the case of a new pandemic. Indian traditional medicine is a great supplement to traditional medical efforts. There is an important green health agenda to be explored by India.

India has the potential to lead the world in addressing the triple environmental crisis of climate change, pollution, and the destruction of nature. Mahatma Gandhi famously emphasised that we must 'be the change we wish to see in the world'. He did not instruct us to become saints, but rather inspired us to change society to improve our way of life.

With India's leadership, we can unite political reform, business innovation, and lifestyle adjustments into a single green wave. Prime Minister Modi has transformed the Indian conversation from the outdated dichotomy of prioritising either the economy or the environment to the contemporary notion of a win-win situation. By adopting policies that promote green growth, we can both protect Mother Earth and uplift every Indian out of poverty. The numerous green initiatives implemented by Prime Minister Modi, such as those focused on green hydrogen, electric cars, battery production, and solar energy, are practical manifestations of these win-win ideals.

Leadership in addressing environmental issues is not only limited to the centre. Several Indian states are also pursuing a similar approach that combines political initiatives, green business practices, and lifestyle changes. For example, Andhra Pradesh is a global leader in ecological farming, and Telangana is renowned for its urban parks. Chief Minister Stalin of Tamil Nadu has launched an impressive climate mission, and Chief Minister Chouhan of Madhya Pradesh is inspiring 80 million people in his state to follow his example by planting one tree each day.

The most fundamental aspect of driving green change is peace. Wars not only kill people but also destroy the environment. They divert our attention from important issues such as environmental protection, poverty reduction, and creating a secure life for the middle class. In a speech delivered in Chicago, Swami Vivekananda highlighted this point:

´Whosoever comes to me through whatsoever form, I reach him; all men are struggling through paths which in the end lead to me.' Sectarianism, bigotry, and its horrible descendant, fanaticism, have long possessed this beautiful earth. They have filled the earth with violence, drenched it often and often with human blood, destroyed civilisation and sent whole nations to despair.

India has the ability to assist the world in resolving conflicts and ensuring that we concentrate on issues that are vital to human life and dignity. Going forward, the way to do so is by linking spirituality, environment and lifestyle changes.

From the Editor's Desk

Dr Sarala Balachandran

Chief Scientist, CSIR

As we embark upon putting forth this Knowledge Book *Towards Sustainable Future: Green Hydrogen, Biofuel, Renewables* which is being released on the occasion of International Climate Summit 2023: LEADING THE CLIMATE CHANGE MITIGATION (ICS-2023), it is essential for me to mention the other two Knowledge Books that were released during ICS 2021 and 2022 respectively. This is the third book in that series.

With the advent of the modern industrial era, our world has added to its problems galore with constantly evolving modern technologies and facilities. These facilities which we enjoy today were a distant dream at the onset of the twentieth century. In our quest to industrialise and modernise, we have been gradually releasing carbon in the form of CO_2 into the air and now it has reached unprecedented levels. Climate change, global warming, depletion of atmospheric ozone, chemical pollution, biodiversity loss, etc. have all been recognised as of great concern for us at present. In the future, if our planet has to support 10 billion people (expected around 2050), we need to think of a sustainable way of doing things in our day-to-day lives.

Some of us have been aware of this impending doom for quite some time. As early as 1861, John Tyndall has alluded to rising atmospheric temperatures due to an increase in CO_2 concentration (J Tyndall, The Bakerian Lecture, Philosophical Transactions 151 (1861). Pp 1-37). From Sweden, S Arrhenius in the year 1896, had mentioned that CO_2 had doubled at that time as compared to preindustrial atmospheric levels and which in turn was leading to an increase in temperature. (On the Influence of Carbonic Acid in the Air Upon the Temperature of the Ground, Philosophical Magazine and Journal of Science 5/41 (1896), pp 237-296). Now this is akin to the classical sword above our heads. We can no longer disregard the then-and-now pictures of melting glaciers, growing acquisition of forest land by humans (disturbing the fauna/flora equilibrium), permafrost getting disturbed, etc.

We cannot afford to ignore the elephant in the room any more. There is no time to waste. The motto needs to be ‘Make haste and Mend your ways’ before the only planet where life can currently exist, succumbs to the vices of humanity and commences to perish at an elevated rate due to the Incessantly increasing tcarbon footprint pushing us over the rim. The exploration of space and discovery of newer ever-expanding numbers of planets, exo-planets, presence of water in such places, etc. is an ongoing process. Even then the possibility of settling human kind elsewhere is still quite impractical. The evidence of destruction of our planet is visible, our survival is being threatened, and it is fast becoming unredeemable.

Albert Einstein once remarked that it’s impossible to solve problems by using the same thinking that was used to create them. So, in order to save the only habitable planet we have at present, a paradigm shift is critical as we are now edging towards a point of no return. Between 1992 and 2019, global emissions of CO_2 rose by about 65% and those of CH_4 by about 25%. (Oliver and Peters, Trends in Global CO_2 and Total Greenhouse Gas Emissions 2019 Report). In 1972, United Nations Conference on the Human Environment in Stockholm was the first world conference to make environment a major issue.

In June 1992, United Nations Conference on Environment and Development (UNCED), also known as the ‘Earth Summit’, was held in Rio de Janeiro, Brazil, to address urgent problems of environmental protection and socio-economic development. Since then there have been a large number of such conferences and now we have the Sustainable Development Goals (SDGs) spelled out for us. This book and event are showcasing a new plan for de-carbonisation in accordance with UN’s SDG Goal 7 (Affordable and Clean Energy) and Goal 13 (Climate Action) and also it leads towards SDG Goal No. 11 of Sustainable Consumption and Communities.

The challenge of maintaining global warming well below a reasonable limit and the dire consequences of the warning signs of impending doom is not something which needs to be elaborated to those who are already well versed in the consequences of the indiscriminate use of fossil fuels and other damages of industrialisation. COP has warned us about the ominous predicaments of not sticking to 1.5°C. A Grubler et al describes ‘A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies’ (Nature energy 526 (2020) pp 515-52).

This Knowledge Book is an attempt to address the problems facing us and the best way to look for solutions. The contents of this Knowledge Book have been chosen in such a manner as to merge our ancient wisdom of Vedic science and frugality with modern scientific solutions and integrating that ancient wisdom with modern green energy requirements.

The UN SDG Goal No. 12 for Responsible Consumption and Action has been discussed in this compilation in chapters devoted to the overall scenario referring to how energy security can be achieved while mitigating the harmful effects of climatic change happening at present. The way forward at present cannot eschew fossil fuels completely, it will still be in use while we bring about more sustainable sources of energy. The current energy landscape and the need to make the transition to more sustainable ways during the climate crisis is discussed in detail.

The CO_2 that has already accumulated due to excessive human negligence needs to be captured and stored away or utilised. The chapter on CCUS deals with this. CO_2, which is a problem now can be of use in so many ways, some known, some yet to be discovered. The chapter on reaction of CO_2 with hydrogen brings forth another way of utilising the excessive CO2 generated. Fossil fuels, a natural resource by itself, are not the problem. It is the mismanagement of natural resources which is to be blamed. How to manage this is an example given in the chapter on coal gasification. There are other natural resources which need to be tapped into – wind energy, hydro energy, solar energy, etc. The sun is the best source of energy at present for us and we are unable to tap the full potential of this free source we have to the fullest extent. A number of pages have been devoted to alternate energy sources which encompass not only solar energy, but also fuel from agro-waste and other kinds of biofuels as well as fuel cells. The book also forays into alternate energy sources. It elaborates the work carried out in aviation fuel in the chapter on Synthetic Paraffinic Kerosene (SPK). The potential of fusion energy seems to be within our reach and needs to be explored further.

An alternative to existing sources, which is extensively discussed in this Knowledge Book, is Green Hydrogen. The PM announced in January 2023 an initial outlay of Rs 19,744 crore to The National Green Hydrogen Mission. This is towards the country’s contribution to the Long Term Low Emissions Development Strategy (LT-LEDS). Various types of hydrogen and different methods of production of green hydrogen, the shortcomings of the current procedures, etc. have been discussed at length. Hydrogen being a highly inflammable gas, the safety concerns of usage, storage and transport need to be looked into in great detail. Several chapters have been devoted to this aspect.

Dimethyl Ether (DME) may be considered as a circular hydrogen carrier which will also be able to store energy for use at times of low renewable power generation. A lucid insight into this area is also discussed in the chapter devoted to it. One of the important ways to achieve a circular economy is by integrating waste into the supply chain in a sustainable, economical and environmentally friendly manner. Green hydrogen production from waste water has also been explored. An innovative way for obtaining green hydrogen is to produce it via membrane technology, and it has also been discussed.

Besides analysis of current situations and possible solutions, the importance of socio-economic aspects like the Environmental Social Governance (ESG) and how carbon credits can be earned and traded as a commodity have also been covered. The solutions for our problem cannot be magical, it lies in the indefatigable endeavour that our scientists put in their ongoing research work. The process is on and some of these are described in the various chapters as summarised here. It is expected that these and more such research work carried out will help us to find real solutions for our country to forge ahead in a sustainable manner in the near future.

It’s time for us to think and rethink the direction we should take and solutions we should find to save our planet and act on it NOW. Renewable energy has an important role to play in this scenario. This book is going to contribute tremendously in the direction by providing useful information in all areas of renewable energy with special emphasis on green hydrogen. As the editorial team of this book searched for relevant topics to be discussed in the book and chapters were sought from think-tanks, policy-makers, subject experts and researchers, we soon discovered that the compilation was growing in size. In order to restrict the size of the book, we had to leave out some important topics.

In the end, I wish to thank my co-editors and everyone else who helped and encouraged me to undertake this venture. If any chapter on relevant topics has been left out, apology is sought from the reader. We will take cognizance of that and ensure we include it in the next compilation on a related topic.

Introduction Aligning with Nature

Dr J P Gupta

Dr Karen Landmark

Two years ago, at the inaugural International Climate Summit in Delhi, we launched the first edition of the Knowledge book titled Self-Reliant India – Harnessing the Power of Hydrogen. It aimed to provide access to knowledge and create awareness of the potential of hydrogen as part of renewable energy solutions, as India was about to include green hydrogen in the political agenda. The first book served its intended purpose.

The second edition of the book, India is an Attractive Destination for Green Hydrogen - A Way Forward, was launched at the International Climate Summit in Bergen, Norway, last year. While hydrogen still played a central role in the narrative, it was accompanied by an acknowledgement that technical solutions alone are insufficient in mitigating climate change and natural resource degradation. A more significant transformation is necessary, involving social and spiritual changes that encourage reflection on our relationship with nature, leading to an environmentally conscious lifestyle that prioritises mindful and deliberate utilisation over mindless and destructive consumption. Ancient wisdom can provide solutions and insights to combat climate change and environmental degradation.

This third edition of the Knowledge Book takes this perspective further, by combining ancient wisdom with renewable energy to offer a novel approach to addressing climate change.

Renewable Energy coupled with ancient wisdom holds the key for a more sustainable and regenerative future

The book emphasises that sustainable consumption, circular and cyclic economies, and renewable energy can help protect Mother Nature, as per the insights from ancient wisdom. As such, the book serves as a guide to understanding how renewable energy can support building a more sustainable and regenerative future, while exploring the spiritual significance of our relationship with nature. The book cites ancient Vedic writings, which highlight the connection between protecting the environment, heavens (*dyaus*), earth (*prithvi*), and the atmosphere (*paryavaran*).

The book's first Section focuses on climate change mitigation, which involves addressing the root causes of climate change and minimising its impact. In contrast, adaptation seeks to minimise the negative effects of climate change and take advantage of any opportunities that arise. The chapter explores energy security, carbon credits, and the importance of ESG as a tool for sustainable value creation.

Section 2 examines clean fuels, particularly green hydrogen, and the challenges and opportunities that come with transitioning to a zero-emissions economy.

Section 3 discusses the need for research and development to accelerate this transformation and acquire the necessary knowledge.

Section 4 emphasises the significance of process safety in the hydrogen economy, while chapter five looks at CO_2 as a potential 'new oil reservoir'.

While Section 5 emphasizes the significance of process safety in the hydrogen economy, Section 6 presents cost-effective technologies capable of producing all the products currently derived from fossil fuels using CO2 extracted from the atmosphere. This entails advancing catalyst development and refining processes for manufacturing these products, which currently rely on petrochemicals routes.

Section 6 also highlights the fusion of ancient wisdom with renewable energy and its potential to promote climate change mitigation. It argues that a spiritual and cultural transformation must occur in conjunction with technical solutions to effectively mitigate climate change. The chapter also discusses regenerative perspectives on business and leadership and the importance of advocating for peace.

In the current context, it is crucial to adopt a more holistic and sustainable perspective to improve the likelihood of addressing the interlinked global challenges. Despite the daunting nature of these issues, we remain optimistic and believe that this book can provide fresh viewpoints and inspiration to the ongoing endeavours aimed at creating a better world for everyone.

SECTION -1

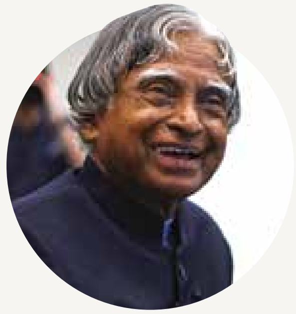
CLIMATE CHANGE MITIGATION

Net Zero India@2047: A Corporate-led Collaborative Policy Approach | Energy Security and Climate Mitigation can Thrive Collectively | Energy Landscape and the Need for Energy Transition against the Backdrop of Climate Crisis | Environmental, Social and Governance (ESG) is a Panacea for Climate Change Mitigation | Unlocking Environmental, Social, and Governance (ESG) Opportunities for Sustainable Value Creation | Genesis and Evolution of Carbon Credit as Decarbonisation Greenback

1.1

Net Zero India@2047: A Corporate-led Collaborative Policy Approach

AMAR NATH, IAS, Addl. Secretary, MoPPG&P



If you want to shine like a
sun, first burn like a sun

Dr A P J Abdul Kalam

The prime minister in his Independence Day address on 15 August, 2021, asked the nation to make a resolution to make India energy-independent before the 100th anniversary of the country's independence. For a country which imports 85% of its crude oil, 50% of its natural gas, and 20% of its coal requirements, the prime minister's call for energy self-sufficiency is ambitious, indeed. Given our commitment to take the global lead to avert the imminent threat of climate change, can India set itself the goal of becoming a net-zero economy by 2047, in addition to becoming self-sufficient in its energy needs? Such a goal would be not only ambitious but audacious as well, but worth pursuing in the coming 25 years, christened as 'Amrit Kaal', an auspicious time.

The conventional perspective, shaped by the development of industrial societies over the past 200 years, may view the goal of India becoming a net zero economy by 2047 as unattainable and unrealistic. However, a closer examination of emerging trends that are transforming societies suggests that India has a unique and rare opportunity to be bold and daring. With the power of digital technologies, a large and young population, significant technical and scientific expertise, and a culture of innovation, India has the potential to leverage these advantages and work towards achieving the ambitious goal of being energy self-sufficient and net zero. This presents a historic opportunity not only for India to chart a path towards sustainable development for itself but also to steer the world towards a more peaceful and sustainable future. India has taken on the presidency of the G20, a group of powerful nations whose decisions can greatly impact the rest of the world. With 85% of global GDP, 75% of international trade, and about two-thirds of the global population, the G20 is a significant player in global governance. India has chosen the theme of Vasudhaiva Kutumbakam, which means 'One planet, one family, and one future', to promote a sense of harmony, healing and inclusivity. With the world facing challenges such as the pandemic, war, and a fractured global governance system, India can play a pivotal role in identifying and implementing solutions to prevent catastrophic impacts of climate change and heal the planet. Economist Nouriel Roubini's latest book, Megathreats, warns of 10 trends that threaten our future, with climate change being one of them.

Why should we worry about climate change? Extreme weather events such as storms, flooding, and heat waves are occurring with more frequency and intensity, causing loss of human life and damage to infrastructure. The Intergovernmental Panel on Climate Change (IPCC) has warned that global warming would increase multiple climate hazards and we will have limited options if current greenhouse gas (GHG) emissions do not decline rapidly. The cost of inaction is higher than the cost of acting now, and while there is a global consensus that we need to do something, there is still a need to agree on what to do, who will do it, and who will pay for it.

Many studies conclude that developing countries such as India are highly vulnerable.[1] A warmer planet will lead to water stress and flooding simultaneously, impacting food production and cattle population, natural disasters such as storms leading to damage to infrastructure, heat waves impacting labour and reducing productivity. Many of these impacts occurring together will be difficult to handle for developing countries. Therefore, investment in mitigation of impact of climate change is critical, especially for developing countries. In order to find solutions to the problem of climate change, we need to understand the root cause of the issue and how modern industrial society has evolved over the past 200 years. Prof. William Nordhaus, a Nobel Prize winner for his work on climate change, has described climate change as the ultimate challenge for not just economists, but for humanity as a whole. Climate change poses a challenge for politics, business, science and psychology, as humans often don't notice long-term or distant dangers.

The problem of climate change has its origins in the invisibility of GHGs and the lack of knowledge about their harmful impact. It was not until recently that a scientific consensus was reached on the damage that GHGs can cause to the planet's ecosystems. The continued emission of these gases can also be attributed to entrenched business interests. Once a business is established and an ecosystem has evolved around it, it becomes difficult to change its course. For example, few people know that in the 1920s, 40% of vehicles in New York City were electric, and only 20% were gasoline-powered, with the rest being steam-powered.

However, Henry Ford's factory mode of production reduced the cost of gasoline-powered cars, making them popular among the masses and crowding out electric vehicles from the market. Finally, consumers of products and services did not pay the cost of carbon emissions, which created, as called by the economists, an unpriced negative externality.

Efforts to address climate change by the global community have not yielded the desired results. In 2015, the Paris Agreement was signed, which committed countries to reducing GHGs voluntarily, with no enforcement mechanism. However, the latest Emissions Gap Report by the UN indicates that the current climate pledges are far from what is needed to meet the Paris Agreement goals. It is unrealistic to expect effective and coordinated action from more than 200 governments. Governments are good at creating regulations and setting rules, but expecting them to take specific action, such as in energy transition, where multiple and competing actors are involved, is flawed. Governments have limited tools at their disposal, such as tax, subsidy, mandates and standards. Additionally, they must balance various competing objectives, some of which are difficult to define and quantify, such as equity and justice.

To overcome the failure of collective action through the UN, a new approach is needed. Rather than trying to reach a consensus among all nations, a coordinated effort by the G20 – a group of 20 nations responsible for the majority of historical and future emissions – would be the most effective way to address climate change. Within the G20, the responsibility for reducing carbon emissions should be placed on the top 100 corporations in each country.

Due to the complex nature of energy transition, multinational corporations, especially larger ones, are better positioned than governments to switch to cleaner sources of energy. These corporations have diverse sources of funding, global supply chains and marketing channels, and more information and revenue than many countries. Therefore, the role of corporations needs to be reconsidered in the fight against climate change. Focusing on the top 100 corporations in G20 countries, which cover a range of sectors and contribute significantly to economic activity, can yield better results as they have significant market capitalisation and are mostly multinational corporations. The market capitalisation of top 100 corporations in many countries is more than the GDP of these countries.

Given their global reach, resources, and investor base, large corporations are the most suitable entities to address climate change. This was the conclusion reached by the Dutch court in the Royal Dutch Shell case. Corporations are better equipped to take the lead on climate change for several reasons:

- Firstly, corporate leaders are more capable of developing and implementing detailed plans and agenda than elected government officials. For example, BP's CEO, Bernard Looney, announced a net-zero target for 2050 and presented an action plan to achieve it.
- Secondly, corporations have access to the best talent, financing, and technology to find solutions and avoid imposing additional social costs.
- Finally, corporate behaviour can be regulated, while nations are not subject to regulation.

To accelerate the energy transition, most effective policy intervention will be imposing a carbon price on the emissions by the top 100 corporations in each G20 country, and mandate them to achieve net zero by a specific year based on their carbon footprint. This group of 2,000 global corporations, 100 in each G20 country, can be a potent force and can achieve remarkable results. While many global corporations have begun to incorporate shadow or implicit carbon pricing in their internal investment decisions, this approach is voluntary and varies considerably among corporations. [State and Trends of Carbon Pricing 2021, World Bank].

What should be the carbon price? The principle of common but differentiated responsibilities and respective capabilities (CBDR-RC) has been enshrined in United Nations Framework Convention on Climate Change (UNFCC), but its practical application has not been defined. The U.S. and Europe have achieved their present level of economic development using fossil fuels and are responsible for a majority of historical emissions. Three main parameters of per capita income, per capita energy consumption and Co2 intensity of GDP, reflect the historical role of fossil fuels. Therefore, carbon price by the U.S. should be taken as the benchmark, and other G20 countries should impose carbon price proportionately, based on these three parameters. A High-Level Commission on Carbon Prices[2] set up by UNFCC and supported by the World Bank, in its 2017 report proposed a carbon price of $50-100/tCo2 by 2030. If the U.S. imposes a Carbon Price of $100/t, based on the above three parameters, India should impose a carbon price of $36/t.[3] In order to prevent firms in G20 countries from being at a disadvantage compared to those in other countries, a carbon adjustment mechanism could be implemented in the form of a uniform tariff on imports from other countries to G20 members.

These corporations must announce their net-zero targets, along with intermediate milestones. The ESG concept is too complex and difficult to implement and monitor. Therefore, a laser-sharp focus should be placed on the GHG emissions reduction by G2000 corporations. A G20 Carbon Reduction Index based on GHG emissions and carbon intensity of the corporations can be developed. Top 100 corporations in India can show the way forward. A G20 Carbon Fund must be created from the proceeds of carbon price from G2000 Corporations and such a fund should be leveraged to finance the R&D and early-stage deployment of technologies.

India, as a responsible nation, has submitted its Long-Term Low-Carbon Development Strategy (LT-LEDS) to UNFCC based on seven key transitions including in electricity, buildings, industry, and mobility sectors committing to a net-zero target by 2070. Can India become carbon neutral by 2047? India has set a target year of 2070 for achieving net-zero emissions, but there is an opportunity to use the energy transition as a means of generating economic growth and employment while also addressing climate change. India can leverage its technical knowledge, digital strength, and young population to not only achieve its net-zero goal by 2047, but also assist the rest of the world in doing the same. However, this will require a shift in mindset and new business and governance models, as noted by the prime minister upon assuming the G20 presidency. The estimates of India's GDP in 2047 vary from $20 trillion[4,5] to $40 trillion.[6] McKinsey, in a recent report on decarbonising India, has estimated that 3/4th of India of 2050 is yet to be built.[7]

Therefore, it has a remarkable prospect to build a new, sustainable India. While building the new India, there is an opportunity for energy-intensive industries worldwide to relocate to this country and make products green, not only for the Indian market but also for the global marketplace.

India is poised to face several significant challenges in the next 25 years, including having the world's largest population, rapid urbanisation, pollution, water scarcity, and waste management. However, these challenges also present an opportunity for India to transform itself during this period, referred to as the Amrit Kaal by the prime minister, leading up to India's 100th year of independence in 2047. India's young, digitally connected population and technical manpower, as well as new infrastructure developments, such as Vande Bharat trains, 5G rollout, air connectivity, and highways, can be harnessed to turn these challenges into opportunities.

To make this happen, however, reliable and affordable energy is crucial. India must undergo twin transitions in the energy space: providing modern energy access to millions of people without it, and reducing GHG emissions while ensuring energy access for citizens and businesses. This quartet of energy transitions must be managed with the first dimension being energy security, which is crucial for any nation's sustained development. India has taken several policy measures to exploit its energy resources to promote self-reliance.

India holds the 5th largest coal reserves. We have invested heavily in thermal power, and related infrastructure. Some of the existing power plants are expected to run for another 30 to 40 years. Coal mining is a crucial source of employment for many communities and a vital contributor to local economies, as well as national supply chains and related ecosystems. Due to the growing economy's energy demands, reliance solely on renewables in the short- to medium-term may not be sufficient, and therefore, investment in coal and thermal energy production is necessary. There are three possible approaches to achieve this: sustainably shutting down old, unviable and hazardous coal mines, efficiently managing viable ones, and designing new mines with minimal energy usage and carbon footprint. A similar approach could be employed for thermal power plants.

The prioritisation of renewable energy over thermal energy should be considered in the short- and medium-term. However, the challenge lies in integrating the grids and ensuring grid flexibility while making energy affordable. In the long run, India must innovate sustainable ways to use coal for power by implementing carbon capture technology and discovering methods to convert coal to liquid and gas. The eastern region of India, including Jharkhand, Odisha, Madhya Pradesh, Bihar, and West Bengal, should be a focal point for these efforts.

Similarly, we have implemented several policy measures to make the oil and gas exploration and production sector more attractive to investors. To reduce our reliance on imported oil, we need to invest in domestic exploration and production, as around 50% of our potential basins remain unexplored. The government may establish a mechanism to provide a guaranteed price for domestically produced oil in order to incentivise investment in this sector. This mechanism could involve a price band that is tied to international prices, with tax and duties waived when the price falls below a minimum level, but increased when it rises above a predetermined maximum. While the government is encouraging investment in various manufacturing sectors through the Production Linked Incentive (PLI) scheme, the energy sector, which underpins the entire economy, cannot be neglected. In addition to focusing on domestic oil and gas exploration and production in the short- and medium-term, we must also implement policies to actively reduce our dependence on oil. These policies could include a swift transition to electric vehicles, promoting public transportation, discouraging inefficient personal transportation, designing urban areas that are conducive to walking and cycling, and reimagining e-rickshaws for last-mile connectivity.

Significant investments are being made to establish a gas-based economy, including the creation of a network of pipelines across the country. By 2026, the city gas distribution will extend to 88% of the country's geographic area and 98% of the population. However, relying solely on imported LNG for this economy is not viable due to market volatility and geopolitical implications. To develop a sustainable gas-based economy, it is necessary to incorporate biogas and green hydrogen, including biohydrogen. This will require investments and innovation that are specific to India.

India has also initiated several steps to increase investment in renewable energy and has set a target to achieve 500 gigawatts (GW) of energy from non-fossil sources by 2030, with solar and wind energy installation targets accounting for 60-70% of the overall renewables target. However, the progress of solar and wind energy may be stymied by a complex land-acquisition process, the precarious financial conditions of state-owned electricity distribution companies, and competition from the EU, U.S., and China to transition to renewables. The government has also set targets for 20% blending of biofuels by 2025 and plans to establish 5,000 compressed biogas plants to utilise organic matter for energy production. Ambitious targets have been set to produce green hydrogen and make India a hydrogen hub. Additionally, the possibility of using nuclear energy through factory-built Small Modular Reactors of up to 300-megawatt (MW) capacity is being explored. Modernising energy sources, such as using paddy straw in brick kilns and thermal power plants, can meet energy needs while reducing pollution and emissions. Investment in exploring and exploiting geothermal and small hydro projects with a capacity of less than 25 MW must also be promoted. At this stage of development, all sources of energy are being explored to meet the increasing energy demand of the country.

In the context of the changing energy landscape, hydrogen is seen as a significant opportunity for India to take a leading position. Hydrogen is one of the four pillars of the energy transition, according to the International Energy Agency (IEA), and is gaining global traction. The prime minister announced in his 2021 Independence Day address that India would become a hydrogen hub, and the government has approved a Rs 19,000 crore incentive package to support this goal. Both private and public sectors have announced various projects and plans to develop hydrogen, particularly for use in industries and long-distance trucking, as long as production costs remain competitive. The government is likely to provide some subsidies for hydrogen projects, but funding will be limited due to competing demands on government resources. To reduce the cost of hydrogen, innovation is needed throughout the

entire value chain, and four approaches can be adopted for the same:

- The **first approach** involves coordinating with the natural gas infrastructure being established in the country. Currently, around $40 billion is being invested in gas infrastructure to create trunk pipelines, set up infrastructure for city gas distribution (CGD) for piped natural gas (PNG), regasification terminals, and compressed natural gas (CNG) stations. While hydrogen may compete with natural gas in the short- and medium-term, in the long-term, hydrogen must leverage the existing natural gas infrastructure to reduce costs. Therefore, it would be beneficial to create hydrogen production facilities along the trunk gas pipelines and inject hydrogen into pipelines or mix it at the neighbourhood level and inject it into PNG pipelines.

- The **second approach** to reduce costs is standardization. In a market economy, companies often differentiate their products and services from others, even if the differences are unnecessary and add to the cost. This can be seen in the example of different chargers for mobile phones. To reduce costs, efforts should be made to develop standardised products that are interoperable and can be used by different projects at different scales. Currently, there are limited efforts by oil and gas companies to develop standard modular infrastructure.

- The **third approach** to cost reduction could be is to maximise the utilisation of infrastructure and land resources. Many projects tend to acquire large plots of land with expansion opportunities in mind. In the past, the government even compiled a database of land resources available with public sector companies. It is necessary to explore how existing infrastructure and resources can be utilised to minimise costs. For instance, a site near a port could be used for multiple purposes such as gas collection and processing, hydrogen production, solar, wave energy, and onshore/offshore wind.

- To lower the production cost of hydrogen, a **fourth approach** could involve promoting collaborative projects that facilitate cost-sharing and risk mitigation. Rather than relying solely on competitive models, it is essential to develop such collaborative business models that encourage the discovery of new technologies and solutions. Furthermore, these innovations should be shared as public goods.

Ensuring energy justice is our second priority to guarantee that all citizens have access to energy, while also emphasising the importance of producing energy from domestic sources to enhance energy security. India's per capita energy consumption is only one-third of the global average, and providing energy to households to improve their living standards is a major challenge faced by the country. While electricity has been provided to almost all villages, there is a need to improve its quality and increase consumption to achieve a better standard of living. Despite rapid urbanisation, it is projected that by 2047, around 800 million people, which is more than the combined population of the U.S. and Europe, will still be living in rural areas of India. Meeting the energy needs of this rural population to enhance their incomes and living standards will continue to be a challenging task.

Therefore, India must adopt a new, targeted approach to rural development that creates high-quality jobs at the local level, while simultaneously increasing agricultural productivity and ensuring food security. To achieve this, the government has implemented several policy measures, including the development of micro, small, and medium enterprises, the initiation of water management projects under the Amrit Sarovar project, and the promotion of One District One Product (ODOP) to leverage local strengths in various areas. In order to promote sustainable growth at the village level, India must exploit locally available energy potential through the use of microgrids and properly sized technology, which will require innovation tailored to the Indian context. Additionally, India should strive to develop Urjagram, an energy self-sufficient and carbon-neutral village similar to Modhera in Gujarat. This modern version of village development envisioned by Mahatma Gandhi will be a significant pillar of new and self-reliant India (AtmaNirbhar Bharat).

This brings us to the third key issue of cost of energy, that energy must be affordable to different segments of society and industry. Factors such as technology, scale, policy, and people's preferences will be crucial in achieving this affordability. Additionally, energy security, energy justice, and affordability must be integrated with the fourth aspect, which is to provide energy sustainably, in line with a low-carbon development path. India's policymakers, businesses, and academic institutions are faced with these profound challenges. To firmly push big corporations to take a leadership role in decarbonising the economy and shaping people's preferences, the most effective policy intervention is a carbon tax on the top 100 corporations. Some of these corporations have already voluntarily announced their targets to achieve net-zero emissions. Furthermore, public sector entities like Indian Railways have also set their sights on achieving net-zero emissions by 2030.

Given the current energy crisis and fluctuating energy prices, there is a need to accelerate the development and use of non-fossil fuel sources. However, investments are also being made in fossil fuel infrastructure to ensure energy security and independence, particularly in Europe. This investment can be seen as a form of insurance premium by countries and should be utilised temporarily for predetermined events such as supply disruptions or energy inflation exceeding a set level. The private sector should receive fair returns on these investments without excessive profits. To protect consumers and businesses from geopolitical risks and market volatility, India should consider passing an Energy Security Act that regulates the production, distribution, and consumption of energy, similar to the Defence Production Act of 1950 enacted by the U.S. during the Korean War. The current focus is on providing reliable and affordable energy, but it is also necessary to manage energy demand. The four main sectors of energy consumption – Buildings, Industry, Mobility, and Agriculture (BIMA) – have great potential for improving energy efficiency. The Energy Conservation Act of 2001, amended in 2022, can be used innovatively to achieve energy efficiency. At COP26, the Prime Minister of India introduced the concept of "Lifestyle for the Environment" (LiFE), as an international mass movement towards 'mindful and deliberate utilisation, instead of mindless and destructive consumption', which calls for the global community to embrace sustainable living and become Pro Planet People (PPP). Guidelines, with 75 action points, have been issued for individuals to reduce their carbon footprint, and a similar initiative is required for businesses to become Pro Planet Business (PPB).

Several policy initiatives and projects are starting simultaneously, but decisions on their implementation may be based on unreliable data and questionable assumptions. There may be competition and conflicting interests in some areas, and industry must decide whether to use coal with carbon capture, switch to solar, gas, or hydrogen. In transportation, consumers must decide whether to switch to EV, CNG, or use petrol, and households must choose between PNG, electricity based on solar, compressed biogas, or LPG for cooking. These choices depend on short-term affordability, logistics, and geography. Given the many policy initiatives and projects starting simultaneously, it is necessary to monitor market and consumer behaviour closely to avoid projects becoming stranded assets.

Multiple and complex processes related to energy, such as production, transportation, storage, distribution, and consumption, will take place simultaneously, creating competition and conflicts, and making it impossible for any single entity to manage or coordinate them effectively. Governments and regulatory agencies operate at various levels, but we require a collaborative and coordinated framework to address this issue. India has a significant number of top-tier educational institutions, including 74 Indian Institutes of Technology (IITs), National Institutes of Technology (NITs), and Indian Institutes of Management (IIMs), among others, which train highly skilled individuals. These institutes have the potential to collect and analyse data, create models and simulations, and provide valuable insights to different entities and governments, thereby becoming a crucial element of the energy transition and innovation. Moreover, investing in these institutions can help train future leaders to manage the energy transition efficiently.

A credit and certification-based internship programme should be established, with a particular focus on IITs/NITs/IIMs. Under this programme, each student would be given the opportunity to work with the top 100 corporations and government as an intern for one year, while still at the institute, to learn and innovate. The faculty should guide and support the process. This collaboration between the top 100 corporations and IITs/NITs/IIMs, facilitated by the government, will represent a joint initiative of business, education, and government. Such an initiative can achieve the desired outcomes by democratising innovation. One possible platform to facilitate this collaboration could be the India Climate Innovation Exchange (ICLiX), which could bring together the government, businesses, and educational institutes to match new ideas with the needs of the energy transition towards clean energy.

With the rise in the proportion of renewable energy in the country's energy mix, it will be possible to decrease the reliance on fossil fuels. However, achieving this transition will require significant changes in existing economic interdependencies, as well as dynamic systems that allow for grid flexibility. The large-scale deployment of digital technologies such as AI/ML will be necessary to predict and match energy loads at the household and business levels across local, regional, and national domains. Given the complexity of this situation, new business and regulatory models will be required to effectively manage the energy transition.

To create a plan for achieving energy self-sufficiency and net-zero carbon emissions, both the government and corporations can establish milestones for the immediate future up to 2025, short-term up to 2030, medium-term up to 2040, and long-term up to 2050. The seven-year period between 2023 and 2030 can be designated as a transition phase towards a carbon-neutral pathway. This period, known as Amrit Kaal in Indian tradition, should prioritise the identification and development of new technologies, the finalisation of business models, and the implementation of policy interventions. It is important to avoid business-as-usual thinking that is based on a destructive development model, and instead, unlearn certain practices to find a sustainable development pathway for India.

In the course of India's journey towards its 100th year of independence in 2047, numerous unforeseeable events will occur. Looking back 20 years to 2000, it was difficult to imagine that Twitter, WhatsApp, and Instagram would be created and become accessible to people even in low-income countries like India. Similarly, no one could have predicted the occurrence of two major black swan events such as the COVID-19 pandemic and the Russia-Ukraine war. India will face various challenges both internally and externally, but it has a dynamic and democratic system, with a government that prioritises its citizens, and a talented youth population with opportunities to succeed. These factors will enable India to manage these challenges and the unknowns that lie ahead.

In conclusion, I believe that India has a reasonable chance to become energy self-sufficient and achieve net-zero carbon emissions by 2047, if we adopt the four policy recommendations mentioned earlier. Firstly, we should impose a Carbon Tax on the top 100 corporations and mandate them to achieve net-zero emissions. Secondly, we should pool the carbon tax collected into a Carbon Fund to invest in innovation. Thirdly, we must involve technology and management institutes of India to democratise these innovations, and finally, we need to develop collaborative business and governance models. While these policy recommendations are challenging, they are feasible. It is our responsibility to make every effort to save our only home, the planet earth.

1.2

Energy Security and Climate Mitigation can thrive collectively

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Nature uses as little as possible of anything.

Johannes Kepler

Abstract

The issue of energy security in India is multifaceted, taking into account factors such as accessibility, availability, affordability, supply and demand, as well as economic and population issues. Energy is also a major contributor to GHG emissions and understanding this is crucial in tackling climate change. Developing countries like India face increased risks from climate change and the challenge of achieving energy security while mitigating climate change is significant.

The move towards a low-carbon and sustainable energy path is gaining momentum globally, with India having diverse natural resources such as solar, wind, water, and biomass. The paper examines the linkages between energy security and climate mitigation and highlights India's response to policy initiatives such as the national hydrogen mission, solar city programme, wind solar projects, product linked incentives, storage systems, biofuels, and ethanol blending. The paper suggests that India can strengthen its energy security by exploiting its own energy resources, building strategic reserves, and developing cleaner coal technologies in the long-term. Ultimately, the paper explores India's preparedness for a non-fossil, non-carbon-based energy focus, utilising renewable and green sources.

1.2.1 Energy Security: India's Quest for Clean Energy[1-14]

India, the third-largest energy consumer and the third-largest oil importer, is making significant efforts to ensure that energy is affordable and accessible to all while also striving to improve the efficiency of energy operations. The aim to offer energy security to India's 1.4 billion people will have far-reaching implications on the country's energy portfolio as it moves towards cleaner energy pathways. The Hon'ble Prime Minister Narendra Modi at the 26th session of the Conference of the Parties (COP26) to the United Nations Framework Convention on Climate Change (UNFCCC) held in Glasgow, United Kingdom, announced the following five 'nectar elements' (Panchamrit) of India's climate action:

- Reach 500 GW non-fossil energy capacity by 2030.
- 50 per cent of its energy requirements from renewable energy by 2030.
- Reduction of total projected carbon emissions by 1 billion tonnes from now to 2030.
- Reduction of the carbon intensity of the economy by 45 per cent by 2030, from 2005 levels.
- Including (Vth) that India will attain the net-zero emissions target by 2070.

This move has aligned India's position with the international mainstream, as well as that of many other developing countries. India has chosen to have a longer transition period, which is understandable given our current position in our development trajectory. However, India, China, the U.S., and Australia have not committed to the pledge to phase out coal.

India has emerged as a significant player in the global market, not only as a large consumer, but also as a nation undergoing transformation with its key agenda of *Panchamrit*. India is a diverse country with 28 states and eight union territories, each with its own unique geographical complexities. However, the per capita energy consumption in India is only one-third of the world average, and more efforts are needed to increase this consumption for the country's inclusive development.

India's pursuit of energy security is closely intertwined with its economic growth and population growth, as well as factors such as accessibility, availability, affordability, acceptability, supply, and demand of energy. The country is aggressively working towards achieving energy security, and has implemented various domestic initiatives while also establishing supplier relationships worldwide across various energy sources, including coal, oil, gas, nuclear, hydroelectric power, solar, and renewable energy, including green hydrogen.

The energy sector accounts to about 75% of the total GHG emissions of the country. The paradigm shift to cleaner energy has a dual objective:

- ensure affordable and reliable energy to all, and
- reduce the country's dependence on fossil-based energy by accelerating the clean energy transition.

The current trend in energy consumption and reliance on imported oil and gas suggest that India is unlikely to achieve complete energy independence in the short- and medium-term. There hasn't been any significant technological breakthrough in alternative energy to free the country from its energy predicament. Therefore, to achieve the aforementioned objectives, India needs to adopt multi-dimensional strategic approaches to energy security.

NITI Aayog states that a country can be considered energy secure when it is able to provide basic energy needs to all its citizens and meet their demand for safe and easy-to-use energy that is affordable and available at all times with a prescribed level of confidence, taking into account the possibility of disruptions and shocks.

Fossil energy is essential for the well-being of billions of people, so completely stopping its use is not feasible. The priority should be on transitioning the energy sector to a cleaner regime, which is already underway. India has always supported a clean energy transition that does not hinder development, as exemplified by the Long-Term Low Emission Development Strategy launched by the Hon'ble Environment Minister Bhupender Yadav. The country's approach to the rational utilisation of resources while ensuring energy security also reflects this commitment.

India's stance at COP27 serves as a message to the world, particularly in recognising the realities faced by developing nations, that a low carbon transition in the energy sector should not hinder energy security, access to energy, and development. The UAE's Special Envoy for Climate Change, Dr. Sultan Al Jaber, echoed the sentiment at COP27 in Egypt that the goal should be to maximise energy while minimising emissions. To achieve this, it is essential to pursue all available pathways without compromising the commitment to reduce emissions from the current energy infrastructure, a position also supported by the Hon'ble Union Minister for Petroleum and Natural Gas Hardeep Singh Puri, in a media interview.

The concept of energy security is not limited to a single field, but rather encompasses various disciplines such as engineering, energy systems analysis, economics, technology studies, earth sciences, political science, international relations, and security and military studies. The growing concerns of climate change, globalisation, and the unpredictable future of fossil fuels have introduced new factors that are interconnected with energy security, such as sustainability, energy efficiency, GHG emissions mitigation, energy poverty, and others. As a result, energy security has become closely linked to environmental, social, political, and security issues.

The key focus here is to examine the major concerns, trends, challenges and available options for India to tackle energy security challenges while simultaneously addressing issues related to climate change.

1.2.2 Government Policies and Initiatives[15-20]

To achieve net-zero carbon emissions by 2070, the Indian government has implemented robust policies and reforms to facilitate the growth of renewable infrastructure capacities for domestic energy players. These policies and reforms promote investment, subsidies, and opportunities for both domestic and international players to develop sustainable and resilient energy technologies. Let's take a closer look at the various initiatives taken by the government at the policy and technology level that are facilitating India's transition to clean energy.

Focus on Non-Fossil Fuels

Decarbonising the country and meeting clean energy targets are among the priorities of the Indian government, which is focused on diversifying its energy sources, particularly through renewable options such as green hydrogen, solar, and wind energy. To enable this transition, the government has implemented policies that promote the adoption of these alternatives.

National Green Hydrogen Mission [21-28]

The National Green Hydrogen Mission aims to provide a comprehensive action plan for establishing a Green Hydrogen ecosystem and catalysing a systemic response to the opportunities and challenges of this sunrise sector. The Green Hydrogen pathway can be a key enabler for India's aspirations to build a low-carbon and self-reliant economy. It is therefore an opportune moment for India to launch the National Green Hydrogen Mission to scale up Green Hydrogen production and utilisation across multiple sectors and align with global trends in technology, applications, policy and regulation.

In January 2023, the Union Cabinet, chaired by the Hon'ble Prime Minister Narendra Modi, approved the National Green Hydrogen Mission with an initial outlay of Rs.19,744 crore. This includes Rs. 17,490 crore for the Strategic Interventions for Green Hydrogen Transition (SIGHT) programme, Rs. 1,466 crore for pilot projects, Rs. 400 crore for R&D, and Rs. 388 crore for other mission components. The Ministry of New and Renewable Energy (MNRE) will formulate guidelines for implementing the respective components.

The Indian government has recently approved the Green Hydrogen Policy to promote the use of green hydrogen, which is produced through the electrolysis of water using renewable energy. With the aim of making India the world's largest hydrogen hub, this policy is expected to significantly reduce emissions – approximately 3.6 gigatons of CO_2 by 2050, which is equivalent to traveling 133.2 trillion km in an average car. With the right facilities, the Green Hydrogen Policy will not only play a critical role in India's transition to clean energy, enabling the country to become self-reliant, but also allow India to become a world leader in the production and application of green hydrogen.

1.2.3 Solar City Programme[29-33]

The MNRE is implementing a programme to develop solar cities throughout India. The objective of this programme is to establish a green city in every state, powered by solar energy or other renewable energy sources. This initiative aims to empower local governments to address their energy requirements and challenges at the city-level. Depending on the population and proposed initiatives, financial support of up to Rs. 50 lakh per city/town will be provided. Recently, the Uttar Pradesh government announced its plan to develop 20 solar cities in the next five years.

1.2.4 Wind Projects[34]

Another initiative that is successfully increasing India's renewable energy capacity is the development of hybrid solar-wind projects. These projects utilise batteries to store excess energy produced by the solar and wind power generators. The main advantage of this system is uninterrupted access to power despite poor sunlight, particularly during the monsoon season. Additionally, this system offers high efficiency, better load management, and low maintenance costs. These hybrid projects help maintain grid stability while optimising land use. Adani Hybrid Energy Jaisalmer One and Tata Power Green Energy are among the notable examples of hybrid power projects.

1.2.5 Product Linked Incentives (PLI) for Battery Manufacturing[35]

To help boost the country's domestic manufacturing capacity of batteries, the government of India launched the Production Linked Incentive (PLI) Programme for Advanced Chemistry Cell (ACC) Battery Storage. As part of this initiative, companies that have signed the agreement will receive incentives to establish Advanced Chemistry Cell manufacturing facilities for battery storage. The companies must establish these facilities within two years to receive the incentives. Reliance New Energy, Ola Electric Mobility, and Rajesh Exports recently signed the programme agreement.

1.2.6 Energy Storage Systems[36]

Though nascent, energy storage plays a critical role in integrating the grid by increasing its overall flexibility. If residential and industrial users leverage energy storage systems, particularly those powered by renewable energy sources, it can greatly enhance the quality of power. This can provide a dependable alternative energy source, lower peak demand, and increase the capacity of distribution and transmission grids, while also helping to avoid or reduce penalties for deviation. The Central Electricity Authority (CEA) is working to create regulations that allow energy storage and demand response to participate in the ancillary services market to balance the grid. The PLI scheme aims to increase India's domestic production of advanced chemistry cell battery manufacturing.

1.2.7 Biofuels[37-51]

The energy demand in India is increasing rapidly, making it necessary to switch to biofuels. According to a recent report by the IEA, India is expected to have the highest percentage increase in coal use globally, surpassing China and the EU. Coal consumption is predicted to rise by approximately 7% or 70 million MT. India still relies heavily on fossil fuels, with nearly 50% being imported, a figure expected to increase to 53% by 2030. To ensure sustained growth and combat climate change, as well as rising fuel prices and power demand, the country must shift to cleaner alternatives like biofuels to achieve energy security, self-reliance, and socio-economic benefits.

As part of its efforts to develop alternative, clean, and green fuels, India is increasingly focusing on producing biofuels to meet its current and future energy needs. The use of biofuels offers a significant advantage as they are generated from waste, which is readily available everywhere.

These fuels are generally produced from agricultural, food, or human-generated waste and serve as a reliable and efficient replacement for conventional carbon-emitting fuels. Biofuels are non-polluting, biodegradable, and cost-effective. By incorporating ethanol blending into its strategy for switching to cleaner alternatives, India aims to achieve a 20% ethanol blending target by 2025. Moreover, the country is expected to advocate for a global alliance on biofuels. These developments acknowledge the immense benefits of biofuels and emphasise their importance in promoting sustainable development, reducing pollution, empowering communities, and strengthening the economy.

Bioenergy is the largest source of renewable energy globally, accounting for 55% of renewable energy and over 6% of global energy supply. To achieve net-zero emissions by 2070, there must be a rapid increase in the use of bioenergy to replace fossil fuels by 2030. Additional efforts are needed to expedite the deployment of modern bioenergy to attain the net-zero scenario promptly, which will see a 10% increase in deployment annually between 2021 and 2030, while ensuring that bioenergy production does not have any negative social and environmental effects.

Biofuels for 3Es

Biofuels can provide much-needed self-sufficiency in energy and can be a game changer in the battle against the alarming rise in air pollution levels. A study by Harvard School indicates that 30% of fatalities in India are due to air pollution caused by fossil fuels, making it critical to search for immediate solutions to address the problem. Therefore, blending ethanol is the best way to reduce carbon emissions and dependence on fossil-fuel imports.

Biofuels, which are produced from agricultural waste, present a significant potential to empower farmers and transform the rural economy. By turning food producers into fuel producers, it is possible to improve the quality of life of people living in the rural areas, create revenue, and generate more employment opportunities. A large number of crops, including rice, wheat, and vegetables, are frequently lost due to unfavourable weather conditions or inadequate storage facilities. Previously, farmers had to discard these crops, but now they can be utilised for the production of biofuels. Additionally, stubble burning is a significant issue that has led to dense smog in cities like Delhi. Crop residue can be converted into a source of income through biofuel production and also contribute to reducing air pollution levels.

1.2.8 Bioenergy Pathway for Net Zero[52-53]

Bioenergy is a crucial element in the transition towards decarbonisation as it is a nearly zero-emission fuel. Its flexibility in terms of context and sectors where it can be utilised makes it highly beneficial. Solid bioenergy and biogases can be combusted to generate power and heat in homes and industrial plants, while liquid biofuels can power cars, ships, and airplanes. Moreover, bioenergy can leverage existing infrastructure, such as bio-methane that can utilise natural gas pipelines and end-user equipment, and several drop-in liquid biofuels that can utilise current oil distribution networks with minor modifications for use in vehicles.

In order to reach the net-zero target, the use of bioenergy must be expanded to a broad range of applications by 2030. Furthermore, the following applications are making good progress towards achieving net zero:

- Bio-jet kerosene used in air travel increases from nearly zero in 2021 to account for over 7% of all aviation fuel demand in 2030.
- Liquid biofuel consumption quadruples from 2.1 mboe/d in 2021 to over 8 mboe/d in 2030, mainly for road transport.
- Bioenergy use in industry increases substantially, from supplying a little over 11 EJ of energy in 2021 to over 17 EJ in 2030, mostly in cement, pulp and paper, and light industry.
- Bioenergy used for electricity generation provides dispatchable, low-emission power to complement generation from variable renewables. Its use nearly doubles, from creating about 750 TWh of electricity (about 2.5% of total demand) in 2021 to about 1,350 TWh (about 3.5% of total demand) in 2030.
- Bioenergy with carbon capture and storage (BECCS) – which creates negative emissions by capturing and storing bioenergy emissions that are already carbon-neutral – also plays a critical role. BECCS captured and stored 2 MT of CO_2 in 2021, and this will increase to around 250 MT of CO_2 in 2030, offsetting emissions from sectors where abatement will be most difficult.

1.2.9 Ethanol Blending[54-64]

The government of India has advanced the target for 20 per cent ethanol blending in petrol (also called E20) to 2025 from 2030. E20 has been rolled out from April 2023.

This measure is aimed at reducing the country's oil import bill and combat environment-related challenges including reduction in CO_2. This new initiative is also part of measures to improve energy security and self-sufficiency. The technology is almost the same as internal combustion engines and simpler modifications can make the engines ready to use the new fuel.

1.2.10 Nuclear Power[65]

- Nuclear power generation relies on uranium, but domestic uranium reserves are scarce. To compensate for this, thorium can be converted into uranium and used for nuclear power generation, as thorium reserves are abundant in India.
- Even though India possesses the world's third-largest thorium reserves, thorium cannot be directly used as a fuel and must undergo several reactions to be converted into its usable fissile form. As of 2022, nuclear power capacity in India stood at 6,885 MWe.

An MIT study conducted in 2018 emphasised the importance of including nuclear power in the energy mix to achieve deep decarbonisation targets at a reasonable cost. This has significant implications for India as well. Nuclear power will continue to be a major component of the energy mix in countries such as the U.S. (20%), EU (20%), and China (10%). Recently, Japan's new Prime Minister Fumio Kishida stressed the need to restart nuclear power plants. China has plans to bring 150 new nuclear reactors online in the next 15 years. However, nuclear power currently accounts for less than 2% of India's electricity generation.

1.2.11 Other Measures for Strengthening Energy Security[65]

Discovering and Exploiting own Energy Resources

- Boosting oil and gas production is a critical component of the Indian government's *AtmaNirbhar Bharat* initiative. The aim is to boost the use of natural gas in India's primary energy mix from the current 6.2% to 15% by 2030.
- To promote domestic oil and gas production, the Indian government has taken various measures, such as encouraging Indian companies to expand their domestic activities, increasing their engagement with multinational corporations, and broadening their opportunities to participate in oil and gas exploration in India.

Exploiting Shale and Its Potential in India

- India has an estimated 96 trillion cubic feet of technically recoverable shale gas located in various basins including the Damodar Valley, Upper Assam, Pranahita-Godavari, Rajasthan, and the Vindhya region.

Building Strategic Reserves

- Strategic Petroleum Reserves (SPR) are stockpiles of crude oil, held by the government of a particular country or a private industry, to use in case of any crisis or emergency. It can act as insurance against imported supplies. Currently, India has three SPR sites with a combined storage capacity of 5.33 million MT (about 38 million barrels).
  - Visakhapatnam (1.33 million MT)
  - Mangalore (1.5 million MT)
  - Padur (2.5 million MT)

Increasing Domestic Production of Coal

- Coal is the only fuel that India has in abundance. Due to the geopolitics of India's coal sector, there has been a 9.01% increase in domestic coal production, resulting in an overall production of 447.54 million MT of dry fuel until November of the current fiscal year. This is a significant rise from the 410.55 MT produced during the corresponding months of FY2020.
- Thermal power plants account for only 59.7% of the total installed generation capacity of 395 GW (as of January 2022). Therefore, coal plays a vital role in India's ongoing efforts to achieve Sustainable Development Goal 7, which aims 'to ensure access to affordable, reliable, sustainable, and modern energy for all'. By using coal, India can strengthen its energy security while working towards achieving this goal.

1.2.12 Conclusion

India's efforts towards achieving energy security have been promising with the collaboration of the government, start-ups, and industry leaders in implementing policies and technological advancements for cleaner energy. The ultimate goal is to attain energy independence while being resilient to climate change.

However, despite the government's efforts, there is still a lot of work that needs to be done to achieve these goals. A well-defined roadmap and the active involvement of the states are necessary to improve the downstream delivery, enhance transmission and distribution infrastructure, ensure access to clean cooking fuel, and maintain uninterrupted electricity supply. These efforts require differential planning and execution.

1.3

Energy Landscape and the Need for Energy Transition in Climate Crisis

Dr A K BALYAN, Chairman & Director Carmine Energy Pte Ltd (Singapore)

> All the powers in the universe are already ours. It is we who have put our hands before our eyes and cry that it is dark.
>
> **Swami Vivekananda**

Mankind has understood the fact that energy is not just a necessity but essential for our lives and all living organisms. Humans have been engaged for centuries in discovering and developing user-friendly energy sources, starting from the early times of biomass as the primary source of energy. The fundamental laws of physics and chemistry have made us aware that the sun is the primary source of all the energy available on earth, directly or indirectly. Furthermore, we recognise that energy does not disappear when consumed, but rather transforms into other forms, states or objects.

The rapid industrialisation of Western countries towards more developed economies, coupled with the aspirations of developing countries to grow, has resulted in phases of high energy consumption rates, with coal assuming the role of primary energy source. With the development of technology, oil and gas have become the preferred sources of energy in the modern world. However, during the rapid and unchecked industrial growth race of the twentieth century, countries used primary fossil energy sources such as coal, oil and gas excessively and irrationally without concerns for their adverse effects on the world's ecosystem.

It is only recently that countries have recognised that emissions, pollution, and environmental degradation are responsible for the greenhouse effect, climate change issues, and that a collective global action plan is urgently needed to mitigate and reverse the adverse impact on the world's ecosystem. The energy sector is a major contributor to this problem.

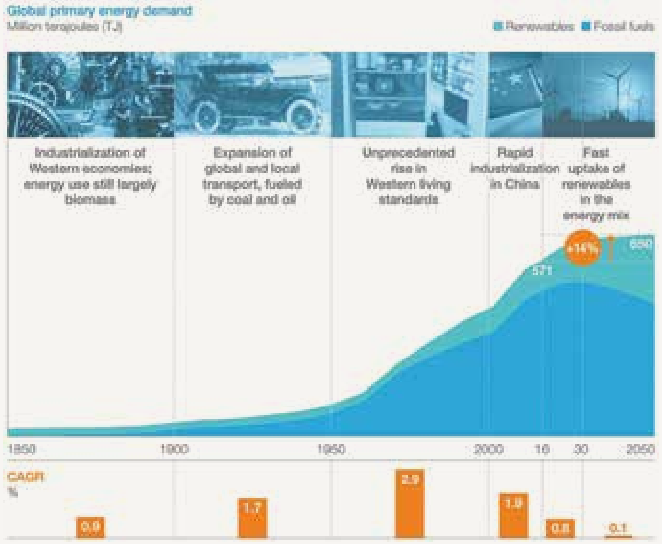
The concepts of sustainability and sustainable development have become increasingly central to all of our development efforts, particularly in the field of energy system management. Understanding the energy landscape has thus become more important. Changes in the quality, quantity, rate of change, and distribution of biomass provide us with vital information on the chemical and thermodynamic processes that affect the growth, development, deterioration, and renewal of the ecosystem. A sustainable energy landscape is one that evolves through the use of locally available renewable energy sources without disrupting the quality of the landscape, biodiversity, food production, and other life-supporting ecosystem processes. Therefore, the application of processes and technologies for the production, storage, transportation, and use of energy sources needs to be evaluated through sustainability assessments.

The choices we make regarding energy production and consumption have a profound impact on the natural systems of our planet, often in ways that are not immediately apparent to us. It is crucial, therefore, that we exercise great care in selecting energy sources, so as to minimise any adverse effects on the environment, or, if possible, avoid them entirely. We must also bear in mind that the true cost of energy extends far beyond its financial value, and encompasses a wide range of economic, political, social, and environmental considerations. Thus, we can no longer view energy use as a disconnected or isolated phenomenon, but rather as a vital component of the complex web of relationships that define our world.

1.3.1 Human Development, Growth & Energy Demand

The growth of global energy demand has been closely tied to both the expanding global population and increasing GDP. While there have been some improvements in energy efficiency over time, overall consumption rates have continued to rise. Looking ahead, projections suggest that the pace of population growth will slow and the world's population may reach around 9.5 billion by 2050. During this period, the global economy is expected to expand at a rate of 2.5% and reach a value of $300 trillion.

The escalating demand for energy is expected to be propelled by the improvement in the standard of living of the burgeoning middle class, which requires energy for transportation, appliances, buildings and cooling purposes. Simultaneously, noteworthy energy conservation measures would also be taken, as the efficiency of appliances, machines and energy systems is enhanced. Consequently, it is predicted that the overall energy demand by the year 2050 may amount to approximately 500 exajoules, representing a mere 12-14% increment over the current levels.



Source: Mckinsey
Energy Insights 2021

1.3.2 Climate Change and Energy Transition

In the light of the adverse effects of GHGs, particularly carbon emissions, which constitute over three-quarters of emissions and mainly consist of CO_2, it is essential that we immediately shift our energy systems towards cleaner technologies and fuels. The continued addition of fresh emissions to the atmosphere from old energy consumption practices has created a significant global problem that needs to be addressed. The global energy sector, which accounts for about two-thirds of emissions, is a major contributor to the problem of climate change and the rise in the world's average temperature. While transitioning to cleaner energy systems driven by renewable sources such as solar and wind, it is crucial to ensure continuity in the availability, accessibility, and affordability of energy supply. Although this change cannot be abrupt as it may disrupt the energy supply chain, it is non-negotiable. The application of emerging technologies such as CCUS offers great opportunities to accelerate the action to combat climate change.

The UN Framework Convention on Climate Change (UNFCCC) of 1992 and the United Nations SDGs of 2015 represent ongoing global initiatives aimed at mitigating the effects of climate change. These frameworks serve as global guiding principles for countries to develop long-term energy strategies for future energy consumption planning.

- U N Framework Convention on Climate Change (UNFCCC) 1992
- United Nations Sustainable Development Goals (SDGs) 2015
- Conference of Parties (COP) under the UN Framework Convention on Climate Change, Paris
- The G-20 summit on November 16, 2022, at Bali
- Conference of Parties (COP) under the UN Framework Convention on Climate Change, November 20, 2022, at Sharm-El-Sheik, Egypt

These significant global meets aimed to establish a consensus and promote a shared agenda for a cleaner and time-bound energy transition. The common goals that garnered consensus among developed and developing economies and served as the agenda for deliberations included:

- Security of energy supply – accessibility, affordability, sustainability
- Application of clean coal technologies/low carbon technologies
- Financing the clean energy initiatives.

International oil and gas companies, energy organisations, and countries have developed various possible scenarios using modern tools to visualise future energy systems and their environmental impact. These scenarios are designed to achieve specific time-bound goals for energy and climate change targets, starting from the existing set of choices or plans to fulfil the energy needs.

Some of the key inputs in energy scenario mapping are:

- **Economic and demographic factors** like, GDP growth rates, population, urbanisation, per capita income & energy consumption.
- **Energy prices of different sources**, including electricity, the fastest growing source of end-use of energy (fossil fuels/nuclear/ renewables)
- **State of technology, innovation & deployment, and costs**
- **Energy policies & Commitments to reduction in carbon footprints.**

Energy Scenario Mapping not only impacts the choice for the energy-mix, technology, and investments but also the intensity with which societies and nations pursue their behaviour and policies.

However, these energy scenarios have some limitations. They are not conclusive since the predictions for the future are not based on empirical data, but rather on estimations that rely on specific assumptions. Additionally, the various stakeholders involved in the current energy sources, as well as political ideologies, can significantly influence the energy policies, their intensity, and the timing of their implementation.

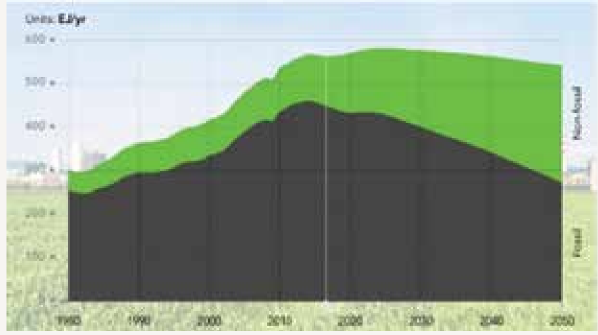
With so many different factors at play, the future energy options may suggest trends but cannot guarantee completely accurate projections.

Some of the credible agencies that have developed expertise to analyse huge data and apply modern tools for developing scenarios are:

- World Energy Outlook by IEA (International Energy Agency)
- World Energy Council
- Greenpeace Energy 2015.

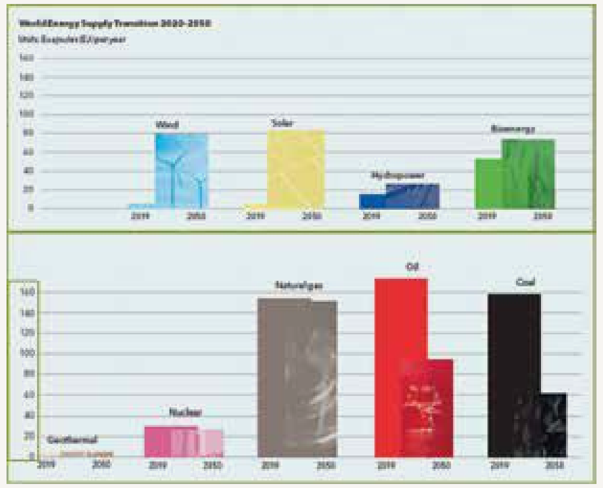
Also, market research organisations like Goldman Sachs, McKinsey, DNV, Rystad Energy, Shell, Wood Mackenzie, IGU, Poten & Partners, etc., have come out with studies on projections of demand for energy and energy commodities.

Despite varying methodologies and data sources, the recommendations of the aforementioned agencies and market organisations tend to converge on the global energy transition trend. Nearly all long-term global energy scenarios suggest that global primary energy demand will begin to decline around 2034 and that by 2050, non-fossil sources of energy will make up approximately 50 per cent of global primary energy.



DNV Outlook on Energy Projections

DNV conducted an interesting trend analysis on the likely transition trends in the global energy scenario. The analysis highlights the changes in the contribution of different energy sources within fossil fuels and underscores the significant role that gas is expected to play until 2050 and beyond.



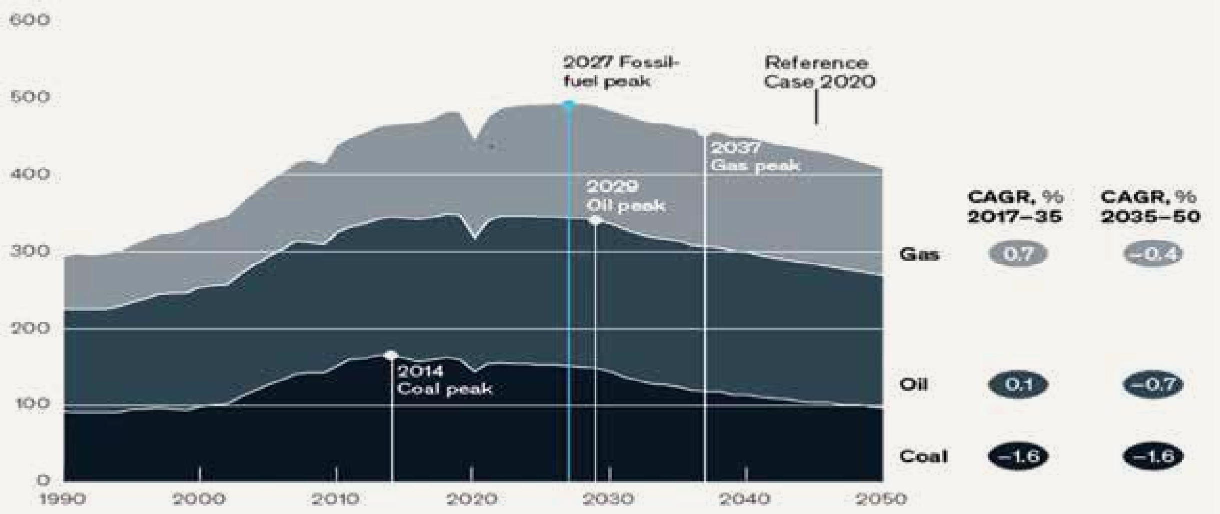
The notable trends of this scenario study are:

- Oil contribution in the global primary energy mix is near its peak.
- COVID-19 Pandemic has shaved off about 8 per cent demand and its impact will be seen up to 2050.
- Global primary energy demand is expected to peak in the mid-2030s and then register a decline. Global natural gas demand is expected to peak around the mid-2030s and is likely be the only fossil fuel with substantial contribution in the primary energy mix by 2050 or beyond.
- Around the same time, it is predicted that half of the road vehicles would be electric.
- Around mid-2040s, the energy intensity would be half compared to that in 2018.
- The share of renewable energy sources in the primary energy mix is increasing at a rapid pace, and it is projected that by 2050, it will account for approximately 50 per cent of the total primary energy.

Although there are serious deliberations among developed and developing economies under the COP on climate change and efforts to restrict the rise in global temperature, countries are not doing enough and there is a large gap in achieving the set targets for emissions control. Global funding falls short for the required actions.

In an extensive and interesting study titled Global Energy Perspective 2021 by McKinsey & Company, a long-term global energy scenario is analysed, taking into account the rapidly changing, volatile energy market impacted by major climate change and global warming factors. The study also incorporates the impact of the pandemic, health issues, etc., and their implications on the energy sector, including investment decisions. The study projects that the decline in global GHG emissions is very slow, even though a common programme for reducing emissions with targets is being pursued under the Paris Agreement.

Primary energy demand per fossil fuel, million TJ

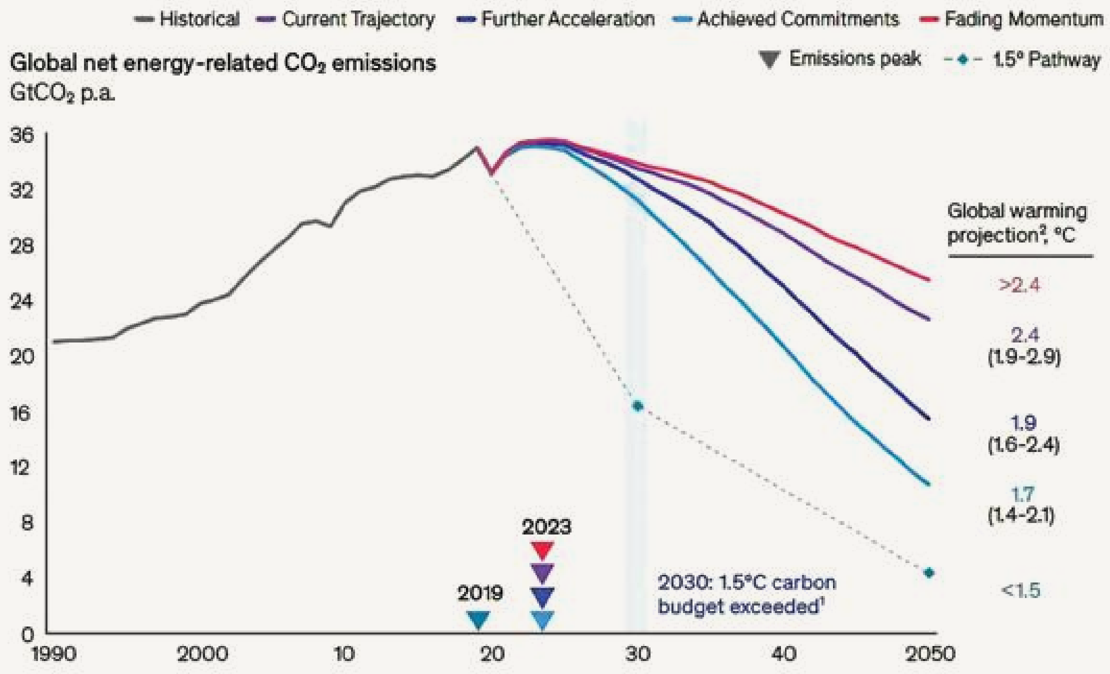


Source: McKinsey Energy insights Global Energy Perspective 2021, December 2020

The study presents four distinct scenarios, each offering a unique perspective on the global energy transition:

- The Reference Case, which reflects the business-as-usual approach and extrapolation of current policies
- The Accelerated Transition, which reflects those factors that can potentially accelerate the energy transition
- The McKinsey 1.5-degree scenario represents the desired energy transition rate
- The Delayed Transition scenario, which assumes that all efforts to mitigate the impact of COVID-19 will largely fail, thereby causing a further delay in the energy transition process.

According to the McKinsey study, the current rate of progress is insufficient to attain the desired 1.5-degree pathway. The prevailing trajectory indicates that we are possibly heading towards a 3.5-degree pathway. Only a resolute political will, coupled with expeditious implementation of concrete programmes on an accelerated scale can shift the course towards the desired 1.5-degree pathway.



Source: Mckinsey Global Energy Perspective 2022

As shown in the figure, the accelerated energy transition is projected to produce 20% less emissions due to faster transition towards renewable energy and adoption of low carbon technologies. Nonetheless, this accelerated approach falls well short of the coveted 1.5-degree threshold. Notably, the Covid-induced impact on emission reduction amounted to a noteworthy 7 per cent. Achieving the desired objective necessitates a comparable level of emissions reduction till 2050. As such, an immediate discontinuation of fossil fuels use by the global community appears unfeasible.

To summarise, the major features of the current energy transition are as follows:

- Multiple energy transitions are occurring, such as the shift from coal and oil to gas, and from fossil fuels to renewables and decarbonised gas.
- There is significant pressure on developing economies to make the right choice of energy sources, as emissions are expected to remain high until 2030.
- Industries and countries are making efforts towards decarbonisation, but not at the pace set out in the Paris Agreement.
- Demand for oil is declining, resulting in a shift towards the cheapest available oil.
- Gas continues to have a strong presence in all scenarios, with LNG set to thrive.

The oil and gas industry is facing mounting pressure from governments, investors, and the public to support the decarbonisation of the energy system. This has led to a cautious outlook on the sector by financial markets, as investors are uncertain about the future growth prospects for oil and gas. In fact, the energy sector of the U.S. S&P 500 has experienced a 48 per cent decline since 2015, making it the worst-performing sector in the index during that period. While the decline in oil and gas prices since 2014 has been a significant factor in the sector's performance, there is still a lack of clear policies and plans for the implementation of decarbonisation efforts or emissions reduction in the fuel and power sectors.

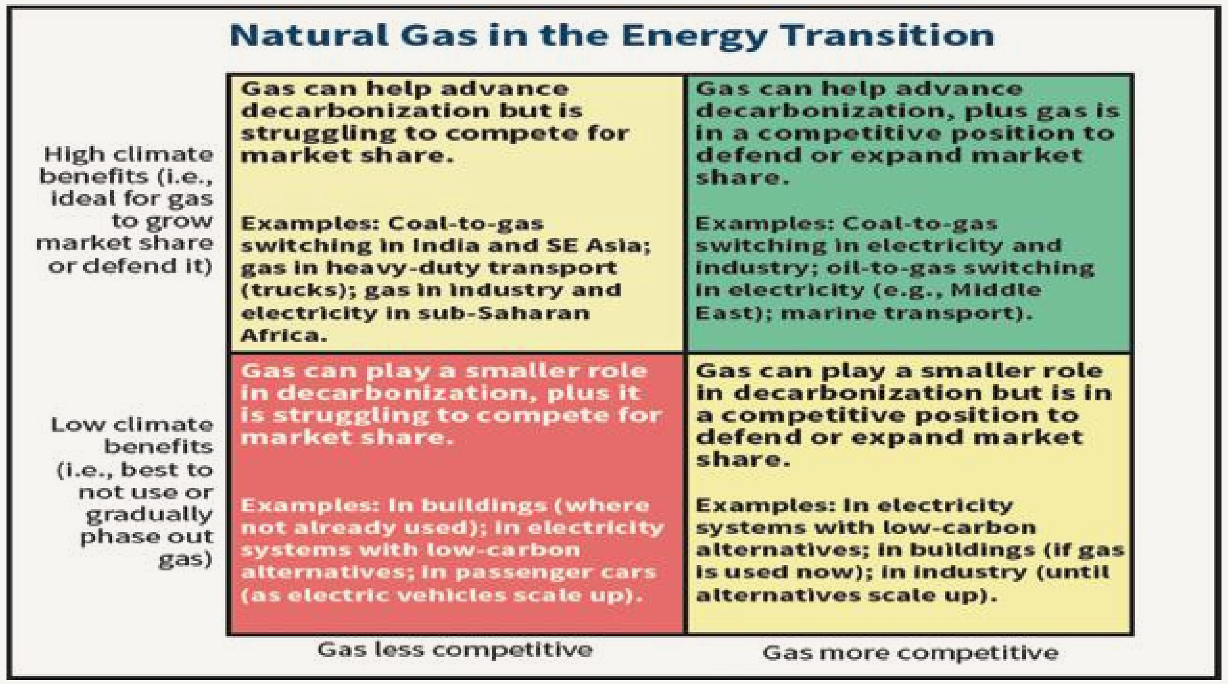
The energy transition has raised serious questions for the oil and gas industry, which must develop and rapidly adopt new strategies for low-carbon solutions. They must offer these solutions to stakeholders while assuring them of healthy returns and a continued meaningful role in the decarbonisation process in the future.

1.3.3 Role of Natural Gas in Energy Transition

As depicted in various energy transition scenarios, natural gas is projected to remain a major, significant source of fossil energy in the primary energy mix until 2050, accounting for approximately 24 per cent of the share. Although there is a clear shift in countries, particularly in developing economies, to transition from more polluting coal to cleaner gas, it is not a simple process to switch quickly to cleaner natural gas due to the large investments required to build gas infrastructure and develop a gas-based economy. Consequently, the process is slow, and several countries, including India, have embarked on the path for a cleaner energy mix.

Many energy experts consider natural gas as a transitional energy source, a bridge that links the fossil-fuel-based economy to a decarbonised and sustainable world of energy in 2050. However, energy transition experts and environmentalists warn of the potential carbon-emitting consequences of using gas as a short-term benefit due to its emissions, flaring and venting. The impact of gas on climate change is 23 times worse than that of CO_2. The role of natural gas as a long-term stable energy source is also being questioned by the rapidly growing contribution of renewable energy, which offers extremely competitive energy prices. However, the success of renewable energy will rely on the development of affordable and commercially viable storage technologies.

With significant investments in upstream gas exploration and production, some energy specialists view gas as a destination fuel rather than a transition fuel. Technological advancements in the next decade could have a significant impact on the role of natural gas as a long-term stable energy source. Moreover, the importance and use of gas differs among countries/regions worldwide. Gas plays different roles in various markets worldwide at different costs. In some markets, moving away from natural gas is viewed as a logical step towards decarbonisation. However, in other markets, promoting the use of natural gas would yield immediate environmental dividends. The use of gas, therefore, has complexities based on energy systems and energy markets worldwide, and a single solution may not be feasible for the entire world.



Natural Gas in the Energy Transition

	Gas less competitive	Gas more competitive
High climate benefits (i.e., ideal for gas to grow market share or defend it)	**Gas can help advance decarbonization but is struggling to compete for market share.** **Examples: Coal-to-gas switching in India and SE Asia; gas in heavy-duty transport (trucks); gas in industry and electricity in sub-Saharan Africa.**	**Gas can help advance decarbonization, plus gas is in a competitive position to defend or expand market share.** **Examples: Coal-to-gas switching in electricity and industry; oil-to-gas switching in electricity (e.g., Middle East); marine transport).**
Low climate benefits (i.e., best to not use or gradually phase out gas)	**Gas can play a smaller role in decarbonization, plus it is struggling to compete for market share.** **Examples: In buildings (where not already used); in electricity systems with low-carbon alternatives; in passenger cars (as electric vehicles scale up).**	**Gas can play a smaller role in decarbonization but is in a competitive position to defend or expand market share.** **Examples: In electricity systems with low-carbon alternatives; in buildings (if gas is used now); in industry (until alternatives scale up).**

An intriguing study by CSIS outlines four distinct roles that natural gas will play in the energy transition across various countries:

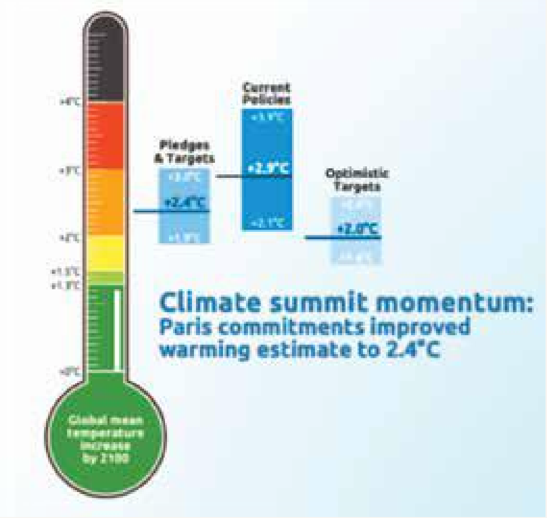
- The first cluster comprises countries where natural gas will continue to dominate and contribute to the decarbonisation process.
- The second cluster includes countries where natural gas plays an important role but needs to be gradually phased out in favour of a low-carbon energy system.
- The third cluster consists of countries where natural gas has the potential to play a significant role in achieving environmental gains, but cannot compete due to primarily economic reasons.
- The fourth cluster includes countries where natural gas has no significant role in climate change goals and no opportunities for growth.

1.3.4 Decarbonisation

Decarbonisation involves decreasing the amount of CO_2 emissions caused by human activities, with the ultimate goal of eliminating them. It is necessary for all countries, governments, and companies to actively work on reducing CO_2 emissions in view of the Paris Agreement. Some countries have set targets to be carbon neutral by 2050, which can only be achieved by transitioning to low-carbon energy sources.

The recommendations of the Paris Agreement are being integrated into policies, plans, and energy systems of many countries. Immediate steps need to be taken to reduce emissions in energy, transportation, construction, and the industrial sector in order to achieve the agreement's goals. According to a joint study by the IEA and the International Renewable Energy Agency, a reduction of up to 70 per cent in energy emissions by 2050 is possible through decarbonisation of the energy economy, which would require a significant investment of $29 trillion and a deep transformation of energy production and use.

The World Economic Forum believes that full decarbonisation of energy systems is the only solution to climate stabilisation. Unfortunately, the world is already behind on the targets set in the 2015 Paris Agreement. Under current policies, the best-case scenario would result in a temperature increase of 2.1 °C , while the worst-case scenario could lead to an increase of 3.9 °C . If global temperatures increase by 3 °C , cities such as Miami, Shanghai, Osaka, and Rio De Janeiro would be submerged, and 275 million people worldwide would need to relocate to avoid floods.



CSIS study

Financial institutions and investors are taking decarbonisation seriously and are concerned about it. Investors are becoming more cautious towards oil and gas projects and prefer to support clean energy projects instead. The CEO of BlackRock, the world's largest investor fund, has stated that sustainability and climate risk are at the centre of the company's investment approach.

Reducing CO_2 emissions is no longer an option and it is necessary to limit them to a low level and eventually achieve net-zero emissions. Achieving this target would require the use of CCS technologies. Currently, commercial CCS technologies are available with capture efficiencies of over 90 per cent. The captured CO_2 can be reused as feedstock in industrial products like soda ash or be sequestered. The cost of commercial CCS solutions is approximately US $30 per MT of CO_2 captured and these costs may be allowed to be offset against the carbon tax.

1.3.5 Sustainability and Energy Transition

The importance of sustainability in business is recognised as a key driver of growth, provided that it aligns with development goals that impact one another. Although all the SDGs are interdependent and have a mutual impact, SDG 7 focuses on policies to achieve universal access to affordable, reliable, sustainable, and modern energy for all by 2030, and has set targets for doubling the rate of improvement of energy efficiency. SDG 7 also proposes the following:

- International cooperation and investment to facilitate access to clean energy research and technology including renewable energy, cleaner fossil fuel technology and energy efficiency.
- To support least developed and developing countries to expand infrastructure and upgrade technology for sustainable energy services.

One of the key challenges for sustainable development today is climate change. SDG 13 emphasises that countries should incorporate climate protection processes in their national policies and collaborate under the UN Framework Convention on Climate Change as the main International Intergovernmental Forum to discuss and develop global response to climate change. In addition, SDG 13 promotes following important initiatives:

- Development of a $100 billion fund – Green Climate Fund from annual contributions from developed countries from 2020 onwards to help developing countries mitigate the impact of climate change.
- Capacity development for processes and systems for planning and implementing policies to address climate change in the least developed countries.

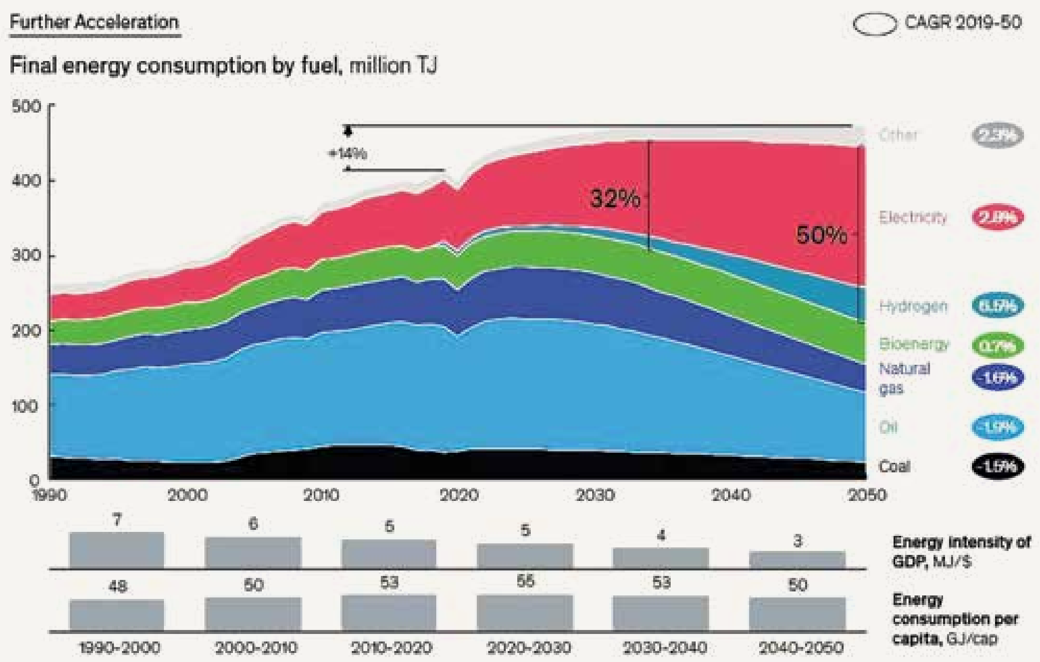
Energy transition should be understood as a planned process to be executed within a given timeframe. Abrupt changes can cause disruptions in the energy system. A sustainable energy transition involves a holistic shift in the entire energy system towards cleaner and carbon-free sources, including production, storage, transmission, consumption, and conversion of energy. This global effort aims to decarbonise the energy industry and minimise the consequences of climate change. Renewable energy sources such as solar, wind, geothermal, hydro, and ocean power are considered sustainable. In modern times, the world has witnessed several energy transitions from biomass to coal to oil and gas to low-carbon cleaner energy sources. However, the present need for energy transition is urgent and requires collective efforts from all countries, companies, and society. Lester Brown, in his book Plan B 2.0, has warned that mankind is exploiting the world's resources faster than what the earth can regenerate. He suggests that we have only a decade to implement a plan to reverse this trend; otherwise, it may become too late and irreversible.

1.3.6 Increasing Electrification Trend

Electrification is one of the main drivers of energy transition. Electricity is a more efficient form of energy for end-use and is emerging as the preferred option. It is projected that the demand for electricity will more than double by 2050, with an average growth rate of over 2.7% per year during 2020-2050. In other words, by 2050, about half of the world's energy services are expected to be provided by electricity.

For a long time, the world has observed a direct connection between GDP growth and energy consumption. However, for the first time, the world is experiencing a disconnect between energy consumption and key economic parameters such as GDP, population, primary energy supply, and energy-related CO_2 emissions.

- While the global economy is growing rapidly and the population is expected to increase by 2 billion, the energy demand is projected to increase by only 14%.
- This is due to the continued reduction in energy intensity of GDP, which is a result of increased end-use efficiency in buildings, transport, and industry.
- The contribution of electricity is expected to grow from around 20% today to around 32% in 2035 and to around 40% in 2050.



- It is projected that doubling the use of electricity and increasing the use of hydrogen will offset fossil fuel consumption, which could be about 40% lower in 2050 compared to today.

According to studies by DNV, the largest contributor to global electricity generation, coal-fired power, which currently stands at around 35%, is expected to decline sharply to just 4% by 2050. This is mainly due to policies supporting cleaner energy and its declining costs, the growing momentum of decarbonisation initiatives, and investor reluctance to finance fossil fuel-based projects. In 2021, approximately 30% of renewable power generation was based on hydropower. By 2050, it is expected that over 80% of grid-connected power will be generated from renewable sources, with variable renewables contributing around 70%.

This increase in the share of electricity can be largely attributed to the policy support for renewable energy, especially solar and wind, as well as innovations in technology, increasing efficiencies and declining costs. These developments are leading to electricity becoming a cheaper energy source compared to other fuels, resulting in increased use of electricity use in sectors where it was not previously utilised. As renewable electricity continues to contribute to the greening of electricity, there is a possible reversal of roles where fossil-fuel-based power generation, particularly gas-based power generation, may increasingly take up the role of balancing or backup power, with fossil-fuel-based power generation contributing just about 12% of the power requirement.

The utilisation of hydrogen as a clean and sustainable fuel source has recently gained momentum, given its remarkable potential in decarbonising various sectors of the economy. Despite its immense benefits, commercial-scale production, storage, and transportation of hydrogen still pose significant technological and economic challenges. However, several promising global developments and innovations have provided a glimpse of the potential of hydrogen as a future fuel source. With its unique characteristics, hydrogen can be blended with natural gas in the automotive sector and can be utilised for power generation. While the global contribution of hydrogen to power generation may remain less than 1%, its use may play a crucial role in regions such as Europe, China, and the OECD Pacific, where its contribution may reach as high as 20%. Moreover, the utilisation of the existing natural gas infrastructure may facilitate the growth of hydrogen as a preferred and the cleanest fuel.

1.3.7 India Initiatives for Cleaner Energy & Net Zero Commitment by 2070

India has been playing a significant and constructive role in global initiatives to combat climate change, given its position as the world's third-largest contributor to GHG emissions. The country is undergoing a transformation, with sustainability, emission reduction, and promotion of low-carbon and cleaner energy becoming central to its policy framework for economic development. India's national and global commitments in the energy sector provide clear guidance to policy-makers, with national targets aligned with India's commitments made at COP21 in Paris. The country's Nationally Determined Contributions (NDCs) outline three targets to be achieved by 2030:

- 40% of installed power capacity to come from non-fossil-fuel-based sources.
- India will reduce the emissions intensity of its GDP by 33-35% compared to 2005 levels.
- India will create an additional carbon sink of 2.5-3 billion MToe, through additional forest and tree cover, by 2030.

Some of the other internal milestones set by India are:

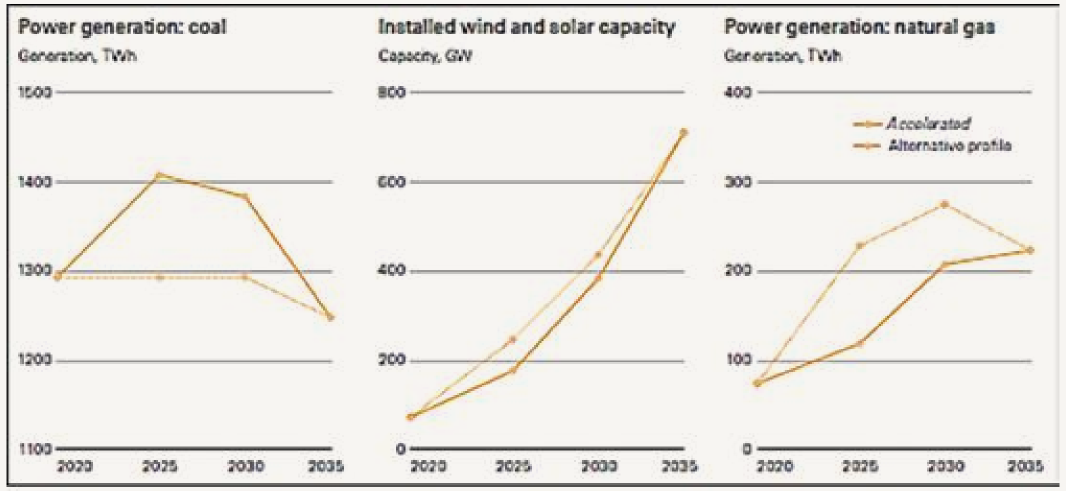
- To achieve net-zero emissions by 2070.
- To meet 50% of power requirement from renewable energy sources by 2030.
- To reduce the emissions intensity of its economy by 45% by 2030.
- To reduce 1 billion MT of CO_2 emissions by 2030.

The Indian government has launched a key initiative to provide fuel gas for cooking and heating in smaller towns and rural areas, aimed at helping households shift away from traditional biomass fuels like wood. The policy framework also supports emerging technologies like hydrogen and battery storage.

India's strong agricultural base provides an opportunity to harness bioenergy from biomass, such as municipal and agricultural waste, and cow dung. In 2018, the government implemented the National Policy on Biofuels to promote advanced biofuels, including compressed biogas (CBG). CBG is produced through the anaerobic decomposition of bio-waste and has a high methane content. After purification, it is compressed and used as an alternative, renewable automotive fuel with similar properties to CNG. To support this initiative, the national oil companies have launched the Sustainable Alternative Towards Affordable Transportation (SATAT) scheme, which aims to establish 5,000 CBG plants across the country in four years. Apart from promoting responsible waste management and reducing carbon emissions and pollution, this initiative supports India's national commitments to achieving its climate change goals.

Around 700 projects are planned throughout the country to be funded under Solid and Liquid Waste Management (SLWM) component of Swatch Bharat Mission – Gramin (SBM–G).

A study by BP specific to India suggests that promoting the use of natural gas can facilitate the country's transition towards a low-carbon energy system. It can accelerate the reduction of dependency on polluting coal and serve as a low-carbon energy source when combined with CCUS technology. BP has developed two scenarios until 2035: the Accelerated scenario, which assumes a rapid increase in renewable energy contribution, and the Alternate scenario, which assumes a greater role for natural gas. While the Indian government aims to move towards a gas-based economy and increase the natural gas contribution in the primary energy mix from the current level of 6.3% to 15% by 2030, policy frameworks supporting this initiative lack speed of implementation. The recent report by the committee on gas prices established by the government has outlined a roadmap to move gas pricing towards a market-driven process.



Reducing dependence on coal after 2020.

6- fold increase renewable capacity.

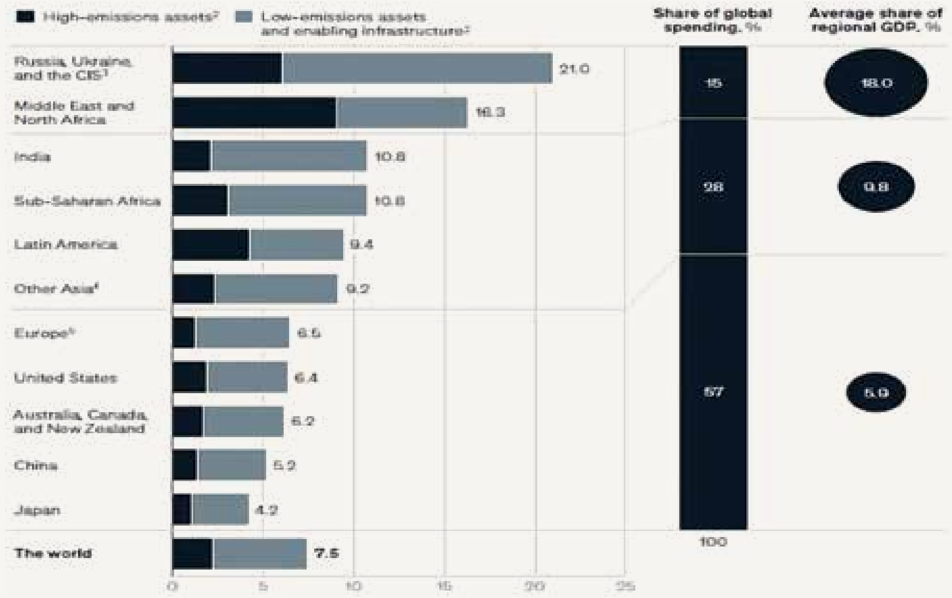
Gas fired power capacity triples.

Source: BP – Energy Outlook 2022

The transition to cleaner energy sources presents significant economic opportunities, but it will require substantial investment. According to the IEA, an investment of $160 billion per year will be needed until 2030 to achieve net-zero emissions by 2070.

The net-zero transition will require each country to invest in physical assets to reduce emissions. A McKinsey study highlights that developing countries face a greater exposure to the energy transition, which raises concerns about inequality and the rate of growth. Based on data from the Network for Greening the Financial System (NGFS), it is projected that India may need to spend around 10% of its GDP from 2021 to 2050, compared to developed economies like the U.S., Europe, and Japan.

Spending on physical assets for energy and land-use systems under NGFS Net Zero 2050 scenario (% of 2021-2050 GDP)



Source: Mckinsey net-zero transition study 2022

1.3.8 Indian Initiatives for Hydrogen – The Cleanest Fuel

With a population of over 17% of the world's total, India has significant energy needs. Over the past two decades, energy consumption in the country has doubled and is expected to continue to grow, making India a major global consumer. Despite this, India has made significant strides in developing innovative strategies to meet its increasing energy demands while still adhering to its strong climate-change commitments.

India has set ambitious goals to become energy independent by 2047 and to achieve net-zero emissions by 2070. To achieve these goals, India is focusing on utilising its vast renewable energy resources and has become the fastest growing country in terms of renewable energy capacity. Renewable energy is crucial for transitioning to a hydrogen economy and reducing reliance on fossil fuels in sectors such as refining, fertilisers, steel, automotive, and more.

As the demand for hydrogen and its derivatives continues to increase globally, India sees an opportunity to become a leading producer and exporter of green hydrogen by utilising its renewable energy resources. Despite challenges such as unfavourable economics, lack of standards, and technological obstacles related to production, storage, and transportation, India's recent successes in research and development efforts give hope that hydrogen will become cost-competitive in the near future.

Currently, India mainly produces grey hydrogen using fossil fuels. However, the government's launch of a National Green Hydrogen Mission to promote the production of green hydrogen and reduce dependence on fossil fuels aims to build the capability to produce at least 5 million MT of green hydrogen per year by 2030, with the potential to enhance the capacity to 10 million MT per year. This will help decarbonise the economy, make India self-reliant with clean energy, and establish India as a leading country in hydrogen technology. The MNRE is responsible for overseeing and implementing the National Green Hydrogen Mission.

1.3.9 Greening of Coal – Opportunity for India

India has been endowed with the fourth-largest coal reserves in the world, with over 315 billion MT of thermal coal. In 2022, India produced over 770 million MT of coal, with an increase of over 8%. More than 75% of the produced coal is used at thermal power plants for electricity generation. However, concerns about climate change and the environment have increased the emphasis on cleaner coal technologies and sustainable ways to use coal reserves. Despite the growth of renewable energy, India is still on track to meet its Paris Agreement commitments, given its growing population and economy, which is expected to quadruple by 2050, adding approximately 500 million people to the subcontinent.

According to a DNV study, fossil-fuel-based energy is still expected to account for over 60% of the region's energy by 2050. Coal faces two main issues in the national perspective:

- Local pollution and GHG emissions with global consequences
- Perception that India has enough renewable energy now so does not need coal, which is a risky and an expensive option.

India should view the abundance of coal reserves as an opportunity, and the challenge is to make coal usage greener by applying clean coal technologies that capture or reduce GHG, as well as non-GHG emissions such as sulphur oxides (SOx), nitrogen oxides (NOx), and particulate matter. Clean coal technologies offer higher efficiencies with lesser environmental impact.

Compared to direct burning of coal, coal gasification is considered to be the most effective cleaner option for utilising the chemical properties of coal. It offers a higher efficiency of around 17-20% when producing electricity. The process can utilise coal gases effectively twice, first by purifying them and firing them in a turbine to generate electricity. The exhaust heat from the gas turbine can then be captured and used to generate steam from a steam turbine generator. Additionally, the gasification process through syngas provides opportunities to manufacture other value-added

products such as urea, methanol and hydrogen, which are imported by the country currently.
Recent developments, such as the Integrated Coal Gasification Combined Cycle (IGCC) and Integrated Coal Gasification Fuel Cell Combined Power Generation Technology (IGFC), offer much higher efficiencies that can offset the higher costs due to CO_2 capture.

The use of clean coal technologies, combined with technologies for capturing, storing, and utilising carbon, can offer a solution for India's growing energy needs while also meeting global commitments to combat climate change. India has acquired valuable experience in coal gasification through the implementation of various ongoing and upcoming projects.
This process has the potential to benefit India in numerous ways. The Indian government has initiated several programmes to support these efforts, with the Coal Gasification Mission being a notable one.

This initiative includes guiding principles and a way forward, with a target of allocating 100 million MT of coal exclusively for gasification by 2030.

The government has held several consultations with the industry to develop a policy framework for gasification and to provide incentives for its success. For the first time, the industry has established the Coal Gasifiers Association of India (CGAI) to create a common platform for discussion and addressing industry issues.

Coal gasification projects under implementation

Company	Coal India	Neyveli Lignite	JSPL	BPCL	ECL	CCL	WCL	SECL
Location	Dankuni	Talcher	Raigarh	Kochi	Sonepur Bazari	North Karanpura	Chandrapur	Maham-aya Mines
Target Product	Methanol	Methanol	2nd Plant	Hydrogen, ethanol etc	Methanol	Ammonium Nitrate	Ammonium Nitrate	Ammonia
Status	Completion 2025	Under construction	Prefeasibility	_	Approved	Approved	Approved	Approved

Coal gasification projects in operation

Serial No	Company	Process/Product	Location
1	Reliance Industries	Power/Feedstock	Jamnagar
2	Jindal Steel & Power	Steel through DRI	Angul
3	BHEL	Methanol	Hyderabad
4	Thermax	Methanol	Pune

1.4

Environmental, Social and Governance is a Panacea for Climate Change Mitigation

MAHENDRA RUSTAGI, CEO, Kreston SNR

> All differences in this world are of degree, and not of kind, because oneness is the secret of everything.
>
> **Swami Vivekananda**

Environmental, Social and Governance (ESG) is a measure of the health and sustainability of any business. Even highly profitable businesses may not be sustainable if they do not score adequately on the environmental, social, and governance aspects of ESG.

ESG is also a tool for assessing the risks associated with a business. It is based on the three elements of nature – planet, people, and profit, and for a business to be sustainable, it must respect and honour these elements in a holistic manner.

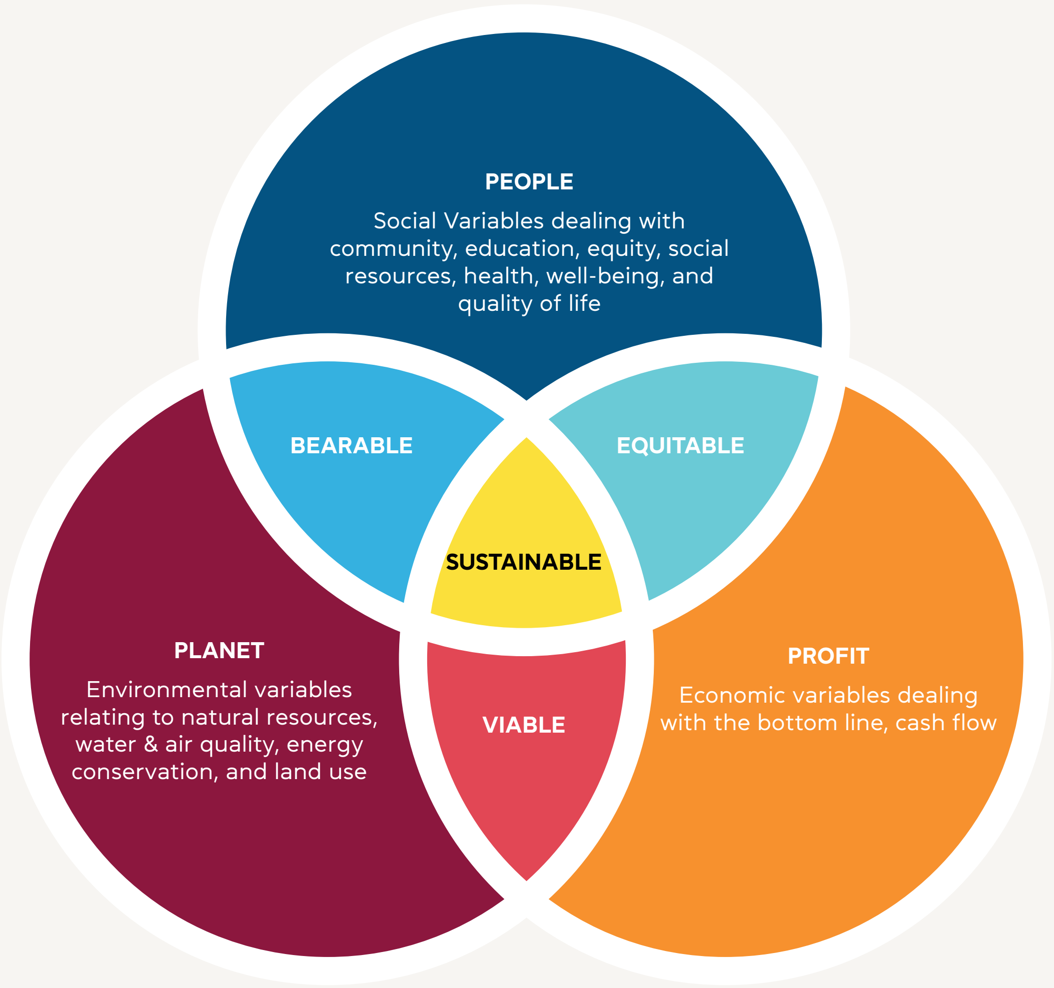
The concept of ESG emerged in the 1980s, when the global economy began to recognise that businesses had a greater responsibility towards the environment and society. Previously, businesses were viewed only from an economic perspective, without considering their impact on the environment and society.

The three elements of ESG are Planet, Profit and People, each representing:

- Planet and Profit = Viable
- Planet and People = Bearable
- Profit and People = Equitable

For any business to be seen as Sustainable, it has to be Viable, Equitable and Bearable. This is explained in the diagram below.

ESG Assessment entails disclosure and working on various elements of the three pillars namely Environment, Social and Governance.



Under Environment: carbon footprint/emissions (type 1, type 2 and type 3), energy usage, waste management, circularity (use/reuse and recycle), water conservation, resource efficiency, compliance with environmental laws, etc.

The Social aspects cover the businesses' impact on their employees: workplace safety, employee engagement, diversity and inclusion, customer satisfaction, vendor relationship, community (local social welfare programmes), human rights, women's rights, gender equality, race equality, etc.

Lastly, the Governance aspect covers business Leadership and structure: board composition, shareholders' rights, investor relationship, conflict of interest in board decisions, business ethics, transparent accounting/audits, anti-bribery and anti-corruption policy, whistle-blower policy, political influence, etc.

The concept of ESG was introduced in India in 2011, when the government established some basic disclosure regulations that encouraged businesses to disclose information related to energy, water, waste, social impact, and governance. Over time, the regulations became more detailed and in 2021, the Securities and Exchange Board of India (SEBI) made ESG disclosure mandatory for businesses.

In the EU, ESG dates back to 1987, but for many years, it was not widely implemented until the Paris Convention led to the creation of 17 SDGs in 2015. In recent years, there has been an increased awareness and development of disclosure frameworks and regulations globally for ESG as a concept.

The availability of ESG investments has been the biggest challenge for the EU. In 2019, the EU devised the European Green Deal with a plan to raise One Trillion Euros to fund the transition. Then, in 2020, the EU introduced the taxonomy, a green classification system that lists economic activities that can be classified as sustainable. This makes it easier for banks and investors to identify sustainable opportunities. One year later, in 2021, the EU launched the decade 2021-2030 plan which includes various action plans, including the Corporate Sustainability Reporting Directives (CSRD). Under the CSRD, sustainability information will be made available and verifiable for a larger number of companies.

In the EU, all large companies (whether listed or not) that meet any two of the three criteria, namely, 250 employees/turnover Euro 40 million/ assets Euro 20 million, will be required to make ESG disclosure annually. It will come into effect in 2024 for FY 2023. CSRD is expected to cover over 50,000 companies.

In addition, international buyers are now seeking ESG ratings for their supply chain. Companies worldwide are facing restrictions on raising funds or listing without meeting ESG criteria, and banks are now considering ESG assessments in their risk assessments for major lending. An ESG assessment has become the norm worldwide for companies seeking to approach the capital market for listing. Many advanced economies have made it mandatory for corporations to disclose their ESG rating while raising money from the public.

The U.S. Securities and Exchange Commission has announced its intention to require climate-related disclosures. New Zealand has announced mandatory climate-related disclosures based on the Task Force on Climate-related Financial Disclosures (TCFD) for all equity and debt issuers. The U.K. has mandated TCFD-aligned climate-related financial disclosures effective from April 2022 that impact issuers. Hong Kong has also mandated disclosure of ESG-related KPIs (key performance indicators) that impact issuers, and Indonesia, Malaysia, and the Philippines are following suit.

ESG ratings are a way to measure a company's exposure to environmental, social, and governance risks that may have long-term financial implications, including issues like energy efficiency, worker safety, and board independence. While traditional financial reviews often overlook these risks, investors who use ESG ratings to supplement their analysis can gain a broader view of a company's potential.

ESG rating agencies, such as Bloomberg, Sustainalytics, CRISIL, MSCI, and Climetrics, evaluate a company's ESG health based on publicly available information from websites and other platforms. It's recommended that companies disclose as much ESG-related information as possible, as this information can be used by rating agencies and investors to make more informed decisions.

The Tokyo Stock Exchange requires listed companies to provide qualitative and quantitative disclosures related to climate risks, while the Singapore Stock Exchange requires listed companies to adopt TCFD-aligned disclosures from 2023. In India, credit rating agencies CRISIL and ICRA have developed their own rating assessment tools based on ESG information in annual reports and other documents.

However, according to a report by CRISIL, out of over 500 companies that were rated, only 10% scored satisfactorily on their ESG commitments. While many companies performed well on social and other fronts, they often lacked in governance-related areas. This underscores the importance of ESG ratings as a tool to evaluate a company's long-term potential and identify areas for improvement.

The Indian government is currently developing regulations for rating agencies to ensure that only qualified individuals with strong track records and the ability to remain independent can enter the profession.

Last year, CRISIL's ratings for 586 companies found that only 20% were categorised as Strong, while the remaining 80% were labelled as Weak/Below Average. CRISIL noted that this trend suggested that ratings were improving due to better disclosure and/or improved performance on ESG parameters. However, CRISIL also found that ESG considerations play a minor role in decision-making due to a lack of fiduciary commitment to ESG. In addition, CRISIL discovered that companies perform more poorly on environmental parameters compared to social and governance criteria.

ESG investing, also known as sustainable investing, prioritises optimal environmental, social, and governance factors or outcomes. It is widely considered a way of investing sustainably, where investments are made with consideration for the environment, human well-being, and the economy. The returns on ESG investing have been higher than on other forms of investing that prioritise only economic returns without consideration for the environment and the society at large.

ESG-compliant companies reap significant benefits over less compliant ones in terms of economic returns, operating costs, employee loyalty, brand image, and overall valuation.

Integrating ESG into business involves a step-by-step process. It starts with an ESG gap assessment, which involves a deeper study of the existing systems and an analysis of the various aspects related to the three elements of ESG. Benchmarking with the industry and other standards, such as the International Finance Corporation (IFC), can help identify the gaps.

This is followed by the Materiality assessment, which involves identification of the stakeholders: shareholders, employees, customers, suppliers, the government, neighbourhood, etc.

The materiality assessment helps identify the material issues that are most important and relevant for a particular company. Material issues can differ from company to company, even within the same industry. Including disclosure on material issues in the ESG report makes it more useful and relevant.

Generating data and information is essential for ESG integration exercises, including for BRSR/Sustainability reports. However, many organisations lack a system for capturing the data required for ESG assessment. Therefore, it is crucial to have an ESG data management system in place that includes data on all types of emissions: 1, 2, and 3.

There are several frameworks available for ESG reporting, such as the Global Reporting Index (GRI), BRSR, and TCFD. In India, SEBI has suggested a comprehensive BRSR framework for reporting, which overlaps with GRI to the extent of 70%.

The Global Reporting Initiative (GRI) is the most widely used framework for reporting on environmental practices as well as human rights practices, governance, and societal responsibilities.

Another framework, Integrated Reporting, provides material information about an organisation's strategy, governance, performance, and prospects in a concise and comparable format, representing a fundamental shift in corporate reporting. The Sustainability Accounting Standards Board (SASB) ESG framework is best suited for analysing financial performance based on the ESG practices followed by an entity.

BRSR requires companies to report their performance against the nine principles of the National Guidelines on Responsible Business Conduct. Reporting under each principle is divided into essential indicators and leadership indicators. Essential indicators are mandatory, while reporting on leadership indicators is voluntary.

A strong ESG proposition can help create enormous business value across the enterprise, including attracting more customers, enabling better access to resources, reducing energy and water consumption, and thereby lowering operational costs. It also helps in building a better brand image and customer loyalty, higher valuation, and long-term viability. ESG can also enhance social credibility, attract talent, boost employee morale, improve productivity, and build stronger community relations.

Sustainability Reports: The growing trend of interest in non-financial performance and reporting worldwide is reflected in Indian corporations as well. The most common means of ESG or sustainability reporting among companies in India is through the publication of annual sustainability reports and integrated annual reports based on the GRI Standards and the Integrated Reporting Framework, respectively. Reporting is no longer limited to traditional backward-looking, stock-taking, and performance measurement initiatives. It has evolved into integrating forward-looking metrics and opportunities assessment, business strategy evolution, indicating an organisation's proactive approach to ESG rather than a reactive approach.

In conclusion, ESG is a tool that sensitises businesses to their responsibilities towards the environment, society, and governance. In order to grow and create value, businesses must take into account the three pillars of sustainability: environment, social responsibility, and governance. Integrating ESG considerations into their processes and reporting, particularly with regard to carbon emissions, can lead to higher ESG scores, which in turn can result in better risk management, increased profitability, and enhanced business value.

1.5

Unlocking ESG Opportunities for Sustainable Value Creation

JATINDER SINGH, Assitant Secretary General, PHDCCI

Truth can be stated in a thousand different ways, yet each one can be true.

Swami Vivekananda

In the last few years, there has been incredible progress in standardising and quantifying companies' performance on ESG criteria. Sustainability is gaining traction in boardroom discussions, and there is increasing interest among the investor community in companies that are making significant advancements in delivering on their ESG commitments. However, despite this, most companies still view ESG as a matter of regulation, compliance, and reporting, rather than as a major component of corporate strategy. They rely on annual CSR budgets, philanthropy, corporate communication, and public relations to create a rosy picture of 'I-do-care'.

ESG topics are becoming more focused on business competitiveness and gaining traction among investors, customers, and talent, rather than simply being a matter of compliance and CSR. Modern customers want to support companies that prioritise sustainability, and strong performance on ESG metrics such as reducing carbon emissions and promoting diversity, equity, and inclusion in the workforce can have a positive impact on investor interest. Additionally, board diversity is a key factor that investors are paying attention to, as it is a visible ESG metric that can be easily monitored.

1.5.1 ESG Investing and Sustainability

ESG ratings and stocks have become highly sought-after by investors as they are now viewed as a critical component for evaluating market feasibility. ESG reporting has transformed how companies make strategic and investment decisions. In the past, only a few investors paid attention to ESG data, while many corporations viewed ESG compliance as a status symbol or a matter of regulation and reporting rather than a corporate strategy. But today's ESG ecosystem is different. Investors widely use ESG data in their fundamental analysis, and constant communication with investors and shareholders has become the norm. New-age investors are increasingly asking questions about a company's strategy and competence in achieving robust ESG performance. As a result, corporations are quantifying their ESG initiatives as part of a long-term strategy for sustainable wealth creation, aligning with investor interests. They are discussing their ESG policies with investors and publicly reporting their progress, emphasising how they are creating a positive environmental and social impact. This clear and transparent communication is generating interest among investors.

1.5.2 Challenges in Developing Effective ESG Actions

Implementing ESG policies requires a commitment that is long-term. During challenging times, such as the Covid-19 pandemic or unexpected events, pursuing profits in an ethical and sustainable manner becomes even more difficult. Organisations often struggle with determining the appropriate focus areas and the extent to which they should communicate their ESG efforts to stakeholders. Achieving ESG goals requires a long-term commitment, regardless of economic fluctuations. Creating sustainable wealth requires patience and perseverance. Institutional investors may pressure companies to prioritise immediate returns over long-term goals, which can compromise corporate governance. Overcoming these challenges can be difficult.

Many corporations tend to limit themselves to simple actions such as improving ESG disclosures, releasing a sustainability report, and holding ESG-focused investor relations interactions, which often seem like mere checkbox-ticking exercises. However, there is a need for greater efforts to encourage the adoption of standardised ESG activities that benefit society as well as the company's bottom-line. Many companies are already realising the competitive advantages of operational efficiencies, such as waste management, taking care of external stakeholders, and improving risk management. But there is still more work to be done. Companies should move beyond superficial measures and focus on integrating ESG considerations into their overall strategy and operations, taking action for social responsibility, environmental sustainability, and good governance. ESG considerations should be incorporated throughout all aspects of the company's vertical and horizontal integration across all business lines.

1.5.3 Responsible ESG Investing

The principles of ESG investing are centuries old, though in different forms. Today, the growing importance of CSR and sustainable development has led to increased investor awareness about ESG investing. As supply chains become more multifaceted, there is a broader cognisance of social, labour and human rights issues and risks for enterprises. Responsible investment is an approach that recognises the significance to the investor of environmental, social and governance factors for long-term stability. Responsible investors may have different purposes; some focus on financial returns considering ESG issues that could impact these while others try to generate financial returns to realise positive results for people and the planet, while avoiding negative ones. In short, this can be interpreted as investment that creates long-term social, environmental and economic (sustainable) value. This combines financial and non-financial value creation, or investment that correctly prices social, environmental and economic risk.

Primarily, ESG efforts reduce capital costs and improve an organisation's valuation. Modern investors are ESG savvy and they would like to invest in organisations with strong ESG benchmarking. Sustainable development practices sustain shareholders' satisfaction with the board and transparency on ESG-related disclosures protects valuations of companies. Investors are interested in companies that walk the talk, committing to their ESG efforts in both letter and spirit. Nobody is interested in intention; results matter. Enterprises that marry ESG policies to their strategy and operations yield more profit than their competitors. Investors reward companies that leapfrog ahead of others in implementing their ESG policies.

1.5.4 ESG Strategy and Operational Efficiency

Often, executives mistake operational efficiency for strategy. While both contribute to an organisation's performance, they do so in different ways. Strategy involves focusing on external competition and setting oneself apart from competitors, while operational efficiency involves addressing internal competition and adopting best practices.

Many management tools and practices such as Kaizen, lean management, total quality management, change management, etc., are a quest to improve productivity, quality and efficiency, but operational efficiency without a strategy will not work. The vision and mission of an organisation are often integrated into its strategy, and it is crucial to recognise this. However, many businesses still struggle to translate these tools into a sustainable bottom line. Simply improving operational efficiency is not enough to gain a competitive advantage since best practices can be easily copied by competitors. In the realm of ESG, companies must align both their strategy and operational efficiency to grow profitably and sustainably. Product design, supply chain management, and operational models are three foundations that define the top line and bottom line, and they should serve as the framework for decision-making. The amalgamation between environmental or social consequences and the resulting changes to the bottom line must become an integral part of the decision-making process at all levels.

ESG issues are not sector agnostic. Organisations must identify strategic ESG priorities and operational efficiencies by determining where to focus their efforts and how to achieve success. "For instance, while the energy and hydrocarbon sectors prioritise strategies for reducing their carbon footprint, the technology sector emphasises the importance of creating an inclusive and diverse workforce and providing equal employment opportunities as part of their ESG imperatives." In some sectors, it can be challenging to determine the link between environmental and social impacts and profits. For example, in the F&B sector, the quality of ingredients and nutritional value of the products is prioritised over the costs involved in supply chains, which can represent more than half of all costs. In the automobile sector, companies are now focused on diversifying their electric vehicle offerings after years of concentrating on reducing vehicle weight, improving fuel efficiency, and complying with pollution regulations. This type of strategic shift is essential in every sector, requiring swift action and delivery. To achieve this, companies must relinquish incremental improvements and make bold, innovative decisions that require business process re-engineering and building a strong foundation for integrating sustainable social and environmental outcomes into the business strategy. The days of incremental improvements are over, and companies must make fundamental strategic choices. Investors will be attracted to a compelling competitive strategy that also yields societal and environmental outcomes, as marginal advances in ESG goals may not suffice.

Legacy companies often cling to outdated business models, sometimes ignoring ESG issues altogether and failing to recognise the connection between social and environmental impacts and shareholder value. Reinventing these models is easier said than done, but it's not too late to start. Companies should communicate a compelling competitive strategy that aligns with environmental and social impact.

ESG Strategy and Operational Efficiency can impact value creation in the following five ways

Companies that prioritise energy saving, water saving, and resource conservation can attract investors, gain positive traction with government and communities, and earn support from the regulators. In contrast, companies with high energy uptakes, excessive water consumption, and resource depletion may dissuade investors, attract fines and penalties, and face increased activism from the media, influencers, and NGOs.

	Strong ESG Outcomes	Weak ESG Outcomes
Cost Reduction	- Energy saving - Water saving - Resource conservation and efficiency	- High energy uptakes - Excessive water consumption - Resource depletion
Investors traction	- Attract Investors	- Dissuade investors
Growth	- Attract customers through sustainable products/services - More innovation and resilience to recession and pandemics	- Lose customers due to poor sustainability practices - Falling prey to recession or pandemics
Government and community relations	- Create - Positive traction with government and communities - Earn subsidies and support from regulators	- Attracts fines/penalties and penal actions - Increased activism from the media, influencers and NGOs
Human Capital Growth	- Improved efficiency of HR - Enhanced mental health and wellbeing - Increased employee satisfaction and attractiveness to young talent	- Increased grievance /disciplinary actions - Poor work life balance - More employee dissatisfaction and high attrition

1.5.5 Purpose-Driven ESG Agenda

Implementing an effective ESG strategy requires the involvement of top executives at the board level and must percolate throughout the entire organisation. While there is a perception that boards are involved in sustainability strategies, this is rare, with some exceptions. To effectively drive ESG goals, there must be a board-driven approach supported from the bottom up, creating an organisational culture where the entire workforce has a crystal-clear understanding of the sense of purpose and a commitment towards driving it. Investors are increasingly seeking companies that effectively link ESG goals to purpose, but some organisations mistakenly believe that pursuing ESG goals comes at the expense of profits. In reality, organisations can redesign their workflows and supply-chain patterns to positively impact both their top and bottom lines. However, this requires moving beyond mere reporting and understanding the convergence of bottom-line and societal benefits to make tough decisions. Only then can we realise the goals of the Paris Agreement and the United Nations' 17 SDGs.

1.5.6 Design thinking and ESG

There are more than 600 ESG reporting standards, creating uncertainty around ESG in different ways, from reporting frameworks to growth strategies, external communications, and stakeholder expectations. To effectively navigate this landscape, any organisation's ESG strategy and operational efficiency can be divided into four parameters:

- Ensuring acquiescence with ESG regulations and other laws
- Sustaining investor interest in the long-term
- Embracing disruptive technologies and innovation tools
- Coordinating ESG tools across all verticals.

Centralising ESG goals is fundamental for operating efficiency, while decentralising ESG activities. As ESG activities unfold, senior executives can guide goal-setting and aid in the movement from centralisation to decentralisation of ESG activities. Many companies are confronted with trade-offs between profit and ESG performance, but by using product design and collaborating with other stakeholders, the trade-offs can often be circumvented. Collaboration with stakeholders such as NGOs, development sector organisations, the government, and the community requires factoring in trust, where everyone endorses the shared agenda. If there is no connection between the environmental and social concerns of the businesses with their strategic choices, they can never deliver on ESG commitments. For a nuanced understanding, companies should conduct a SWOT analysis to assess their current positioning on ESG issues and trends across business units. This deep-dive may give an understanding of where one should focus the effort. For example, cutting CO_2 emissions from the manufacturing processes and transportation sector should be a critical priority to reduce the threat of climate change. Similarly, recycling, adopting principles of circular economy and secondary materials should be important determinants of the growth strategy.

In the social spectrum, favouring inclusive and equitable policies in talent acquisition and team building should be ingrained in the HR policy. To counter skill redundancy in the dynamic working environment, continuous up-skilling and reskilling of employees are called for. It is observed that the demand for ESG skills is outpacing supply. For example, there is a scarcity of climate risk specialists. Enterprises can publicise desired ESG skills that will encourage universities to prioritise ESG courses and arouse eagerness in young students to take courses on ESG. Companies can only meet ESG goals with responsible sourcing and hiring of a skilled workforce. The elements of design thinking should permeate deeper at all levels of HR to build robust sustainability paradigms.

1.5.7 Exploring the 'G' in ESG Reporting

In today's dialect, in some organisations ESG is synonymous with corporate social responsibility (CSR), keeping the interest of stakeholders and caring for the planet. CSR departments are normally very small and are not involved in making decisions on strategy and operational efficiency. The focus is primarily on local communities and government relations and very little on ESG reporting. In general parlance, ESG is generally about the E and S; G has no link with environment or stakeholders or social issues like inclusion, equal employment opportunity or gender balance. The "G" policies may sometimes align with the shareholders' perspective that prioritises generating returns for investors, even if it means making short-term gains such as selling the company, which can pose risks to other stakeholders. This can lead to increased costs for companies to comply with regulations.

A strengthened system of corporate governance offers robust accountability to investors, to carry out a plan of long-term growth without short-circuiting any pillar of corporate governance. Mainstreaming "G" back in alignment with ESG requires implementing sustainable, stakeholder-aligned strategies to create profits. This requires perseverance and persistence and the willingness to bear hardships during challenging times. A first step is to draft department-wise ESG KPIs that are endorsed by the board, supported by senior executives and included in HR work plans and compensation management policies. From a governance perspective, a sustainability committee, consisting of a workforce at the supervisory level, is essential to deliver ESG policies after considering cross-pollination of work processes across all divisions.

ESG is a cornerstone of corporations, and its individual elements – E, S, and G – are interconnected. Achieving E and S metrics is critical, and governance plays a paramount role. Excelling in governance means prioritising transparency rather than just submitting a compliance report. Many enterprises appoint a Chief Sustainability Officer (CSO) to coordinate activities across divisions and align KPIs across all business units. However, the individual elements of ESG are intertwined. Environmental principles often overlap with social principles, and governance principles focus on ensuring transparency with regulators, as reflected in published reports.

1.5.8 Employees and Consumers – the Sharks in the ESG Tank

Of late, social media has taken up the cause of ESG. People now endorse companies that take a stand on environmental and social issues. Employees are increasingly interested in working for companies that prioritise sustainability, and many companies are responding by aligning with the values of their employees and customers to remain competitive. HR departments are tailoring their policies to attract, retain, and motivate talent based on ESG values. The younger generation is especially drawn to companies that prioritise ESG and offer a sense of purpose beyond profit. A strong ESG policy helps to attract, motivate, and retain high-quality employees by instilling a sense of sustainability. The perception of employees regarding the impact of their work is directly linked to proactive and productive actions taken by the company.

1.5.9 ESG Toolkit for MSMEs and Start-ups

Micro, Small, and Medium Enterprises (MSMEs) and start-ups are vital to many economies, contributing to 60% of global employment, around 35% of GDP in developing countries, and around 50% in developed countries. They are the main drivers of economic growth. However, start-ups and MSMEs, particularly micro and small enterprises, often operate in survival mode and are often hesitant to consider ESG. To address this, founders/co-founders can start by identifying key risks that can be avoided. Every MSME or start-up operates in a specific sector that can help identify ESG risks. For example, for Edtech start-ups, data privacy is a significant risk. Many start-ups risk losing essential contracts by inadvertently sharing information with advertisers from the data they collect from customers. Therefore, start-ups need to have robust policies on data security and privacy.

Regardless of the sector, start-ups should create a list of material risks that may have a financial impact when balancing their core business

priorities. One key element on this list should be a net-zero plan, as this can help establish credibility with investors who are increasingly demanding transparency in this area. Investors cannot achieve their ESG goals unless the companies they invest in share the same goals. Net-zero plans can also enable start-ups to integrate sustainability goals into their supply chains as they grow. In an environment where there is fierce competition to attract talent, start-ups tend to hire and fire in bulk. However, it is important for start-ups to establish strong social connections with their employees and prioritise their mental health by implementing work-life balance policies. More than half of the workforce suffers from burnout and mental health issues, and creating diverse and inclusive cultures can help alleviate these problems.

Embarking on the journey towards sustainability can be difficult and challenging in the beginning, but the rewards at the end are worth it. Companies that fail to make ESG a vital part of their goals will struggle to survive, while those that do have ESG policies in place can achieve long-term sustainability. Start-ups and MSMEs should act immediately. Continuous efforts to build the capacity of the workforce in the value chain on sustainability issues will yield positive results. Start-ups have a competitive advantage over large corporations whose decision-making culture is embedded in various layers of hierarchy. By incorporating ESG into their DNA from the beginning, start-ups can create a competitive differentiator.

1.5.10 Evolving ESG Landscape

Instilling a sense of purpose for ESG starts with the board, which should establish appropriate control systems and defined processes to achieve its goals. Top executives should create an ecosystem where the company's vision and mission are embraced by the entire workforce, encouraging open and transparent communication and seeking input from employees.

Investors are increasingly attracted to companies whose performance aligns with ESG metrics. To demonstrate the positive impact on the environment and society, companies must develop a transparent and operational ESG strategy. Without a clear purpose and strategy, companies cannot have a sustainable corporate strategy, and investors cannot earn sustainable returns. Today, ESG is more than just compliance reporting; it is a necessity for responsible corporate decision-making. Global ESG assets are predicted to reach $53 trillion by 2025, and corporations view ESG as a key competitive advantage, not just a box-ticking exercise.

Many countries have committed to and set a target date for adopting net zero emissions. Net zero commitments go beyond compensating for carbon emissions to eradicate GHG. In the long run, net-zero may also mean a net-zero bottom line if any enterprise does not conform to ESG practices.

Focusing on shared value and impact will lead organisations to make strategic decisions for capital investments and operations, which will generate significant opportunities for competitive advantage. Systemic inertia at different levels is a roadblock. This journey, though somewhat arduous, will positively impact the top line and bottom line and create a macroeconomic environment that enables inclusion, reduces inequalities, and restores the much-desired ecosystems.

1.6

Genesis and Evolution of Carbon Credits as Decarbonisation Greenbacks

UMESH SAHDEV, Executive Chairman, Hydrogenium Resources Pvt Ltd. India

Man is a complex being; he makes the deserts bloom and lakes die.

Gil Stern

Journey from Kyoto to Paris & beyond 2030

Clean Development Mechanism is one of the three key market-based mechanisms that evolved from the Kyoto Protocol to the UN Framework Convention on Climate Change. It introduced the first environmental investment and credit scheme that provides a standardised emissions offset instrument, known as a CER (Emission Reduction Certificate), which ultimately became known as Carbon Credits.

The Kyoto Protocol, which is the world's only legally binding treaty to reduce GHG emissions, takes its name from the 3rd Conference of the Parties (COP) held in the Japanese city of Kyoto. The instrument was adopted on December 11, 1997, with the aim of reducing the emissions by 5.2% from the 1990 level, as the emissions contributed to global warming and climate change. The protocol became international law on February 16, 2005.

Parties that committed under the Kyoto Protocol, also known as Annex B Parties, accepted targets for limiting or reducing emissions. These targets are expressed as levels of allowed or permitted emissions or assigned amounts over the 2008-2012 commitment period. Countries that ratified the Kyoto Protocol were assigned maximum carbon emission levels for specific periods and participated in carbon credit trading. If a country emitted more than its assigned limit, it would be penalised by receiving a lower emissions limit in the following period.

The Kyoto mechanism involved three main components.

- Clean Development Mechanism (CDM)
- Joint Implementation (JI)
- Emissions Trading (ET).

The CDM and JI are two project-based mechanisms. CDM involves investing in emission-reduction projects in developing countries, while JI enables developed countries to invest in emission-reduction projects in other developed countries. These two mechanisms help to fuel the carbon market.

Emissions trading, as outlined in Article 17 of the Kyoto Protocol, allowed countries with emission units to spare to sell this excess capacity to countries that exceeded their targets. This created a new commodity in the form of emission reductions or removals. As CO_2 is the principal GHG, people referred to this as trading in carbon. Carbon is now tracked and traded like any other commodity. This is known as the **carbon market**, and the traded product is Carbon Credits or simply Carbon.

Compliance of parties to the Kyoto Protocol during the first commitment period was quite encouraging. Of the 36 countries that fully participated to the first commitment period, 27 duly achieved their targets and only nine emitted higher levels of GHGs than committed under the Kyoto Protocol.

The countries involved in the Kyoto Protocol implemented various strategies to comply with their commitments. These strategies included participation in projects and purchasing carbon units from other countries, encouraging the use of carbon credits by the private sector, and implementing climate policies to incentivise domestic emission reductions. Despite these efforts, while most countries met or exceeded their targets, a significant portion of the overachievement was attributed to “hot air” emissions reductions that had occurred prior to 1997 in economies in transition.

To fulfil their Kyoto obligations in a cost-effective manner and transition towards a low-carbon economy, EU member states created the EU Emission Trading Scheme (EU ETS) in 2005. This scheme established a liquid market for emission reductions within member states and played a significant role in enabling EU states to comply with Kyoto targets at a low cost.

The scheme ratified by all member states of the EU was based on the fundamental principles of:

- Strong compliance framework with ‘Cap and Trade’ system
- Primarily focus on CO_2 emissions, initially, from large industrial emitters like power and heat generating energy-intensive industries.
- Emissions allowances allocated periodically with periodic reviews and possibility to expand to other polluting gases and industries.
- Use of CDM and JI for implementing worldwide opportunities and linking with compatible schemes of other countries.

During the first commitment period of 2008-2012, the EU ETS covered more than 15 polluting industries. However, through the CDM and JI, EU countries were able to invest in emission-reduction projects in various industries in third countries. The emissions savings from these projects, in the form of Certified Emissions Reductions (CERs), were credited to EU member investors towards their own emission targets. This created a win-win situation for both stakeholders, investors, and third countries as the cost of generating one CER or Carbon Credit for a EU country was much lower than the cost of saving 1 MT of CO_2 in the EU. During the first commitment period, the cost of abating 1 MT of CO_2 was approximately in the range of Euro 110-120/MT in Europe, whereas a much lower investment was required in a developing country to generate the same emission savings.

As a further fillip to facilitate climate change mitigation and for the success of Kyoto Protocol, EU ETS was the first trading scheme that recognised CERs generated through CDM and JI as equivalent to European emissions allowance – 1 EUA= 1 CER = 1 ERU and thus fully allowed to be traded under the scheme.

Thus, the beginning of the first commitment period of the Kyoto Protocol saw the EU ETS providing investors in CDM and JI projects in developing countries with the necessary confidence, thereby encouraging substantial investments and transfer of technology, helping the developing countries to equip themselves to meet their sustainable development goals.

As a result, the mechanisms of CDM and JI became the most important factor and key to creating a vibrant commodity of Carbon Credits and put a reference price on the unit of commodity when invested in or traded.

1.6.1 Compliance and Voluntary Carbon Markets

Kyoto Protocol also created a ‘Compliance Market’ environment with the use of CERs or ERU/ Carbon Credits.

Following the establishment of EU ETS and compliance market, voluntary carbon offset programmes also began to develop after 2005, as the CDM became more established, and the CSR community began to recognise the demand for these instruments beyond regulated companies and countries under the Kyoto Protocol. There are now various carbon offset programmes primarily (or exclusively) serving the voluntary market, consisting mainly of corporations wishing to make GHG emission reduction claims.

Through EU ETS’s ‘Cap and Trade’ system, which sets a cap on emissions and enables those who emit less than the cap to sell their ‘unused rights’ to those who exceed their caps, a demand and supply mechanism for carbon credits was created, paving the way for pricing of emissions known as Carbon Pricing in the industry.

World Bank defines Carbon Pricing *as ‘an instrument that captures the external costs of GHG emissions and ties them to their source, through a price, usually in the form of a price on the Carbon Dioxide emitted’.*

The reasoning is quite rational – that creating a cost for carbon emissions sends clear signals to polluters to decide for themselves if they would like to reduce and stop polluting and reduce emissions or to continue to emit and bear the costs.

Kyoto Protocol remains a landmark treaty for the development of environment commodity market. Through internationally binding targets for emissions reduction, the protocol became the harbinger for Carbon Emission Trading of Carbon Credits and related financial instruments in emissions abatement. Similarly, EU ETS is the cornerstone of the EU’s policy to combat climate change and its key tool for reducing GHG emissions cost-effectively through a trading mechanism for Carbon Credits. It is the world’s first major carbon market and remains the biggest one.

1.6.2 Doha Amendment

After the expiry of first commitment period in December 2012, parties to the Kyoto Protocol met in Doha COP18 and adopted an amendment to the Kyoto Protocol called the Doha Amendment that extended Kyoto Protocol to 2020, adding new emission-reduction targets for the second commitment period 2012-2020.

1.6.3 Paris Agreement

The ephemeral Doha Amendment was short-lived. In 2015, at the Paris COP21, all UNFCCC members signed a landmark environmental pact to address climate change and its negative effects, with a goal to limit global warming to well below 2°C, preferably 1.5°C, compared to pre-industrial levels. In contrast to the top-down approach to setting climate and emissions targets implemented under the Kyoto Protocol, the Paris Agreement, adopted by 196 members at COP21, embraces a bottom-up approach in which each country sets out the mitigation contributions it pledges to undertake to reduce its emissions.

Specifically, each party is required to submit a Nationally Determined Contribution (NDC) describing its mitigation contributions and climate actions. To achieve their NDCs, many countries have included the use of ‘cooperative approaches’ as recognised by the treaty.

To achieve long-term plans, the Paris Agreement provides a framework for financial, technical, and capacity-building support to countries that need it. One of the key provisions is Climate Finance, which is critically required for adaptation as significant financial resources are needed for a low-carbon transition to net zero. Article 6 of the Paris Agreement, ratified at COP26 at Glasgow, recognises the role of both cooperative approaches and the UNFCCC mechanism in incentivising the private sector to implement mitigation activities worldwide.

These mitigation activities allow for the development of Carbon Credits that can be transferred internationally and used in other countries to meet the aims of NDCs or other compliance uses. These instruments, by delivering an investment signal to the private sector, enable countries to achieve scale in mitigation action, which in turn may help contribute to adaptation action.

There is widespread expectation that the Article 6 rulebook will create the conditions for effective and robust international carbon markets to thrive, including continued, significant growth in private sector investments through voluntary carbon offset projects. It is clear that carbon markets are a more effective means than carbon taxes to establish a cap on emissions and set a price for carbon emissions through a demand-supply matrix, while also assisting governments in achieving their NDCs.

However, some uncertainties surround Article 6 for carbon markets. Participants in voluntary carbon markets will closely examine the implications for investors in terms of balancing investments in corresponding adjusted versus non-corresponding adjusted credits and accessing high-quality projects, including carbon removal credits. A *corresponding adjustment* is a tool that countries use to ensure carbon offsets are not double-counted when sold and transferred internationally. VCMs are particularly affected by this uncertainty to investors if their invested projects would be authorised credits or not. In particular, the authorisation status of a credit is expected to affect its pricing. Both VERRA and Gold Standards have different views and processes for the same.

There is hope that as rules, guidance, and frameworks from regulated and market-led initiatives consolidate, this would create the regulatory certainty to ensure the environmental integrity that investors seek.

Carbon Credits Post 2020/Paris Agreement

The Paris Agreement, that superseded the Kyoto Protocol as the principal treaty of parties and as a regulatory instrument, did not extend Kyoto beyond 2020 after the Doha Amendment. At the COP26 in Glasgow, it was announced that CDM would no longer be applicable for emission reductions occurring after December 31, 2020. Therefore, no new registration of projects or renewals of crediting periods for CDM projects, or further issuance of CERs can take place under the CDM for emission reductions after this date. Instead, the Paris Agreement provides for a new international carbon market mechanism to support sustainable development and contribute to the mitigation of GHG emissions, which will be responsible for transitioning credits.

Article 6 of Paris Agreement and its implications for carbon markets.

According to the Paris Agreement, there is a growing need for urgent action on climate change and for developing robust carbon markets that can generate revenue through third-party carbon investments without affecting countries' ability to meet their NDCs. The World Bank is playing a vital role in creating a globally connected International Carbon Market infrastructure that is transparent and auditable, potentially using distributed ledger technology (blockchain) and digital monitoring, reporting, and verification (MRV). This approach has the potential to significantly reduce the time needed to generate and trade emission reductions. By automating the entire process from generating a credit to transacting it, this initiative aims to create a digital system that ensures transparency, increases efficiency, and improves the accuracy of data related to emission reductions.

Some of the key initiatives being undertaken by the World Bank to catalyse next generation of Carbon Markets and Carbon Credits transparency per Paris Agreement include:

- The **Supporting Bank Operations for Mitigation Outcomes Programme,** which generates Carbon Credits from the World Bank's lending programmes to assist countries gain practical experience in creating credits from projects. These credits can be used for a country's own climate goals or sold in voluntary or compliance carbon markets.

- **Invest4Climate** builds capacity to better understand how Carbon Credits can be monetised, and develops innovative approaches for structuring carbon revenues.

- The **Climate Market Club** is piloting institutional elements of Article 6.2 needed at the national level to decide which Carbon Credits could be sold, how they should be priced, and how a country can ensure it's able to report on them.

- The **Partnership for Market Implementation**, which supports countries in building capacity and scaling up carbon pricing instruments, including international carbon markets.

It is evident that Carbon Credits and carbon markets will play a crucial role in achieving net-zero commitments by private companies and corporations as per the Paris Agreement. This will lead to a significant growth in the voluntary Carbon Credits market, which is expected to increase from $1 billion per year to $50-100 billion/year by 2030. The VCM has already removed or avoided 850 million MT of GHG emissions over the past decade. To achieve net-zero targets, there is a need for substantial investment of up to $100 trillion by 2050, and private sector capital must be harnessed to realise the funding and mitigation potential of the VCM. The VCM is based on two fundamental principles: high-integrity demand and high-quality, impactful supply.

The Paris Agreement has created opportunities for innovative initiatives in climate action and a huge carbon economy, with Carbon Credits becoming a greenback for climate action. Different global players are bringing creativity, transparency, and value propositions to attract carbon investments and financing for an accelerated transition to net zero. Governments and international institutions are also increasingly paying attention to the potential of green fintech to help tackle climate change.

- A global investment platform to sell and track Carbon Credits using blockchain technology is being launched by a partnership including the International Finance Corporation (IFC), part of the World Bank Group.
- The tokenisation of green bonds using public and permissioned immutable blockchains (distributed ledgers) is being explored. The green bonds market currently suffers from a lack of liquidity and high entry barriers. Tokenising green bonds via smart contracts based on distributed ledger technology enables an automated, compliant, verifiable, and tamper-proof manner to finance green projects, bringing required liquidity to this closed market. Tokenised green bonds democratise green investment, accelerating the transition to a more sustainable future.
- A prototype is being developed for the tracking, delivery, and transfer of digitised mitigation outcome interests – essentially Carbon Credits recognised under national verification mechanisms compliant with the Paris Agreement, attached to a bond.
- The European Union has reached a political deal to overhaul its carbon market, cutting global GHG emissions faster and imposing new CO_2 costs on fuels used in road transport and buildings from 2027 onwards.
- UNFCCC announced an online Carbon Credits platform that would allow individuals, families, and businesses to shop for options to offset their carbon footprints. They can buy

Carbon Credits tied to specific CDM projects and cancel out or offset their personal emissions. It's an excellent idea for all those CDM credits that were waiting for a market.

1.6.4 Potential Power of Carbon Market

It is noteworthy that the realisation of the need to put a price on emissions has led to the establishment of carbon markets in more regions, with larger volumes and higher value trades. Currently, there are 30 compliance Emissions Trading Systems (ETS) operating around the world, purchasing and trading emissions allowances (such as Carbon Credits or carbon offsets) with a total trade value of more than $850 billion. In addition, more than 22 markets – both compliance and voluntary – are either under development or planning, indicating that there will be even larger markets in the future.

Apart from new markets, there is a need to ramp up size and goals to accelerate decarbonisation, place a higher price for carbon emissions for speedy transition to net zero and voluntary markets to gain momentum. Carbon markets around the world are currently fragmented and largely asynchronous. With the emergence of different markets with different designs, the issue of carbon market linkages has become paramount. A harmonised international carbon market initiative by the World Bank could facilitate coordination between carbon markets, ensure environmental integrity, and ultimately ensure ecological integrity, thereby stimulating greater ambition for climate action.

The gusty carbon markets of recent years have finally become a key and widespread tool for driving climate action. In 2021, as much as 21% of the world's emissions were covered by carbon pricing, up from 15% in 2020. The global Carbon Credit trading market is projected to reach $200.6 billion by 2027, up from an estimated $67.3 billion in 2022, at a CAGR of 24.4% from 2022 to 2027. The value of the global carbon market thus soared 164% in 2021 to a record high of Euro 760 billion, mainly due to increased demand for carbon permits which led to surging prices.

1.6.5 Monetary Value of Carbon Credit *to Include Social and Economic Cost of Abatement*

The importance of Carbon Credits/carbon offsets in the overall carbon economy is well-established. These tradeable instruments are rightly considered as the currency of the carbon/green economy – the greenbacks.

However, the value of this greenback is being increasingly scrutinised with the establishment of carbon pricing in several countries in the form of taxes and ETS. This has spurred active businesses to move towards sustainable operations and inputs.

With the increased commitments of governments worldwide to tackle climate change and achieve net zero, carbon pricing is expected to become an important factor of climate policy. While today, energy input costs constitute the major component of the price of carbon, it has yet to factor in the high social costs and economic costs of emission reduction. The social cost of carbon is the estimation of monetary costs of the damages caused by emitting 1 MT of carbon.

Emitting carbon causes damages both today and in the future. It's measured in terms of the burden (that includes changes in agricultural productivity, damages caused by rise in sea levels, and decline in human health and labour productivity) caused to present and likely future generations by emitting 1 MT of carbon. Now it's been measured in terms of dollars per ton of CO_2 emitted which is currently estimated at \$190/MT of CO_2 in the U.S. It's argued that if you have a policy that costs \$60/MT of CO_2, it passes such a cost-benefit test as one is paying less than the benefit it gets. The social cost becomes very important there.

In the near future, climate policy would most probably include the social cost of carbon, making carbon pricing the pillar of the carbon change mitigation process.

In all likelihood, imposing a market-conforming price on GHG emissions should supplement and address the market's dynamics by incentivising businesses and households to take the social costs into account and reduce emissions, either through innovation and technology switching or through reduced consumption.

1.6.6 Indian Carbon Markets

As part of the Paris Agreement committed NDCs, India is feverously working towards achieving the same and working on the development of an Indian trading platform for Carbon Credits.

India's carbon trading platform is set to roll out soon. On December 12, 2022, the Energy Conservation (Amendment) Bill 2022 was passed by parliament, paving the way for a carbon market in the country. The proposed platform aims to develop a voluntary carbon market in India to overcome barriers in the market for Energy Saving Certificates and facilitate the participation of voluntary players in meeting India's NDCs.

The responsibility of developing and administrating the market has been given to the Bureau of Energy Efficiency (BEE), which currently runs the Perform, Achieve and Trade (PAT) programme under the National Mission for Enhanced Efficiency. BEE will formulate the complete framework, systems, and methodologies for both voluntary markets and later for compliance markets for various industrial sectors. The Ministry of Power and Environment will issue notifications on the carbon markets with its final decision on the framework of the markets.

The framework for the voluntary market is expected to roll out within 2023, while the compliance market, which requires setting targets and timelines for industrial sectors, will take another 2-3 years to be launched. The PAT scheme, which operates on compliance-backed trading at IEX, will transition into the compliance market. The power exchanges that enable trading of Energy Saving Certificates (ESCs) are expected to be the trading platform for carbon credits under the carbon market framework, according to the director-general of BEE.

In line with these developments, India's biggest energy trading platform, the Indian Energy Exchange (IEX), has announced the establishment of a wholly owned subsidiary, the International Carbon Exchange Pvt. Ltd., to explore business opportunities in the voluntary carbon markets.

According to the chairman and MD of IEX, the government is working on creating a compliant carbon market that is expected to be regulated by CERC. He expects that REC and ESCs would be merged to create a single carbon attribute, and with fungibility built in, it could be converted into Carbon Credits. The plan for the compliance market is expected to be introduced next year, in 2024. Due to NDCs and large corporations taking net-zero/decarbonisation targets under ESG, the requirement for voluntary carbon credits is expected to increase. He expects that the voluntary carbon market, which is trading about 500 million units at the international level as of now, would be trading about 1.5-2 billion units, an increment of 3-4 times from the present level. By 2030, India is expected to sell almost 200 million Carbon Credits, with demand from corporations expected to be 120-130 million. India, Africa, and Southeast Asia have a large opportunity to generate Carbon Credits.

The latest news is that India has finalised a list of activities that will be eligible for trading Carbon Credits under a bilateral or cooperative approach in the international carbon markets as per the Paris Agreement rule book.

The broad list of activities includes renewable energy with storage, solar thermal power, offshore wind, green hydrogen, compressed biogas, mobility solutions with fuel cells, high-end energy efficiency solutions, sustainable aviation fuel, process improvement in hard-to-abate sectors, tidal energy, ocean thermal energy, ocean salt gradient energy, ocean wave and current energy, HV direct current transmission, green ammonia, and carbon capture, utilization, and storage.

Entities can generate and accumulate credits through these activities that can be traded on international platforms. High-emitting industries can purchase credits from those who have earned them through the listed activities.

1.6.7 Conclusion

The use of Carbon Credits/carbon offsets is not only a market instrument to drive global climate actions but also an important tool to facilitate an equitable and just energy transition for at-risk communities in emerging and frontier markets. This is especially relevant for the 6.1 billion people, or 80% of the world's population, living in developing markets.

Finally, the demand for Carbon Credits is predicted to rise significantly, primarily due to the increase in corporate climate commitments that will accelerate the voluntary market's growth. Currently, more than one-third of the world's largest publicly traded companies have declared net-zero goals that will rapidly stimulate the carbon market and the carbon greenback.

SECTION -2

GREEN HYDROGEN AND OTHER CLEAN FUELS

Energy Systems in India | Solar Energy Technologies and Potentials | Decoding Hydrogen Ecosystem in India | Government's Initiatives, a Key Growth Driver for Green Hydrogen | Hydrogen Status: Challenges and Opportunities | Hydrogen Fuel Cells | Hydrogen Fuel Cells, Ancient Wisdom in Modern Times | Fuel Cells Based on Hydrogen | Hydrogen – Storage Technologies | Lifestyle for Environment: An Industrial Perspective for CCUS | Green Hydrogen Applications – Ammonia, Ceramic, Steel, Cement, Etc | Production of Green Hydrogen from Agro-Waste: Thermo Chemical Conversion of Biomass | Biomass to Chemicals and Energy | Synthetic Paraffinic Kerosene (Sustainable Aviation Fuel) | Biofuels: Status Today and Outlook for the Future

2.1

Energy Systems in India

ODA MARIE ELLEFSEN, R&D Coordinator & Project Manager Hydrogen, Asia
CHARLY BERTHOD, CTO Solar Energy, at Greenstat Energy

The world is so empty
if one thinks only of
mountains, rivers and
cities; but to know
someone here and there
who thinks and feels with
us, and though distant, is
close to us in spirit – this
makes the earth for us an
inhabited garden.

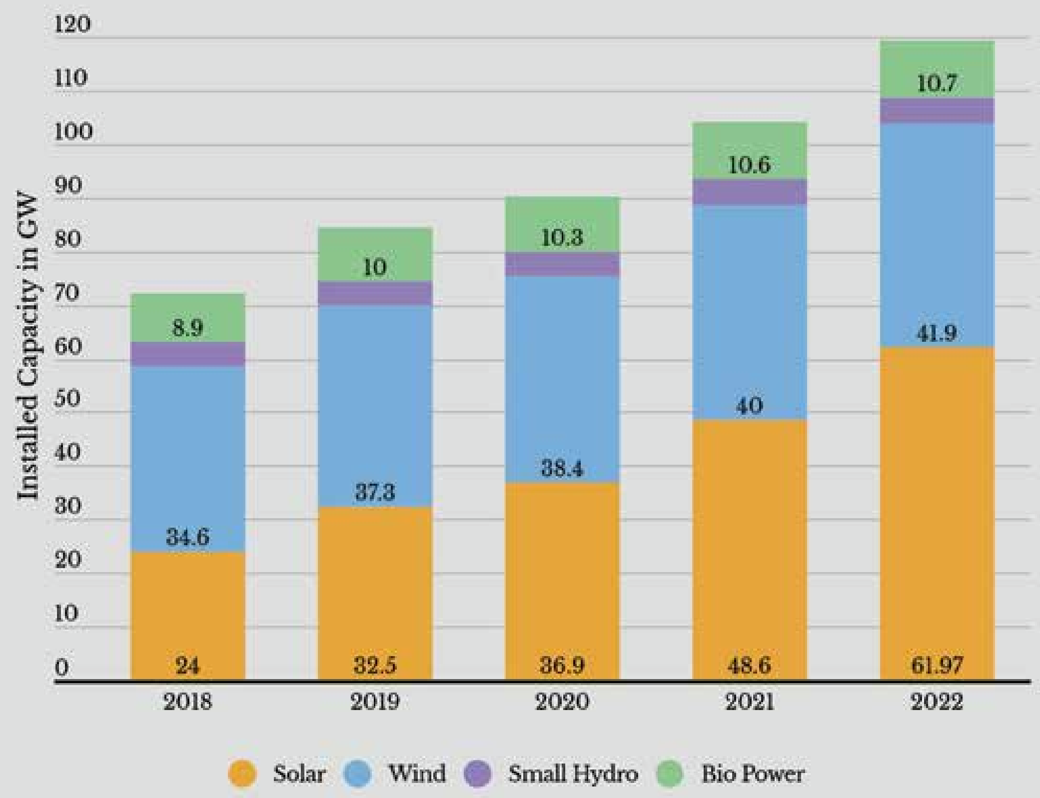
Johann Wolfgang von Goethe

As of October 2022, India has reached a renewable energy capacity of 166 GW, which surpasses the 175 GW target set in 2015. Despite disruptions in the supply chain and fluctuating raw material prices caused by the COVID-19 pandemic, these results demonstrate the effective tender mechanisms in the country and the power grid's capacity to integrate renewable energy. The MNRE plans to increase the installed renewable energy capacity to 450 GW by 2030.

2.1.1 Renewable Energy Production

To achieve 166 GW of renewable energy capacity, India has mainly increased its capacity in wind and solar energy, as seen in Fig. 1. The wind energy capacity increased by 21% between 2018 and 2022 while the solar energy capacity increased by 258%. This is partly explained by solar energy becoming the cheapest source of energy.

The electricity generation mix for the financial year 2021-2022 was still dominated by coal (72.7%) with a large part from renewable energy: large hydro (10.2%), solar (5%) and wind (4.6%). Small hydro-power plants represent only 0.7% of the generation mix and biomass with other renewable energies 1.2%. The increase in penetration of intermittent renewable energy put new constraints on the grid and can cause curtailment of power. Curtailment, also known as energy rejection or spilling, refers to the practice of shutting down or reducing the output of renewable energy sources, such as wind and solar power, when there is excess generation that cannot be absorbed by the grid. This can happen for a variety of reasons, such as a lack of transmission capacity, grid congestion, or issues with the stability of the grid.



Source: Installed Capacity Report, 2018-2022, published by Central Electricity Authority (CEA)
Note: All values are as of November that year

Fig. 1: India's Installed Renewable Capacity Increased 66% Since 2018

In recent years, India has faced significant curtailment issues, particularly with its wind and solar energy generation. This is due to a lack of transmission infrastructure and grid integration, as well as issues with forecasting and scheduling of renewable energy generation.

To address curtailment issues, India is investing in transmission and distribution infrastructure, as well as in grid integration and management. This involves upgrading the existing transmission and distribution system, building new transmission lines, and implementing advanced grid management techniques to better integrate and balance renewable energy generation. Additionally, forecasting and scheduling of renewable energy production will also be important to minimise the amount of curtailment.

It is worth noting that, India has been taking measures to reduce the curtailment and the government has announced a series of policy measures to reduce the curtailment such as increasing the capacity of inter-state transmission systems, introducing the concept of Renewable Energy Management Centres (REMCs), and forecasting and scheduling of renewable energy.

2.1.2 Transmission of Power

Renewable energy production is often planned where the natural resources are abundant, rather than close to where energy consumption is happening. This creates a need for high levels of transmission infrastructure to transport the energy to where it is needed.

The investment needed for transmission infrastructure in India to facilitate an increase in renewable energy generation depends on several factors, such as the specific types of renewable energy being developed, the locations where the energy is generated, and the locations where the energy is needed.

According to a report by the IEA, India will require an investment of around $250 billion in transmission and distribution infrastructure by 2030 to meet its renewable energy goals. This investment would be used to build new transmission lines, upgrade existing ones, and improve the overall transmission and distribution system.

It is important to note that this is just an estimate and the actual cost and investment required may vary depending on the specific projects and plans implemented. Additionally, there are also other factors such as storage and integration which will be important for India to address to meet its renewable energy goals.

The Indian government has demonstrated its commitment to addressing these issues through the implementation of the Green Energy Corridor initiative. This project involved the construction of approximately 8,700 km of transmission lines and nearly 20,000 MVA of substations to facilitate the evacuation of over 20,000 MW of large-scale renewable power.

The Honourable Prime Minister of India Narendra Modi announced the 'One Sun One World One Grid (OSOWOG)' initiative at the first assembly of the International Solar Alliance in October 2018. The goal of the initiative is to connect energy supply across borders, primarily through the use of submarine cables due to India's geographical location, being surrounded by sea on its east, south, and west borders, and the world's highest mountains to its north. One of the key objectives of the initiative is to enable power transmission between countries, as the sun is always shining somewhere in the world. Solar power will be generated in one country and transmitted through power cables along the longitude.

2.1.3 Innovative Energy Systems

To optimise energy systems and deliver more consistent power to the grid, hybridisation has become a popular solution. Specifically, the combination of solar and wind energy systems, known as colocation, has been gaining significant attention. This can involve various methods, such as connecting a wind turbine and solar panel to a single power inverter or constructing a joint wind and solar farm.

Hybridisation of solar and wind energy has several benefits:

- It allows for the efficient use of land, as the same area can be used for both solar and wind energy generation.
- It can also help to increase the overall energy yield, as solar and wind energy tend to have complementary patterns of availability.
- It can also reduce the dependency on fossil-fuel-based power generation during the non-availability of one of the sources.

Hybrid systems can be further integrated with energy storage solutions to ensure that the energy generated is stored during low demand and consumed during high demand. This can help reduce the need for expensive grid upgrades, and can also provide a more reliable and stable source of electricity.

India has been exploring the potential of hybridisation of solar and wind energy, with several pilot projects currently underway. The government has also announced several policy measures to encourage the development of hybrid renewable energy systems in the country. A 350 MW tender from Adani Electricity Mumbai Limited

(AEML) was opened in 2019 and more recently Solar Energy Corp. of India (SECI) launched a 1.2 GW hybrid wind-solar tender. For the latter, there are strict criteria on the proportion of each energy system as well as for an energy storage system.

Co-locating wind and solar energy systems can provide a more stable, predictable, and dispatchable power output. The variability in power output due to cloud cover or gust changes can be levelled out to some extent when both systems work together. By locating the systems together, grid capacity can be reduced as power is more likely to be produced where it is needed. However, power still needs to be distributed from coastal areas with high wind speeds to inland areas.

Another possibility which is still at an early development stage is the hybridisation of floating solar energy with hydropower. The reservoirs of hydropower plants are used to build floating solar power plants. The combination of the two energy sources gives more robust energy systems, especially to climate change. Some of the key benefits of this system are:

- Seasonal complementarity: Dry periods enhance the production of solar energy while rainy seasons will increase power production from the dam.
- Floating solar plants reduce the evaporation of water and increase the amount of water available for the hydro-power plant.
- Daily variations and infrastructure: The combination of the two sources optimally uses the existing infrastructure for evacuating the power and gives a 24/7 power production.

2.1.4 The Role of Green Hydrogen on Energy Systems

The establishment of renewable energy plants that will power the production of green hydrogen or green ammonia before 2025 will be granted free inter-state power transmission for 25 years. This incentive will enable developers to install their plants in locations with the best natural resources, and it is a significant step towards the development of the green hydrogen economy in the country. However, one possible drawback is that it could further strain the grid and potentially lead to increased curtailment of power.

To produce green hydrogen, the electricity used must come from 100% renewable or decarbonised sources, which can only be achieved by connecting an electrolyser to a renewable energy source. It is unlikely that India will fully decarbonise its electricity mix in the near future. Recent studies in Germany have shown that co-locating an electrolyser with a combination of solar and onshore wind generation is the most cost-effective method. Large hybrid solar and wind power plants are likely to emerge in the future to produce green hydrogen or ammonia. Geographical locations with the best solar and wind resources and good complementarity between the two will become India's hydrogen hub. The government has approved a $2.3 billion scheme to support the production, use, and export of green hydrogen, with the aim of making India a global hub for this nascent industry. The hydrogen will be used domestically and exported as well.

The hydrogen economy will therefore rely on and test the knowledge acquired from the existing energy systems in India and around the world. The focus of future renewable energy plants will not only be on producing electricity at the lowest cost, but also on utilising intelligent energy systems to provide more consistent and predictable power.

2.1.5 Industrial Symbiosis

Enhancing the sustainability of green hydrogen production can be achieved through the concept of industrial symbiosis. Industrial symbiosis involves sharing resources, such as heat, water, and materials, among different industries to reduce the overall environmental impact and increase system efficiency.

This section explores the potential for industrial symbiosis in green hydrogen production, examining different types of symbiosis, such as heat integration and material sharing, and their potential benefits. We also provide examples of industrial symbiosis implemented in green hydrogen production, highlighting both the

successes and challenges.
Furthermore, we will investigate the potential for industrial symbiosis in green hydrogen production to create circular economy systems, where waste from one process becomes the raw material for another. This approach allows for the utilisation of waste streams and by-products from other industries, making green hydrogen production more sustainable and economically feasible. In this section, we will explore how industrial symbiosis can contribute to circular economy systems in green hydrogen production and provide examples of successful implementations.

Additionally, the potential for co-locating green hydrogen production with other industries, such as refining and chemical production, will be discussed. This approach can enable the sharing of infrastructure and resources, thus reducing costs and increasing the efficiency of the entire system.

Overall, this chapter aims to provide an overview of the opportunities and challenges associated with industrial symbiosis in green hydrogen production, and to demonstrate how this approach can contribute to a more sustainable energy system. It should be noted that in order to be able to utilise the waste heat, the right infrastructure and equipment must be in place to capture and transport the heat to where it is needed.

2.1.6 Waste Heat

Due to the efficiency losses that occur during the process of hydrogen generation in electrolysers, heat is produced as a by-product. When the electrolyser operates above the thermo neutral voltage, losses are generated in the form of heat. To ensure optimal operation and durability, electrolysers are usually water-cooled. Heat pumps can be incorporated into the system to convert the low-temperature heat source into a higher-heat sink temperature using a refrigerant. Typically, PEM and alkaline electrolysers operate at a temperature of 80 °C. Depending on the application of the waste heat, a heat pump can increase this temperature to over 100 °C. In other applications, a heat exchanger can be used to raise the temperature of an external heat supply. The research on the management of heat produced during PEM electrolysis has shown that a significant portion of the heat generated can be extracted through a dedicated cooling system, increasing the efficiency of the electrolysis process. For instance, a study conducted by TU Delft revealed that a 290-KW electrolyser could extract 92% of the heat produced through a cooling circuit, leading to a 14% increase in efficiency. However, further analysis is required to identify potential uses for the excess heat generated.

Other studies, such as the Power to Hydrogen and Heat (P2HH) analysis[1], have also explored the potential use of electrolysers to not only produce hydrogen, but also to provide heat. Additionally, research on mass manufacturing of PEM electrolysers[2] has shown that an increase in production volumes can lead to a significant reduction in costs.

Modelling tools like Aspen Plus have also been used to develop models of small electrolysers[3], but these studies have not focused on the utilisation of excess heat. A challenge for the PtG technology is to optimise the duration of electrolysis and utilise any excess heat produced during operation. Depending on the location, infrastructure availability, and hydrogen technology used, there are several options for utilising the waste heat generated.

The waste heat produced during electrolysis can be utilised to provide district heating or cooling to nearby buildings, which can increase comfort for occupants while reducing energy costs and environmental impact. In district heating systems, a central boiler or heat exchanger generates hot water or steam, which is then transported to buildings through a network of pipes. District cooling systems operate similarly but generate chilled water to cool buildings.

Industrial processes: Waste heat can also be used to power industrial processes, such as drying or heating materials. This can help reduce energy costs and environmental impact while improving efficiency and productivity. For instance, waste heat can dry materials like timber, paper, or textiles or heat materials such as metals, ceramics, or plastics during manufacturing processes.

Greenhouses: Moreover, the waste heat produced can be utilised to heat greenhouses and grow crops. This can reduce energy costs associated with crop cultivation and even extend the growing season for certain crops.

Power generation: The excess heat produced during PEM electrolysis can be utilised to generate electricity by means of cogeneration or combined heat and power (CHP). In cogeneration systems, a heat engine, such as a gas turbine or reciprocating engine, is used to convert the heat energy into mechanical energy, which is then used to generate electricity. This approach not only improves the overall efficiency of the PEM electrolysis process, but also provides an additional source of electricity.

Desalination: Seawater can be desalinated with the help of waste heat, making it suitable for irrigation and drinking. Desalination is the process of purifying seawater to make it appropriate for irrigation and human consumption by removing dissolved salts and other pollutants. Before passing through a membrane or another desalination method, the seawater can be heated using the waste heat.

Algae cultivation: Algae, which belong to a category of microorganisms, can be cultivated in large amounts using uncomplicated techniques, utilising the extra heat generated during electrolysis. These algae have versatile uses such as the production of biofuels, as well as being a source of food and nutrients, among other products.

Aquaculture: The excess heat resulting from electrolysis can be utilised to warm up aquaculture systems that are employed for rearing aquatic organisms, such as fish, shellfish, and seaweed. Aquaculture, which involves the cultivation of marine life, can benefit from the waste heat by elevating the water temperature, potentially enhancing the growth and survival rates of aquatic species.

Bitumen production: The waste heat generated during PEM electrolysis can be used to produce bitumen and other asphalt products, which can be used in road construction and other industrial applications. Bitumen is a type of asphalt that is used in road construction and other industrial applications. The waste heat can be employed to heat the substances needed to generate bitumen, leading to enhanced efficiency and quality in the production process.

2.1.7 Oxygen

Water electrolysis produces 8 kg of oxygen and 1 kg of hydrogen, and while the oxygen is typically released into the atmosphere, there exist alternative ways to use the gas in various sectors. However, it is important to ensure that the cost of producing and transporting the oxygen is economically feasible compared to other methods like pressure swing adsorption or fractional distillation. Therefore, it may be necessary to co-locate production and utilization facilities. Some opportunities for oxygen utilisation are listed below:

Industrial processes: Oxygen is a versatile element that finds applications in multiple industries, including steel and glass manufacturing, chemical synthesis, and wastewater treatment. In the steel-making process, oxygen aids in the elimination of impurities from molten steel, enhancing its durability and quality. In glass production, it helps regulate the burning of fuel used for heating the glass. In chemical synthesis, it functions as a key reactant for many chemical reactions.

Oxy-fuel combustion: Oxygen is employable in oxy-fuel combustion, which involves burning fuel

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[1] Li et al., “Operation Optimization of Power to Hydrogen and Heat (P2HH) in ADN Coordinated With the District Heating Network.”

[2] Burrin et al., “A Combined Heat and Green Hydrogen (CHH) Generator Integrated with a Heat Network.”

[3] Botsis, Vasileios, “Development of a Stationary and a Preliminary Dynamic Model for Proton Exchange Membrane (PEM) Electrolyser”; Sánchez et al., “Aspen Plus Model of an Alkaline Electrolysis System for Hydrogen Production.”

using pure oxygen rather than air. This method can lead to increased combustion efficiency and reduced emissions, as the combustion process is more thorough. The utilisation of oxygen in combustion processes that capture CO_2 can significantly improve the efficiency of these processes, due to its effects on gas streams.

Medical and healthcare: Oxygen is a vital component in many medical and healthcare applications, including respiratory therapy and anaesthesia.

Research and Development: Oxygen can be used in R&D activities such as in labs, to study and conduct research on materials, chemical reactions, and other phenomena that require a high-purity oxygen environment.

Aquaculture: The presence of oxygen is crucial for the survival of fish and other aquatic creatures in aquaculture systems. In this industry, oxygen is essential for sustaining a healthy environment that promotes the wellbeing of the fish and other aquatic animals.

Water treatment: Oxygen can be used in water treatment processes, such as aeration, which helps to remove impurities from water and improve its overall quality. It is used to oxidize pollutants, and to promote the growth of beneficial microorganisms that can break down pollutants.

Environmental applications: Oxygen can be used in environmental applications such as in remediation of contaminated soil, or treatment of contaminated water. In these applications, oxygen is used to promote the growth of microorganisms that can degrade pollutants and clean up the environment.

2.1.8 Sector Coupling

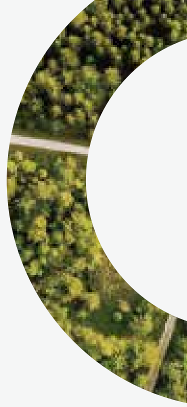
The production of green hydrogen can act as a catalyst for the emergence of new industrial symbiosis. Due to its status as both a chemical and an energy carrier, green hydrogen has a broad range of potential uses. However, achieving high efficiencies and obtaining valuable side streams may provide a significant incentive for circularity by design. Nevertheless, capital investment and planning are necessary to take full advantage of synergies with other sectors and applications.

Establishing the commercial feasibility of such industrial symbiosis can often be challenging, and the return on investment may not be immediate. Therefore, recognising opportunities and promoting collaboration across different industries are crucial for creating these synergies.

Green hydrogen production can provide economic benefits and employment opportunities for local communities, especially in the rural areas. By establishing green hydrogen production facilities, rural communities can experience an economic revival. Additionally, primary sector coupling, which involves integrating green hydrogen production with agricultural practices, can increase food availability and diversify agricultural practices, further contributing to economic growth in rural areas.

2.1.9 Conclusion

To successfully transition to sustainable energy systems in India and globally, it is important to acknowledge and consider the challenges that come with it. This includes issues such as the increased use of intermittent energy sources, uncertainty around energy costs, and greater demand for infrastructure. However, a comprehensive approach that considers multiple technologies, hybridisation, and industrial symbiosis can increase the likelihood of a successful green transition.



2.2

Solar Energy Technologies and Potentials

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Nature goes her own way
and all that to us seems
an exception is really
according to order.

Johann Wolfgang von Goethe

Abstract

The use of solar energy is expected to increase to approximately 27.7% of the total usable energy by 2050, as part of a worldwide initiative to achieve net-zero emissions and prevent global warming. The amount of energy reaching the earth's surface from the sun is more than ten thousand times the world's energy needs. There are many areas on earth where there is sufficient solar irradiation available for proper harnessing and use. Solar panels can be used to harvest solar energy, which is provided by the sun free of cost. Nowadays, there are public investments available worldwide in the solar energy sector, and India is also investing heavily in this sector as it receives sufficient sunshine throughout the year.

However, the solar energy sector faces several challenges, such as limited energy efficiency of around 20%, supply chain constraints due to materials shortage, waste generated through solar panels, leading to environmental and health issues, and complex and expensive recycling processes. To address these challenges, research is going on to develop better materials and devices for improved efficiency, durability, and cost-effectiveness. One approach to enhance solar cell efficiency is to use a different type of multilayer to absorb various wavelengths of light. Light concentrators are also recommended to focus the light and increase solar cell efficiency.

Tandem solar cell structures combining silicon and perovskite have shown the highest efficiency of around 32.5%, which can complement the established silicon technology. However, silicon-perovskite tandem solar cells face issues such as degradation and scaling that require attention before commercialisation. Several emerging PV technologies such as organic solar cell (OSCs), perovskite, and DSSC have also been developed, but these technologies face device stability and reproducibility issues.

Solar cells can be broadly divided into three generations based on their development: first generation (silicon wafer-based solar cells), second generation (thin film-based solar cells), and third generation (emerging solar cells). The first- and second-generation solar cell technologies have already been commercialised, and the third-generation solar cell has the potential to be the cost-effective PV technology of the future. This chapter will discuss these solar cells in detail, along with some applications of solar thermal briefly.

2.2.1 Introduction

Ensuring energy sustainability is crucial for a country's progress, as it supports industrialisation, urbanisation, economic growth, and overall enhancement of living standards. With the world experiencing rapid industrial and population growth, there is a significant rise in energy demand. Thus, it has become crucial to provide clean and affordable energy for both domestic and industrial purposes while also preserving the ecological balance. Each country needs to devise its strategies and policies to address this issue.

The world's conventional non-renewable energy sources are depleting rapidly and also causing harm to the environment by releasing CO_2 and other pollutants, which have reached dangerous levels and pose a threat of climate change and natural disasters. Due to the increasing demand for energy and the high cost of conventional sources, it has become imperative to explore sustainable, nonconventional, eco-friendly alternative energy sources that can keep the environment pollution-free (Shafee and Topal, 2009; Kannan and Vakeesan, 2016).

Energy consumption is crucial for modern society and is equivalent to food for humans. Energy is used for various purposes like heating homes, transportation, manufacturing goods, communication, food production, and even reading this chapter. Energy cannot be produced; it can only be converted from one form to another to make it more usable. Many different methods for energy conversion have been developed by humanity. The most prosperous and technologically advanced countries consume the most energy per person. However, their economies are relatively stable and do not show rapid growth, which would further increase power consumption.

The World Energy Outlook (WEO)[2] states that developing countries have a 30% increase in energy consumption and a high birth rate, contributing to the global population growth. As of May 2017, the world population was 7.5 billion[3] and consumed 12.3 TW of power[4]. By 2050, the global population is projected to reach 10 billion[5-6] with an estimated energy need of 18-20 TW or 16-18 billion tonne of oil equivalent (toe) (1 toe = 11.63 MW)[4]. This poses a supply-demand energy challenge, which can be addressed by increasing total energy production[1].

The second challenge we face is that our energy infrastructure heavily relies on fossil fuels such as oil, coal, and gas. Due to our high consumption, these resources will become depleted soon. In addition, the combustion of fossil fuels releases greenhouse gases (GHGs) such as carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur fluoride into the atmosphere. This has resulted in the increased trapping of insolation in the atmosphere, causing the Earth's global average temperature to rise by around 1°C between 1885 and 2016.

The rise in temperature has various impacts such as the elevation of sea levels, which puts major cities like New York and Mumbai at the risk of flooding. There is also an increase in the occurrence of extreme weather events, and a negative impact on agricultural productivity in lower latitude regions due to disruptions in climate patterns. The retreat of glaciers, like Arctic sea ice, worsens the situation by increasing GHG emissions. The increase in ocean temperatures forces fish to migrate to higher latitudes, leading to acidification of oceans and coral bleaching, which affects human health[7-11]. There are concerns that the human species itself could face extinction in the not-so-distant future. This is because the survival and extinction of humanity is connected to the health of the planet's ecosystem, which seems to be on an irreversible decline. These predictions are based on educated speculations[12].

All these horrific changes are in part due to consumption of fossil fuels which emits GHGs as undesirable by-products[13]. These changes forced world leaders to engage in discussions to take coordinated measures to reduce consumption of fossil fuels in particular and stop climate change in its tracks. At the 21st Conference of Parties, world leaders committed themselves to holding the global average temperature increase to well below 2°C above pre-industrial levels and pursue efforts to limit the increase to 1.5 °C[14].

2.2.2 Solar PV Technologies and Potentials

Photovoltaic technology converts sunlight into electricity directly using the photovoltaic effect, which generates voltage and electric current in a material when it is exposed to light. These devices consist of p-n junctions made from semiconductor materials. Essentially, these devices work by giving additional energy (photoenergy) to activate electrons, which move from a lower energy state (valence band) to a higher energy state (conduction band) when exposed to sunlight. This process creates a number of holes and frees electrons in the semiconductor material. The electron-hole pair is separated by an in-built junction field and then collected by metal electrodes at the top and bottom of the device, resulting in the production of electricity.

Despite the simplicity of the design of PV devices, there is room for improvement to increase their effectiveness (Green, 2000). The first generation of solar cells and photovoltaic devices used mono-crystalline, poly-crystalline, and multi-crystalline silicon, while the second generation incorporated amorphous and microcrystalline silicon, copper indium diselenide, copper zinc tin sulphide, and cadmium telluride thin film. Third-generation PV devices based on organic semiconductors and perovskites are also gaining attention, although they are still in the research and development stage and currently lack efficiency and stability. The choice of materials is influenced by various factors such as cost, availability, technological complexity, and efficiency. However, the global PV industry is currently dominated by flat-plate PV systems based on silicon solar cell technology, which holds more than 90% of the market share (Razykov et al., 2011).

Solar Photovoltaics as an Alternative Energy Source

To effectively reduce GHG emissions, it is important to consider the desire of developing and underdeveloped nations to achieve living standards similar to those of the resource-intensive industrialised nations, which place a significant emphasis on energy consumption. Therefore, humanity must not only seek alternative and environmentally friendly energy sources to combat climate change, but also transition to a socio-economic system in which the marginal environmental cost of economic growth decreases over time. Achieving the former objective involves utilising renewable energy sources that do not emit GHGs.

Renewable energy sources have the potential to address the challenges outlined above. These are energy sources that can be replenished by natural processes at a rate comparable to or faster than human consumption. Examples of renewable energy resources include hydro, wind, and solar energy. However, certain sources such as hydroelectricity and nuclear power are not trusted by the public due to understandable safety concerns. The Fukushima Daichi nuclear plant accident in Japan has exacerbated public distrust of nuclear power. In addition, the increasing frequency of extreme weather events poses a significant risk to the viability of dams and hydroelectric power plants, which are also vulnerable to geological activities.

Nuclear energy is a potential alternative to traditional sources of power, as it produces low carbon emissions and is considered a clean source of energy. However, the inherent threat of radioactive hazard must be taken into account. Biomass is also a well-utilised source of energy, but it generates harmful gases. Other renewable energy sources, such as hydro-power, wind, geothermal, and tidal energy, have significant potential, but their use is limited due to various factors. For example, wind energy requires tall turbines with long blades spread over a large area, which may not be practical to meet the balance between energy supply and demand.

Solar energy may be the most potential alternative to fossil fuel, as it is virtually cost-free and an infinite, clean, reliable, and renewable source that can meet the world's future energy demands. The sun emits energy at a rate of 3.8x1023 kW, of which the Earth captures approximately 1.8x1014 kW (Panwar et al., 2011). There are two technological solutions available to harvest solar energy: solar thermal and solar photovoltaic (PV), which convert solar radiation energy into thermal and electrical energy, respectively. Solar PV devices have greater potential as they convert solar energy directly into electricity, evident from the remarkable growth of the PV industry, with an average increase of more than 40% in the last 15 years (Armaroli and Balzani, 2007; Kropp, 2009). The efficiency of solar PV devices is determined by the intensity and distribution of solar radiation. Solar PV systems do not cause noise pollution and can be used anywhere, including remote places, to generate power ranging from milliwatts to several megawatts. The deployment of PV systems worldwide for the effective utilisation of solar energy is rapidly increasing.

The earth receives a continuous influx of around 173,000 TW of solar energy, which is over 10,000 times the planet's total energy consumption[15]. Thus, the only requirement is the technological capability to harness it. Solar energy, especially solar PV, has emerged as a mature and trustworthy technology within the broader spectrum of renewable energy technologies. That's why it has witnessed an average annual growth rate of 50% in recent years[16]. Solar PV is particularly important in solar energy technologies since it is much easier to install at the individual or household level, and the entire power evacuation infrastructure is not needed, which requires huge upfront capital investment.

The cost of solar cell electricity can be reduced by decreasing production costs and increasing power output. To be competitive, the cost of modules should be below $1/W and the price of cells should be below 30 cents/W. The global PV industry has been experiencing rapid growth, with a global installed capacity of 97.5 GWp in 2017 alone and a cumulative installed capacity of 405 GWp at the end of 2017[17]. The industry has had a compound annual growth rate of approximately 24% from 2010 to 2018 and reached 505 GWp by the end of 2018[18]. Although the annual global market for PV only increased slightly in 2018, it was enough to surpass the 100 GWp level (including on- and off-grid capacity) for the first time. This is a significant increase compared to the global total of around 15 GWp only a decade earlier (See Fig. 1).

Despite the single-digit growth rate of the global market in 2018, solar PV has become the world's fastest-growing energy technology, with gigawatt-scale markets in an increasing number of countries. Demand for solar PV is spreading and expanding as it becomes the most competitive option for electricity generation in a growing number of markets – for residential and commercial applications and increasingly for utility projects[18].

Why Silicon Photovoltaic?

Silicon-based solar photovoltaic (SPV) has emerged as one of the most attractive pillars of clean energy architecture for four main reasons. Firstly, it offers stable power output for over two decades. Secondly, silicon is the second most-abundant material in the earth's crust. Thirdly, silicon is non-toxic in bulk. Finally, technical know-how for silicon is readily available due to pioneering efforts by the microelectronics industry. Despite initial promises, thin-film-based solar cells have not lived up to expectations, and the SPV market is still dominated by crystalline and multi-crystalline silicon-based solar cells.

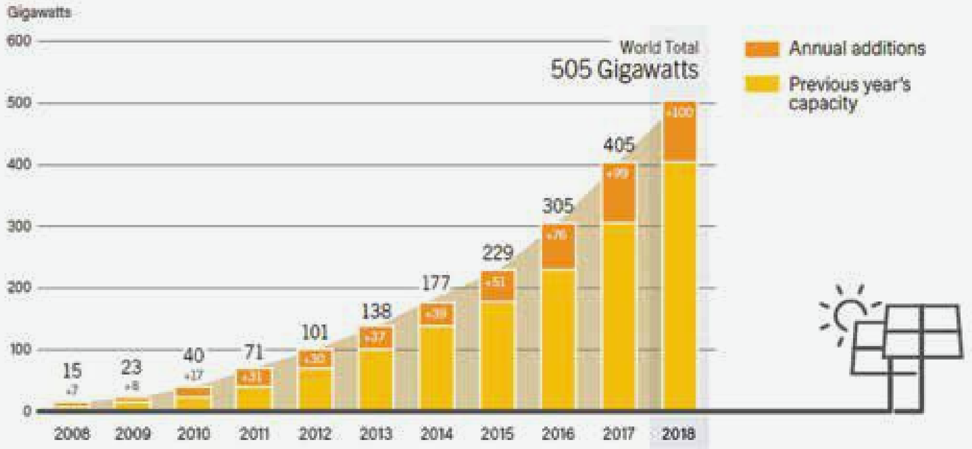


Fig. 1 Solar PV global capacity and annual addition, 2008-2018[18]

In recent times, due to price reductions across the entire value chain and a larger packing fraction of multi-crystalline silicon solar cells at the module level, multi-crystalline silicon-based solar cells are outpacing single-crystalline silicon-based solar cells, despite the latter having an edge at the cell level due to recombination in the former at the grain boundaries, for a similar level of technology deployment. Fig. 2(a) shows the price trend for silicon-based solar cells, which has fallen since 1977. The cumulative PV capacity over the last decades allowed for a reduction in PV module costs, which is represented as the logarithmic Swanson's Law learning curve in Fig. 2(b).

The price drop for silicon over time became possible due to the fact that Si has dominated materials and technology in the semiconductor and photovoltaic industries for several decades. Si currently holds over 90% of the total PV market, with its shares split between different Si-based technologies, including multi-crystalline Si (mc-Si) (60.8%), monocrystalline Si (c-Si) (32.2%), and amorphous Si (a-Si) (0.3%) in 2017, as shown in Figure 3[17]. The total share of thin film technologies is 4.5%, with CdTe having the largest share (2.3%), followed by CiGS (1.9%), and a-Si (0.3%) having the smallest share. These significant market shares have led to the development of various technologies.

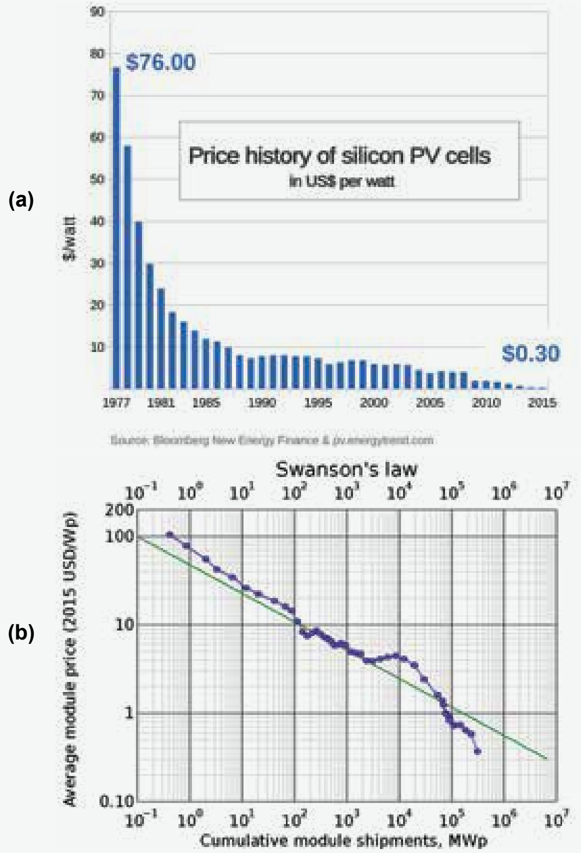


Fig. 2 (a): Price reduction for silicon PV cells since mass production started in 1977 till 2015, (b): Swanson's learning curve for silicon Si PV modules[20]

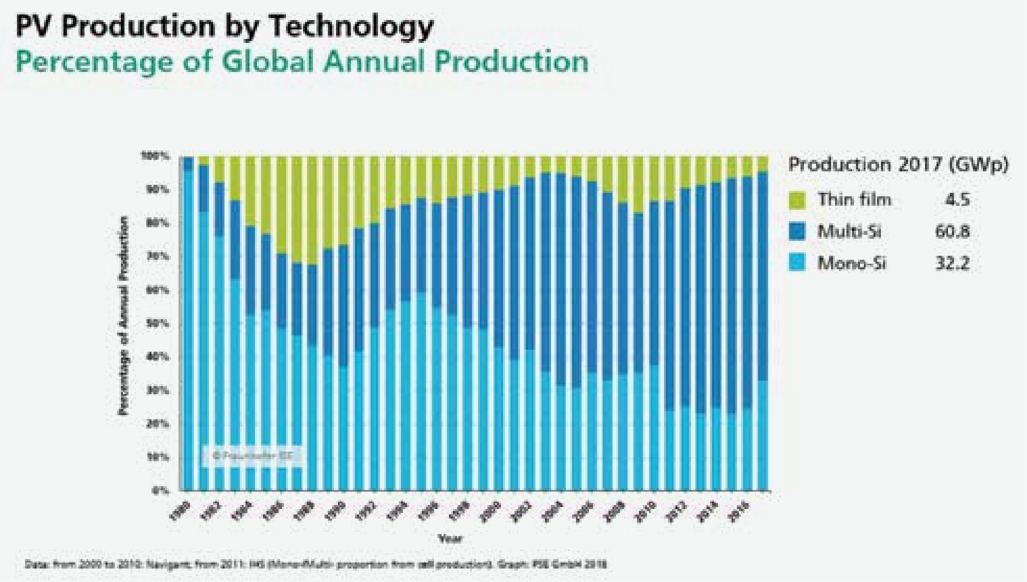


Fig. 3: Global PV production by technology: Percentage of global annual production of PV by technology (from 1980- to 2017)[17]

Many different promising PV technologies offer a combination of high-power conversion efficiency and low production cost. However, Si has enormous potential for further use in the PV industry. The development of new technologies that can optimise efficiency, reduce production cost, or both will keep Si as the dominant technology in the PV market for several decades. Therefore, Si solar cells are the most promising technology as a renewable energy source, guaranteeing a sustainable future for us and future generations.

Solar cell basic structure

The basic structure of a typical p-n junction silicon solar cell is schematically shown in Fig. 4(a). Extensive research has been conducted on solar cells, and their operation is well understood. A device must possess three properties to function as a solar cell:

- The ability to absorb incident radiation to generate excess, unbound, and mobile electron-hole pairs.
- A steady population of electrons and holes must be maintained by suppressing their recombination before they are collected.
- The electron-hole pairs must be spatially separated in the space charge region (diffused p-n junction) or Schottky junction and eventually collected by the electron and hole collection terminals to drive current through the external circuit.

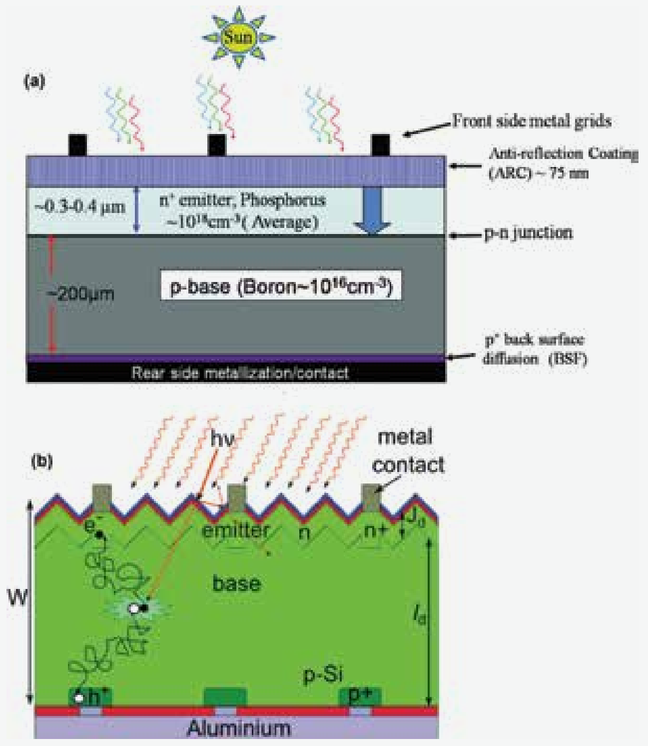


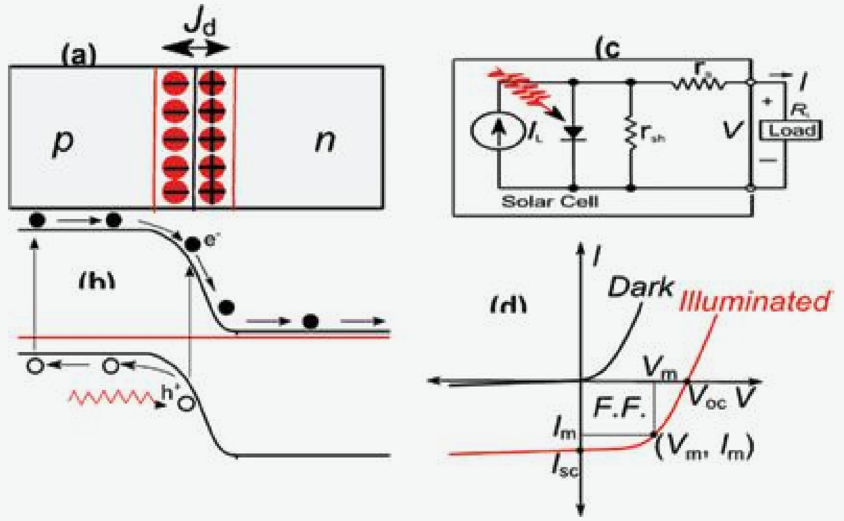
Fig. 4 (a) Schematic of a typical basic structure of flat-plate (planar) p-n junction silicon solar cell. All the layers are labelled. (b) Schematic of an advanced Si solar cell with ARC and surface (µ-pyramids) texturing.

In this scheme, typical cell thickness, W ~200 µm, is used to absorb the light and the charge carriers collection is primarily from the diffusion region (l_d) where $l_d >> J_d$, the junction drift region. Further, the light absorption and carriers collection are in the same direction (longitudinal to the solar cell surface). Also, concept of front and back surface passivation is employed. Instead of full area BSF, localised BSF (p+) is used in the rear. And selective emitter (high doping under the metal contacts and relatively light doping in light active regions) is also used. Fig4.(b): Reprinted/adapted by permission from Springer: Ref.[26], Copyright (2016).

The quality or performance solar cell is evaluated by using its dark and illuminated I-V (or J-V) characteristics. There are different performance parameters such as open circuit voltage, short-circuit current, fill factor, dark saturation current, maximum power point, and power conversion efficiency (PCE).

The principle of solar cell operation can be understood from Fig. 5. It is based on an unbiased p-n junction diode connected to a load (R_L) to generate power[22-23]. At the junction of the p- and n-type semiconductors, there is a region of high (built-in) electric field known as the depletion region (labelled as Jd). Here, photo-generated charge carriers (electrons and holes) are separated by the built-in electric field, producing a current. Additionally, carriers generated within a minority charge carrier diffusion length (ld) of the depletion region in either the p- or n-type regions can be collected at the junction and contribute to the total current.

The key criteria for efficient solar cells are high absorption of the incident light in the active region of carrier collection and minimal loss of carriers due to recombination (bulk and surface defects).



Conventional wafers-based crystalline silicon solar cells rely primarily on thick diffusion regions (~200 µm), compared to the much thinner drift region (J_d), for carrier collection as schematically illustrated in Fig. 4(b). This scheme is necessary due to the poor light absorption of silicon across the solar spectrum[22]. Therefore, relatively thick silicon is used to effectively absorb the incident light in a wide spectral range.

However, as illustrated in the cross-sectional view of typical high efficiency planar silicon solar cell geometry (Fig. 4(b)), the charge carriers generated away from the junction have to diffuse long distance to reach the junction (without recombination) for collection, therefore, requires large diffusion length. This requirement restricts the quality of the silicon materials to be reasonably high. Thus, high-efficiency silicon solar cells require defect-free material with long minority carrier lifetimes (or large diffusion lengths). The current record efficiency under terrestrial illumination conditions (AM 1.5 G, 100 mW/cm^2) for silicon solar cell is 26.7%[21]. This efficiency is quite close to the maximum theoretical efficiency ~31% predicted for a single junction solar cell by Shockley-Queisser, also known as Shockley-Queisser limit[22]. However, the fabrication costs are quite high for such record efficiency cells. Commercial silicon solar cells' efficiency typically range from~17 to 23% depending on solar cell structure and design[21-24, 25.]

Fig. 5(a) depicts a schematic of a p–n junction showing the depletion region (Jd) with ionised immobile dopant charges, while Fig. 5(b) shows the corresponding energy-band diagram. Incident light creates an electron-hole pair that is swept across the junction by the built-in drift electric field to the charge-neutral regions.

Fig. 5(c) shows an equivalent circuit of a practical solar cell connected to an external load (RL), with parasitic resistances (series, rs, and shunt, rsh), also illustrated. Fig. 5(d) shows typical I-V characteristics of a p-n junction solar cell under dark and illumination conditions, with the solar cell's basic performance parameters also indicated in the I-V characteristics. Reprinted/adapted by permission from Ref.[26], Copyright (2016) by Springer.

Solar cell basic parameters:
The expression for net current (I) flowing across the load can be expressed as,

$$I = I_L - I_0\{\exp(q(V+Ir_s)/nkT)-1\} - (V+Ir_s)/r_{sh}\}$$

I_{SC}: Short circuit current; J_{sc}: Short circuit current density
I_L: light generated current,
I_0: dark saturation current,
$V_{OC} = kT/q\{\ln(I_L/I_o)+1\}$: open circuit voltage {since at V_{oc}, I=0)
Where, k is Boltzman's constant, T temperature in Kelvin, q is the electronic charge.
V_m and I_m: Operating point yielding the maximum power output.
Fill Factor (F.F.) = $V_m I_m / V_{OC} I_{SC}$

Power conversion efficiency (η):
$\eta = P_{max}/P_{in} = V_m I_m/P_{in} = F.F. V_{OC} I_{SC} / P_{in}$

In solar cell operation, the key aim is generally to generate power by (1) generating a large short-circuit current, Isc, (2) a large open-circuit voltage, Voc, and (3) minimising parasitic power-loss mechanisms (particularly series and shunt resistances) to maximise the fill factor (FF)[22, 23].

Silicon Solar cell Technologies and their Status
This section will provide an overview of different Si-based solar cell technologies, their latest status, and future prospects.

Several high-efficiency solar cell technologies based on advanced cell structures have been developed and improved over the years. These technologies offer several advantages and potential cost reductions. However, the PV industry is still dominated by conventional screen-printed industrial solar cells. The high-efficiency cell technologies, such as HIT and IBC cells, also have a significant role to play. The PERC concept is now being adopted rapidly in the PV industry.

The state-of-the-art efficiency performance of the different high-efficiency cell technologies:

- Al-BSF based Screen Printed solar cell technology: Overview of process and technology (mono and multi):
  Below figure displays the schematic structure of such a solar cell based on a p-type crystalline silicon wafer, with a front phosphorus diffusion and a back aluminium-doped region. The choice of p-type material for the classic dopant-diffused homojunction silicon solar cell stems from both historical and technological reasons. In the 1950s, silicon solar cells were first used to power satellites, where p-type cells offered improved space radiation hardness compared to their n-type counterparts. This n+pp+ solar cell structure has historically been referred to as BSF or back surface field or Al-BSF and is also known as screen-printed solar cells []. The most widely used industrial fabrication method for wafer-based silicon solar cells is described below.

Silicon solar cell manufacturing typically starts with chemical etching and surface texturing of the wafers [B1:74]. Usually, texturing is achieved by immersion of the wafers in a wet chemical bath, yielding identically textured surfaces at the front and back surfaces. The same step also removes several mm of damaged material resulting from the wire sawing. Potassium hydroxide (KOH) etching of (100)-oriented monocrystalline silicon wafers is anisotropic and results in randomly sized square pyramids with (111) faces, [B2:75] which reflect and refract the incident light at oblique angles, resulting in excellent antireflection and light trapping properties[B3:76].

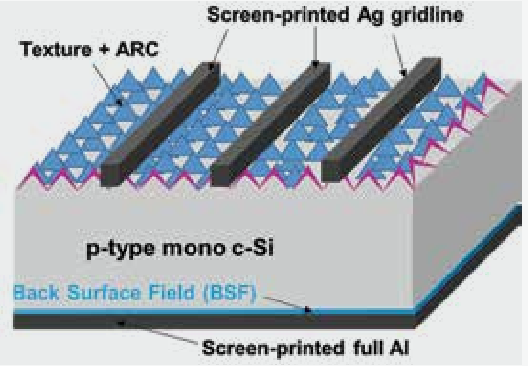


Fig. 6: Typical structure of an Al-BSF solar cell schematic

Texturing of multi-crystalline silicon, which has grains of many different orientations, requires isotropic wet etching, typically using acidic solutions [B4-B7:77-80]. The reflectance of multi-crystalline wafers after acidic texturing is higher than that of monocrystalline silicon after alkaline texturing. However, after the deposition of an antireflection coating and encapsulation under glass in the module, the total photogeneration in a multi-crystalline cell can reach 99% of that in a monocrystalline cell [B8:81]. Various types of submicron texture have been proposed to further improve reflectance for multi-crystalline wafers [B9-B10: 82,83]. Plasma texturing has also yielded very good results [B11:31].

After surface texturing (particularly after alkaline etching), the wafers need to be cleaned. Several strategies, usually involving at least two steps, are possible. First, a chemically oxidising agent, such as an acidic peroxide solution, forms an oxide that "encapsulates" potentially harmful impurities present on the surface. After rinsing in de-ionised water, the oxide is removed with a reducing chemical, typically hydrofluoric acid, resulting in relatively inert (111) surfaces with hydrogen termination [B12:84]. The wafers are now ready for dopant diffusion, typically with phosphorus for a typical p-type silicon wafer or with boron if an n-type wafer is used.

The diffusion process involves exposing wafers to a gas mixture containing phosphorus atoms in high-temperature quartz furnaces. This gas mixture usually consists of nitrogen saturated with phosphorus oxychloride (POCl3) and a small amount of oxygen to allow the growth of a phosphorus-silica glass on the wafer surfaces. The actual diffusion of the dopant atoms into the silicon wafer occurs from this glass. The temperatures used for diffusion are typically between 760 to 850 °C for phosphorus and slightly higher for boron. However, since the doping process is not selective, a diffused region is also created on the edges and rear of the wafer which must be etched off later. The resulting n+-type layer typically has a sheet resistance of between 50 and 100 Ohm/square. After diffusion, hydrofluoric acid is used to etch the phosphorus-silica glass, and a small amount of silicon can also be etched to adjust the sheet resistance if necessary.

The main reason for creating a diffused region is to enable charge separation. This is achieved by creating an electron-selective contact or transport region at the front surface of the n+-type layer, where the concentration of electrons is much higher than that of holes. It is desirable to have a high concentration of phosphorus to achieve this but exceeding the maximum electrically active concentration of about 3 × 1020 cm^3 can cause negative electronic effects such as band gap narrowing and three-particle Auger recombination [B13-B15:85–87]. These effects can draw holes into the n+ region, reducing its selectivity and ability to block holes. Additionally, excess phosphorus can form precipitates that cause additional recombination. These processes not only limit the achievable voltage but also reduce the blue response of the solar cell [B14:86].

The n+ layer also serves the purpose of connecting the wafer absorber region to a metal electrode. To ensure a low contact resistance between the metal and the semiconductor, a high concentration of phosphorus (usually around 1×1020 cm^{-3}) is necessary to enable quantum-mechanical tunnelling across a thin potential barrier created by the differing electrochemical potentials of the materials [B16:88]. The typical method used in the industry, to achieve a low contact resistivity, is to implement a phosphorus diffusion process with a high surface concentration [B17:89], which produces a shallow junction depth of 0.2-0.3 μm to reduce absorption of ultraviolet and blue light and maintain a reasonable blue response. However, this diffusion process is vulnerable to surface recombination losses, so a passivating insulator is usually deposited to prevent these losses [B18:34].

Since the metal contact covers only a small portion of the front surface (about 5%), the diffused region also needs to enable horizontal movement of the collected electrons towards the metal fingers that create the front electrode. Balancing the various factors of carrier separation, surface and bulk recombination, and lateral current transport complicates the process of optimising the front dopant diffusion.

Phosphorus diffusion offers the additional advantage of impurity gettering. Briefly, gettering is the process where transition metals like iron, nickel, chromium, etc., [B19-B21:90–92] diffuse from the bulk of the wafer towards the phosphorus diffusion [B22, B23: 93,94]. Once they are in the highly doped n^+ surface region, these impurities are no longer harmful to device operation [B24:95]. This means that relatively impure, and thus cheaper, wafers can be used, making the complete cell process more cost effective. Phosphorus gettering has undoubtedly enabled the development of multi crystalline silicon solar cells.

Wafers are subsequently covered by an antireflection coating with a high transparency across the visible and infrared regions of the spectrum [B25, B26:96,97]. The refractive index of the coating should be the geometric mean of the refractive indices n of glass (n ~ 1.5) and silicon (n ~ 4 in the visible), while its optical thickness dictates the wavelength at which minimum reflection occurs, which for terrestrial application is preferentially set around 600 nm.98,99 Hydrogenated amorphous silicon nitride (thickness ≈ 75 nm, n ≈ 2 in the visible), often just called silicon nitride, deposited by plasma-enhanced chemical vapour deposition at intermediate temperatures (about 400 °C) has been very successful for this purpose [B27: 100]. Like the phosphorus diffusion, this layer has multiple functions. In addition to its antireflective properties, silicon nitride provides very efficient passivation of the phosphorus-doped surface [B18:34]. Combined with a moderately doped n^+ diffusion (sheet resistance of about 100 Ω/cm), it can result in low recombination current densities of 100 fA/cm^2 or less [B28:19].

Such excellent passivation is due mainly to hydrogen termination of silicon dangling bonds at the surface [B29:35]. In addition, silicon nitride layers contain a high positive fixed charge density (~10^{12} elementary charges per cm^2), [B30, B31: 101,102] which further increases the concentration of electrons and decreases that of holes at the surface, resulting in a reduced statistical probability of recombination, according to the Shockley-Read-Hall (SRH) model. Hydrogenated silicon nitride has an added beneficial effect for multi crystalline silicon wafers, as the hydrogen contained in these films is released into the silicon wafer during the so-called contact firing step at the end of the cell process [B4: 77, B32:103].

The beneficial effect of hydrogenation on defective Si was already established in 1980 [B33:104]. Firing of the front metal contact through the silicon nitride layers has proven to passivate defects in multi crystalline silicon wafers very effectively, and it complements the prior POCl3 gettering step [B34, B35:105,106]. The achievement of minority-carrier lifetimes exceeding 100 μs is attributed to a combination of techniques such as gettering, hydrogenation, and advancements in ingot growth technologies.

The front surface is completed by printing a set of silver finger gridlines (width 50-100 μm), typically connected by multiple busbars and covered by copper-tin stripes (width 1-2 mm), onto the antireflection coating. The printing paste comprises metal powder, glass frit binder material, and silicon nitride, which react and bind to the silicon wafer during firing at high temperature. As the wafer cools, the silver particles stick to the surface [B36-B39:107–110]. The width of the grid lines needs to be minimised to maximise the short-circuit current and minimise shading, but this comes with a trade-off between shading and resistive losses. It is crucial to reduce the metal/semiconductor contact fraction to achieve high voltage, but the contact fraction must be balanced against an increased contact resistance loss.

During the same firing-through step, the back contact is also formed. Usually, a screen-printed aluminium paste is applied over the full rear surface of the wafer [B36:107, B40-42:111–113]. During firing, the aluminium forms a eutectic melt with silicon, consuming a similar amount (about 5-20 μm) of silicon. This fully melts and compensates (over-dopes with aluminium) the parasitic n-type region formed at the rear during phosphorus diffusion. During cooldown, a heavily aluminium-doped p-type epitaxial silicon layer forms near the rear surface of the wafer.

In addition, this p-type region acts as a hole-selective contact to the p-type silicon absorber. Similar to what was observed above about the n^+ region, it would be desirable to implement a very high concentration of aluminium dopant atoms (hence of holes), but the solubility of aluminium in silicon is limited to about 1 ×10^{19} cm^{-3}. The selectivity of this contact region in terms of blocking electrons is limited by heavy-doping effects such as band gap narrowing [B43, B44: 114,115] and Auger recombination, [B45:116] whereas impurity and carrier–carrier scattering, which limit the minority-carrier mobility, are beneficial in this instance.

The presence of the eutectic mix on the wafer surface prevents the application of dielectric coatings to passivate the wafer, unless the mix is removed by etching. This can cause significant recombination losses. To prevent minority electrons from reaching the metal/silicon interface at the rear, a thick p+ layer is used to increase the total conductance for electrons. Aluminium-doped regions that are optimised can achieve a recombination current parameter J0 of around 500 fA/cm2, [B46:117] but a value of 1000 fA/cm^2 is more typical. The latter can be expressed in terms of an effective surface recombination velocity of about 1,000 cm/s (note that, for a given aluminium-doped region, the surface recombination velocity scales inversely with the dopant density of the wafer, in low injection).

The aluminium also acts as a back reflector, albeit a poor one [B47, B48:118,119] (that is made even worse by the alloying process), reflecting back into the silicon absorber a fraction of the infrared light that has not been fully absorbed during the previous passage through the silicon wafer [B49:120]. Silver-paste strips are usually printed on the rear to enable soldering to the copper interconnects, which ‘string’ the front grid of one cell to the back contact of the neighbouring cell in a module. Finally, the parasitic phosphorus diffusion present at the edges is removed by laser scribing around the perimeter of the wafer.

Following the fabrication of solar cells, each one undergoes individual testing and sorting based on its efficiency and current output. The latter is particularly crucial, as the cells are linked together in series to form strings, and each cell needs to contribute an equal current. The final step involves encapsulating the strings between a glass plate and a back sheet made of either PET or TPA, using a lamination process that involves melting an EVA sheet.

Silicon solar cells manufactured using the process explained previously, or its modifications, usually have efficiencies ranging from 18-19.5% for monocrystalline and 16-18% for mc-Si substrates. However, due to losses during interconnection, frame and other factors, the module efficiencies are generally 1.5-2% lower than the cell efficiencies, referred to as CTM (cell-to-module) loss.

Fig.7: Typical picture of modules of mono and multi-Si solar cells

Above figure provides the images of typical mono and poly (multi)-crystalline Si solar cells with 2-basbars (old technology) and with the current 4-busbars of screen-printed metal contacts technology.

Currently, mc-Si technology is the dominant technology in the PV market with a share of over 55% due to its simplicity and robustness. However, the price of silicon has decreased, and its electronic quality has improved in recent years, making c-Si more attractive for solar cell fabrication, with a current market share of about 35%. To fully exploit the advantages of using higher quality silicon, more advanced device designs and fabrication processes are required to ensure cost-effectiveness and high efficiency. The push for higher efficiency solar cells is driven by several factors, including lower balance of system costs, higher energy densities, and better performance at high temperatures and low illumination levels.

Although research and development on silicon solar cells can achieve efficiencies of over 25%, the production of industrial cells is limited by cost factors. The manufacturing processes that enable high efficiency often require expensive equipment and resources. Nevertheless, recognising the limitations of conventional processes has paved the way for new, innovative approaches that aim to achieve higher efficiencies at lower costs. Consequently, there are several advanced structured Si solar cell technologies that have been developed to improve efficiency, and these are briefly described below.

Passivated Emitter and Rear Cell (PERC) Technology

Limiting the proportion of Al alloyed p+ region to only 1-5% of the rear surface and passivating the rest with insulating material can have significant benefits in terms of electronics and optics. This approach is known as PERC, PERL or PERT and involves creating local contact openings on the insulator layer using laser ablation. An aluminium paste is then printed over the full rear surface and fired to form p+ regions within the openings. This method creates an almost perfect back surface mirror that benefits from the low refractive index material between the metal and the Si wafer, improving internal reflection. This approach avoids free carrier absorption in the traditional, uniformly doped p+ Al region. Laser-fired contacts use a similar method where local openings are made after the final rear metallisation.

By adapting and scaling up such concepts, the PV industry is currently developing similar cell designs. The first paper describing the PERC cell appeared in 1989 [[1: A.W. Blakers, A. Wang, A.M. Milne, J.Zhao, M.A. Green, 22.8% Efficient Silicon Solar Cell, Appl.Phys.Lett. 55 (1989)1363-1365.], although the structure was conceived several years earlier. The attractive technical features were the reduction of rear surface recombination by a combination of dielectric surface passivation and reduced metal/semiconductor contact area, while simultaneously increasing rear surface reflection by use of a dielectrically displaced rear metal reflector.

A comprehensive review of PERC solar cell technology has been reported by Martin A. Green, a photovoltaic technology expert, highlighting various aspects from the inception of the concept to the mass production of the cells. The review also describes the key issues and challenges in the development of this technology and its commercial implementation, including a review of recent adoption rates and how they are likely to evolve in the future. [M.A. Green, "The Passivated Emitter and Rear Cell (PERC): From Conception to Mass Production," Solar Energy Materials & Solar Cells 143 (2015) 190–197].

Manufacturers are now aiming for efficiencies beyond 20%, and the traditional Al-BSF method used for the past three decades is being replaced by a more efficient approach. While rear junction and heterojunction methods have achieved high efficiency in production, they rely on specialised, high-quality n-type monocrystalline wafers (to be discussed in the subsequent sections). On the other hand, the PERC cell approach can work with both monocrystalline and multi crystalline substrates of any polarity, while achieving similar efficiencies to the aforementioned methods on high-quality substrates.

This technology's robustness and compatibility with existing production lines have helped it surpass the standard approach in terms of capacity share by 2020 (as reported by source [39] and to be confirmed by ITRPV2020, 21 and 2022). The adoption of PERC technology is expected to accelerate the increase in silicon solar cell performance as its full potential is yet to be realised. Just as commercial solar cell efficiencies have surpassed the best laboratory Al-BSF solar cells, it is expected that the PERC technology will also approach laboratory cell efficiencies of 25% [source 5 from MA Green] through ongoing incremental improvements. Recent simulations have confirmed the possibility of achieving such efficiencies through the continuous development of existing technologies [source 55 from Green].

In this series, a record industrial partial rear contact (PERC/PERL) solar cell on p-type Si wafers was recently announced by Trina Solar, China, reaching an independently certified efficiency of 22.13%. Record of efficiency (≥25%) of single junction Si solar cell has been achieved using such solar cell concepts at laboratory scale [PERL), 1999]. Recently, LONGi Solar, a subsidiary of LONGi Green Energy Technology, has achieved 23.6% efficiency with its p-type c-Si PERC solar cells – a new industry record in production line and this technology is growing rapidly in the PV industry. The PERT, PERL also belongs to the PERC family.

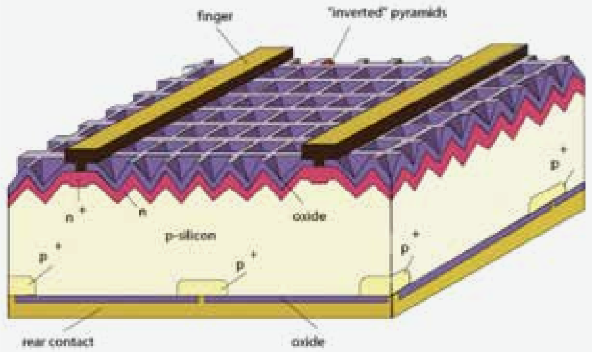


Fig. 8: Schematic of high efficiency laboratory PERL cell

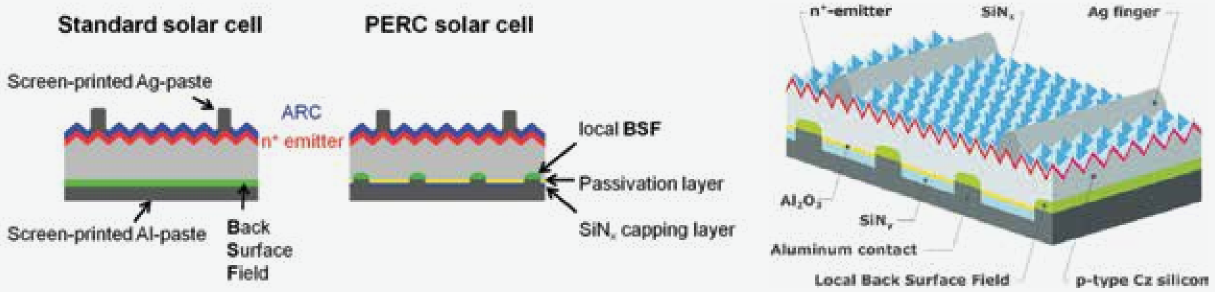


Fig. 9: Comparison of standard solar cell (extreme left) and PERC solar cell (middle) and schematic of a typical PERC cell structure (extreme right).

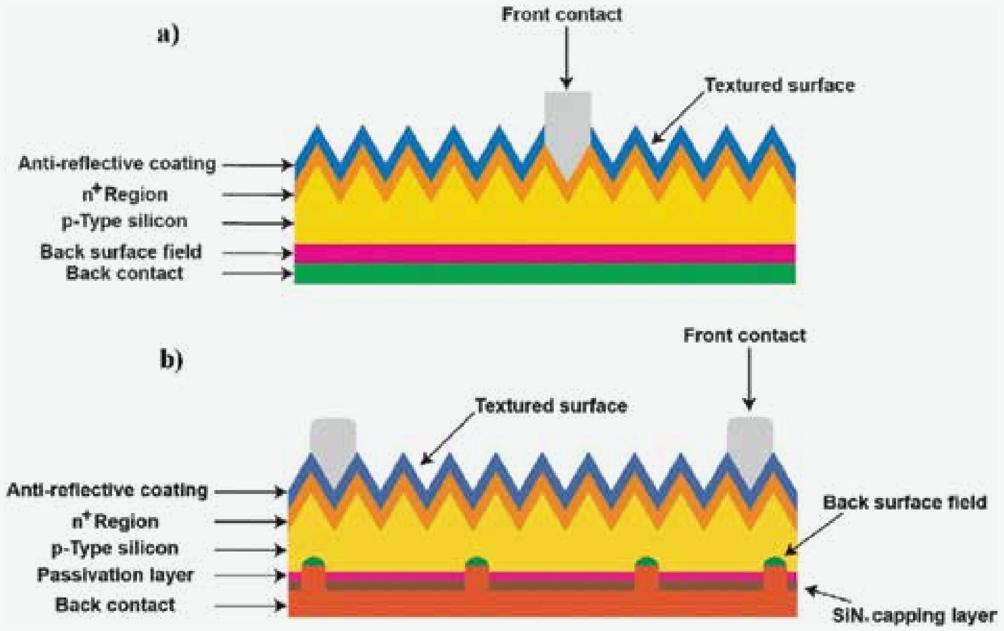


Fig. 10: Cell Structure of a conventional a) Al BSF Cell and b) cell.

Tunnel Oxide Passivated Contact (TOPCon) Solar Cell Technology

One of the main challenges of PERC solar cells is the creation of rear-side contact openings, which involves opening grooves in the passivating layers [T1:5]. This process can potentially damage the bulk Si layer. Moreover, the current generated by the cell must travel a longer distance due to the presence of localised metallic contacts. TOPCon technology, which is considered the next generation of PERC, can be integrated into traditional cell manufacturing processes.

TOPCon technology involves the addition of an ultra-thin layer of silicon oxide (SiO_x) and a layer of polycrystalline silicon (poly-Si) doped with phosphorus (P). Unlike PERC, which has localised metallic contacts, conventional monofacial TOPCon solar cells have full-area rear-side metallic contacts, eliminating the need for laser-assisted contact openings or crowding of charge carriers at localised contacts [T2:17].

The successful devictorial of the TOPCon structure depends on four major processes, namely: (i) developing an ultra-thin SiOx tunnelling layer, (ii) depositing a highly doped a-Si or a-Si:H layer onto the ultra-thin SiOx layer, (iii) heating the layer to high temperature to make it polycrystalline, and (iv) post-annealing hydrogenation treatment to minimise the defect states within the doped poly-Si layer [T3:21]. The schematic diagram of a TOPCon solar cell is depicted in Fig. 11, which features tunnel oxide passivated rear contact and a diffused boron-doped p+ emitter.

The improvement of each processing step can contribute to the production of high-efficiency TOPCon solar cells. The use of rear side light management and selective emitter can also increase the power output of these cells. The average stabilised efficiency of large area n-TOPCon solar cells in mass production is higher than that of p-PERC solar cells, which currently dominate the market [T4:19].

While TOPCon can achieve higher efficiencies than PERC, its theoretical maximum efficiency is 23.7%, with current TOPCon technology achieving a little over 22%. However, Chinese PV module manufacturer Jolywood has recently developed 700 W bifacial TOPCon solar modules with a maximum cell level efficiency of 25.4%, the highest reported efficiency so far for large area industrial TOPCon solar cells [T5: 22]. Their module level efficiency ranges from 21.73% to 22.53%, which is higher than the average stabilised efficiency of TOPCon solar modules in mass production.

On the other hand, LONGi, another well-known solar module manufacturer, has successfully developed 25.19% p-type TOPCon solar cells using commercialised monocrystalline CZ c-Si wafers, demonstrating the industrial viability of p-TOPCon solar cells. It is worth noting that TOPCon is the logical next step after PERC and does not add significant additional cost to the finished product.

The passivated contact-based solar cells will gain the highest market share in the near future. Thus, the R&D in silicon solar cell architectures are primarily focused on PERC and TOPCon solar cells. However, due to the challenges like rear contact openings and carrier crowding at localised metallic contacts, market dominating PERC solar cells are likely to be replaced by TOPCon solar cells in the future.

The first report on the development of TOPCon solar cells was published in 2013 by Fraunhofer ISE [T8:T20]. In the article, Feldmann et al. revealed that inserting an ultra-thin silicon dioxide (SiO_2) layer along with a P-doped poly-Si layer at metal-semiconductor interface may significantly reduce the surface recombination at the rear side of n-type crystalline Si solar cells. The chemically grown SiO2 layer was kept as thin as 1.4 nm so that current can tunnel through it easily and efficiently. Onto this ultra-thin oxide layer, a 20 nm P-doped amorphous silicon (a:Si) layer was deposited by PECVD technique, followed by a high temperature annealing process to transform this doped a:Si layer into doped poly-Si layer. Depending on the annealing conditions, a very good surface passivation was observed, which in turn provided a very high implied open-circuit voltage (iVoc) of above 710 mV and a very low recombination current density (J_0,rear) of about 9-13 fA/cm^2. This novel approach was named the Tunnel Oxide Passivated Contact (TOPCon) structure, and the solar cells that comprise this TOPCon structure are known as TOPCon solar cells. To reduce the front side surface recombination, a boron-doped p$^+$ emitter was passivated by a stack of atomic layer deposited (ALD) aluminium oxide (Al_2O_3) layer and PECVD -SiNx layer.

Furthermore, it has been established that SiNx layer also serves anti-reflection coating (ARC), enhancing optical confinement inside the solar cell. Using this novel structure, in addition to a high implied voltage (iVoc), a high implied fill factor (iFF) was also achieved in both maximum power point (MPP) and open-circuit conditions. During the cell fabrication process, front side metallic contacts were realised by thermally evaporated Ti/Pd/Ag seed layer and subsequent electroplating of Ag layer. The width of the metallic fingers was kept as 20 µm.

On the other hand, a thermally evaporated Ti/Pd/Ag stack was used as the rear-side metallic contact. Eventually, the best cell with an active cell area of 2 × 2 cm^2 based on 200 µm thick, <100>-oriented, 1 Ω-cm n-type FZ Si wafers demonstrated a PCE of 21.81%, featuring a Jsc of 38.4 mA/cm2, a Voc of 690.8 mV, and an FF of 82.1%. In contrast, the best PCE of 19.6% with a Voc of 638.3 mV, Jsc of 37.8 mA/cm2, and FF of 81.1% was achieved for identical solar cells without the TOPCon structure at the rear side.

Therefore, the importance of incorporating the TOPCon structure at the rear side of crystalline Si solar cells is well realised. The process flow of the TOPCon solar cell reported by Feldmann et al. is as follows: 1. Selection of shiny-etched 200 µm, <100>-oriented, 1 Ω-cm n-type FZ Si wafers (2 × 2 cm2). 2. Cleaning of wafers by the standard RCA process. 3. Diffusion of B into a random pyramid textured front side. 4. Deposition of a 1.4 nm SiOx layer (wet chemical process), PECVD growth of a 20 nm P-doped a:Si layer at the rear side. 6. High-temperature annealing (~ 850°C) in an N2 atmosphere. 7. Deposition of ALD-Al2O3 layer and PECVD-SiNx onto the front p+ emitter. 8. Front-side metallisation by a thermally evaporated Ti/Pd/Ag seed layer, followed by electroplating of an Ag layer. 9. Rear-side metallisation by a thermally evaporated Ti/Pd/Ag layer.

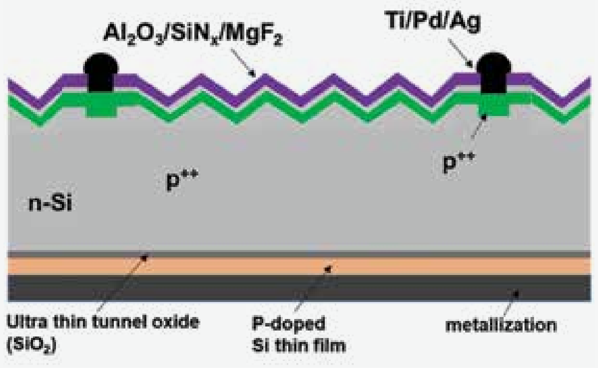


Fig. 11: Schematic of TOPCon solar cell

Since then, significant progress has been made in TOPCon technology, with improvements in materials, interfaces, process steps, and device design aimed at enhancing the performance of solar cells and the technology on a large scale. These advancements include the use of both-side TOPCon structures based on p-type and n-type c-Si wafers, bifacial TOPCon solar cells, large area TOPCon solar cells, and integration with PERC and HIT/HJT structured Si solar cells. D.K. Ghosh et al. [T9: SURFIN2022] provided an extensive review of TOPCon solar cell technology, covering its fundamentals and future prospects. Currently, the highest reported efficiency stands at 25.8% (Voc = 725 mV, Jsc = 42.5 mA/cm2, and FF = 83.3%), which is in close proximity to the theoretical efficiency limit established by Shockley-Queisser for a single-junction c-Si solar cell.

Moreover, larger area solar cells and modules have been produced that generate a higher power output compared to the current market-dominating PERC solar modules. Additionally, the PV industry has developed bifacial TOPCon solar cells and modules with the highest reported front side PCE being as high as 25.4%. Thus, the significance of TOPCon solar cells in the PV industry is easily understandable.

However, certain areas require further investigation such as the fabrication of thin TOPCon solar cells and the improvement of evanescent light reflection from the backside of the cells by incorporating a suitable interfacial layer between the doped poly-Si layer and rear side metallic (Ag) contact. The impact of using metal oxide-based carrier selective contact layers as an alternative to doped poly-Si layers and the simplification of processing steps in the fabrication of TOPCon upgraded PERC solar cells also needs to be explored.

Interdigitated Back Contact Silicon Solar Cells (IBC)

The first designs of interdigitated back contact (IBC) solar cells were studied by Lammert and Schwartz [Ref:I1-207]. IBC cells are considered as one of the advanced silicon solar cells that were initially conceptualised in the late 1970s for use in concentrated light applications [I1-I3:207–209]. The first successful commercialisation of IBC cells was carried out by SunPower, which based its device architecture on earlier work done at Stanford University [I4-210]. The development and commercialisation of monocrystalline Si cells were carried out by the Swanson group and the SunPower Corporation in the U.S. Currently, back contact solar cells are being produced by the SunPower Corporation. High-efficiency back-junction solar cells have a collecting junction on the rear surface of the solar cell while the front surface is well passivated. Since the minority carriers, which are mainly generated at the front surface, have to travel a long distance to reach the rear junction, back-junction solar cells require a high ratio of bulk diffusion length to cell thickness.

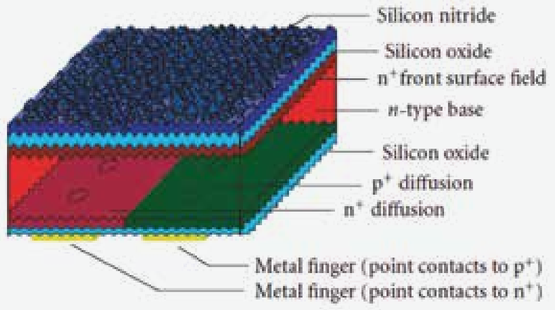


Fig. 12: Schematic drawing of IBC solar cell developed by Sun Power

Sun Power demonstrated IBC solar cells with efficiencies of 21.5% [Ref-I5]. In production, the average efficiency is estimated to be over 20%. Later, Sun Power reported a record certified efficiency of 25.2% [Ref-I6]. With its most recent technological improvements, SunPower has demonstrated an efficiency of 25.2% under one-sun operation [Ref I6-12]. A Sun Power module has achieved a 22.8% conversion efficiency, which is the current world record for a large-area crystalline silicon photovoltaic module (15 739 cm^2 aperture area; a smaller module with a 778 cm^2 designated illumination area by UNSW reached an efficiency of 22.9%) [Ref I6-12].

An important factor for this high performance is the fact that IBC cells achieve high short-circuit currents by completely eliminating metal grid shading at the front surface. In the IBC design, both electron and hole collection occur at the rear side of the device. This permits a high degree of freedom in the optical and electronic design of the front side of the cell, evidenced by a Jsc as high as 41.33 mA cm^2 for the record IBC cell. Front surface passivation, for example by SiOx in combination with SiNx as an antireflection layer, can be complemented by a lightly diffused n-type layer, which suppresses the concentration of holes near the pyramidally textured surface.

Other possibilities for maximising light coupling into the wafer include the use of black Si as a broadband ARC.

The compatibility of optical schemes with high-quality surface passivation is crucial. To achieve this, boron diffusion is selectively applied to part of the back surface to transport holes, while phosphorus is locally diffused in the remaining part of the back surface to collect electrons. The cell structure consists of alternating stripes of n-type and p-type doped regions.

To ensure effective carrier collection, it is important to optimise the widths of the stripes, which depends on the carrier diffusion length and the recombination properties of the doped regions. In moderately doped Si, the higher electron mobility favours a one-dimensional flow to holes in some IBC structures. This is achieved by covering a larger fraction of the rear side with a p+ region, reducing the build-up of hole concentration at the front surface, which could lead to recombination. Electrons mostly flow laterally towards the n+ rear stripes, through both the n-type wafer and the front n+ diffusion. However, the IBC cell structure must be optimised for a specific set of recombination and transport properties.

A thin insulating layer is used to passivate the back surface of the wafer [I12:216]. Electrical contact is made by metal stripes through local openings etched into the passivation layer. The metal stripes are aligned to the doped regions, but they are slightly narrower, to avoid overlap with neighbouring stripes, which would cause a shunt. The openings must be large enough to extract current with minimal contact resistance losses and small enough to minimise recombination losses caused by the direct contact of the metal to the Si. A high FF of 82.7% was achieved for the record IBC cell, despite its large area, with this local contact design.

A significant advantage of placing both metal contacts at the rear is that they can be optimised without having to trade off resistance for shading. The metal stripes can, in fact, almost fully cover the rear surface, and thus simultaneously act as a back reflector. The thin dielectric layer between the Si and the metal stripes helps to minimise parasitic plasmonic absorption of infrared light in the metal layer [I13:132].

An alternative to minimising the contact area between the doped Si and the metal stripes is to incorporate passivating contacts based on doped poly-Si layers [I14: 287] which can relax those requirements. With a Voc of 737 mV, the record IBC cell demonstrates remarkable bulk lifetime, surface passivation and contact passivation. Si heterojunction technology can provide even better performance than IBC in terms of Voc. However, the fabrication of IBC solar cells is limited by the requirement of Si wafers with high minority carrier lifetimes, which restricts the choice of Si quality. Nevertheless, the wide tolerance on the wafer thickness and resistivity help to keep the wafer cost tolerable.

Heterojunction with Intrinsic Thin Layer (HIT) Cell

Sanyo developed the HIT solar cell, which combines amorphous silicon and monocrystalline silicon [H1:13], achieving a total area solar cell efficiency of over 20% [H2: 62]. This approach was very successful, and in 2000, they achieved a record efficiency of 20.7% on a large area (100.5 cm2). The high efficiency of HIT solar cells is due to the excellent passivation ability of the HIT structure on monocrystalline silicon.

The HIT solar cells use a peculiar structure where a non-doped (intrinsic) amorphous silicon (i-type a-Si:H) film is sandwiched between p-type a-Si:H and n-type monocrystalline silicon wafer on the front side of the solar cell, forming a heterojunction emitter. The efficiency was further improved by implementing a back surface field (BSF) formed from an i-type a-Si:H film sandwiched between n-type a-Si:H and the n-type monocrystalline silicon wafer on the rear side of the solar cell.

During production [H2: 62], a plasma chemical vapour deposition (CVD) process is used to deposit a very thin layer of intrinsic amorphous silicon (i-type a-Si:H) and p-type amorphous silicon (p-type a-Si:H) on the front of a n-type Czochralski monocrystalline silicon wafer that is approximately 200 µm thick and has a solar grade resistivity of about 1 Ωcm. The total thickness of the i-type a-Si:H and p-type a-Si:H layers is about 10 nm. Similarly, a very thin layer of i-type a-Si:H and n-type a-Si:H with a total thickness of about 20 nm is deposited on the rear side of the wafer. To form transparent conductive oxide (TCO), sputtering is used on both sides of the wafer. Ag electrodes are then formed on both sides of the wafer using silk screen printing. All the processes are performed at temperatures below 200˚C to avoid thermal damage to the wafer, and there is no need for photo-masking or processing cycles at high temperatures up to 1,000˚C. The HIT structure is symmetrical, which allows for electricity generation from the rear side when the solar cell is illuminated. A schematic drawing of this solar cell type is shown in Figure 13.

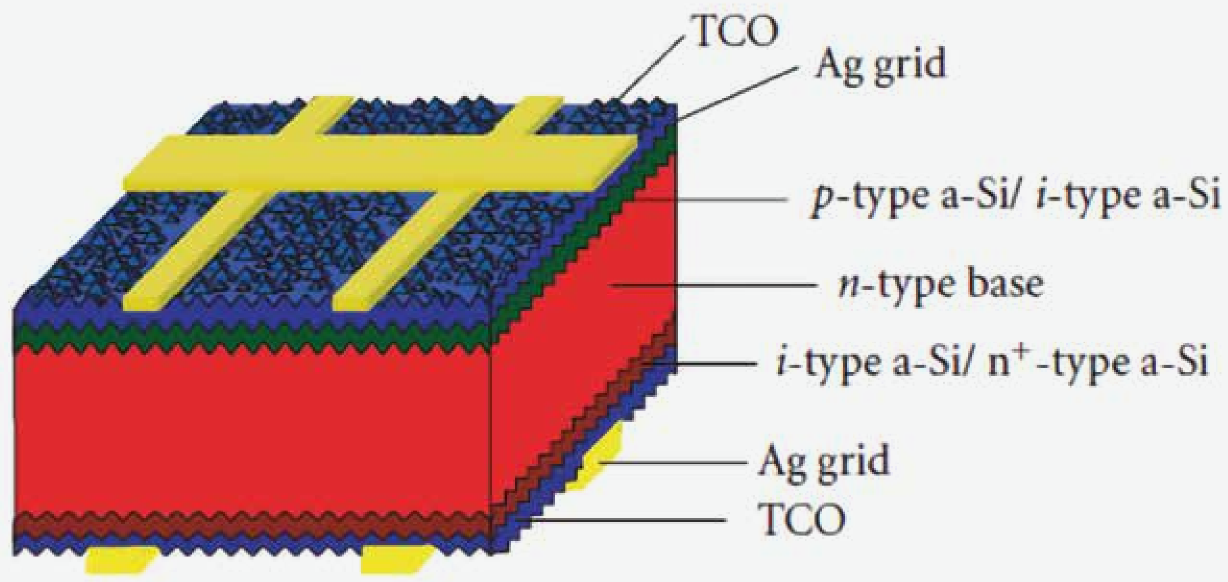


Fig. 13: Schematic of HIT solar cell structure developed by Sanyo Corporation, Japan

Sanyo developed the HIT structure and demonstrated cell efficiencies up to 21.5% [H3: 63]. After implementation of the HIT solar cell fabrication process into production, the average cell efficiency is estimated to about 18% to 20% according to their module power output. Another feature of the HIT solar cells is its excellent temperature characteristics, better than the temperature dependence of conventional *pn junction* solar cells. This superior temperature dependence results in up to 10% higher module power output at standard test conditions. An efficiency limitation of today's HIT solar cells is obviously in the moderate short circuit current density of around 36 mA/cm^2, possibly due to the transparency of the transparent conductive oxide layer on the solar cell front side.

The silicon HIT solar cell was pioneered in the early 1990s by Sanyo which was then acquired in 2010 by Panasonic and has been commercialised under the HIT trademark. Using this concept, Kaneka, Japan, has recently achieved a cell efficiency of 25.1%. Panasonic's HIT technology now yields commercial module efficiencies approaching 20%.

In 2014, Panasonic achieved a new world record for efficiency in solar cells by combining their HIT technology with the IBC concept, reaching 25.6%. More recently, Kaneka Corporation Ltd. Demonstrated a world record efficiency of 26.7% for HIT cells by incorporating a back contact solar cell structure with heterojunction. It developed a heterojunction interdigitated back contact solar cell that achieved a conversion efficiency of 26.6% (on a designated area of 180 cm^2) which was independently confirmed by the Fraunhofer Institute for Solar Energy Systems Callab. This efficiency is very close to the theoretical limit of approximately 31% for a single junction silicon solar cell.

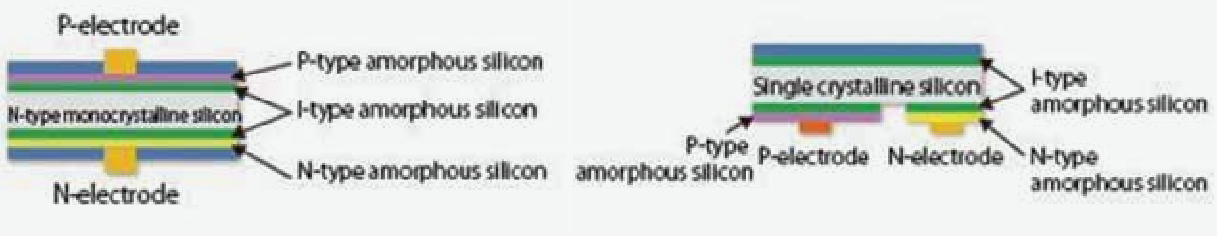


Fig.14 (a): HIT solar cell and Fig. 14 (b): Heterojunction back contact solar cell

Future industrial solar PV technologies

Champion cell announcements vs. industrial reality

The Solar PV technology using bifacial Passivated Emitter and Rear Cell (PERC) has been recognised as the new leader in the energy markets as of 2020. However, since PERC has reached its maximum efficiency, the question now is what will be the next breakthrough in solar technology? Will there be a swift transition from PERC to n-type technology, similar to the shift from Al-BSF to PERC that occurred about five years ago? According to PV Tech Research, as shown in Fig. 15[3], and as agreed upon by most of the PV community, it is highly likely.

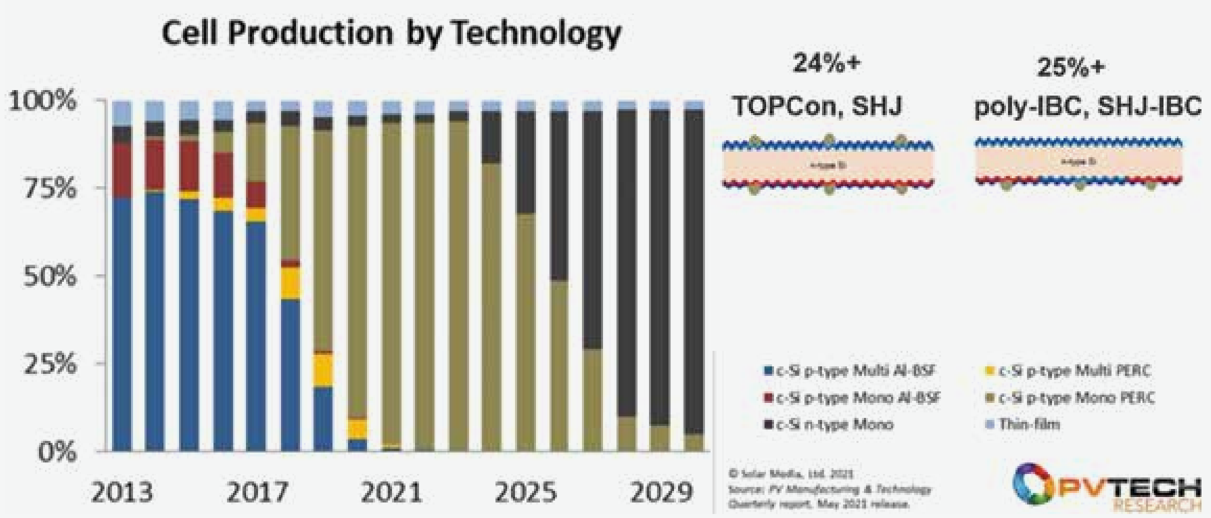
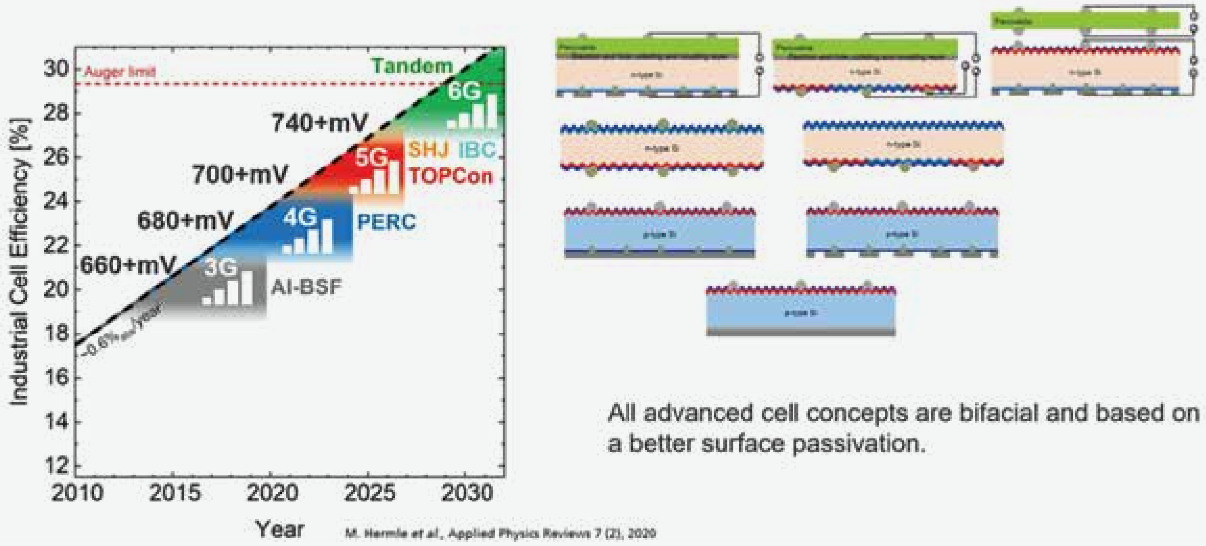


Fig. 15: (left) Historical data showing the switch form Al-BSF technology (blue and red bars) to PERC (brown bars) and forecast of a switch to n-type technology (grey bars) in coming years[3]. (right) Schematic cross sections for TOPCon, SHJ and poly-Si- and SHJ-IBC

But which technology will become the new mainstream? Will it be HIT-Silicon Heterojunction, TOPCon, or a combination of both in an Interdigitated Back Contact (IBC) structure? Or perhaps tandem cells? The competition is intensifying and there are many announcements being made to showcase the strengths of each technology. Tier 1 manufacturers are making announcements about advancements in PERC on cell and module levels to demonstrate that the technology still has room for improvement. Meanwhile, N-type technology announcements are pointing towards the direction of the future.

In theory, this is quite simple. Fig. 16 depicts the linear yearly growth of cell efficiencies in industry of about 0.6% absolute, as presented first by Martin Hermle[4]. In 2016, the switch from Al-BSF to PERC was initiated, as Al-BSF technology reached its efficiency limit. This is mostly due to the limited passivation of the rear side by homogeneous Al-BSF, which is depicted in the cross section on the right.



All advanced cell concepts are bifacial and based on a better surface passivation.

Fig. 16: (left) Efficiency (voltage) improvements and limits of c-Si technologies in the past and coming years with analogy to mobile networks 3G-6G. The graph is adapted from[4]. (right) Schematic cross sections for Al-BSF, mono and bifacial PERC, TOPCon, SHJ, IBC and 2-, 3- and 4-terminal tandem configurations.

A better rear-side passivation can be realised with a dielectric stack (AlOx/SiNx) below the Al-Paste and Al-BSF point contacts, leading to average voltages of 680 mV and a maximum of 690 mV. To overcome 700 mV, passivating contacts with poly-Si in TOPCon or a-Si in SHJ technology have to be applied. In the next step, to overcome the Auger or even the Shockley-Queisser limit, tandem structures have to be used. So, this linear curve is based, in the first order, on improvements in voltage by better passivation with advanced cell structure.

An analogy can be made between these solar technologies and the mobile network's evolution. The old 3G technology (Al-BSF) is now outdated, and the current standard is 4G (PERC), with 5G (passivating contacts) already implemented. However, for most uses, 4G is still adequate, and 5G, which is more expensive, is unnecessary. Nevertheless, in a few years, 5G will be ubiquitous, and efforts will be made to pave the way for 6G (tandem) technology.

Announcements of high efficiency solar cells only demonstrate the practical limit of each technology, as shown in the graph in Fig. 16. However, there is a difference of around 1% absolute between what is achievable (with process flow and measurement tricks) and what is realistic in production. In 2019, we wrote a blog post *Future industrial PV technologies: Champion cell announcements versus industrial reality*, where we explained in detail how high efficiency solar cells are fabricated and measured using various tricks that often have little to do with their industrial counterpart, even if the technology is named the same. Additionally, these measurements often involve tricks such as using conductive and reflective chucks or measuring only the active area without a busbar.

Table 1 provides a summary comparing the record-breaking announcements with the average efficiencies achieved in production and the available module efficiencies in the market, along with their potential.

Table. 1: High efficiency announcements versus industrial reality of all relevant c-Si technologies on the PV market.

Technology	Equipment	Announcements of cell efficiency [%]	Average cell efficiency in production [%]	Available module efficiency [%]	Average voltage potential in production [mV]	Average efficiency potential in production [%]
Al-BSF	standard	20.29 [6]	19.5 – 20.0	< 20%	670	20.5
PERC	standard PERC based	24.06 [10]	22.5 – 23.5	20.2 – 21.1 [7]	690	23.5
TOPCon	standard PERC based	25.25 [11]	23.5 – 24.5	21.4 [7]	725	24.5
low cost IBC	standard PERC based	25.04 [12]	23.5 – 24.5	21.3 [7]	735	25.0
low cost SHJ	thin film based	25.26 [13]	23.5 – 24.5	21.9 [7]	735	25.0
complex SHJ	thin film and electronic industry based	25.26 [14]	24.5 – 25.0	21.7 [7]	740	25.5
complex IBC	thin film and electronic industry based	26.1 [15], 26.6 [16]	25.0 – 25.5	22.0 – 22.8 [7]	740	26.0

Al-BSF (3G) is becoming obsolete in the PV market due to its mono-facial nature. The average cell efficiencies in production are around 20%, with voltages of approximately 665 mV. The module efficiencies on the market are generally less than 20%. The current leader in the energy markets, bifacial PERC or 4G technology, has an average solar cell efficiency of around 23% in production. The PERC modules available on the market are mostly below 21%, although Trina's modules can reach up to 21.1%[7]. However, the recently announced 23.03% PERC module efficiency by Trina [8] is not representative of their standard product, and the measured efficiency is only based on 'active area' measurement.

The standard module efficiency is typically calculated by dividing t'e electrical output power (Pmpp at STC) by the irradiance captured by the total area of the module (i.e. the product of module length and width). However, the 'active area module efficiency' considers only the area of the cells themselves, resulting in a significantly higher efficiency value that approaches the cell efficiency. In other words, the active area module efficiency does not take into account the area of the gaps between cells, the area occupied by bussing ribbons and junction boxes, or the mandatory gaps between the outer solar cells and the edge of the laminate.

Therefore, the active area module efficiency is not relevant for assessing the benefits of high module efficiency in terms of savings for area-related balance of system costs. In a recent study conducted at CPVT in China, module efficiency was reported to reach as high as 23.53%[9], although the study did not mention the active area measurement. LONGi achieved a record PERC cell efficiency of 24.06% in 2019[10] by using a selective poly-Si (PERC plus) on the front and other features that are not yet implemented in industrial production, and most likely never will be.

PERC-based technologies like 'TOPCon' and 'PERC-based IBC' benefit from the PERC cost structure and are therefore cost-effective. However, one major challenge faced by almost all n-type technologies is the reduction of Ag-consumption for the metal contacts. In production, TOPCon (5G) cells achieve an average efficiency of about 23.5%, while Jinko Solar recently demonstrated an efficiency of 25.25%[11]. Although the exact process flow and cell architecture used by Jinko Solar have not been published, it is likely that they used a selective poly-Si(B) – a more complex technology that is not yet ready for industrial mass production – in addition to other non-industrial features.

The cost of ownership (COO) for a standard TOPCon cell is currently about 20-30% higher than that of a PERC cell. However, the higher efficiency, higher bifaciality, lower degradation, and lower temperature coefficient of TOPCon cells make them attractive not only for rooftop applications, but also for utility-scale solar installations, as well as regions with hot climates and high albedo.

PERC-based IBC (5G) technology, which is available from Jolywood, SPIC, Trina, and ValoeCell, has been demonstrated at 25.04%[12] by Trina and is currently being produced at around 24%, with a potential of 25%. At present, such cells are mostly suited for rooftop PV applications, but with the reduction of Ag-metallisation, the bifacial version could also be used in utility-scale installations in the future. Low-cost SHJ (5G) technology, which is available from REC, Meyer Burger, and Maxwell, achieved an efficiency of 25.26%[13]. Complex SHJ (Panasonic and Kaneka) (5G) reached record efficiencies of 25.26%[14], as shown by LONGi. Complex IBC (5G) cells are produced by Sunpower and LG, and ISFH demonstrated 26.1%[15] on a POLO structure, while Kaneka achieved 26.6%[16] with SHJ-IBC technology.

It is now time, over the next two to three years, to completely switch to low-cost 5G technology. The timing of the transition to 6G technology will depend mostly on the stability and other challenges for perovskites.

Future Prospects of Silicon Solar Cell Technologies

The solar photovoltaics market is currently dominated by cell concepts with diffused and passivated p-n junctions and passivated rear sides, such as PERC, PERL, PERT, and TOPCON, according to the ITRPV 2021 report. The report also predicts that BSF will mostly be produced on cost-efficient mc-Si wafers and will likely disappear after 2025. Interestingly, the market share of PERC, PERL, PERT, and TOPCON in 2020 slightly exceeds IHS Market assumptions, as shown in Fig. 15. Furthermore, Fig.16 illustrates that TOPCon solar cells are expected to gradually capture a market share of approximately 50% (considering only PERC and TOPCon cells) within the next decade, indicating their dominance in the solar photovoltaic industry.

On the other hand, Si-heterojunction (HIT/HJT) solar cells are expected to gradually increase their market share to around 10% in 2025 and 18% in 2031, as shown in Fig. 13. The dominance of double-sided contact cell concepts over other technologies in terms of market share is again confirmed. The current low market share of HIT/HJT or IBC solar cells can be attributed to their high cost, complex processing steps, requirement for significant modification of current cell processing technology, and lower throughput, among other factors[4]. (from Review of TOPCON in Surfin)

According to ITRPV 2022 report, The BSF cell concept was to be phased out in 2022. However, the diffused and passivated pn junction concept, which has matured, will continue to be used in mainstream production, along with other rear-side passivation technologies such as PERC, PERL, PERT, and TOPCON.

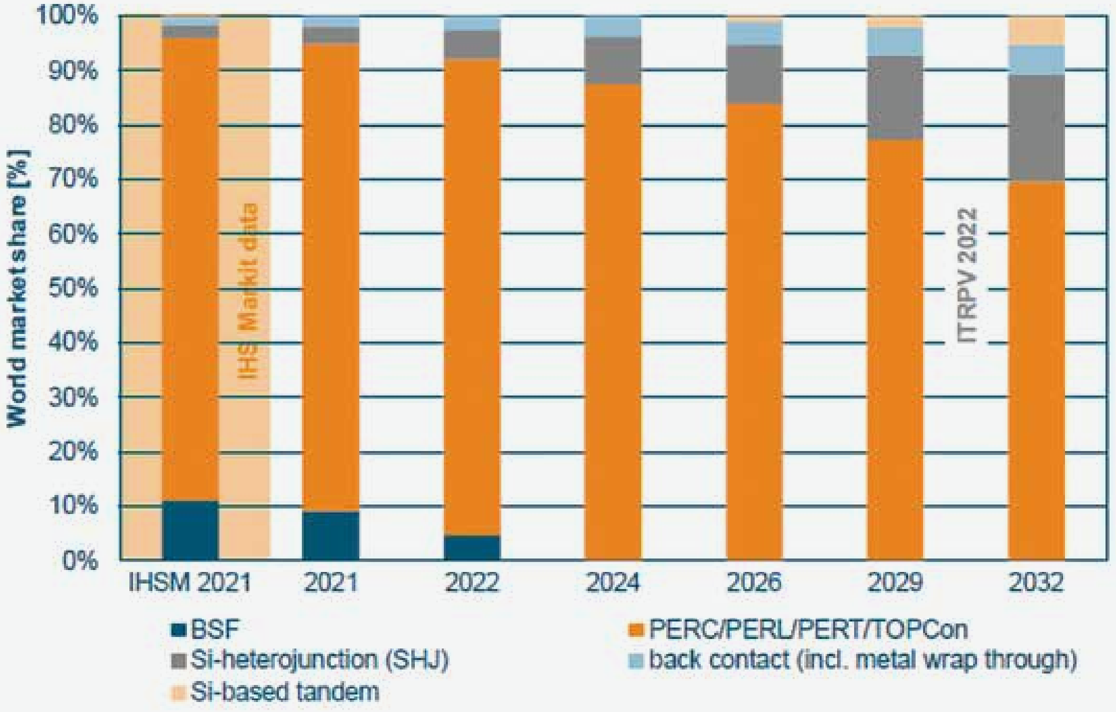


Fig. 17: Market share for different cell technologies. IHS Markit data for 2021[19].[From ITRPV2022 report]

The 2021 market share of PERC/PERL/PERT/TOPCON was found to be approximately 85%, as shown in Fig. 17, which is in line with the assumptions made by IHS Markit [19]. It is expected that PERC/PERT/PERL/TOPCON will continue to dominate the market over the next few years. SHJ cells are predicted to gain a market share of around 10% after 2024 and close to 20% by 2032.

Fig. 17 also confirms the market dominance of double-sided contact cell concepts. Rear-side contact cells are not expected to have a significant market share, with a projected change from around 2% in 2021 to nearly 5% in 10 years. Si-based tandem cells are expected to appear in mass production after 2024, which is a delay compared to the assumptions made in the 12th edition.

The trends in cell technologies with passivated, diffused pn junction on the front side and passivated rear side are highlighted in Fig. 18 There are different approaches to realise such cells. The most mature approach uses p-type material with a passivating layer of Al2O3 and a SiNx capping layer, as discussed in Chapter 6.2. In 2021, about 10% of PERC cells were produced using this technology with p-type mc-Si material, while 85% were PERC on p-type mono-Si. This share is expected to remain at a similar level in 2022, but it is expected that the PERC on p-type mono-Si share will decrease to about 40% within the next 10 years. PERC on mc-Si material will also be phased out by 2025. Concepts on n- and p-type material with passivated contacts, using tunnel oxide passivation stacks on the rear side, are expected to gain market share from about 10% in 2022 to 58% within the next 10 years. It is estimated that n-type bulk material will become mainstream for concepts with passivated contacts, and only a much smaller share will use p-type material.

All cell types discussed in Fig. 17 as well as SHJ cells, can capture the light from the front and from the rear side if the electrical contacts are designed accordingly. This cell type can therefore be perfectly used for bifacial light capturing. Fig. 19 shows the expected market trend for bifacial cells. The market share of 50% in 2021 is expected to increase significantly to 85% within the next 10 years. Bifacial cells can be used in modules with a transparent rear side (bifacial modules) or in conventional, monofacial modules.

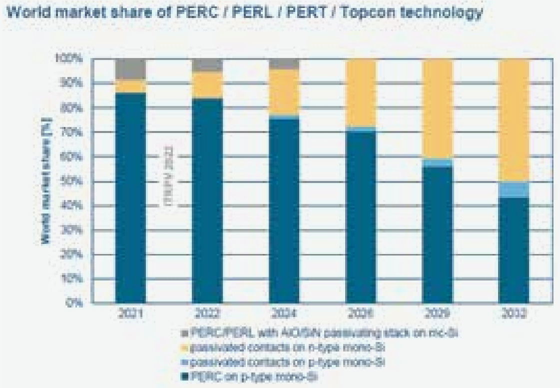


Fig. 18: Market share for c-Si cell concepts with pn-junction on the front and different rear side passivation technologies.

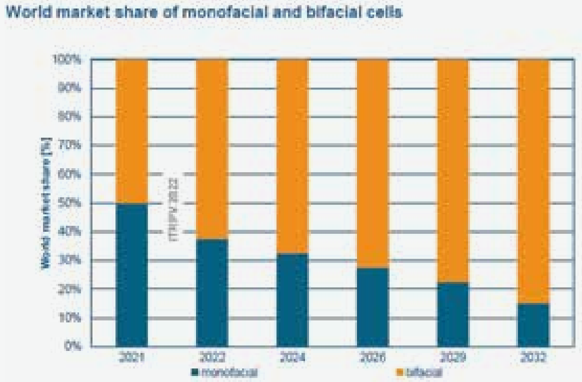


Fig. 19: Market share for bifacial cell technology.

Cells using n-type materials have the highest potential for efficiency among today's cell technology concepts. We found that p- and n-type mono-Si cells with a diffused pn junction on the front side will reach up to 24.5% and 25%, respectively, in the next 10 years. Cells using n-type materials and tunnel oxide passivated contacts at the rear side show higher efficiencies than all p-type cell concepts, as shown in Fig. 19. Other n-type-based cell concepts like SHJ and back-contact cells will reach higher efficiencies of up to 25.7% in mass production within the next 10 years. Nevertheless, we see that Si-based single junction cell concepts are converging to a practical efficiency limit of about 26%, close to the theoretical upper limit of 30%[26]. Tandem cells will overcome this limit. The mass production cell efficiencies of Si-based tandem cell concepts are expected to start at about 27%. Their introduction in the market is expected after 2024, according to Fig. 17 (ITRPV2022).

2.2.3 Thin Film Photovoltaics

Thin-film solar cells are considered a second-generation technology, as they are made by depositing one or more thin layers of photovoltaic or semiconductor materials onto substrates such as glass, plastic, or metal. The thickness of these films can range from several nanometres to tens of micrometres, which is significantly thinner than the traditional first-generation crystalline silicon solar cells that use wafers that are approximately 200 μm thick. Due to their thinner structure, thin-film solar cells are more flexible, lighter, and have lower resistance [T1-T3].

While thin-film solar cells have many advantages, crystalline silicon (c-Si) solar cells have been a market leader for a while due to their high performance (approximately 26.7%), ease of fabrication, and environmentally friendly features [T4]. Additionally, c-Si modules from the 1970s are still functioning, indicating their longevity. Moreover, single crystal panels are able to withstand harsh conditions [T5].

While c-Si solar cells have many advantages, they are not efficient at absorbing light and are also inflexible and relatively fragile, making them suitable only for high-performance applications. The main difference between thin-film and c-Si solar cells lies in the pairing of PV materials. Thin-film solar cells/panels are cheaper than mature c-Si wafer cells/panels and are also more flexible and easier to handle. Additionally, they are less vulnerable to damage compared to their c-Si counterparts.

Although thin-film solar materials have a lower PCE (power conversion efficiency), they can outweigh the cost-benefit considering various applications. Recently, a short topical review of primary thin film solar cells and technologies was presented by ErtezaTawsifEfaz et al. [T6]. To address the issues with solar cell materials, several research groups have made intensive experimental efforts [T4, T7-T10].

Technologies Based on Thin Film Solar Cells

Thin film solar cell technologies primarily use three materials – amorphous silicon (a-Si) based thin solar cells, copper indium gallium selenide (CIGS) and cadmium telluride (CdTe) thin film solar cells. There are different types of approaches available on the advances of solar cells regarding amorphous silicon (a-Si) [T7], copper indium gallium selenide (CIGS) [T8], and cadmium telluride (CdTe) [T9]. A brief outline of each state-of-the-art technology for these three primary types of thin-film solar cells is presented below.

Amorphous Silicon (a-Si) Solar Cell

Initially, a-Si solar cells were deposited in the p-i-n structure, but it is now possible to fabricate the device in an n-i-p formation sequence as well [T10]. Since its inception in the early 1970s, a-Si based solar cells have undergone significant progress. Starting with a PCE of around 2.4% in 1976-77 with a single junction solar cell [T11, T12], a PCE of over 14% (14.04%) was reported in 2016 for a triple junction cell (verified at AIST, Japan) [T13]. Additionally, single junction a-Si solar cells have reached a PCE of 10.22% [T13, T14, T15].

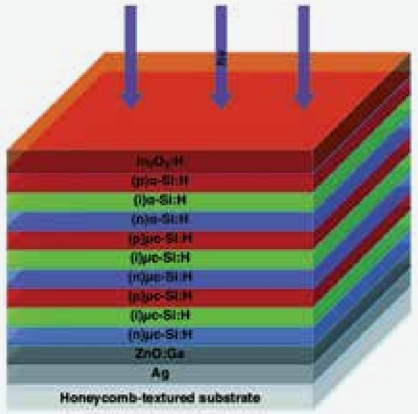


Fig. 20: Layout of a triple junction n-p-a-Si:H/μc-Si:H/μc-Si:H solar cells adapted from [T13]

This solar cell with a random crystal structure is usually developed on a fluorine (F)-doped tin oxide (SnO2:F) (FTO) fabricated glass substrate for single-junction or periodically (honeycomb)-textured substrate (HTS) for a micromorph (tandem) structure. To reduce reflective loss and increase conductivity, usually silver (Ag) and gallium (Ga)-doped zinc oxide (ZnO:Ga) coatings are applied on the substrate, successively. Then hydrogenated-a-Si (a-Si:H) is generally deposited by a diode or triode PECVD employing CO_2, phosphine (PH_3), diborane (B_2H_6), silane (SiH_4), and hydrogen (H_2) dopant gases.

After the previous process, a transparent conducting oxide (TCO) film, usually made of indium tin oxide (In2O3:Sn) or hydrogenated-indium oxide (In2O3:H) (IOH), is deposited as the front window using radio frequency (RF) magnetron sputtering. The grid electrode can be made of Ag, and a moth-eye-based anti-reflection coating (ARC) can also be applied to improve cell performance [T13].

In the latest technology, the single-junction [SLG/Ag/GZO/(n)α-Si:H/(i)a-Si:H(diode/triode)/(p)α-Si:H/ITO/Ag] device was fabricated by diode PECVD, whereas the tandem (triple-junction) [HTS/Ag/GZO/μc-Si:H/μc-Si:H/a-Si:H(diode/triode)/IOH/Ag] device was fabricated by triode PECVD.

For the triple-junction module, reactive ion etching was used to isolate the cells along with nano-crystalline silicon oxide (nc-SiOx) layers. The device was arranged with a hydrogenated-micro-crystalline Si (μc-Si:H) as the bottom (~1.8 μm thick), a μc-Si:H as the middle (~1.6 μm thick), and a a-Si:H as the top (~230 nm thick) cell. Each of the μc-Si:H cells were stacked as the given substrate type arrangement:

(n)μc-Si:H/(n)nc-SiOX/(i)μc-Si:H/(p)nc-SiOx/(p)μc-Si:H [T13].

The schematic layout of the state-of-the-art layout of a triple-junction n-p a-Si:H/μc-Si:H/μc-Si:H solar cell is shown in Fig. 20 In the case of the a-Si:H solar cell, due to the creation of an electron-hole pair by an absorbed photon in the intrinsic layer, the electric field induced across the intrinsic layer causes electrons to drift to n-layer and holes to p-layer. A thin graded interface layer is usually employed to reduce the p/i interface defects-responsible for low open-circuit voltage (Voc) and short-circuit current (Jsc), to improve the cell performance.

Commercially, TEL Solar from Switzerland has shown the most promising results with 12.3% efficiency for a-Si multi-junction business modules. Some of the critical issues identified with a-Si solar cells include: (i) The deposition process needs improvement for large-scale manufacturing of this solar cell [T16]. (ii) The light scattering properties need to be addressed by improving the optoelectronic properties of the front TCO component [T17]. (iii) The Staebler-Wronski effect needs to be resolved by finding a way to prevent the light-induced degradation of the device structure [T18].

Copper Indium Gallium Selenide (CIGS) Solar Cell

The CIGS solar cell initially had a simple p-CuInSe2/n-CdS heterojunction structure [T19], but over time, the device structure has been modified to include a substrate/Mo/CIGS/CdS/ZnO/AZO/Al configuration [T20, T21]. In flexible substrate geometry, the CIGS solar cell has achieved a PCE of 20.56% [62], while on the rigid substrate configuration tested at AIST Japan, a PCE of 23.35% was achieved in 2019 [T22].

The CIGS solar cell, with a chalcopyrite crystal structure, is typically grown on ultrasonically cleaned and dried rigid substrates. Polymeric flexible substrates are also being used [T23]. Molybdenum (Mo) is used as the back contact and reflector of most unabsorbed light and is usually sputtered onto a soda-lime glass (SLG) substrate. The absorber layer, Cu (In,Ga)(Se,S)2, with a thickness of approximately 2 μm, is created by physical vapour deposition, followed by sulphurisation-after-selenisation of the precursor layers, generally using hydrogen selenide (H2Se) gas. This process naturally gives rise to a Mo(S, Se)x film between the absorber and back contact.

In some cases, caesium (Cs) is applied to the absorber layer through thermally evaporated caesium fluoride (CsF), after which a cadmium sulphide (CdS) layer (~50 nm thick) or a cadmium (Cd)-free buffer layer, typically produced through chemical bath deposition, is deposited on top [T22]. Then, an intrinsic zinc oxide (i-ZnO) layer (~100 nm thick) covered by aluminium (Al)-doped ZnO (ZnO: Al) as the TCO layer is grown on the CdS buffer through chemical vapour deposition to prevent external damage [T24]. In the latest technology, a second buffer layer of magnesium (Mg)-doped ZnO (ZnO: Mg) (~50 nm thick) was deposited by ALD on the first Cd-free Zn(O, S,OH)x (~50 nm thick) buffer to enhance cell performance.

The boron (B)-doped ZnO (ZnO: B) layer as TCO was deposited by metal-organic chemical vapour deposition. After that, aluminium and magnesium fluoride (MgF2) were evaporated through electron beam evaporation to produce the electrode and ARC, respectively. The ratio of Ga to (Ga+In) was around 0.3, and metal compositions like this were deposited with an additive such as sodium (Na) to form the precursor layers [T22]. A schematic of the state-of-the-art rigid-substrate double-buffer CIGSSe solar cell is shown in Fig. 21 T22].

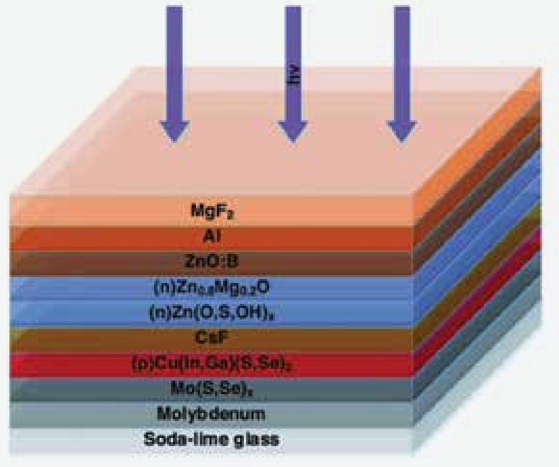


Fig. 21: Layout of a rigid-substrate double –buffer CIGSSE solar cell [adapted from T22].

In the case of CIGSSe solar cells, the ZnO: Al (AZO) layer is used as a TCO to collect and transfer electrons out of the cell while allowing maximum transmission of light. Due to environmental concerns and limitations in resources, researchers have turned to the CZTS solar cell, which is made up of entirely earth-abundant elements.

Some critical issues related to CIGS solar cells include

- Developing a deposition process for flexible substrates at lower temperatures is necessary for the large-scale manufacturing of these solar cells.
- (ii) While many materials used in the device are abundant on earth, indium (In) is a rare metal, leading to the search for alternative materials.
- (iii) The deposition of the CdS layer using CBD involves the use of toxic Cd and thiourea (CH4N2S), leading to waste production. Additionally, selenide (Se) compounds like H2Se are highly toxic and need to be minimised [T25].

Cadmium Telluride Solar Cell

In the beginning, the CdTe solar cell was configured as a substrate formation, but the structure was changed to a superstrate arrangement [T26, T27]. The first CdTe/CdS solar cell was developed by a thin-film graded gap and a 3-step process, including high-temperature vapour phase deposition (VPD) for p-CdTe and high vacuum evaporation for the n-CdS film in 1972 by Bonnet & Rabenhorst with PCE of 6% [T28]. The technology has progressed over the years. During 2011-2016, First Solar Inc. demonstrated CDTE thin film solar cells of PCE over 19% [T29-T34] with state-of-the-art PCE of 22.1% in superstrate arrangement [T35]. The CdS/CdTe hetero-junction cell was developed on a glass substrate by the CSS method, t. The CdS window layer was fabricated by VTD following the deposition of the CdTe absorber layer. Further research continued towards the highest efficient, commercialised device.

The solar cell with a zinc (Zn) blended crystal structure is typically developed on ordinary glass substrates, preferably a heat strengthened front SLG. The TCO is frequently SnO_2:F (FTO), In2O3:Sn (ITO), or cadmium tin oxide (Cd2SnO4), which acts as the front contact and functions as a window layer. The n-type CdS layer, which is approximately 100 nm thick and is now used as a buffer layer, can be deposited by CBD, sputtering, vacuum evaporation, etc. [T27, T36]. The p-type CdTe absorber layer, which is about 5 µm thick, can also be deposited using PVD, sintering, screen-printing, etc. The back contact (metal contact) can be made of Al, Mo, gold (Au), nickel (Ni), or platinum (Pt) using the vacuum thermal evaporation (VTE) technique [T10].

In the latest technology, the cell is laminated between two layers of glass, with the second layer typically being a heat-tempered back SLG. Additionally, a transparent encapsulate sheet, ideally ethylene vinyl acetate (EVA), a polymeric adhesive, is used for protection and sealing from delamination due to possible chemical degradation. After applying the copper (Cu)-doped zinc telluride (ZnTe:Cu) metal contact, the CdTe film is created using closed-space sublimation (CSS), followed by a cadmium chloride (CdCl2) treatment. The CdS film is created using vapour transport deposition (VTD). The FTO as TCO is coated with an optional buffer layer (SnO2, ZnO, ZnO:Mg) by MOCVD on the front glass [T37-T39]. The schematic layout of the state-of-the-art superstrate glass-glass CdTe/CdS solar cell is shown in Fig. 22.

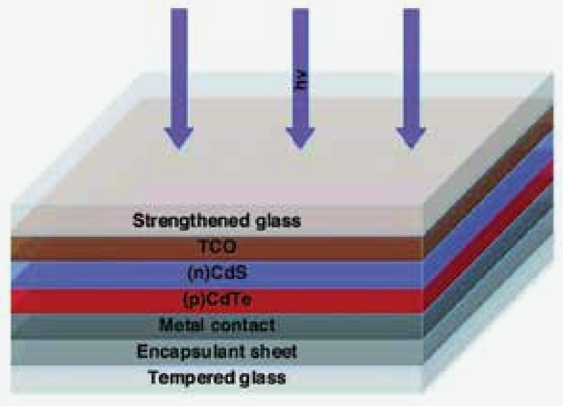


Fig. 22: Layout of a superstrate glass-glass CdTE/CDS solar cell, adapted from [T4].

The CdTe/CdS solar cell primarily uses TCO as a front contact and a lateral current-carrying conductor. The $CdCl_2$ treatment is used to increase grain size and significantly improves the overall conversion efficiency.

There are some critical issues with CdTe solar cells that have been identified, including: (i) during the active lifetime of the solar cell, there is a risk of modules breaking down and causing fire hazards that need to be addressed, and (ii) tellurium (Te), which is a rare element obtained as a by-product of Cu refining, is used in CdTe solar cells and may create a material shortage in the future. [T40]. (iii)One of the primary elements, Cd, is very toxic and known as a carcinogenic as well as environmentally hazardous material, though the produced PV compound has reduced toxicity and increased stability [T41].

Commercial Status of Thin Film PV Technology vs c-Si

The laboratory efficiency record for α-Si single-junction is 10.22% and for multijunction it is 14.04%. Currently, the highest performance for CIGS solar cells on rigid substrate is 23.35% and on flexible substrate 20.56%. Meanwhile, the highest performance for superstrate CdTe solar cells is 22.1%. The thin-film industry saw significant growth from 2001 to 2009, with production increasing from 14 MW to 2,141 MW and the participation of over 100 companies [T35].

In terms of laboratory-developed solar cells, the highest performance is recorded by mono-crystalline Si modules, with a maximum efficiency of 26.7%, while poly-crystalline Si has a maximum efficiency of 23.2%. The highest recorded efficiency for a-Si solar cells is 14.04% for multi-junction cells, for CIGS on a rigid substrate it is 23.35%, and for CdTe it is 22.1%. Among thin-film technologies, CIGS has the greatest prominence in terms of laboratory-developed modules. TEL Solar from Switzerland has shown the most promising results with 12.3% efficient a-Si multi-junction business modules. In the thin-film industry, CIGS on a rigid substrate has the highest efficiency of 19.2% for a commercialised module, produced by Solar Frontier in Japan. First Solar Inc., a reputable CdTe company from the U.S., is manufacturing devices with the highest efficiency of 19%.

Over the last few decades, it has been observed that c-Si technology has dominated the global PV production, with the shipments of Si modules increasing from 87% in 2010 to 95.5% in 2019. Among these shipments, the share of single-crystalline Si increased from 38% to 63%, while that of multi-crystalline Si decreased from 49% to 32.5%. Although thin-film modules have shown a continuous decline from 13% in 2010 to 4.5% in 2019, CdTe has consistently held the highest portion of production with 8% and 2.3%, respectively. At the same time, the shipments of CIGS decreased from 2% to 1.9%, while those of a-Si lowered significantly from 3% to 0.3% [T6].

2.2.4 Third Generation Solar Cells: The Emerging Solar PV Technology

The third-generation solar cells, which include dye-sensitised solar cells (DSSCs), organic solar cells (OSCs), perovskite solar cells (PSCs), and quantum dot solar cells, are aimed at solving issues such as cost, materials, low efficiency, and toxicity that were associated with second-generation solar cells. These third-generation solar cells have efficiencies of approximately 13.4% (QDSSCs), 11.9% (DSSSCs), 19% (OSCs), and 25.7% (PSCs), respectively. However, commercialisation of these solar cells is hindered by the issue of degradation. These solar cells are still in the exploratory stage and require further research to improve their efficiency and durability. The evolution of the efficiency of third-generation solar cells can be observed from the NREL chart presented in the reference. Now, let's discuss each of these third-generation solar cells in detail.

Organic Solar Cells (OSCs)

The OSCs are a promising solar cell technology for the future and can also contribute to current energy needs. Integrating OSCs into the current infrastructure can expand their application range and reduce installation costs compared to second-generation solar cells. Single junction OSCs have achieved efficiencies of around 19%, while tandem structures have achieved even higher efficiencies. This success is due to the work of various scientific communities, including physics, materials science, and chemistry, who have addressed various aspects of the technology, such as interface engineering, charge transport, and other related device issues.

The working of OSCs can be understood by studying the photovoltaic effect of active layer materials used in OSCs, such as conducting polymers. The bilayer OSCs were reported initially in 1986 by Tang et al. as having an efficiency of ~ 1% and fill factor (FF) of ~ 65%. Thanks to the Nobel prize-winner of 2000 for conducting polymers, Prof. A.L. Heeger and his group, for the discovery of conducting polymers useful in electronics and other optoelectronic applications.

The alternating single and double carbon-carbon polymer bonds are responsible for their conducting properties. The carbon atom and polymer chain are SP^2 hybridised, leaving the pz orbital unhybridized, sticking out of the polymer plane, as shown in Fig. 23.

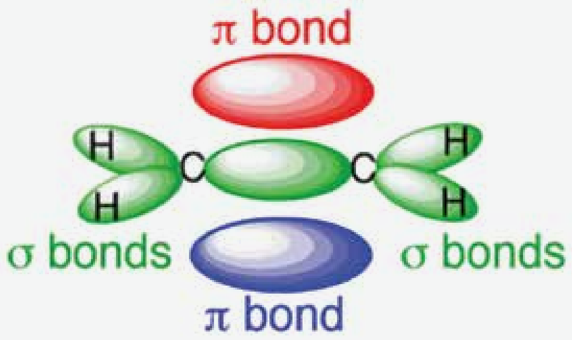


Fig. 23: π-bond from sp2 hybridization in ethylene providing delocalized electrons for electricity conduction.

These free π orbital electrons are responsible for conducting the electricity. These π- orbital electrons split into two bands: bonding and anti-bonding. The bonding band, filled up to the highest occupied molecular level, is known as HOMO. The empty π-anti bonding band is known as LUMO (lowest unoccupied molecular level).

Exciton

The generated charge carriers due to absorption of incident photon on the active layer of solar cell have binding energy $E_B \sim q_1q_2/4r\pi€€_0$, with q_1 and q_2 of opposite kind of charges, r is the distance between them, and the others are the usual constants. The dielectric constant of polymeric materials is usually low with respect to the inorganic one. Hence, the binding energy of organic semiconducting materials exciton is higher than the inorganic one. The electron and hole in the bounded condition are known as an exciton, having binding energy ~ 0.1-1.4 eV for organic conductors and 1-40 meV for inorganic ones. The tightly bound excitons (known as Frenkel excitons) diffuse only a short distance of ~ 1-10 nm with respect to micrometres for inorganic semiconductors.

Theictorion processing route of OSCs has addressed the cost-related issues of Si-based devices, making OSCs a promising next-generation solar cell technology. OSCs that use conjugated polymers are particularly popular due to their low cost, availability of new materials with improved optoelectronic properties, scalability of production techniques, flexibility, being lightweight, and availability of transparent and semi-transparent structures. The device structure of OSCs depends on the nature of the materials used, and different structures have been reported so far, including monolayer, bilayer, bulk heterojunction (BHJ), and Tandem structures, as demonstrated in Fig. 24-28.

Monolayer OSC$_s$

The organic semiconductor sandwiched between two electrodes of different work functions makes a monolayer structure. The electric field, generated due to the difference in the work function of electrodes, provides a driving force for the dissociation of excitons generated in the organic materials. The recombination loss dominates in monolayer solar cells as the transport of charge carriers occurs in the same semiconducting material. Hence, power conversion efficiency (PCE) is very low, ~ 0.1 %.

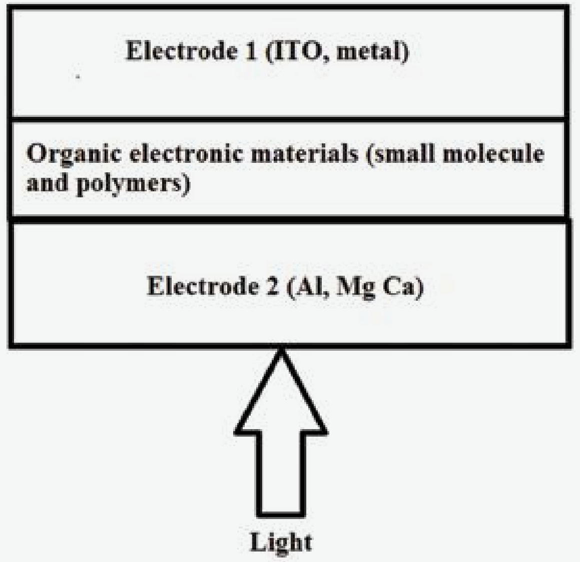


Fig. 24: Schematic of monolayer OSCs.

Bilayer OSCs

The shortcomings of monolayer OSCs can be overcome by introducing bilayer OSC devices. In bilayer OSCs, the donor and acceptor materials are sandwiched above each other between two electrodes. The offset energy of the HOMO of the donor and LUMO of the acceptor provides a driving force for the dissociation of excitons at the D/A interface. The concept of a bilayer provides efficient charge separation and less recombination, resulting in improved device performance. However, interfacial dissociation of excitons limits its device performance due to limited exciton diffusion length.

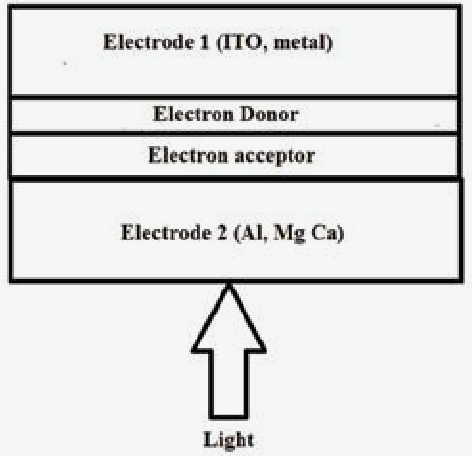


Fig. 25: Schematic of bilayer OSCs

Bulk heterojunction organic solar cells (OSCs) address the limited diffusion length issue of bilayer cells by mixing the donor and acceptor materials together, creating a blend with homogeneous characteristics at the nanoscale. The device structures shown in Fig. 26 and Fig. 27 can be either conventional or inverted, depending on the direction of charge carrier extraction.

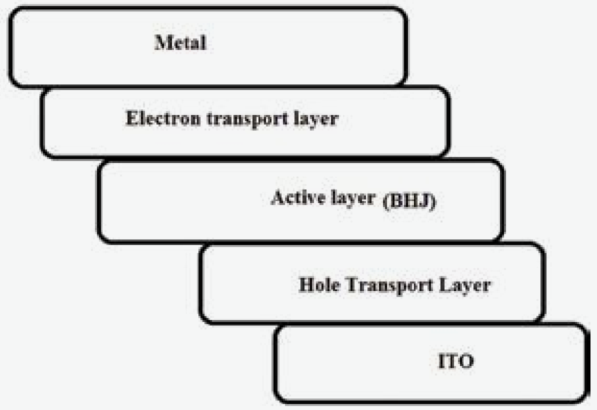


Fig. 26: Schematic of conventional bulk heterojunction (BHJ) solar cells

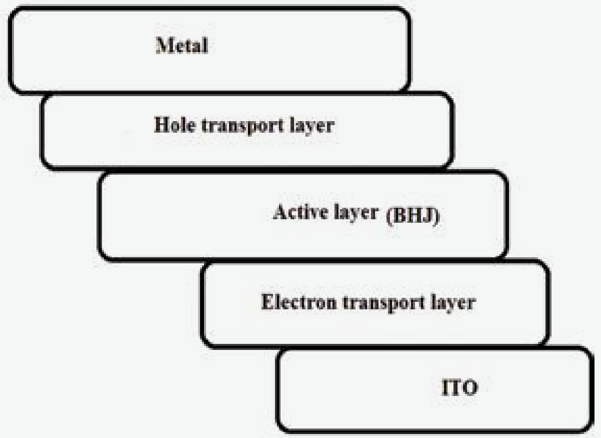


Fig. 27: Schematic of inverted bulk heterojunction (BHJ) organic solar cells (OSCs)

The above device structures were invented by Prof. A. J. Heeger and his group in 1995, and they are known as bulk heterojunction (BHJ) organic solar cells. The increased D/A interface in BHJ enhances charge carrier photogeneration, resulting in improved device performance. BHJ structures have been the most popular and have been under investigation since their invention. However, BHJ structures require more interfacial and material engineering for better device performance. Various new and innovative active layer materials have been developed to boost device performance, such as new donor materials like P3HT, PCDTBT, PTB7, PCPDTBT, and PCE10, which are blended with PC61BM or PC71BM to enhance solar spectrum absorption.

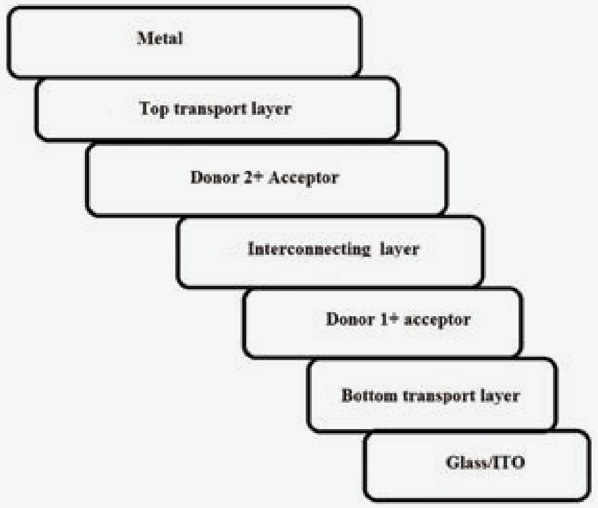


Fig. 28: Schematic of Tandem OSC device

The limited absorption spectrum range (Eg:1.6 – 2.0 eV) of single junction BHJ and the limited mobility of charge carriers limit the device performance of single junction solar cells. However, this absorption range limit can be overcome by fabricating a device that can expand the absorption range. This can be achieved by using multilayers with complementary absorption properties, which can be in series or parallel, known as Tandem solar cells, as depicted in Fig. 28.

Working Principle of Organic Solar Cells (OSCs)

The electron-hole pair generated through the absorption of photons on organic materials and held together by Coulombic forces is known as an exciton. The exciton needs to be separated by additional energy and processes to become free charge carriers. The various steps involved in this operation are known as the working principle of OSCs.

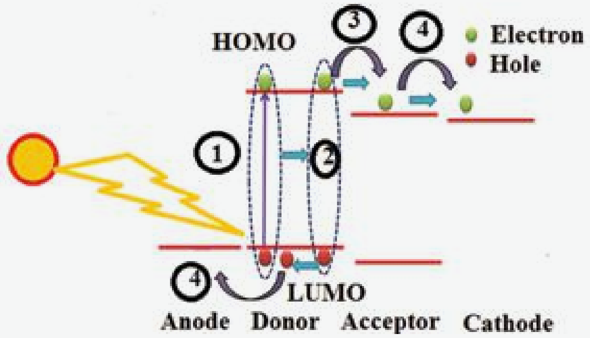


Fig. 29: Schematic of Energy level diagram of an OSC and its operation mechanism (1) light absorption and exciton generation (2) Exciton diffusion (3) Exciton dissociation (4) charge collection.

Absorption of Light and Generation of Excitons

The basic principle of solar cells is to generate charge through the absorption of photons. For this to happen, the energy of the incoming photons must be greater than the band gap (E_g) of the semiconductor used in the solar cell. When this condition is met, the photon is absorbed, resulting in the creation of a Coulombically bonded electron-hole pair, also known as an exciton. This exciton then travels through the material, with its diffusion distance depending on the quality of the polymer used. However, before it can be separated into free charge carriers, the exciton faces the problem of recombination, which can limit its efficiency. Therefore, the thickness of the film is an essential factor in ensuring efficient charge separation.

The photons absorbed within the effective exciton diffusion range at the D/A interface contribute to the device power conversion efficiency (PCE). The exciton dissociation is done with the help of an appropriate electrode that provides a built-in voltage for exciton dissociation. It is crucial to select suitable electrodes with the correct work function for efficient functioning of organic solar cells. Typically, the cathode should have a low work function near the LUMO level, while the anode should have a higher work function near the HOMO level. At the interface of the donor and acceptor materials, exciton separation can occur.

- **Exciton Diffusion**

  Excitons generated in regions that are distant from the D/A interface need to traverse the interface to become free charge carriers, and this process can result in recombination and loss of excitons. Therefore, the thickness of the film is a crucial factor that needs to be optimised to ensure that the maximum number of excitons survive within the materials domain.

- **Exciton Dissociation**

  Proper selection of electrodes is crucial for the dissociation of excitons. The built-in voltage of the electrodes must overcome the exciton binding energy to facilitate dissociation. In BHJ solar cells, the dissociation of excitons can only occur at the D/A interface. The charge transfer process is very fast, occurring within 300 femtoseconds, which is much faster than the recombination process. For efficient electron-hole separation, acceptor materials with higher HOMO and LUMO values than the donor are necessary. Otherwise, charge transfer may occur from materials with higher band gaps without exciton splitting, leading to eventual recombination at the D/A interface.

  To dissociate the exciton properly, the electron needs to jump from the donor LUMO level to the acceptor LUMO level while the holes remain at the HOMO level. The energy difference between the two LUMOs should be significant enough to overcome the Coulomb field of one charge on the other. However, the LUMO-LUMO energy difference should not be too large compared to the exciton binding energy, which could cause a loss to Voc. The energy of the exciton needs to be greater than the electron-hole pair binding energy, known as the charge transfer state (CTC), for proper exciton dissociation to occur. The charge transfer results in the hole at the donor and the electron at the acceptor. The separated charges then need to travel to the respective electrodes for collection.

- **Charge Collection**

  The separated charge carriers are driven to the respective electrodes by the electric field created by electrodes of different work functions. They move through hopping processes. The electrons are transported to low work function metal electrodes, and holes are collected at ITO. The OSCs are characterised by the standard protocol of AM 1.5G spectrum of solar illumination (100mW/cm^2) for the extraction of different device parameters, such as efficiency, fill factor (FF), open circuit voltage (V_{oc}) and short circuit current (J_{sc}).

- **Configurations of OSCs.**

  The BHJ OSCs consist of different components such as (i) active layer materials (donor and acceptor), (ii) electrodes (cathode/anode) (iii) interfacial layers (electron transport layer/ hole transport layer).

The most popular donor materials for OSCs are P3HT, PCDTBT, PTB7, PCE10, PCE11 etc., along with the most popular acceptor, PC61BM and PC71BM. However, non-fullerene acceptors (PDI-based) are widely developed and studied in BHJ OSCs to enhance their efficiencies. These acceptors have tunable band gaps with rigid band gap fullerenes. The ITO is used as an anode (work function (~ 4.8 eV), and Al (work function 4.3 eV), Ag (work function ~ 4.2), Ni, and Au are widely used as cathodes. The interfacial layers, such as electron transport layer (ETL) and hole transport layers, facilitate easy charge collection at various electrodes. The conventional device structure uses the ETL between the active layer and the metallic cathode. However, in an inverted device, ETL is used between the active layer and ITO.

Moreover, in the traditional solar cell structure, a hole transport layer (HTL) is positioned between the indium tin oxide (ITO) and active layer, while in the inverted configuration, it is placed between the active layer and the ITO. The choice of ETL or HTL depends on their electrical properties and energy levels. These layers serve several functions, including modulation of energy barriers, selective contacts for single charge transport, interface passivation, and inhibition of diffusion and reactions between the electrodes and the active layer materials. The most common ETLs include calcium (Ca), barium (Ba), magnesium (Mg), and alkali metal compounds like caesium carbonate (Cs2CO3), lithium fluoride (LiF), titanium oxide (TiOx), zinc oxide (ZnO), and tin oxide (SnO2). Fig. 9 illustrates the materials frequently used as ETLs and HTLs in the production of high-performance OSC devices.

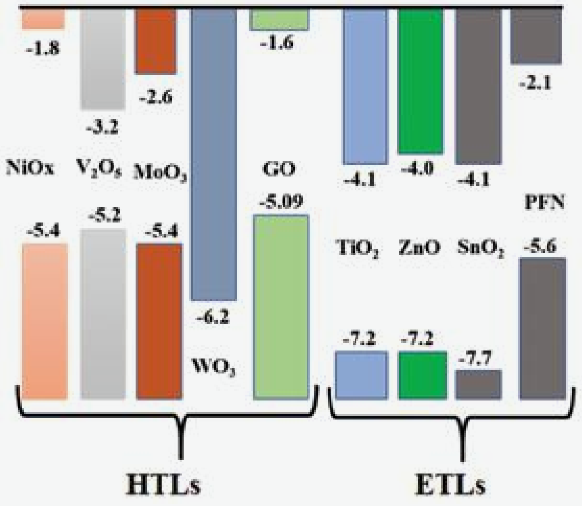


Fig. 30: Schematic of energy-level diagram with some charge carrier transport materials used in organic BHJ solar cells.

Perovskite Solar Cells (PSCs)

The initial demonstration of a perovskite solar cell in 2012, with an efficiency of 9.7% and a device structure in the p-i-n configuration, generated significant interest from the scientific community involved in materials, devices, chemistry, and device physics, especially because of its ~500-hour lifetime. This invention originated from the instability of MAPbI3 in DSSCs with polar electrolytes. Over the past 11 years, the efficiency of perovskite solar cells has increased from 9.7% to 25.7%, achieved by optimising the perovskite film morphology, the interface layer, the ETL, HTL, and the device fabrication strategy. The efficiency of PSCs now exceeds that of multi-crystalline silicon (~22.8%), CSGS (23.4%), and CdTe (~22.1%).

Initially, the focus of PSC development was on creating devices with higher efficiency and understanding hysteresis. To achieve this, various techniques, such as compositional, interface, and solution engineering, were explored. The study of fundamental observations showed that the charge diffusion length was greater than the film thickness in the sub-micron range of p-i-n or n-i-p configurations. Looking ahead, the goal for PSCs is to achieve theoretically predicted efficiency values, which will require transferring the knowledge gained from small-area devices to large-area modules for commercialisation. To be commercially viable, PSCs must have guaranteed long-term stability and reproducibility, which will require establishing proper standards and operating protocols.

Furthermore, combining established silicon technology with perovskite technology may lead to innovative devices, such as silicon-perovskite tandems or heterojunctions. Tandem devices that incorporate a PSC as the top cell and Si or CIGS as the bottom cell with a current match have been reported to be the most efficient (~32.5%) and may be a promising approach for pushing perovskite-based technologies into the PV market. Theoretically predicted efficiencies of ~39% could be achieved with this type of device.

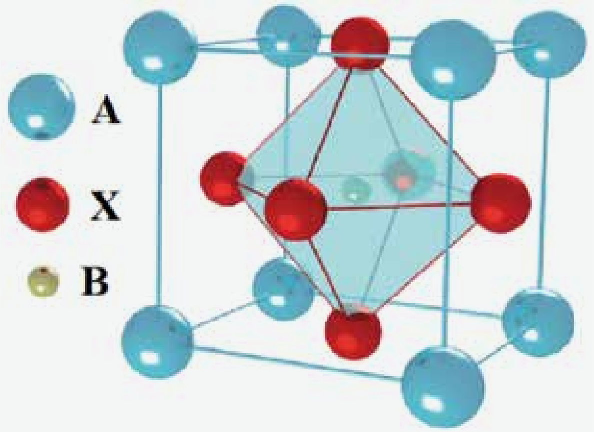


Fig. 31: Pictorial representation of crystal structure of perovskite (Y. Chen, L. Zhang, and Y. Zhang RSC Advances 8(19),10489-10508)

The research community working on PSCs publishes numerous articles each year, highlighting the importance of this innovative and potentially futuristic technology. The main component of PSCs is perovskite materials, which were first invented by Russian scientist L.A. Perovski in 1839. Perovskite materials have a crystal structure of ABX3 type (as shown in the figure), with A representing a large monovalent cation at the Cubo octahedral site in the cubic space, B representing a divalent metal cation at the octahedral site, and X representing an anion, which can be halogen for perovskite materials used in PSCs.

In addition, the stability can also be affected by the ratio of the divalent cation radius (RB) to the radius of the anion (Rx). For halide perovskites, these factors should fall within the range of 0.81-1.11 for RB and 0.44-0.90 for Rx.

Working Principle of Perovskite Solar Cells
Understanding the operational mechanism of OSCs is essential for comprehending the functioning of PSCs. Fig. [insert figure number] provides a schematic representation of the operational mechanism of PSCs. The perovskite absorbing material, upon absorbing light, generates electron-hole pairs, which are collected at their respective electrodes during device fabrication.

The operational mechanism of PSCs involves three main steps: (1) absorption of photons and free charge carrier generation, (2) charge transport, and (3) charge extraction. When light is absorbed by the perovskite material, excitons are generated, and they are subsequently separated at the perovskite-charge transporting layer interface. The separated electron moves towards the anode through the ETL, while the hole is collected at the metal electrode through the HTL. The electrons and holes are then transported to an external circuit to generate current.

Perovskite Device Configurations
PSCs can operate in different architectures depending on the materials present exterior to the cell, which are known as conventional (n-i-p) and inverted (p-i-n) structures. These conventional and inverted structures can be further divided into mesoscopic or planar structures. Moreover,

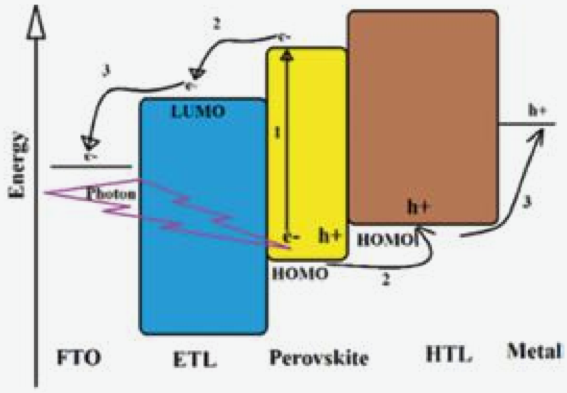


Fig. 32: Pictorial demonstration of the working principles of perovskite solar cells (PSCs).

experimental testing has been carried out on device structures without ETL or HTL. As a result, a total of six types of PSC device structures have been observed and experimented with over the last 11-12 years.

The six different device structures are: (i) mesoscopic n-i-p configuration, (ii) planar n-i-p configuration, (iii) planar p-i-n configuration, (iv) mesoscopic p-i-n configuration, (v) ETL-free configuration, and (vi) HTL-free configuration.

- **Regular n-i-p structures**
  The first structure that was tested for PSCs was the mesoscopic n-i-p configuration. In this structure, light harvesting was accomplished using lead halide perovskite semiconducting materials instead of dyes that were commonly used for DSSCs. Hence, the structure was similar to that of DSSCs. The structure became even more interesting when the liquid electrolyte was replaced by solid hole-conducting materials.

  The mesoscopic n-i-p configuration consists of a transparent FTO-coated glass as the cathode, followed by the deposition of ETL, a perovskite layer, an HTL, and capped with a metallic anode.

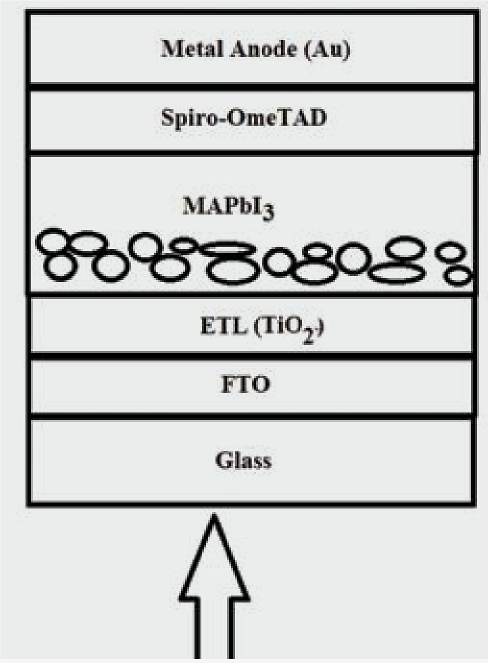


Fig. 33: (a) n-i-p mesoscopic PSCs.

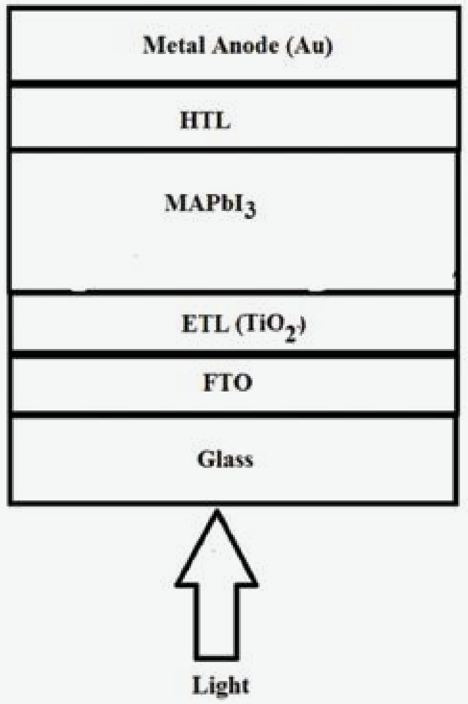


Fig. 33: (b) n-i-p planar PSCs configuration.

  Furthermore, planar structures are an evolution of mesoscopic structures. In planar structures, the perovskite layer is sandwiched between ETL and HTL without a mesoscopic layer, making the structure more straightforward. Planar devices can be fabricated using a low-temperature process, unlike mesoscopic structures. However, perovskite materials need to be controlled carefully for proper device performance.

- **Inverted p-i-n Structures**

  The unique property of perovskite, which allows for self-transportation in the HTL, has compelled scientists to develop p-i-n structures similar to OSCs. The p-i-n structure option facilitates the exploration of a wider range of selective layers, ranging from organic to inorganic materials/oxide materials as HTL, for fabricating p-i-n devices. These devices are also privileged with low-temperature processing with negligible hysteresis.

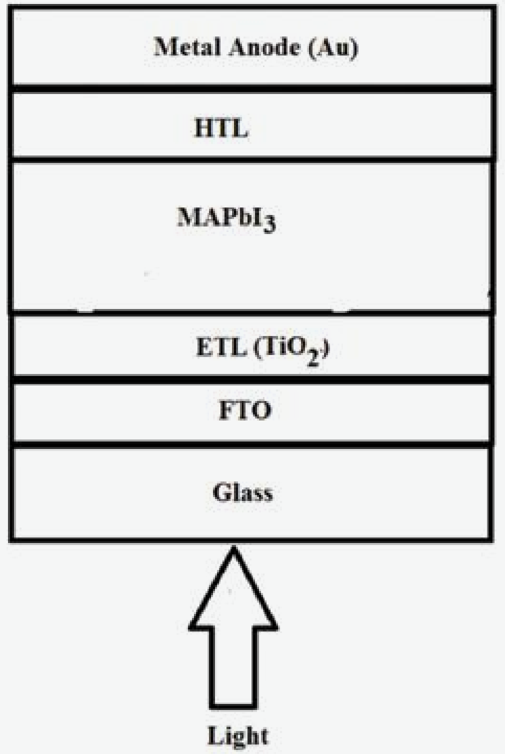


Fig. 33: I p-i-n planar PSCs configuration.

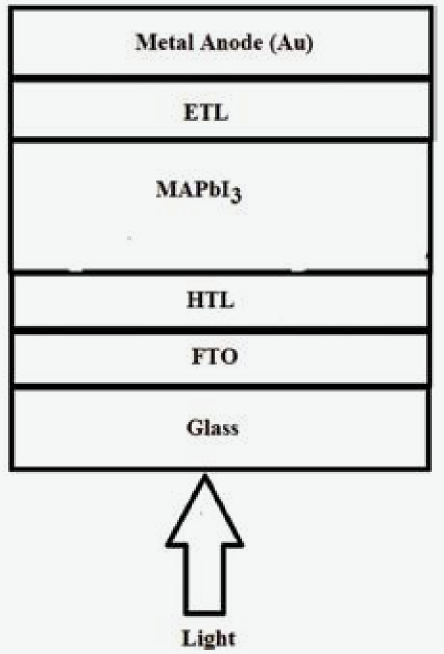


Fig. 33: (d) p-i-n mesoscopic PSCs configuration.

- **ETL-free PSCs**

  The transparent conducting oxide (TCO), coated with n-type metal oxide, is needed to construct a conventional planar structure. The schematic demonstration of ETL of ETL-free perovskite solar cell structure is given below.

Fig. 33: (e) Schematic of ETL-free perovskite configuration.

- **HTL-free PSCs**

  The schematic representation of HTL-free devices is given below.

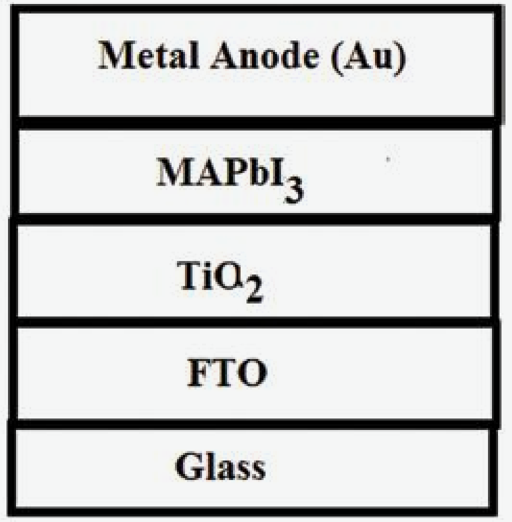


Fig. 33: (f) Schematic of HTL-free perovskite solar cell (PSCs) configuration.

Materials Used in Development of Perovskite Solar Cells

(i) The PSCs are fabricated using different kinds of materials, such ai) Transparent conductive oxide (TCO) (ii) Electron transport layer (ETL) (iii) Light harvesting perovskite materials (iv) hole transporting materials (HTL) (v) metal contact materials.

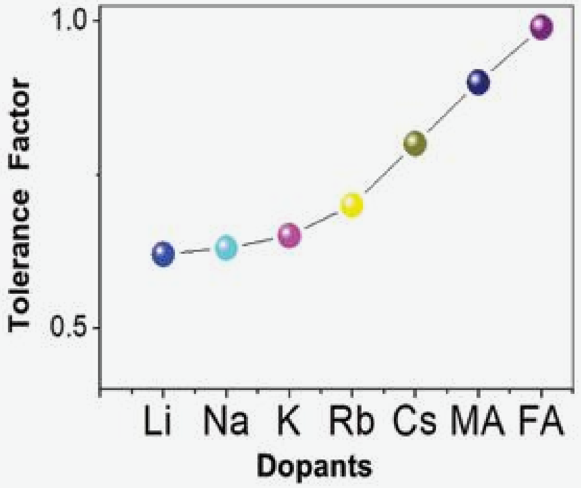


Fig. 33: (g) Tolerance factor of perovskite materials with different dopants.

As discussed, perovskites are made up of a combination of mono and divalent cations, along with halide ions, and are commonly used in PSCs as light absorbers, with MAPbI3 being the most popular. However, researchers are exploring alternatives to lead-based perovskites due to toxicity concerns and using strategies such as cation exchange/mixing to optimise the materials for improved PSC performance, particularly in terms of sub-optical band gap and stability issues. Lowering the band gap of MAPbI3 by partially replacing MA with FA can enhance light harvesting, but this creates stability issues due to crystallisation of FAMAPbI3 in non-photoactive phases. Mixed cation and mixed anion or halide-cation anion perovskites are also being investigated due to their potential advantages over MAPbI3.

ictorialrial representation of the tolerance factor, plays an essential role in substituting MA with other monovalent cations, the alkali metals such as Li, Na, K, Rb and Cs other than FA and MA. Although $CsPbI_3$ have excellent stability, the band gap of this perovskite is ~1.73 eV and not so useful for outdoor photovoltaic in single junction devices. Organic-inorganic double cation exploration had reached the replacement of MA with Cs improving its light absorption and morphology of the perovskite film. The triple cation perovskite is also explored for better device performance.

Multiple permutations and combinations of cations and anions are attempted for better performance of PSCs. In addition to cation management, halide substitutions have also tried for performance enhancements of PSCs. The optoelectronic properties can also be managed by halogen ion replacement for favourable PSC performance. The iodide can be replaced by Br^-, Cl^- for the development of $MAPbCl_3$ and $MAPbBr_3$. Cl, Br and iodine substitution can easily manipulate the optical properties of $MAPbI_3$ for a favourable PL for applying PSCs. Perovskite materials such as $MAPbI_3$ and $MAPbBr_3$ are suitable for single-band gap absorbers or even for tandem solar cell applications. The combination of perovskites such as $(FAPbI_3)_{0.85}(MAPbBr_3)_{0.15}$ has an advantage over their constituent perovskites. Compositional management is a technique for getting better perovskite for PSCs application.

Furthermore, a novel approach of replacing or mixing divalent metal cations can be effective in obtaining superior perovskite materials for PSCs. This technique is particularly suitable for creating Pb-free perovskites for commercial and IoT power solutions. Various metals such as Sn, Ge, Cu, Sb, Bi, and Sr can be used to replace Pb in the perovskite structure. The combination of Sn-Pb based perovskites, such as MAGeI2.7Br0.3, shows promising results. The quality of the perovskite film is crucial for achieving optimal device performance.

- **Electron Transport Layer (ETL)**
  To enhance the performance of PSCs, both organic and inorganic materials can serve as ETL. Typically, organic materials are utilised in inverted OSCs as ETL, whereas inorganic materials are utilised in conventional perovskite devices. ETLs must have an energy level that is consistent with that of perovskite materials to allow for efficient electron movement towards the electrode. Additionally, high electron mobility is necessary for swift electron transport. The diagram displays the energy levels of various ETLs that are beneficial for device production. Inorganic materials such as TiO2, SnO2, ZnO, In2O3, WOx, and CeOx are employed to produce perovskites. Furthermore, PC61BM, ICBA, and PC71BM are used as ETLs for PSC production. The primary function of HTL is similar to ETL and works as a contact point for selecting holes and carrying holes to metal contact. The different classes of HTLs are small molecules, polymers, as well as inorganic and have their own merits and demerits for being used as HTL in PSCs. Spiro-OmeTAD, polyaniline (PANI), poly(triarylamine) (PTAA), P3HT, CuI, NiO, and CuSCN are some well-known HTLs in PSC fabrication. The energy level of some famous ETLs and HTLs used in perovskite solar cell fabrication. A schematic of ETL and materials used in PSC fabrication are shown in.

- **Dye Sensitized Solar Cells (DSSCs)**
  The cost issue associated with silicon solar cells can be addressed by using DSSCs instead of silicon-based devices. DSSCs utilise titanium oxide (TiO2) and a sensitising dye extracted from various natural resources. The unique characteristics of these devices allow them to function in darker conditions, such as dawn, dusk, or even cloudy weather. The efficient use of these devices makes them an excellent option for indoor applications such as windows and sunroofs.

  The DSSCs research activity was started in 1991 by O'Regan and Gratzel. As per the report by NREL. A schematic representation of DSSCs.

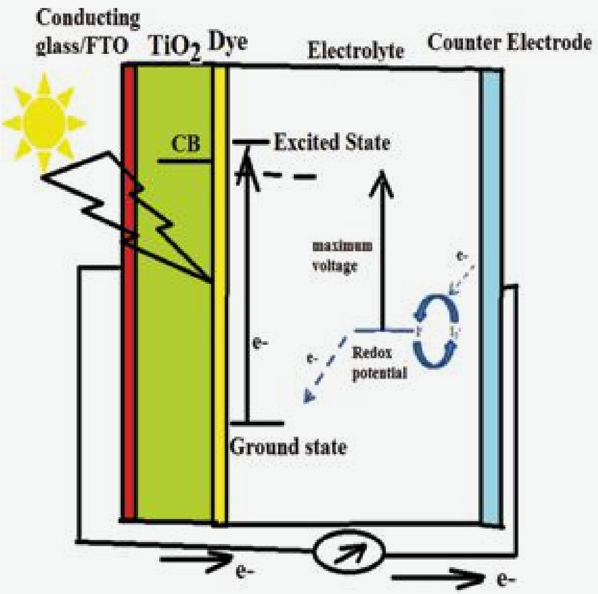


Fig. 34: Schematic of DSSCs working principles.

DSSCs work on four basic steps such as (i) light absorption, (ii) electron injection, (iii) transportation of carriers, and (iv) collection of current. Briefly, on the absorption of photons by the sensitiser, the electron is excited from the ground state to the excited state of the dye. The absorption of most of the dyes is at ~ 700 nm, corresponding to ~ 1.72 eV. The excited electrons, with a lifetime in the range of nanoseconds, are subsequently injected into the conduction band of TiO_2. Subsequently, the injected electron is transported in nano crystalline TiO_2 diffusing towards the back contact and reaching the counter electrode. These electrons at the counter electrode reduce I^{-}_{3} to I^{-}. In addition, TiO_2 also absorbs photons from UV-region, which oxidises the dye. The generation of the ground state of dye takes place on the acceptance of electrons from the I^{-} ion redox mediator, and I^{-} (Fig. 34) gets oxidised to I^{-3} (Fig. 34). The oxidised mediator (I^{-3}) diffuses towards the counter electrode and is reduced to an I ion. However, these devices are limited by their extrinsic and intrinsic stability.

Fig.34 illustrates that DSSCs consist of a working electrode, sensitiser, redox mediator, and counter electrode. These components are assembled by soaking a sensitiser or dye onto working electrodes and sealing them to a counter electrode coated with a thin layer of electrolyte. This is done using a hot melt tape to prevent electrolyte leakage. The essential components of a DSSC are a transparent and conductive substrate, which is fabricated using two sheets of conductive and transparent materials acting as a substrate for semiconducting and catalyst deposition that work as a current collector. This substrate should be at least 80% transparent with high electrical conductivity, and materials such as ITO/FTO are best suited for this purpose. The working electrode is created by depositing TiO_2, Nb2O5, ZnO, SnO2 (n-type), or NiO (p-type) on ITO/FTO. Among these, the anatase phase of TiO_2 is most popular due to its band gap of approximately 3.2 eV. TiO_2 is preferred for DSSC fabrication due to its non-toxic nature, low cost, and easy availability. However, its low absorption of light in the UV region requires coating with a mixture of photosensitive molecular sensitizers and a solvent.

The porous nature of TiO_2 binds a high number of dye molecules. Subsequently, it increases the light absorption on the working electrode. Dye increases the absorption of light. So basically, the dye should be luminescent and should cover Uv-visible and near-infrared regions. Dye should have proper HOMO and LUMO levels so that HOMO should be far from the surface of the conduction band of TiO_2, and LUMO should be close to the surface of TiO_2. Homo should also lie lower than that of the redox electrolyte. Further, the dye should be hydrophobic to increase the cell's long-term stability. The aggregation of the dye on TiO_2 may be checked using some co-absorbers.

Famous electrolytes such as I^{-}/I^{-}_{3}, Br^{-}/Br^{-}_{2}, SCN^{-}/SCN_2, Co (II)/Co(III) have main components such as redox couple, solvent, additives, ionic liquids and cations with the properties such as (i) ability to regenerate the oxidised dye should be stable, non-corrosive and matching absorption spectra with the dye. In addition, it should be able to permit fast diffusion of charge carriers and should create effective contact among working as well as counter electrodes. Finally, the counter electrodes are primarily prepared using platinum (Pt) or carbon (C). However, Pt's costly and less availability motivates other alternative electrodes, such as CoS, Au/GNP, FeSe, $CoNi_{0.25}$, etc.

In the 1960s, the use of organic dyes to produce electricity was demonstrated by employing these dyes in electrochemical cells. In 1972, chlorophyll extracted from spinach was sensitised with a zinc oxide electrode, and in the same year, excited dye molecules were used to inject electrons into a wide bandgap semiconductor, thus converting photons into electricity. Despite extensive research on the single crystal of ZnO, the efficiency of these dye-sensitized cells was poor due to only 1% absorption of incident light on the monolayer of dye molecules. Further, the use of porous oxide electrodes increased light absorption. It increased the efficiency of DSSCs up to ~ 7% in 1991, known as Graztel cells which were later improved up to ~ 8% under simulated light and 12% in diffuse daylight. These cells were of ~ 12 mA/cm^2 of current along with higher stability. Additional efforts improved the efficiency by up to 9.6% in 1993 and 10% in 1997, recognised by the National Renewable Energy laboratory. The sensitisers are–COOH, $-PO_3H_2$ and $–B (OH)_2$.

In contrast to silicon solar cells where silicon serves as the source of photoelectrons and creates an electric field for charge separation, in DSSCs, the semiconductor aids in charge transport provided by the photosensitive layer. Theoretical efficiency of DSSCs is around 20%, which has led several research groups to focus on device design and improving efficiency. As a result, the field's primary focus is on enhancing the performance of DSSCs by improving light-harvesting materials, electrodes, electrolytes, and other related components.

2.2.5 Solar Thermal Energy-based Technologies

Solar thermal energy (STE) represents the thermal energy component of the incident solar flux on earth. This energy can be used for various applications in commercial, industrial, and societal settings. It has been found that the solar radiation received by a typical house's roof is enough to exceed its yearly energy consumption. STE can be used for purposes like cooking, heating, cooling, refrigeration, mechanical work, and even for generating electricity. In 1878, Augustin Mouchot demonstrated the use of a solar thermal-based cooling engine for making ice cream, and in 1910, Frank Shuman demonstrated a steam engine powered by steam generated from solar thermal energy. One of the advantages of STE is its ability to store the generated heat for future use, making it a promising technology in combination with other renewable energy sources like wind and solar photovoltaics (PVs). There are many direct applications of solar thermal energy, as follows:

Solar Cooker

A solar cooker is a device that uses sunlight to cook food. It works by using reflective surfaces, such as mirrors or metal plates, to focus sunlight onto a cooking pot or other container. This concentrated sunlight heats up the pot and its contents, allowing food to be cooked without the need for conventional fuels such as gas or electricity. Solar cookers can be used in a variety of settings, including rural and off-grid areas where access to fuel or electricity is limited, as well as in environmentally conscious households looking to reduce their carbon footprint [2]. They are also used in remote areas or disaster relief situations to provide a means of cooking without relying on traditional fuel sources. There are different types of solar cookers, including box cookers, parabolic cookers, and panel cookers.

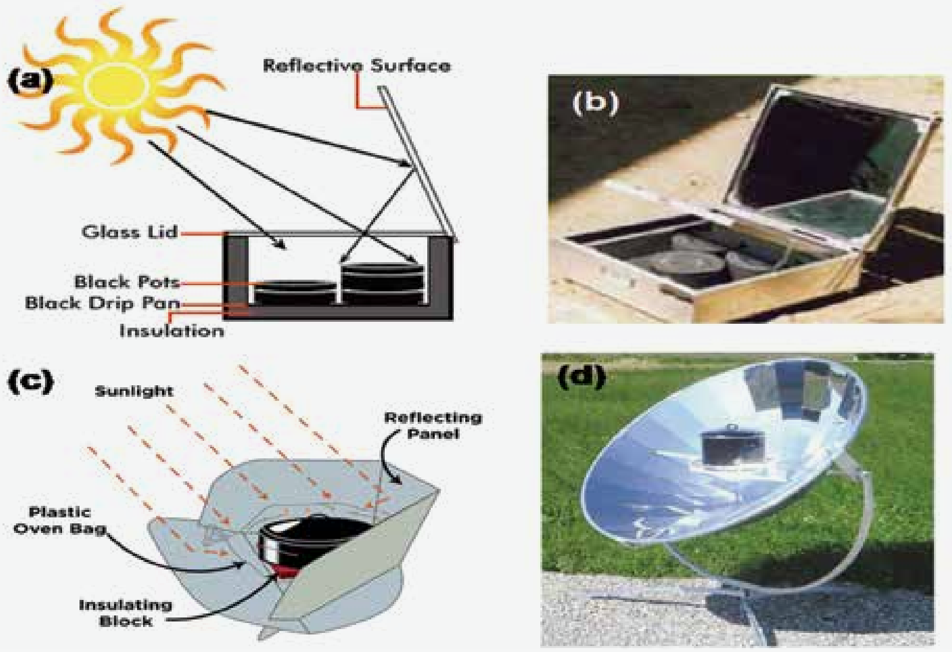


Fig. 35: (a) Schematic and (b) Actual picture of box type solar cooker; (c) Schematic of panel type and (d) Actual image of parabolic concentrator type solar cooker.

Box type cookers (Fig. 35a & 35b) are insulated boxes with a glass or plastic lid that allow sunlight to enter and heat the food inside. A reflective surface, often made of metal or aluminium foil, is used to reflect the sunlight onto the exterior of a black pot or pan, which maximises heat absorption, resulting in temperatures of up to 150°C. The pot or pan is usually insulated to keep the heat inside, and the food is cooked using the concentrated sunlight. Box type cookers can be used to sterilise water or cook most types of food that can be made in a regular oven or stove, including bread, vegetables, and meat, over a period of hours[3].

In contrast, panel type cookers (Fig. 35c) use reflectors to collect large amount of sunlight and direct it towards a black cooking pot placed inside a high temperature oven bag. The air inside the bag that surrounds the pot is the insulation that retains the heat and ultimately food is cooked[4]. To achieve even higher temperatures (up to 300°C) (Fig. 35d), parabolic cookers are used, which utilise a curved reflective surface to focus sunlight onto a small area, creating very high temperatures that can quickly cook food. The reflective surface is usually a parabolic dish made of a highly reflective material such as aluminium-coated PET film or glass mirrors. The dish reflects the sunlight onto a cooking pot or pan placed at the focal point, where the heat is concentrated[5]. Compared to conventional solar cookers, parabolic concentrator type solar cookers can be more efficient because they can reach higher temperatures and cook food more quickly. However, they are also more expensive and may require more maintenance than conventional solar cookers.

In addition to these designs, other advanced variants like Scheffler cooker (which has a rotation mechanism to focus the sun on the cooking pan all day long thus increasing the effectiveness of the process and speed of cooking) and vacuum tube type oven (fast enough to cook food as quickly as 20 minutes) are also gaining in popularity. In general, solar cookers are often seen as a sustainable and eco-friendly solution for cooking food, as they do not produce GHG emissions, and do not contribute to deforestation. Additionally, they are a cost-effective solution, as they do not require any ongoing expenses for fuel.

Solar cookers are known to be a healthy method of cooking as they can preserve food nutrients. They can also be used to purify water, which is particularly useful in areas where clean water is scarce. However, there are some limitations to solar cookers. They require direct sunlight to function and may not be suitable for use in areas with frequent cloud cover or heavy rain. In addition, they generally have longer cooking times than conventional stoves, which may not be practical in all situations. Despite these limitations, solar cookers are important in providing clean and affordable cooking methods in many parts of the world.

Solar Dryer

A solar dryer is a device that uses the energy of the sun to dry various types of food or other products especially to enhance their shelf life. The basic principle behind a solar dryer is to capture the heat and energy from the sun and use it to create a controlled environment for drying.
A solar dryer (depicted in Fig. 36) typically comprises a drying chamber constructed from a material that can retain and absorb heat, such as dark-coloured plastic or metal. The chamber is then covered with a transparent material, such as plastic or glass, which permits the sun's rays to enter while trapping the heat inside, resulting in a warm and dry environment suitable for drying food and other products. Natural convection or a fan circulates the air inside the chamber, which helps to hasten the drying process[7].

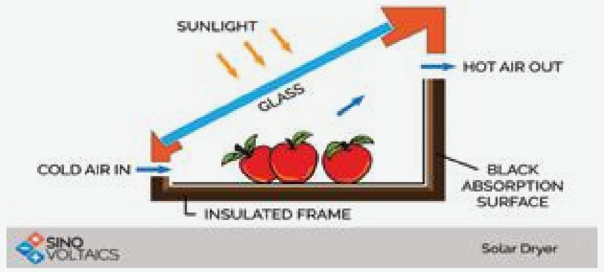


Fig. 36: Schematic of a solar dryer[6]

Solar dryers can be used to dry a wide range of products, including fruits, vegetables, herbs, grains, and meat. They are particularly useful in areas where traditional drying methods are not feasible, such as in humid or rainy climates, or where access to electricity is limited. Solar dryers can also be used for other products that require drying, such as clothes, lumber, and leather. Overall, solar dryers are an innovative and a sustainable solution for drying various products, especially in regions where traditional drying methods are not feasible.

There are various types of solar dryers available, including direct solar dryers which are low-cost and rely on natural convection to circulate air, making them ideal for drying small quantities of food like fruits and vegetables. Indirect solar dryers are more complex and use a heat exchanger to transfer heat from a solar collector to the drying chamber, making them suitable for drying large quantities of food like grains and meat. Hybrid solar dryers combine solar energy with another energy source like electricity or biomass to create a more efficient and reliable drying system. Despite some limitations, solar dryers are a cost-effective and environmentally friendly way to increase the shelf life of products, reduce post-harvest losses, and preserve the nutritional value and flavour of the product, resulting in a higher quality end-product. However, like other solar thermal devices, they require direct sunlight, have limited drying capacity, and require a high initial investment that may only be cost-effective in the long run[8].

Solar Thermal Freezer

A solar thermal freezer (STF) is a type of device that uses solar energy to power refrigeration system to generate the necessary cooling for preserving food or other perishable items[9].

A typical STF (Fig. 37) consists of a solar heat collector, an insulated storage chamber, and a refrigeration system. The solar collector, which is usually made of blackened metal or plastic, absorbs the heat from the sun and transfers it to a fluid, such as water/air or a suitable phase change material (PCM)[10]. The heated fluid is then circulated through the refrigeration system, which uses it to drive the cooling process.

STFs are frequently utilised in homes, farms, and small businesses that are not connected to the power grid. Additionally, they can be found in isolated regions, such as military outposts, relief camps, and research stations, where refrigeration is critical for preserving food and medicine. Nonetheless, their efficiency can be affected in regions with limited sunlight or during unfavourable weather conditions. Furthermore, STFs may require higher initial costs for installation and maintenance than conventional electric freezers.

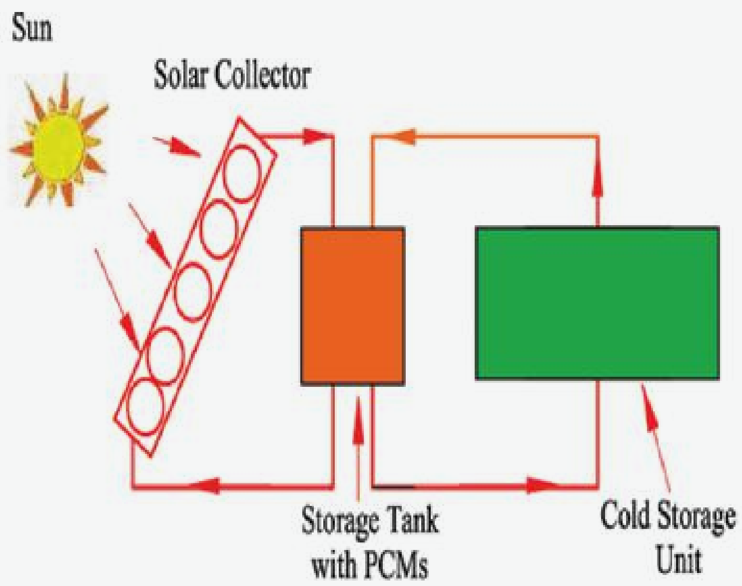


Fig. 37: Schematic of solar thermal refrigeration system[9]

Solar Thermal Heaters

Solar thermal heaters (STHs), which are also known as solar water heaters, are systems that use solar energy to heat water. These systems typically include a solar thermal collector and a storage tank that holds the heated water for later use. Solar water heaters can be classified as either active (pumped circulation) or passive (convection-driven circulation). They may use water only, or both water and a working fluid, and can be heated directly or via light-concentrating mirrors. The solar collector can be of different types, such as flat-plate collectors (FPCs) or evacuated tube collectors (ETCs).

The FPCs (Fig. 38a) essentially consist of a flat insulated box with a glass or plastic cover, and a dark-coloured absorber plate. They are much less effective when the water temperature exceeds the ambient air temperature. The evacuated tube collectors (ETCs) (Fig. 38b) are made up of multiple glass tubes that are evacuated to reduce heat loss and contain a metal absorber. In full sunshine, flat-plate collectors (FPCs) are generally more efficient than ETCs, but in foggy or extremely cold weather conditions, the energy output of FPCs is more likely to be reduced compared to ETCs[11].

STHs have versatile applications including domestic hot water, space heating, and industrial processes. They are commonly found in various settings such as residential, educational, and commercial buildings, as well as industries like food processing and textile manufacturing. STHs are an economical and eco-friendly alternative to conventional water heating systems since they utilise renewable energy and curtail the use of fossil fuels, ultimately leading to lower energy bills[12]. Nevertheless, the performance of STHs is influenced by different factors, such as the amount of available sunlight, collector size and orientation, and water temperature. Furthermore, the installation cost of STHs can be high initially, but it can be compensated over time through energy saving.

Fig. 38: (a) Flat-plate solar thermal collector, viewed from roof-level (b) Evacuated tube solar water heater on a roof[11]

Solar Desalination

Potable water is scarce in arid, semiarid, and coastal locations, where solar desalination provides an eco-friendly way to harness abundant sunlight to turn saltwater into potable freshwater[13].

In these systems, sunlight is directed into a shallow, dark basin containing saltwater using an airtight, transparent glass cover (Fig. 39). This results in the evaporation of pure water vapour from the brine (impure saline water source) due to solar radiation passing through the coverings. Purified water is produced when the generated vapour condenses on the cold roof interior.

To provide drinkable desalinated water in areas with a scarcity of water, the condensed water flows down the sloping roof, collects in the troughs at the bottom, and then is transferred into a water storage tank. The amount of purified water produced is proportional to the solar collection surface area and the incidence angle of solar flux, resulting in a value of about 3-4 L/m^2. These systems are feasible for daily production capacities of 200 m^3/day or less due to their production capability, space requirement, and construction material cost. However, the cost of desalinated water per litre is lower in these systems compared to other electrical energy-based technologies.

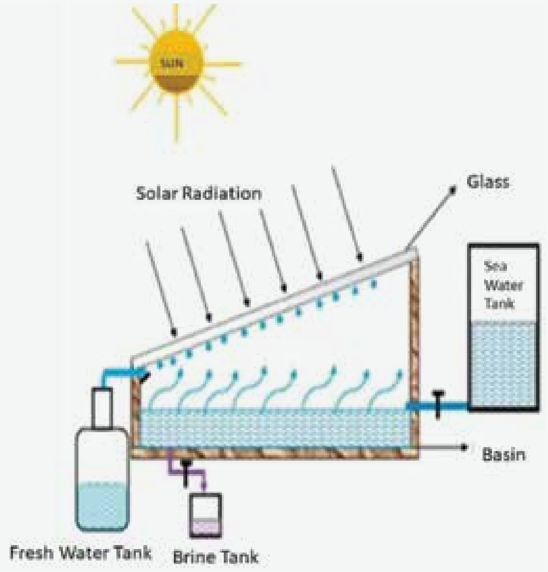


Fig. 39: Schematic diagram of the solar desalination system

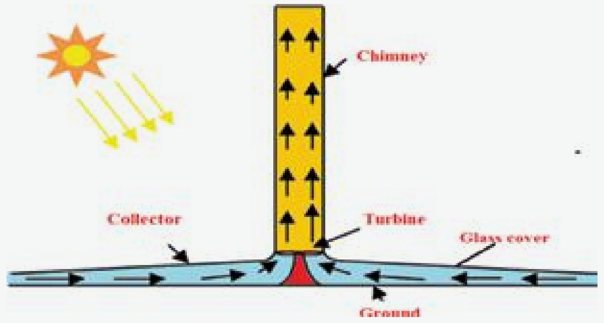


Fig. 40: Schematic diagram of a solar chimney

Solar Chimney

Solar chimneys are a relatively modern technology in the field of renewable energy used for indoor air ventilation. The system operates based on the air pressure difference created by a temperature gradient. The solar chimney comprises three main components (Fig. 40) – a solar collector, a chimney, and a wind turbine.

The concept behind a solar chimney is to use sunlight to heat the air in the chimney, causing the air to rise and create a draught that expels the heated air from the building. As the hot air is expelled from the top, cooler air from below is drawn into the chimney to be heated. A wind turbine installed in the bottom portion of the chimney facilitates air circulation and provides ventilation for the building[14].

There are several factors that can influence the efficiency of a solar chimney, such as environmental factors, geometry and installation of the apparatus, seasonal changes, quality/types of materials used, and geographical location[15]. The geographical latitude of the solar chimney is one of the most important factors to consider when constructing the system[16]. The solar chimney needs to be installed in an area that receives direct sunlight, and its installation is economically viable in regions with more sunny days. The materials used for the chimney should be able to absorb heat while also taking into account their thermal characteristics, which typically includes a black frame, tinted glass, and insulated glazing[17]. The dimensions of the system, including the height of the chimney, the width of the channel, and the height-to-width ratio, are also important factors to consider[18].

Solar Ponds

A solar pond is a large body of water (Fig. 41) used to store solar energy in heat reservoirs located at the bottom of the body of water, which can subsequently be used later for practical purposes. A solar pond has a wide range of uses, including room heating, industrial process heating, and powering a turbine to produce electricity by evaporating an organic fluid with a low boiling point. A salinity gradient solar pond uses a significant amount of saltwater carefully in order to collect, store, and retain the thermal energy from the sun's descending rays. It is made up of three distinct layers: the upper convective zone (surface zone), the lower convective zone (storage zone), and the intermediate zone (gradient zone) between them.

The layer located at the top of the pond is called the upper convective zone (UCZ), which has a low salt concentration, a shallow depth, and captures some solar radiation that is then transferred to the layer below. This layer contains water that is mostly fresh (2–3% salty) and has temperature variations that are consistent with the ambient mean temperatures.

The non-convective zone (NCZ), a gradient layer known as the intermediate layer, grows in salinity from the upper NCZ to the lowest NCZ. This zone can be identified by the gradient concentration of salty water, whose concentration varies with depth as measured from the top convective zone's boundaries to the lower convective zone's limits. The concentration of salty water rises as the depth is increased. The zone's purpose is to maintain heat convection from the zone's thickest point as a transparent insulation, producing a zone that is highly efficient at trapping energy and maintaining heat inside the pond. The corresponding gradient of concentration helps to prevent heat loss from natural convection.

The lower convective zone (LCZ), which is the lowest layer, contains very highly salinized water that attracts and collects the solar thermal energy

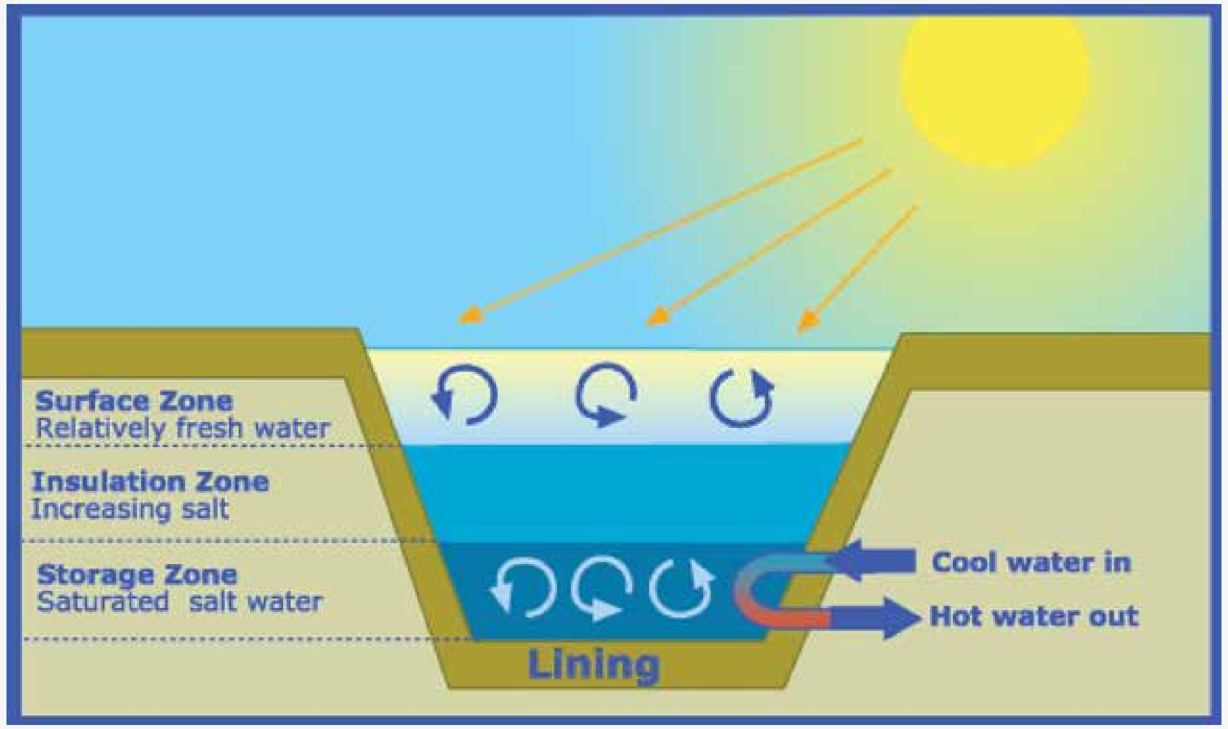


Fig. 41: Schematic diagram of salinity gradient of solar pond.

that enters the LCZ in the form of radiation. The region with the highest salt density is the LCZ, which stores heat. At the zone boundary, there is no difference in salt content. It has uniformly high saline water that absorbs heat from solar radiation and travels through surface and intermediate zones before being stored at the pond's lowest point.

2.2.6 Conclusion

Technologies based on solar energy can convert sunlight into electrical energy through PV panels, which are usually made of silicon wafer or thin film. Alternatively, solar radiation can be converted into thermal energy for driving utility-scale electric turbines through concentrating solar power (CSP). Another application of solar energy is in solar heating and cooling (SHC) systems.

There are various silicon wafer-based solar cell designs, such as BSF, PERC, PERL, PERT, TOPCON, HIT, HJT, IBC, which hold a market share above 95%. The remaining market share is for thin films like CdTe and CIGS. The market share of amorphous silicon was about 10% in 2010, but currently, it has almost disappeared. However, amorphous silicon layers are still used with other silicon wafer-based technologies such as HIT.

The BSF cell design, produced mostly on cost-efficient mc-Si wafers, is an older concept that will probably disappear after 2025. The matured concept of diffused and passivated pn junctions' solar cells will be further used in the mainstream with different rear side passivation technologies (PERC/PERL/PERT/TOPCON).

Currently, the solar photovoltaics market is dominated exclusively by silicon wafer-based cell concepts with diffused and passivated p-n junctions and passivated rear sides (PERC/PERL/PERT/TOPCON) having a market share of about 85%. The market share of PERC/PERL/PERT/TOPCON in 2020 slightly exceeded IBC. TOPCon solar cells will gradually grab a market share of approximately 50% next decade from its current market share of about 6%, indicating its dominance in the SPV industry. The Si-heterojunction (HIT/HJT) solar cells will progressively gain a market share of about 10% in 2025 and about 18% in 2031. High cost, complex processing steps, the requirement of significant modification of current cell processing technology, and less throughput may be responsible for the lesser market share of HIT/HJT or IBC solar cells in the present scenario.

The Si-based single junction cell concepts are approaching a practical efficiency limit of about 26%, which is close to the theoretical upper limit of 30%. Tandem cells are expected to overcome this limit, with mass production cell efficiencies of Si-based tandem cell concepts starting at about 27%. In the laboratory, perovskite/silicon tandem junction solar cells with efficiencies above 30% have been demonstrated. However, stability remains a major concern for the commercialisation of organic photovoltaic (OPV) and perovskite solar cell technologies.

Studies have shown that the solar radiation that falls on the roof of an average home is greater than the energy consumed by the home during a year. This solar energy can be used for various purposes such as heating, cooling, refrigeration, cooking, mechanical work, and even to generate electricity.

Hence, it can be inferred that solar energy technology will be highly sought-after in the coming decades, as the world faces the urgent need to transition to a fully sustainable energy infrastructure to meet the growing global energy demand.

2.3

Decoding Hydrogen Ecosystem in India

DR J P GUPTA, MD, Greenstat Hydrogen India Pvt. Ltd.

Arise! Awake! And stop not
until the goal is reached.

Swami Vivekananda

India is currently the third-largest contributor to climate emissions, highlighting the urgent need for green investment in the country. As India is poised to become the world's third-largest economy in the next few years, the country's role in addressing global climate, environmental, and resource challenges is crucial. India is actively involved in global policy development and negotiations on climate and the environment and has already set a goal to become a world leader in green hydrogen.

While historically having low GHG emissions, emerging markets like India must ensure that their growth and energy demands are met with low-emission solutions. India is committed to implementing strategic measures to reduce climate emissions while also promoting energy independence and access for its citizens and industries.

One of the key requirements for reducing emissions and meeting energy needs in India is transitioning to green hydrogen. This involves moving away from fossil-fuel-based feedstock and using green hydrogen and ammonia as energy carriers.

2.3.1 Hydrogen

Hydrogen is a chemical that can be stored just like oil and gas. It becomes a liquid under high pressure and cryogenic conditions. Unlike electricity stored in batteries, the energy content of hydrogen remains constant over a long period of time. Additionally, it is much easier to trade hydrogen overseas compared to electricity.

Units

Hydrogen Units	Energy Units	Oil Equivalent	Energy Density /Kg (Fuel)
1 metric ton of hydrogen = 1,000 kilogram of hydrogen = 11,000 normal cubic meters (Nm3) of hydrogen	33 MWh of energy (LHV) = 39 MWh of energy (HHV)	3 tons of oil equivalent = 880 gallons of diesel = 1,020 gallons of gasoline	H2 = 33.4 kWh Gasoline = 12.7 kWh CNG = 13.88 kWh

2.3.2 Role of Hydrogen – Transition to Clean Energy

Flexibility

- Multiple generation options available
- Scalable applications – Industrial and automotive use

Stability

- Overcome intermittency of renewable
- Storage stable for long time

Operation

- Lower refuelling time
- No duplicity of charging infrastructure – cost effective at scale.

2.3.3 Colour Classification of Hydrogen

GREY H_2	BLUE H_2	GREEN H_2
Grey hydrogen - from natural gas though Steam Methane Reforming.	Blue hydrogen - produced from fossil fuels with carbon-capture technology.	Green hydrogen – Zero CO_2 pathway.
More than 76% global hydrogen being produced through this route.	CO_2 can be reduced by 85%.	Electrolysis using solar/wind electricity and bio-based pathways are prominent.
Relatively cheap (~$2/kg) but emit large amounts of CO_2 (10 kg CO_2 per kg H_2).	Adds to the cost of hydrogen (~1.5 times) - $80-$120/ton of CO_2.	Currently expensive ($5-$6/kg) but long-term forecast attractive ($1.5 - $2/kg).
Being used in all refineries.	Transportation of captured CO_2 utilisation adds complexity.	

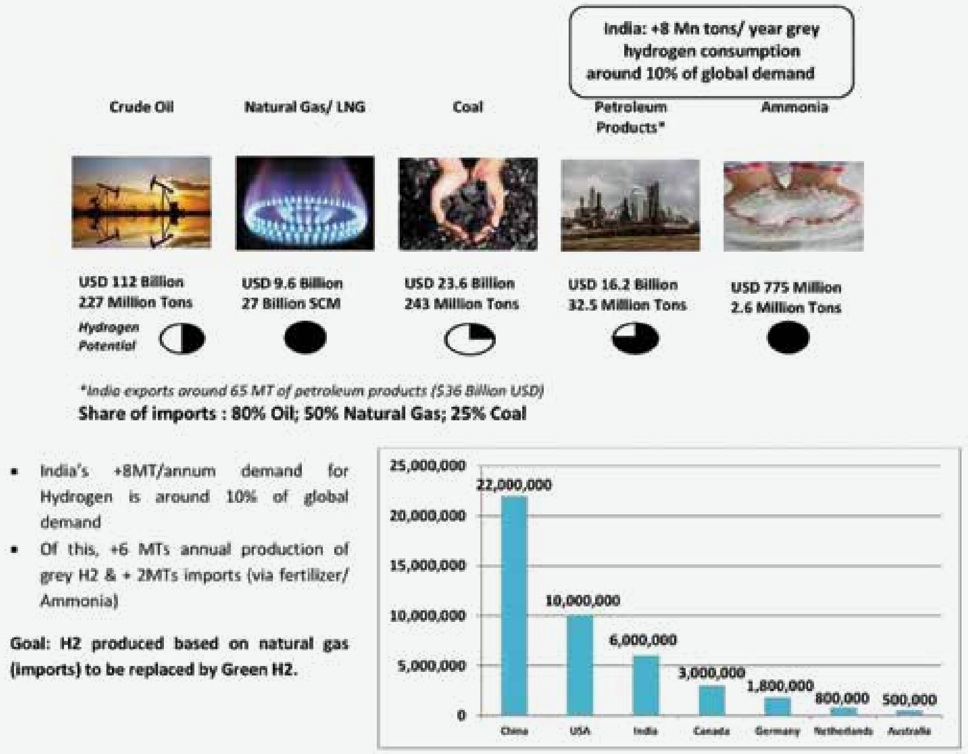
Others

- Turquoise – Methane splitting
- Pink – Nuclear
- White – Geological hydrogen through fracking

2.3.4 Substantial Potential of GH2

India's annual import bill for fossil fuels is increasing and currently stands at around $160 billion.

India is one of the largest importers of ammonia in the world, with a significant portion of it being produced from grey hydrogen.



*India exports around 65 MT of petroleum products ($36 Billion USD)

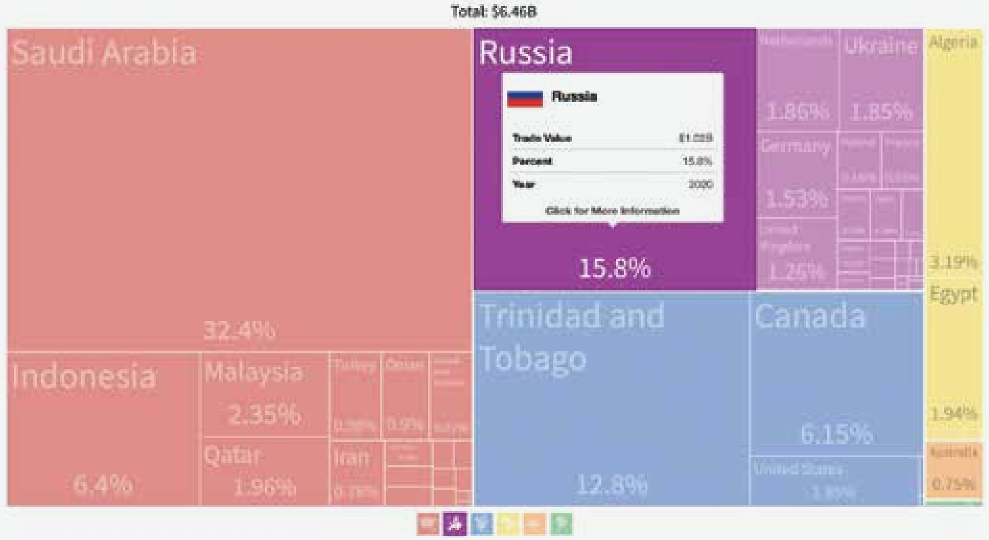
Share of imports : 80% Oil; 50% Natural Gas; 25% Coal

- India's +8MT/annum demand for Hydrogen is around 10% of global demand
- Of this, +6 MTs annual production of grey H2 & + 2MTs imports (via fertilizer/ Ammonia)

Goal: H2 produced based on natural gas (imports) to be replaced by Green H2.

Source: PtX, NITI Aayog, WRI

Exporters of Ammonia (2020)



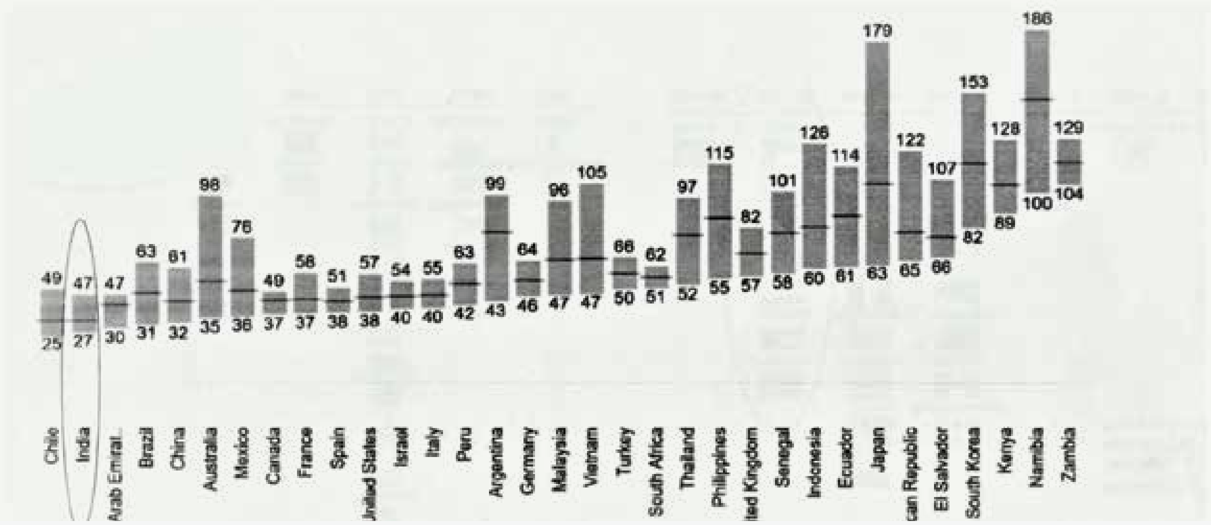
(Source: Observatory of Economic Complexity)

Importers of Ammonia (2020)

Total: $6.46B

(Source: Observatory of Economic Complexity)

2.3.5 India Generates Solar Power at World-record Low Cost



Comparison of Cost (LCOE in USD/MWh) in 2022 (Source: PtX, Quelle: BNEF 2022)

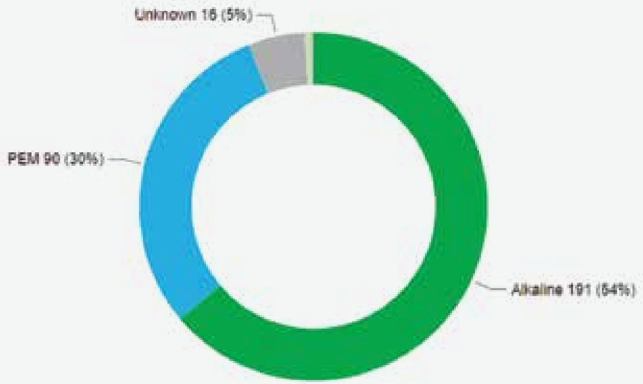
2.3.6 Green Hydrogen Use in Sectors

Green hydrogen has the potential to replace fossil fuels in various sectors, including refining, fertilisers, iron and steel, and bulk chemicals. Additionally, green hydrogen can serve as an energy carrier for various applications such as energy storage, blending with natural gas, maritime and shipping, and long-haul mobility.

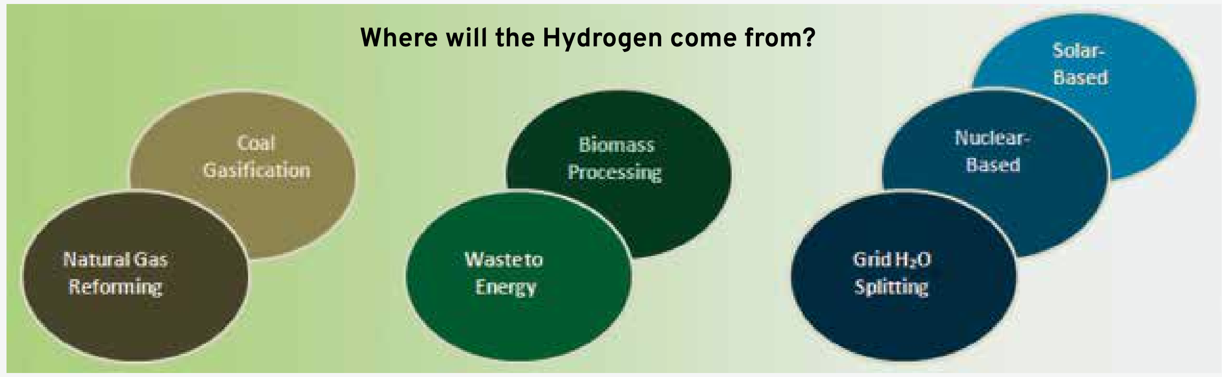
2.3.7 Green Hydrogen and Electrolysers – Global Landscape

The capacity of electrolysers announced for installation between 2021 and 2030 has been significant. Additionally, a report by Global Market Insights predicts that the electrolyser market value will reach $53 billion by 2030.

Company	Country
Sunfire GmbH (Industrial Electrolysis Co.)	Dresden, Germany
Asahi Kasei Corp. (chemicals company)	Chiyoda City, Tokyo, Japan
ITM Power (Hydrogen Economy Co.) / Linde Plc (chemical company)	Sheffield, United Kingdom / Dublin, Ireland, UK
McPhy (clean hydrogen production and distribution equipment)	France
Siemens	Munich, Germany
Nel (fuel cell company) / Proton Onsite	Oslo, Norway Wallingford, Connecticut, United States
CockerillJingli Hydrogen	Suzhou, China
Hydrogenics (energy company)	Mississauga, Canada
Cummins Inc (power technology company)	Columbus, Indiana, United States
Others	-



2.3.8 Pathways for Green Hydrogen for India



Widespread Adoption Timeline

Fossil Resources	Waste/Biomass	Water Splitting
Low-cost, large-scale H2 production with CCUS options	Options included biogas reforming & fermentation of waste streams	Grid electrolysis is proven process being improved with innovation Emerging nuclear/solar options offer long-term sustainable H_2

(Source: US Department of Energy)

Currently, more than 95% of the total global hydrogen production comes from fossil sources, mainly through the reforming of natural gas.

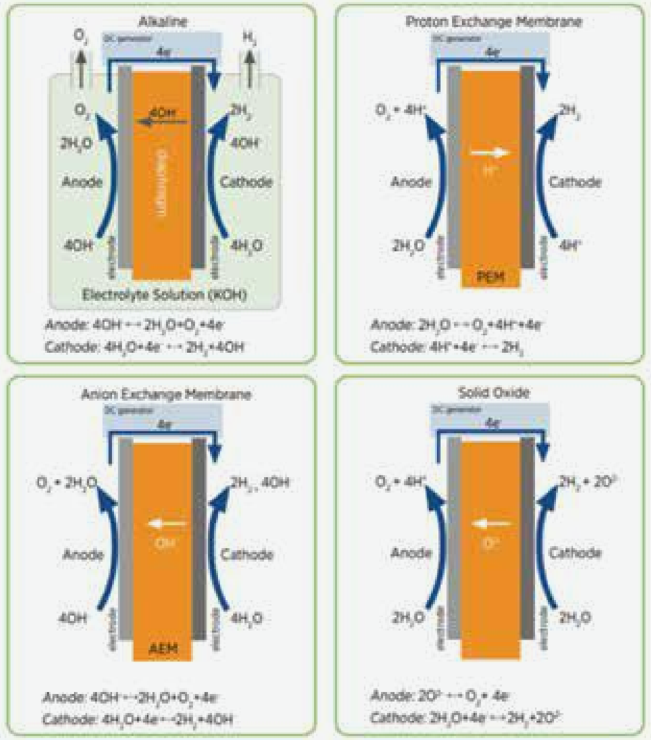
Water Electrolysis

- PEM/ Alkaline/ SOEC using Solar PV/ Wind Energy (utilisation of cheap electricity)
- Water splitting (photo electrochemical) lab scale.

Green Hydrogen from Water through Electrolysis

Technology	POLYMER ELECTROLYTE MEMBRANE ELECTROLYSIS	ALKALINE ELECTROLYSIS	SOLID OXIDE ELECTROLYSIS
	(Mature at 2 MW scale)	*(Mature at 10 MW scale)*	*(At demo scale)*
Feedstock	Pure H_2O, 80 ° C	30% KOH, 80°C	STEAM, 800°C
Input (Electricity)	48-55 kW-hr/kg H2	50-60 kW-hr/kg H2	35-38 kW-hr/kg H2
CAPEX (IHS) – 20MW	$1000/kW - $ 1250/kW	$850/kW - $950/kW	Not Commercial
Power Profile	Can take up intermittent renewable power (large transient range)	Need continuous rated renewable power (low transient range)	Need continuous rated renewable power (low transient range)
Applications	Mobility / Stationary (Hybrid)	Larger footprint - stationary large-scale applications	Larger footprint - stationary large-scale applications

Different types of commercially available electrolysis technologies



Electrolyser Characteristics

		57-65 kWh/kg-h2 (total with BoP)		35-40 kWh/kg-h2 (total with BoP)
	Alkaline	**PEM**	**AEM**	**Solid Oxide**
Operating temperature	70-90 °C	50-80 °C	40-60 °C	700-850 °C
Operating pressure	1-30 bar	< 70 bar	< 35 bar	1 bar
Electrolyte	Potassium hydroxide (KOH) 5-7 $molL^{-1}$	PFSA membranes	DVB polymer support with KOH or NaHCO3 1 $molL^{-1}$	Yttria-stabilised Zirconia (YSZ)
Separator	ZrO2 stabilised with PPS mesh	Solid electrolyte (above)	Solid electrolyte (above)	Solid electrolyte (above)
Electrode /catalyst (oxygen side)	Nickel coated perforated stainless steel	Iridium oxide	High surface area Nickel or NiFeCo alloys	Perovskite-type (e.g. LSCF, LSM)
Electrode/ catalyst (hydrogen side)	Nickel coated perforated stainless steel	Platinum nanoparticles on carbon black	High surface area nickel	Ni/YSZ
Porous transport layer anode	Nickel mesh (not always present)	Platinum coated sintered porous titanium	Nickel foam	Coarse Nickel-mesh or foam
Porous transport layer cathode	Nickel mesh	Sintered porous titanium or carbon cloth	Nickel foam or carbon cloth	None
Bipolar plate anode	Nickel-coated stainless steel	Platinum-coated titanium	Nickel-coated stainless steel	None
Bipolar plate cathode	Nickel-coated stainless steel	Gold-coated titanium	Nickel-coated stainless steel	Cobalt-coated stainless steel
Frames and sealing	PSU, PTFE, EPDM	PTFE, PSU, ETFE	PTFE, Silicon	Ceramic glass

Specifications of different Electrolyser Technologies

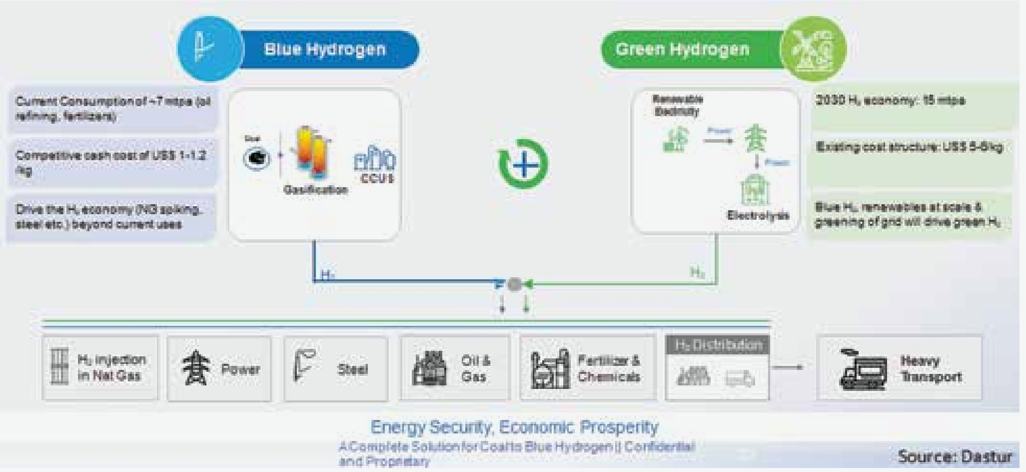
Types of Technology	**AEM**	**AWE**	**PEM**	**SOEC**
Charge carrier	OH^-	**OH^-**	**H^+**	**O^{2-}**
Reagent	**Water**	**Water**	**Water**	**Water**
Water purity	**< 1 µS/cm @25°C**	**< 5 µS/cm @25°C**	**< 1 µS/cm @25°C**	**< 5 µS/cm @25°C**
H2 purity	99.999%	99.9%	99.999%	99.99%
Electrolyte	Anion Exchange Membrane	KOH 20-40 wt% water	Proton Exchange Membrane	YSZ
Electrode	Ni, NiO, Co-based catalyst	Raney Ni, Fe. Co, Mn	Pt/C, IrO_2	CNM, LSM
Current density	1.2-1.5 A/cm^2	0.2-0.5 A/cm^2	2.4-3.0 A/cm^2	0.5 – 1 A/cm^2
Temperature	40-50°C	40-90°C	20-80°C	700-800°C
H2 outlet pressure	10-35 bar	10-30 bar	10-30 bar	< 1 bar
Cathodic reaction (Hydrogen evolution reaction)	$2H_2O$ (l) + 2e- H_2(g) + 2HO-(aq)	$2H_2O$ (l) + 2e- H_2(g) + 2HO-(l)	2H+ (aq) + 2e- H_2(g)	$H_2O + 2e^- H_2 + O^{2-}$
Anodic reaction (Oxygen evolution reaction)	2HO-(aq) H_2O (l) + ½ O_2 (g) + 2e-	2HO- (aq) H_2O (l) + ½ O_2 (g) + 2e-	H_2O (l) ½ O_2 (g) + 2H+ (aq) + 2e-	O^{2-} ½ $O_2 + 2e^-$
Electricity consumption	50-60 kWh/kgH2	50-73 kWh/kgH2	47-73 kWh/kgH2	35-40 kWh/kgH2
System lifetime	35,000-40,000 hrs	60,000 hrs	50,000-80,000 hrs	40,000-50,000 hrs

Preference of Electrolyser

	Technology	System Cost	Efficiency	Response Time	H_2 Output Pressure	O_2 Output Pressure	Temperature
COMMERCIAL IN DEVELOPMENT	**Alkaline Electrolysis**	$700/kW	80%	15 min	10 bar	Atmospheric	60-80°C
	PEM Electrolysis	$1200/kW	62-80%	5 Sec	30-50 bar	Atmospheric	50-80°C
	Solid Oxide Electrolysis	>$2000/kW	95%	TBD	10 bar	Atmospheric	700-900°C
	Market Needs/ Targets	$500/kW	High	<15 Sec	200+ bar	30+ bar	Low temp = easy maint.
	Power to Hydrogen	<$700/kW*	85% (1.75V)	<5 Sec	200+ bar	200+ bar	60-80°C

* Realised cost considering future equivalent manufacturing scale

Preference for Green Hydrogen



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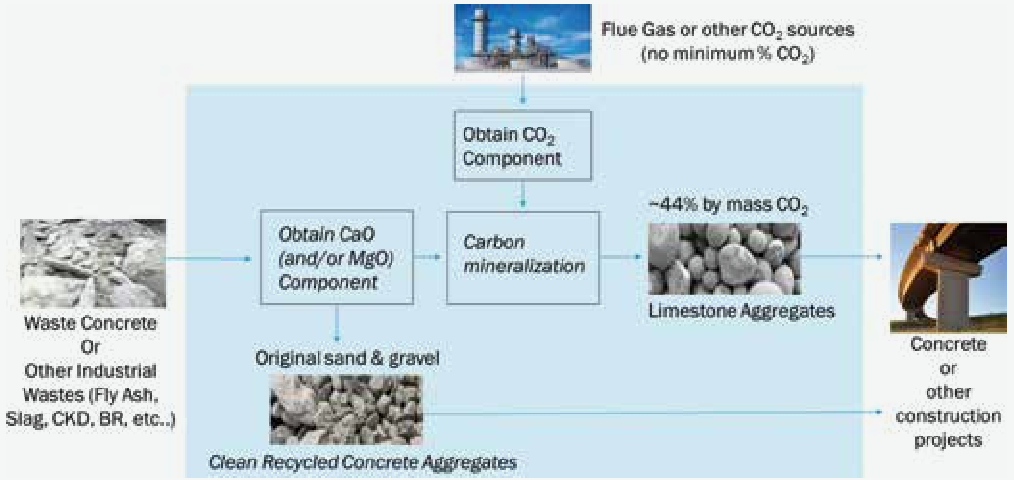
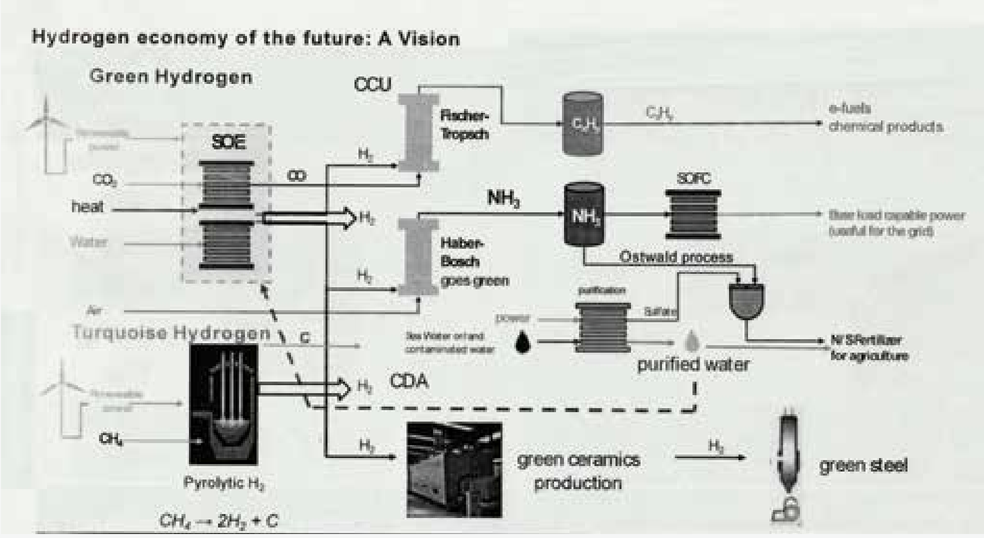
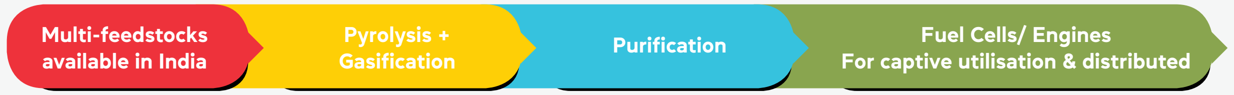


Source: Blue Planet



Hydrogen from Biomass in India

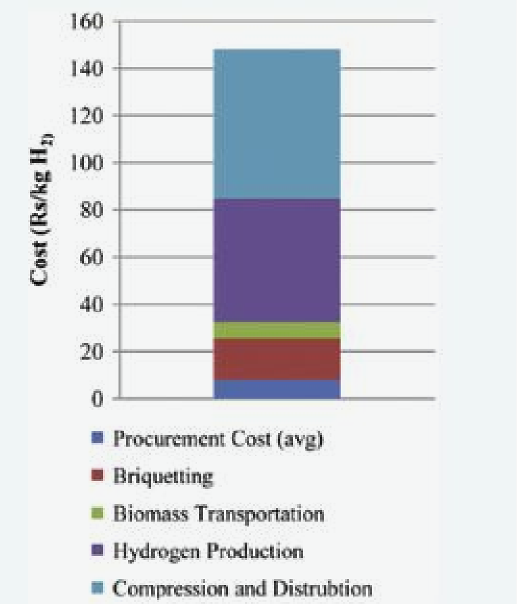


Multi-feedstocks available in India → **Pyrolysis + Gasification** → **Purification** → **Fuel Cells/ Engines For captive utilisation & distributed**

Waste to Hydrogen

- Reforming of compressed biogas (CBG)
- Biomass gasification
- Annual Biomass production: 683 million MT
- Surplus biomass availability: 120-150 million MT/year
- Viable option for centralised hydrogen generation

There's a need for an optimal model for rural India and captive power production that utilises scalable technology with lower carbon footprints.



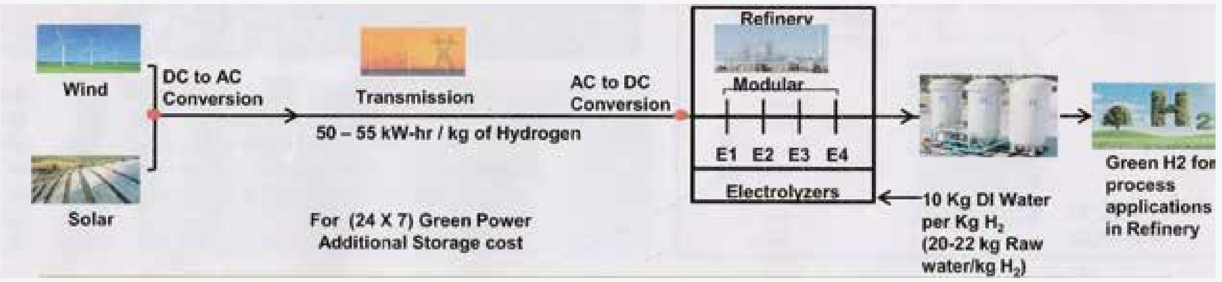
2.3.9 Coal-to-Hydrogen Opportunity

Teaming up with carbon management, coal-to-hydrogen technology can play a crucial role in meeting the primary goals of a hydrogen economy, including energy security, economic advantages, and environmental benefits. Coal can serve as a cornerstone for a diverse hydrogen supply mix by integrating hydrogen production into the co-production of power and synthetic fuels.

India has 163 billion MT of proven coal resources out of a total of 344 billion MT. To serve one-third of the transportation demand, approximately 18% more coal would need to be mined and converted to hydrogen.

There is a tremendous opportunity to increase domestic energy supply without adding transmission capacity by producing hydrogen, power, advanced tactical fuels for the military, fuels for energy markets, and specialty chemicals.

2.3.10 Long Hydrogen Supply Chain Needs Integrated Partnerships



2.3.11 Cost of Green Hydrogen from Renewable Power

- Producing 1 kg of GH2 requires 9 litres of water and 45-55 kWh of electricity.
- At a renewable electricity cost of Rs 5/kWh plus battery storage, the cost would be Rs 250/kg of GH2.
- The cost of the electrolyser would add another Rs 150-250 depending on the utilisation factor.
- The current cost of green hydrogen is at least Rs 400/kg, which is much higher than coal and natural gas-derived hydrogen.

Constraints
- The cost of electrolysers has fallen by 40% in the last five years but needs to decrease further to be affordable.
- Another constraint is the availability/allocation of green power for this purpose.

2.3.12 Cost of Hydrogen Production from Various Sources (in $/kg)

Sr. No.	Hydrogen production method	Other costs	Feedstock cost	Cost of hydrogen produced
1	Cost of hydrogen production from natural gas reforming in a central plant	0.29	1.03	1.32
2	Cost of hydrogen production from coal gasification with carbon sequestration	1.62	0.48	2.10
3	Cost of hydrogen production from biomass	0.88	1.34	2.22
4	Cost of hydrogen production from ethanol	2.66	4.82	7.48
5	Cost of hydrogen production from PEM Electrolysis	0.75	3.46	4.21
6	Cost of hydrogen production from SOEC	1.35	2.48	3.83

2.3.13 Electrolysers for Green Hydrogen Production

Technology
- Continuous reliable mode of production.
- High performance and durability.
- Standardisation of components.

Scale
- Large throughput required.
- GW scales not yet validated.

Manufacturing
- Limited manufacturing capacities available.
- Ancillary ecosystem absent.
- Long lead time.

Economics
- Higher $/KW cost.
- Noble metals.
- Replacement/Recycling.
- Opex-kWh/kg H_2.

2.3.14 H_2 Transport in Existing Natural Gas Pipelines

It is a low-cost option to transport large volumes of hydrogen, which can be transported as a mixture with natural gas (H_2-NG) or as standalone hydrogen. However, further studies need to be done and separation technologies need to be developed. Repurposed pipelines can also be used. Currently, there are dedicated hydrogen pipeline networks in several countries, such as the U.S. (1,600 miles), Belgium (400 miles), Germany (250 miles), and France (200 miles).

There are challenges to overcome in using hydrogen pipelines, including the need to control hydrogen permeation and leaks, as well as developing lower-cost, more reliable, and more durable hydrogen compression technology to address technical concerns related to pipeline transmission.

Guidelines for Maximum H_2% (v/v) in Existing NG Pipeline
- European Commission JRC Final Report up to 10% V/V
- NREL Report up to 15%
- CEN / ISO Draft Roadmap & ASME B31.12 up to 100%
- (Metallurgy plays a very important role)

2.3.15 Liquid Organic Hydrogen Carrier

Challenges and Opportunities

Liquid Organic Hydrogen Carrier (LOHC) technology has several challenges and opportunities. Some of the challenges are:

- Catalyst for hydrogenation and dehydrogenation devices: The use of noble metals such as platinum (Pt), rhodium (Rh), palladium (Pd), and rhenium (Re) as catalysts for LOHC increases the cost of the technology.
- Limiting side reactions and decomposition pathways: The LOHC technology faces the challenge of controlling side reactions and decomposition pathways during hydrogenation and dehydrogenation processes.
- Eco-toxicity and biodegradability assessment of LOHC: The environmental impact of LOHC technology should be assessed, including the eco-toxicity and biodegradability of the carrier molecules.
- On-board dehydrogenation devices for mobility applications: LOHC technology for mobility applications requires on-board dehydrogenation devices that must be efficient, safe, and compact.
- Reactor configurations: The LOHC technology requires high conversion and limiting side reactions, which can be achieved by designing efficient reactor configurations.

Despite these challenges, LOHC technology presents several opportunities, including:

- Safe and efficient hydrogen storage and transportation: LOHC can store and transport hydrogen safely and efficiently, without the need for high-pressure vessels or cryogenic tanks.
- Renewable energy integration: LOHC technology can help integrate renewable energy sources into the energy system by providing a way to store and transport excess energy in the form of hydrogen.
- Carbon capture and utilisation: LOHC technology can be coupled with carbon capture and utilisation to produce low-carbon hydrogen.
- Energy security: LOHC technology can enhance energy security by providing a reliable and sustainable source of hydrogen.

Overall, the LOHC technology has the potential to play a significant role in the hydrogen economy, and research and development efforts are ongoing to address the challenges and leverage the opportunities presented by this technology.

- Catalyst for Hydrogenation and Dehydrogenation Devices
    - Noble metals (Pt, Rh, Pd, Re) increase the price
    - Limiting side reactions and decomposition pathways
- Eco-toxicity and biodegradability assessment of LOHC
- On board dehydrogenation devices for mobility application
- Reactor configurations: high conversions + limiting side reactions.

2.3.16 Government of India Targets of GH_2 by 2030

Government of India has set targets for the production and usage of green hydrogen by 2030, which includes:

- Production of 5 million MT of green hydrogen
- Achieving 54 million MT of CO_2 savings through the use of green hydrogen
- Establishing a manufacturing capacity of 24 GW per annum
- Installing 100-130 GW of electrolyser capacity
- Generating 175 GW of green-hydrogen-based energy.

2.3.17 India's National Green Hydrogen Mission Targets

2030	**500 GW Non-fossil capacity** **50% of installed capacity from non-fossil fuels** **Reducing emission intensity of GDP to 45% below its 2005 level**
2047	**Energy Independence**
2070	**Net Zero Carbon**

2.3.18 Way Forward for India

The main points of recommendations for the Indian government to promote and accelerate the adoption of hydrogen as an energy source include:

- Removing the classification of hydrogen by colour until 2030 and promoting the production and use of hydrogen in all industries without delay.
- Adoption of international standards for the entire value chain of hydrogen, and developing Indian standards as needed.
- Establishing test beds for testing and accrediting electrolysers and storage tanks.
- Providing incentives for industries to shift to using hydrogen as an energy source, and exempting the import of electrolysers from duties until 2030.
- Mixing hydrogen with natural gas and biogas, and using existing pipelines to distribute it.
- Utilising agro waste to produce green hydrogen as a priority, which would support rural economies.
- Making coal gasification a national mission alongside the hydrogen mission.
- Setting up Centres of Excellence in hydrogen safety and capacity building, using artificial intelligence and virtual reality to train workers.
- Establishing a government-owned electrolyser manufacturing PSU to produce electrolysers based on different technologies.
- Creating a national hydrogen research organisation in partnership with world-class research institutes, to conduct research on hydrogen production, storage, CCU, and applications.
- Using 5 MMT of green hydrogen production as part of the green hydrogen mission for export.

Overall, these suggestions aim to create an ecosystem that supports the use of hydrogen in a sustainable and efficient manner, and to position India as a leader in hydrogen research and development.

2.4

Government's Initiatives, a Key Growth Driver for Green Hydrogen

DR S P SHARMA, Chief Economist | DSG

Most of the important things in the world have been accomplished by people who have kept on trying when there seemed to be no hope at all.

Dale Carnegie

2.4.1 Recent Policy Developments

India's commitment to achieve net-zero emissions by 2070 is a significant step towards sustainable development. However, as the country continues to grow economically, its energy demand is expected to rise further, with energy consumption projected to increase by at least 25% by 2030. India's current reliance on imported fossil fuels, which account for over 40% of its primary energy requirements and cost over $90 billion annually, underscores the need for a transition to renewable sources. Sectors such as mobility and industrial production, which heavily depend on imported fossil fuels, require a shift towards cleaner and more sustainable technologies. The country's long-term vision is to become self-reliant and a developed economy by 2047, marking 100 years of independence. Achieving this vision would require a concerted effort towards promoting renewable energy and reducing carbon emissions.

Producing green hydrogen using renewable energy sources has the potential to play a vital role in creating low-carbon and self-reliant economic systems. Green hydrogen can help utilise abundant renewable energy resources across regions, seasons, and industries, and serve as fuel or feedstock in various applications. It can replace fossil-fuel-based feedstocks in industries such as petroleum refining, fertiliser production, and steel manufacturing. Hydrogen-powered vehicles and ships can help reduce carbon emissions in the transportation sector. Green hydrogen is a versatile energy carrier that can be particularly beneficial in providing sustainable energy to remote areas and islands.

The governments of many large economies have announced hydrogen strategies as part of their efforts to address climate change and promote clean energy. These strategies aim to address challenges related to increasing the production of green hydrogen, expanding its use in various sectors, developing new technologies, and creating supportive policies and regulations. The strategies also prioritise government funding for research and development, initiatives to stimulate demand, and financial support for the manufacturing and development of infrastructure.

As the world increasingly moves towards achieving net-zero emissions, there is a growing impetus for the utilisation of green hydrogen and its various derivatives. However, varying levels of demand and production capabilities for green hydrogen across different countries and regions may lead to an increase in international trade of these products, including green ammonia and green methanol. Moreover, the recent geopolitical tensions and supply chain disruptions caused by the COVID-19 pandemic have further highlighted the fragility of fossil fuel markets, thereby hastening the transition towards sustainable fuel and feedstock. Against this backdrop, India finds itself uniquely positioned to leverage its abundant renewable energy and land resources to become a leading exporter and producer of green hydrogen and its derivatives, thereby capitalising on the growing global demand for such products.

Despite the promising prospects and inherent benefits, the widespread adoption of green hydrogen or its derivatives in place of fossil fuels and fossil-fuel-derived feedstock has been hindered by a variety of factors, including unfavourable cost economics, a lack of harmonised standards and regulations, supply chain obstacles, and the need for costly enabling infrastructure. Nonetheless, recent developments and analysis suggest that, buoyed by technological advancements, decreasing costs of renewable energy and electrolysers, and the implementation of ambitious national strategies by major economies, green hydrogen is poised to become a viable and cost-effective alternative in a variety of sectors, including industry, transportation, and beyond, within a relatively condensed timeframe.

The green hydrogen pathway can be a key enabler for India's aspirations of building a low-carbon and self-reliant economy. It is therefore an opportune moment for India to scale up green hydrogen production and utilisation across multiple sectors, while also aligning with global trends in technology, applications, policy, and regulation. To achieve economies of scale, rapid deployment of renewable energy and electrolysers will be necessary, along with the establishment of associated infrastructure and regulatory frameworks for the delivery, storage, transportation, and use of green hydrogen in various applications. Additionally, accelerated technological development aimed at improving performance, efficiency, safety, and reliability will be crucial to the success of this endeavour. As the global value chain for green hydrogen is still in its nascent stages, international cooperation and engagement may further bolster national efforts.

Therefore, coordinated efforts and diverse policy interventions across all domains are imperative, and the government of India has implemented a comprehensive and integrated approach through various central and state government agencies, with the Ministry of New and Renewable Energy leading overall coordination for policy implementation, and other ministries and departments taking focused steps to ensure a conducive policy environment.

2.4.2 National Green Hydrogen Mission

In his address to the nation on the occasion of India's 75th Independence Day, the esteemed Prime Minister Narendra Modi announced the establishment of the National Green Hydrogen Mission, with the ambitious objective of positioning India as a central hub for the production and export of green hydrogen. This proclamation arrives at a decisive moment in India's energy landscape, as green hydrogen assumes a critical role in empowering the nation to achieve self-reliance and energy independence. The Union Cabinet, under the leadership of the Honourable

A Snapshot of Green Hydrogen Mission

S. No.	Mission Components	Description
1	Demand Creation – Exports Markets	India's green hydrogen production costs are expected to be among the lowest in the world. A global demand of over 100 MMT of green hydrogen and its derivatives like green ammonia is expected to emerge by 2030. Aiming at about 10% of the global market, India can potentially export about 10 MMT green hydrogen/green ammonia per annum.
2	Competitive Bidding for Procurement	MNRE will frame model guidelines for transparent competitive bidding for procurement of green hydrogen and its derivatives, and develop a suitable regulatory framework for certification of green hydrogen and its derivatives as having been produced from RE sources. The bidding guidelines will be technology agnostic to allow both electrolysis and biomass-based generation of green hydrogen.
3	SIGHT Programme	Under the Strategic Interventions for Green Hydrogen Transition (SIGHT) programme, two distinct financial incentive mechanisms – targeting domestic manufacturing of electrolysers and production of green hydrogen – will be provided under the mission.
4	Pilot projects	The mission will also support pilot projects in emerging end-use sectors and production pathways. Regions capable of supporting large scale production and/or utilisation of hydrogen will be identified and developed as green hydrogen hubs.
5	Domestic Manufacture of fertilisers using Green Ammonia	MNRE, in collaboration with the Department of Fertilisers, will formulate model bidding guidelines for procurement of green-hydrogen-based fertilisers. The aim is to establish two facilities for the production of green-hydrogen-based urea and green- hydrogen-based DAP (Diammonium Phosphate) through a competitive bidding process. The objective is to replace all imports of ammonia-based fertilisers with domestically produced green ammonia-based fertilisers by 2034-35.
6	R&D Projects	Public-Private Partnership framework for R&D (Strategic Hydrogen Innovation Partnership – SHIP) will be facilitated under the mission. R&D projects will be goal-oriented, time-bound, and suitably scaled up to develop globally competitive technologies.
7	Skill Development	A coordinated skill development programme will also be undertaken under the mission.
8	Transport	Financial assistance will be provided in a phased manner to support the deployment of Fuel Cell Electric Vehicles (FCEV) buses and trucks on a pilot basis, taking into consideration the higher capital cost of FCEVs in the initial years. The aim is to bridge the viability gap. The insights gained from these pilot projects will be used to help inter-city bus and truck operators, including state transport undertakings, gain experience in the deployment and use of hydrogen fuel cell vehicles and refuelling technologies. The mission will also investigate the feasibility of incorporating green-hydrogen-based methanol/ethanol and other synthetic fuels derived from green hydrogen into automobile fuels.
9	Steel	The mission will support efforts to enhance low-carbon steel production capacity. Considering the higher costs of green hydrogen at present, steel plants can begin by blending a small percentage of green hydrogen in their processes. The blending proportion can be progressively increased as cost-economics improve and technology advances. Further upcoming steel plants should be capable of operating with green hydrogen. This would ensure that these plants are able to participate in future global low-carbon steel markets. Green field projects aiming at 100% green steel will also be considered
10	Shipping	Prospects include development of green hydrogen/ammonia refuelling hubs at Indian ports; development and operation of green hydrogen/ammonia-fuelled vessels; use of green hydrogen/ammonia to fuel zero-emission technologies for vehicles and terminal equipment at ports; and development of supply chains and capabilities to support future export of green hydrogen/ammonia from India

Source: PHD Research Bureau, PHD Chamber of Commerce and Industry

Prime Minister Narendra Modi, granted approval for the National Green Hydrogen Mission on January 4, 2022. India currently spends more than $160 billion annually on foreign energy imports, a figure that is projected to double within the next 15 years in the absence of corrective measures. With the approval of this plan, India is well-positioned to emerge as a global leader in the green hydrogen arena.

The National Green Hydrogen Mission will commence with an initial outlay of Rs 19,744 crore. This amount includes Rs 17,490 crore designated for the Strategic Interventions for Green Hydrogen Transition (SIGHT) programme, Rs 1,466 crore for Pilot Projects, Rs 400 crore for Research & Development, and Rs 388 crore allotted towards additional mission components. The MNRE will take responsibility for devising the scheme guidelines to execute the respective components.

Green Movement on the Ground

India's green hydrogen policy provides several incentives to encourage the establishment of green hydrogen facilities. These measures are intended to promote the transmission of renewable energy and the establishment of green hydrogen facilities close to consumption sources. The incentives include:

- Single-window clearance for faster project approvals
- Allotment of land in renewable energy parks
- Priority access to inter-state transmission network
- Open access procurement within 15 days, waiver of inter-state transmission charges
- A 30-day energy banking policy.

Intergraded Mission Strategy

All the concerned Ministries, Departments, agencies and institutions of both the central and state governments will take focused and coordinated steps to ensure successful achievement of the mission's objectives. They will provide support for pilot projects in challenging sectors like steel, long-range heavy-duty mobility, shipping, energy storage, etc., for replacing fossil fuels and fossil-fuel-based feedstocks with green hydrogen and its derivatives.

S. No.	Ministries	Description
1	**Ministry of New and Renewable Energy (MNRE)**	Responsible for overall coordination and implementation of the mission and will formulate schemes and programmes for financial incentives to support production, utilisation and export of green hydrogen and its derivatives. The ministry will ensure planned deployment of renewable energy and green hydrogen capacities, support pilot and R&D projects, undertake capacity building and promote international cooperation efforts.
2	**Ministry of Power (MoP)**	Implement policies and regulations to ensure delivery of renewable energy for green hydrogen production at least-possible costs, including through development of the necessary power system infrastructure. MoP will also work with state governments, distribution companies, regulators and technical institutions to align the electricity ecosystem for large-scale green hydrogen production.
3	**Ministry of Petroleum and Natural Gas (MoPNG)**	Facilitate uptake of green hydrogen in refineries and city gas distribution through both public sector entities and private sector. MoPNG will also enable development and facilitation of regulations through the Petroleum and Natural Gas Regulatory Board (PNGRB). New refineries and city gas projects will be planned and designed to be compatible with maximum possible green hydrogen deployment, with a goal to progressively replace imported fossil fuels.
4	**Ministry of Chemicals and Fertilisers**	Encourage adoption of indigenous green-ammonia-based fertilisers to progressively replace imports of fertilisers and fossil-fuel-based feedstocks (natural gas and ammonia) used to produce fertilisers. This will enable decarbonisation of the sector and reduce dependence on imports. The ministry will enable procurement of green ammonia for its designated entities to create bulk demand.
5	**Ministry of Road Transport and Highways**	Enable adoption of green hydrogen in the transport sector through regulations, standards, and codes, primarily for heavy commercial vehicles and long-haul operations. MoRTH will also facilitate technology development for adoption of green hydrogen in the transport sector through testing facilities, pilot projects, and provide support for infrastructure development.

6	**Ministry of Steel**	Drive adoption of green hydrogen in the steel sector. The ministry will identify and facilitate pilot projects for use of green hydrogen in steel production and undertake policy measures to accelerate commercial production of green steel.
7	**Ministry of Ports, Shipping and Waterways (MoPSW)**	Facilitate development of the required infrastructure including storage bunkers, port operations equipment, and refuelling facilities. MoPSW will also drive the adoption of hydrogen/derivatives (ammonia/methanol) as propulsion fuel for ships. The ministry will also work towards making India as a green hydrogen/derivative refuelling hub.
8	**Ministry of Finance**	Explore suitable fiscal and financial frameworks to promote production, utilisation and export of green hydrogen and its derivatives.
9	**Ministry of Commerce & Industry**	Encourage investments, facilitate ease of doing business, and implement specific industrial and trade policy measures for low-cost production and trade of hydrogen and its derivatives. The ministry will also formulate necessary policies and programmes for development of an ecosystem for manufacturing eight of the specialised equipment needed in the green hydrogen value chain.
10	**Ministry of Railways**	Railways are also expected to play an integral role for transporting green hydrogen and its derivates. For this, the ministry will put in place the necessary regulations and standards.
11	**Ministry of External Affairs (MEA)**	Instrumental in building bilateral and multilateral partnerships for supporting the green hydrogen ecosystem development in India and abroad. MEA will also aid collaborations of government agencies, institutions and industry with global partners.
12	**Ministry of Skill Development and Entrepreneurship**	Take steps in coordination with MNRE and other ministries for building skill sets ensuring employability in this sector. Suitable courses and programmes will be developed to ensure skilled manpower across the value chain, including manufacturing of equipment, green hydrogen project installations, and operations and maintenance.
13	**Ministry of Education**	Work towards coverage of hydrogen technologies and latest developments in the pedagogy and curriculum at various levels. Practical experience of technologies through guidelines for laboratory set-ups in schools and higher education institutions will also be encouraged.
14	**State Governments and State agencies**	States will have an opportunity to establish themselves as front-runners in this sunrise sector through project development, manufacturing, setting up of renewable energy capacity, and promoting export of green hydrogen derivatives. For this, the states will be requested to put in place fair and rational policies for provision of land and water, suitable tax and duty structures and other measures to facilitate establishment of green hydrogen projects.
15	**Other Coordinated Efforts**	MNRE will anchor this activity in partnership with the Department for Promotion of Industry and Internal Trade, Bureau of Indian Standards, Ministry of Petroleum and Natural Gas, Ministry of Road Transport and Highways, and associated agencies. Scientific Departments and agencies, including MNRE, the Office of the Principal Scientific Advisor to the Government of India, Department of Science and Technology, Department of Scientific and Industrial Research, Department of Space, Defence Research & Development Organisation, Ministry of Environment Forests and Climate Change, and other public research and innovation institutions will pool resources to build a comprehensive goal-oriented Research and Innovation programme in collaboration with the private sector.

Source: PHD Research Bureau, PHD Chamber, Compiled from various sources

MISSION GOVERNANCE FRAMEWORK

Empowered Group

- Chaired by Cabinet Secretary
- Members: Principal Scientific Adviser to the Government of India, CEO,NITI Aayog, and Secretaries of Ministries of New and Renewable Energy, Petroleum and Natural Gas, Power, Road Transport and Highways, Steel, Heavy Industries, Ports, Shipping and Waterways, Skill Development and Entrepreneurship; and Departments of Fertilizers, Science and Technology, Scientific and Industrial Research, Promotion of Industry and Internal Trade; and experts from the industry.

Advisory Group

- Chaired by the Principal Scientific Advisor to the Government of India.
- Members: Experts from academic and research institutions, industry, and civil society.

Mission Secretariat

- Headquartered in MNRE.
- Headed by Mission Director.
- Comprise subject matter experts and professionals.

Source: PHD Research Bureau, PHD Chamber, Compiled from various sources

2.4.3 Recent Green Initiatives by Industry

India has joined the global race to develop a green hydrogen economy to bolster its energy security. After the release of India's green hydrogen policy, private and state-owned companies have made a flurry of announcements about setting up projects to produce green hydrogen. Reliance Industries Limited (RIL) aims to reduce the production cost of green hydrogen below $1/kg by the end of this decade. To meet its goal, it announced a capital outlay of Rs.75,000 crore ($9.4 billion) over the next three years to develop manufacturing capacities for clean energy technologies, which include electrolysers to produce green hydrogen.

The state-owned power generator NTPC has set ambitious targets to reduce its production costs for hydrogen to below $2/kg by 2025-2026, which is faster than the global projections. These targets reflect the Indian government's plans for the sector. NTPC is currently working on India's first hydrogen-to-electricity project, which will use solid-oxide electrolysers and fuel cell technology from the US-based company, Bloom Energy. NTPC's floating solar plant will provide power to the electrolysers to produce green hydrogen, which will then be converted into carbon-neutral electricity by Bloom Energy's hydrogen fuel cell technology. This electricity will be used to power NTPC's Guest House in Simhadri, Visakhapatnam, without any combustion.

Green Hydrogen Big Ticket Announcements

In June 2022, an Indian renewable energy developer, ACME Group, signed a memorandum of understanding (MOU) with the Karnataka government to develop an integrated solar to green hydrogen to green ammonia facility worth Rs.52,000 crore ($7 billion). The facility will produce 1.2 million MT per year of green hydrogen by 2027 in Karnataka. The state government would possibly facilitate project land, off-takers, and export-related facilities to support the execution of the project. ACME Solar, an ACME Group company, has commissioned the world's first commercial pilot of an integrated green hydrogen and green ammonia production facility in Bikaner, Rajasthan. ReNew Power is another Indian renewable energy developer looking to synergise its expertise in the green hydrogen space. In April 2022, it announced a joint venture with state-owned Indian Oil Corporation (IOC) and engineering and construction major Larsen & Toubro (L&T) for green hydrogen production.

ReNew Power's Big Green Hydrogen Announcement

The MOU signed between India and Egypt in July 2022 outlines an investment of $8 billion for the establishment of a green hydrogen plant in the Suez Canal Economic Zone. The plant will initially have a 150 MW electrolyser capacity, powered by 570 MW of renewable energy, and will produce 20,000 MT of green hydrogen per year. The plant will later be upgraded to have a 1.5 GW electrolyser capacity, powered by 5.68 GW of renewable energy, and will produce 220,000 MT of green hydrogen per year. The project is being developed by ReNew Power in collaboration with several government agencies, including the New & Renewable Energy Authority of Egypt, the General Authority of the Suez Canal Economic Zone, the Egyptian Electricity Transmission Company, and Egypt's Sovereign Fund.

Green Hydrogen for Refining

Petroleum refining is another viable use case for hydrogen. Large state-owned oil and gas companies such as IOC, Oil India Limited (OIL) and GAIL (India) Limited have announced green hydrogen projects. IOC targets green hydrogen production of 70,000 MT annually by 2030, accounting for 10% of its overall consumption by that time. OIL is setting up a 100-kw electrolyser plant to manufacture green hydrogen at its Jorhat oil field in Assam.

In December 2021, GAIL announced that it would commission 10 MW of electrolyser capacity to produce 4.3 MT of green hydrogen per day. In May 2022, GAIL awarded the contract to an unnamed awardee to build this facility using Proton Exchange Membrane (PEM) electrolyser technology in the Guna district of Madhya Pradesh. GAIL will blend the green hydrogen with natural gas.

More Announcements from State-owned Entities

In April 2022, Gujarat Industries Power Company Limited (GIPCL) issued an expression of interest (EoI) to set up a 5 MW–10 MW electrolyser capacity for green hydrogen projects and associated facilities at Vadodara or any suitable site in Gujarat. GIPCL will supply the hydrogen generated from this plant to fertiliser factories, refineries, and chemical industries in the area. These plants could help the industries meet the Green Hydrogen Consumption Obligation (GHCO) norms, which the Indian government may formulate in the second phase of the green hydrogen policy. Another Gujarat state government-owned company – Gujarat Alkalis and Chemicals Limited (GACL) – signed an MOU with NTPC to set up green ammonia and green methanol plants.

Industry Initiative So Far (Brief Summary)

Sr. No.	Industry	Initiatives
1.	**Reliance Industries Limited (RIL)**	To reduce the production cost of green hydrogen below US$ 1/kg by the end of this decade.
2.	**NTPC**	To reduce production costs below US$ 2/kg by 2025-2026, much faster than global projections.
3.	**ACME Group**	To develop an integrated solar to green hydrogen to green ammonia facility worth Rs 52,000 crore ($7 billion). The facility will produce 1.2 million MT per year of green hydrogen by 2027
4.	**ReNew Power**	A joint venture with state-run Indian Oil Corporation (IOC) and engineering and construction major Larsen & Toubro (L&T) for green hydrogen production.
5.	**Total Energies (French oil and gas giant) with Adani Group subsidiary Adani New Industries Limited (ANIL)**	To invest $50 billion in 10 years to produce green hydrogen.
6.	**Indian Oil Corporation (IOC)**	Green hydrogen production of 70,000 MT annually by 2030, accounting for 10% of its overall consumption. Setting up a 100-kw electrolyser plant to manufacture green hydrogen at its Jorhat oil field in Assam.
7.	**Gas Authority of India Limited (GAIL)**	Commission 10 MW of electrolyser capacity to produce 4.3 MT of green hydrogen per day
8.	**Gujarat Industries Power Company Limited (GIPCL)**	Expression of interest (EoI) to set up 5 MW–10 MW electrolyser capacity for green hydrogen projects.
9.	**Gujarat Alkalis and Chemicals Limited (GACL)**	To set up green ammonia and green methanol plants.

Source: PHD Research Bureau, PHD Chamber of Commerce and Industry, Compiled from various sources

2.4.4 Green Growth Budget 2023-24

In the Union Budget 2023-24, greening the economy is one of top seven priorities (Saptarishi). It will help in implementing many programmes for green fuel, green energy, green farming, green mobility, green buildings, and green equipment, and policies for efficient use of energy across various economic sectors.

Ethanol blending with petrol, the National Green Hydrogen Mission, promotion of electric vehicles and tremendous push on the renewable energy front are some of the significant initiatives that India is pursuing towards a clean and green energy future. These initiatives are playing an important role in India's energy transition and in providing large-scale green job opportunities.

India stands committed to reducing the emissions intensity of its GDP by 45% by 2030 and achieving net-zero emissions by 2070. To achieve this goal, India is guided by its enhanced National Determined Contribution (NDC) and Long-Term Low Carbon Development Strategy, which prioritise clean and efficient energy systems, disaster-resilient infrastructure, and planned eco-restoration. India's net-zero goal will require a five-decade journey, and its strategy must be adaptable to accommodate new developments in technology, the global economy, and international cooperation.

2.4.5 India's Capacity Building in Green Hydrogen

With a vision to make India an energy-independent nation, and to decarbonise critical sectors, the government approved the National Green Hydrogen Mission on January 4, 2023 with an initial outlay of Rs 19,744 crore. The mission will facilitate demand creation, production, utilisation and export of green hydrogen, as well as mobilisation of over Rs 8 lakh crore of investment by 2030.

India's progress in realising its green energy potential could be a game-changer, not just for its citizens, but for global efforts to tackle climate change, and as a guide for other countries investing in green energy. The introduction of the Green Hydrogen Policy will enable India to achieve energy independence by 2047, as reflected in the Long-Term Low Emissions Development Strategy (LT-LEDS).

Amid the growing global momentum on green hydrogen, India can position this decarbonisation opportunity not just within the context of a low-carbon economy, but also as an enabler of energy security and economic development for the country. It is crucial for decarbonising harder-to-abate sectors such as fertilisers, refining, methanol, maritime shipping, iron and steel, and long-haul transport. Green hydrogen is also an important element of India's LT-LEDS.

The Indian government has set a target of producing 5 million MT per annum of green hydrogen by 2030. Presently, all of the 6 MT/year of hydrogen used in India for heating fuel in refineries and petrochemicals, and as a feedstock in fertiliser production is produced using fossil fuels. The proposed National Hydrogen Energy Mission aims to make India a global hub for hydrogen and fuel cell technology across the entire value chain, with specific strategies for the short-term (four years) and broad-stroke principles for the long-term (10 years and beyond).

S. No	Parameter	Budget Announcement	Impact
1	**Green Growth**	Vision for "LiFE", or Lifestyle for Environment, to spur a movement of environmentally conscious lifestyle.	India is moving forward firmly for the *panchamrit* and net-zero carbon emissions by 2070 to usher in a green industrial and economic transition. This budget builds on our focus on green growth.
2	**Green Hydrogen Mission**	National Green Hydrogen Mission, with an outlay of Rs 19,700 crores.	It will facilitate transition of the economy to low carbon intensity, reduce dependence on fossil fuel imports, and make the country assume technology and market leadership in this sunrise sector. Our target is to reach an annual production of 5 MMT by 2030.
3	**Energy Transition**	This budget provides Rs 35,000 crore for priority capital investments towards energy transition and net zero objectives, and energy security by the Ministry of Petroleum & Natural Gas.	It will prioritise capital investment towards energy transition and net zero objectives, and energy security by the Ministry of Petroleum and Natural Gas.
4	**Renewable Energy Evacuation**	The Inter-state transmission system for evacuation and grid integration of 13 GW renewable energy from Ladakh will be constructed with investment of Rs 20,700 crore including central support of Rs 8,300 crore.	The ultra-mega solar project of Ladakh shore up the region's economy but will also be India's major stride towards carbon-neutrality to meet its ambitious declaration for producing 500 gigawatts (GW) by 2030 is running behind schedule with tenders yet to be floated.
5	**Energy Storage Projects**	To steer the economy on the sustainable development path, Battery Energy Storage Systems with capacity of 4,000 MWh will be supported with Viability Gap Funding.	The viability gap funding for battery storage and a proposed framework for pumped storage power plants will help achieve India's renewable energy targets by mitigating the intermittent nature of such sources.
6	**Green Credit Programme**	To encourage behavioural change, a Green Credit Programme will be notified under the Environment (Protection) Act.	This will incentivise environmentally sustainable and responsive actions by companies, individuals and local bodies, and help mobilise additional resources for such activities.
7	**GOBARdhan scheme**	500 new 'waste to wealth' plants under GOBARdhan (Galvanizing Organic Bio-Agro Resources Dhan) scheme will be established to promote a circular economy.	It aims to positively impact village cleanliness and generate wealth and energy from cattle and organic waste. The main focus areas of GOBAR-Dhan are to keep villages clean, increase the income of rural households and generate energy and organic manure from cattle waste.

Source: PHD Research Bureau, PHD Chamber, Compiled from Union Budget 2023 -24

A report by NITI Aayog in June 2022 revealed that renewable tariffs in India have decreased in recent years, and the cost of electrolysers is expected to decrease in the future. According to a 2020 report by the International Renewable Energy Agency, the cost of electrolysers is critical for making green hydrogen economically viable. The report highlights innovation in electrolyser technology and rapid increases in production scale as the primary drivers of decreasing the cost of electrolysers and green hydrogen.

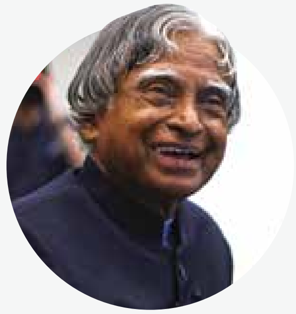
NITI Aayog's report estimates that the cumulative value of the green hydrogen market in India will be $8 billion by 2030 and $340 billion by 2050. The electrolyser market is expected to be worth around $5 billion by 2030 and $31 billion by 2050. The adoption of green hydrogen is also expected to reduce CO_2 emissions by 3.6 Giga tonnes by 2050, leading to significant energy import savings, price stability for industry inputs, and long-term strengthening of foreign exchange reserves.

YEAR	Facilitate	Green Fertilizers	SIGHT	Pilots & Hubs	Regulations & Standards	R&D
2022-23			Consultation and Market Review	Roadmap for key sectors	Procedure for regulatory approval of plot projects	Formulation of R&D Roadmap
2023-24	Notification of targets as may be decided by EG	Notification of Bids Award of Capacity	Notification of Incentive Schemes	Call for Proposals Phase Implementation	Adoption of relevant international standards	Call for Proposals Phase I Implementation
2024-25	Preparatory steps for implementation	Construction			Continuous Review and Monitoring	
2025-26	Implementation	Green Fertilizer Production	Implementation of incentives	Call for proposals		Call for proposals
2026-27				Phase II implementation		Phase II Implementation
2027-28						
2028-29						
2029-30						

2.5

Hydrogen Status: Challenges and Opportunities

ALOK SHARMA, Executive Director and Head Centre for High Technology MoPNG & Dr R K MALHOTRA, Chairman, SARV Energy Solutions PVT. Ltd.



Man needs difficulties
in life because they are
necessary to enjoy the
success.

A P J Abdul Kalam

2.5.1 Production Pathways for Hydrogen

India has a unique opportunity to lead the way in creating a new low-carbon model for inclusive growth. This is because the country's energy future depends on buildings, factories, vehicles, and appliances that have yet to be constructed or purchased. While India has made great strides in developing renewable energy capacity in recent years, current trends suggest that this will not be enough. This is due to the intermittency of renewable energy sources, which means that other sources of power will be needed to fill the gaps. Currently, coal and natural gas are the most reliable sources of power and make up about 80% of the world's primary energy supply. It is likely that fossil fuels will continue to play a key role in India's energy system for the foreseeable future. However, India can reduce its carbon footprint by improving energy efficiency, increasing the role of gas, and decarbonising its energy mix through the use of renewable energy sources like biomass, solar, wind, nuclear, and green hydrogen. Despite these efforts, climate scientists and agencies believe that injecting anthropogenic CO_2 into the sub-surface will be necessary to meet global warming targets. India has committed to becoming net-zero by 2070.

According to a study by The Energy and Resources Institute (TERI), between 2010 and 2035, more than half of the total CO_2 abatement in India will come from energy efficiency improvements (~51%), followed by 32% from renewables, 8% each from nuclear and CCS, and 1% from biofuels. In a low-carbon scenario, electricity consumption in India is projected to rise from 1,000 TWh in 2019 to 6,000 TWh in 2050. This increase will come almost equally from five sectors: green hydrogen, transport, industry, residential, and commercial.

Green hydrogen is becoming an increasingly attractive option for developing countries to meet their sustainable energy goals and decarbonisation strategies, while also addressing environmental concerns. By producing hydrogen locally, countries can enhance their energy security by reducing their reliance on imported oil, which is subject to price volatility and supply disruptions. Moreover, green hydrogen presents an economic opportunity for policymakers to develop local industries.

There is a significant amount of research underway to develop technologies for hydrogen production, and it is worth noting that hydrogen can be generated from a wide range of feedstocks that are readily available worldwide. Many processes are being developed with minimal environmental impact, which may reduce the world's dependence on fuels from unstable regions. By producing hydrogen domestically, countries can increase their energy and economic security. Additionally, hydrogen's versatility in terms of feedstocks and production processes could make it a widely available fuel source, accessible to all regions of the world. As these technologies continue to evolve and improve, hydrogen may ultimately become the most widely used fuel available.

Currently, hydrogen usage is mainly seen in the industrial sector, such as oil refining, and the production of ammonia, methanol, and steel. However, almost all the hydrogen used in these industries is produced from fossil fuels, so clean hydrogen could significantly reduce emissions. For hydrogen fuel cell cars to become more competitive, it's essential to reduce fuel cell costs and improve the availability of refuelling stations. For trucks, the priority is to decrease the cost of delivered hydrogen. Hydrogen-based fuels offer a significant opportunity in the shipping and aviation sectors, which have limited low-carbon fuel options. In buildings, hydrogen could be added to existing natural gas networks, especially in multi-family and commercial buildings in dense cities. In the long term, hydrogen could be directly used in fuel cells or hydrogen boilers. Hydrogen is also one of the top options for storing renewable energy in power generation, and gas turbines can use hydrogen and ammonia to increase the flexibility of the power system.

The use of hydrogen and its by-products is crucial for reducing emissions in sectors that have limited options for decarbonisation, such as shipping, aviation, heavy industry, and heavy-duty transport.

Global hydrogen demand reached 94 MT in 2021 (Refining 39.8 MT; Ammonia 33.8 MT; Methanol 14.6 MT; Iron and Steel 5.2 MT; Others 0.9 MT). However, most of this demand was met by hydrogen produced from unabated fossil fuels. To achieve the net-zero scenario, there needs to be a significant increase in demand for hydrogen, particularly in new applications. By 2030, the demand for hydrogen is expected to double, with almost half of it coming from new applications in heavy industry, power generation, and the production of hydrogen-based fuels.
(Source: https://www.iea.org/reports/hydrogen-supply)

Hydrogen is not a primary fuel as it is not found in its pure form in nature, but rather as part of compounds like water and methane. It needs to be produced using primary energy resources such as natural gas, coal, biomass, nuclear, and renewables like solar, wind, hydroelectric or geothermal energy. The availability of diverse domestic energy resources to produce hydrogen makes it a promising energy carrier and important for ensuring energy security.

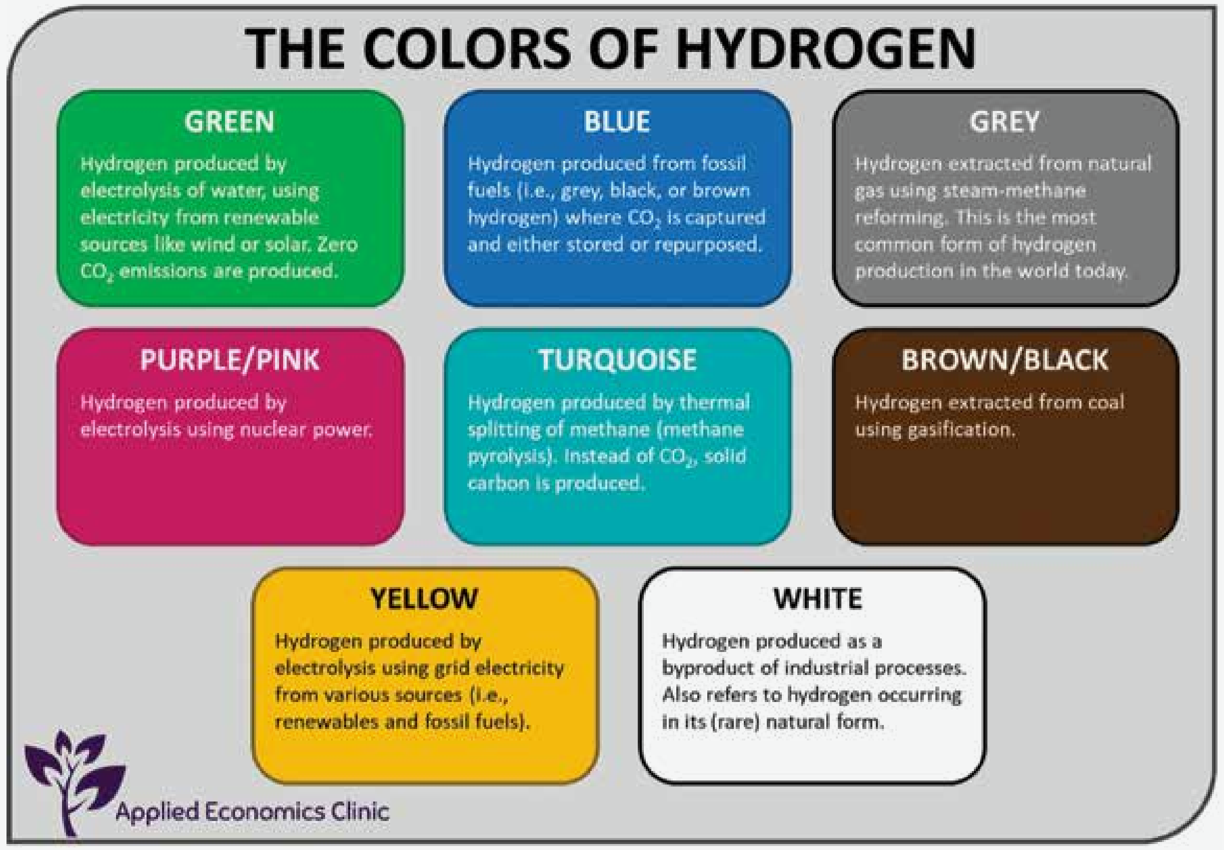
The focus on solar power in the battle against climate change has been well documented, but only recently has attention turned to the potential of green hydrogen in conjunction with renewable energy. One significant advantage of hydrogen is its ability to store energy for extended periods of time, making it a solution to the intermittent supply issues associated with weather-dependent renewables like solar and wind. The cost of renewable energy production can also be lowered through the use of hydrogen storage. As green hydrogen is produced using renewable sources like solar, wind and biomass, it can serve as an effective way to store excess renewable energy.

Hydrogen can be produced using different methods, such as thermal processes (natural gas reforming, biomass, and coal gasification), electrolysis (using various energy resources), and photolysis (splitting water with sunlight using biological and electrochemical materials). Currently, hydrogen production is dominated by fossil fuels, with 48% generated from natural gas steam reforming, 30% from oil/naphtha reforming, 18% from coal gasification, and 3.9% from water electrolysis. In India, 5 MMT of grey hydrogen is consumed each year, with 99% used in petroleum refining and ammonia production.

The colour of hydrogen varies depending on the source or process used to produce it. There are different shades, including green, blue, grey, brown or black, turquoise, purple, pink, red, and white. It is beneficial to produce hydrogen using different resources and methods.

Coal Gasification

India is known to possess the world's fourth-largest coal reserves, estimated at approximately 352 billion MT as of April 1, 2021. The country is also the second-largest producer and consumer of coal globally, having mined 777.31 million MT in FY 2022. Furthermore, India is the second-largest importer of coal, mainly coking coal, which is required by its steel plants because of high demand and poor domestic coal quality. Indian coal has a low calorific value (GCV 3100-5100 kcal/kg) and high levels of inorganic impurities, particularly silica, making it abrasive. Coal gasification, which produces synthesis gas by reacting coal with steam, is considered the best method for enhancing coal conversion efficiency. The resulting clean synthesis gas can be used in power plants to generate electricity, as well as in chemical production processes and to produce hydrogen after eliminating harmful emissions.



THE COLORS OF HYDROGEN

GREEN
Hydrogen produced by electrolysis of water, using electricity from renewable sources like wind or solar. Zero CO_2 emissions are produced.

BLUE
Hydrogen produced from fossil fuels (i.e., grey, black, or brown hydrogen) where CO_2 is captured and either stored or repurposed.

GREY
Hydrogen extracted from natural gas using steam-methane reforming. This is the most common form of hydrogen production in the world today.

PURPLE/PINK
Hydrogen produced by electrolysis using nuclear power.

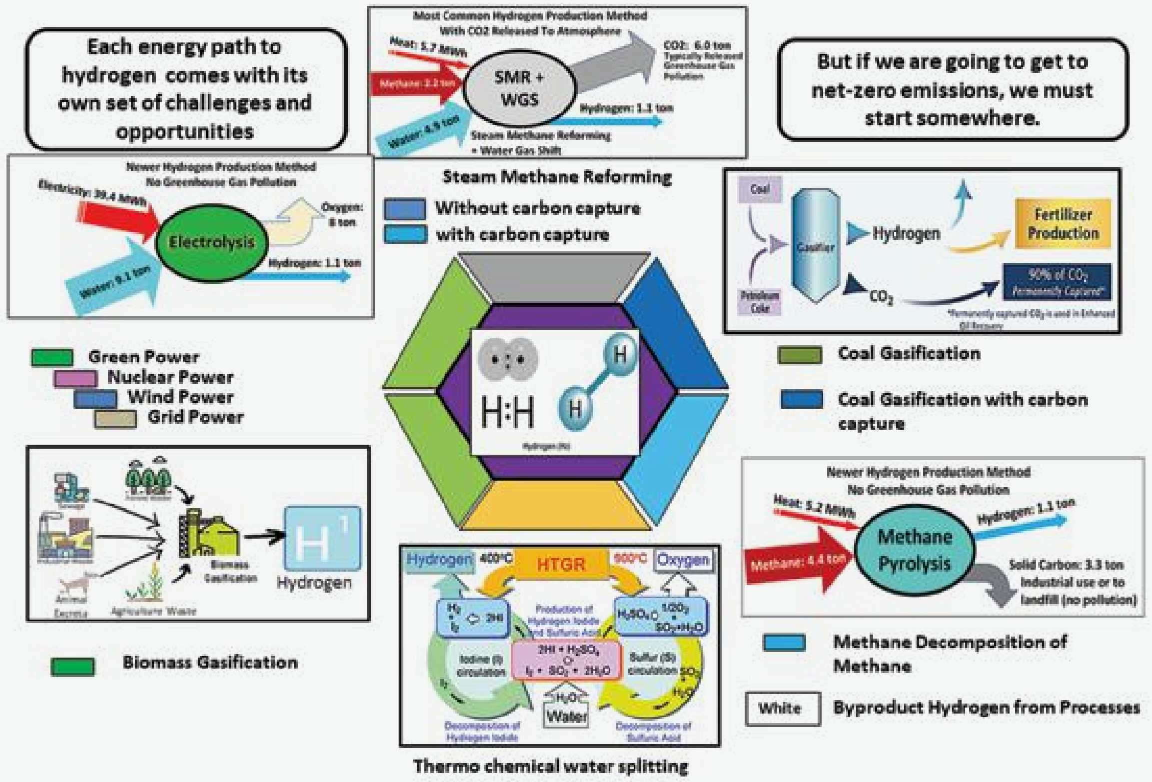
TURQUOISE
Hydrogen produced by thermal splitting of methane (methane pyrolysis). Instead of CO_2, solid carbon is produced.

BROWN/BLACK
Hydrogen extracted from coal using gasification.

YELLOW
Hydrogen produced by electrolysis using grid electricity from various sources (i.e., renewables and fossil fuels).

WHITE
Hydrogen produced as a byproduct of industrial processes. Also refers to hydrogen occurring in its (rare) natural form.

Applied Economics Clinic



Hydrogen Production Pathways

The gasification process involves a chemical reaction between carbon in coal, oxygen (O_2), and steam to produce a mixture of carbon monoxide and hydrogen, which is called synthesis gas. The carbon monoxide reacts with steam through a process called water-gas shift reaction to produce additional hydrogen and CO_2. Although gasification has the potential for CO_2 capture, it needs to be combined with CO_2 sequestration to be environmentally friendly.

Gasification is considered an environmentally friendly technology because it produces lower amounts of sulphur dioxide (SOx) emissions, as sulphur exits as hydrogen sulphide (H_2S) which can be easily converted into sulphur or sulphuric acid, and lower amounts of nitrogen oxides (NOx) because nitrogen exits as nitrogen gas. However, the high ash content in Indian coal poses a significant challenge that requires appropriate technology suitable for coal with high ash content. Various downstream technologies for gas clean-up, methanol, urea, hydrogen, power, and synthetic natural gas are commercially available. Gasification is also well integrated with fertilisers as the air separation unit used for producing O_2 for gasification also provides nitrogen for urea synthesis. Both CO_2 and H_2SO_4 are available as by-products for fertilisers.

Steam Methane Reforming

The steam methane reforming (SMR) process is a well-established and widely used method for producing hydrogen due to its high efficiency and low operational and production costs. SMR involves reacting methane with steam in the presence of a catalyst at high temperature (700–1000°C) and pressure (3–25 bar) to produce a mixture of hydrogen, carbon monoxide and CO_2 called syngas. The syngas is then passed through a catalytic water-gas shift (WGS) reactor to increase the amount of hydrogen and decrease the carbon monoxide content. Finally, impurities such as CO_2 are removed through pressure swing adsorption to obtain pure hydrogen.

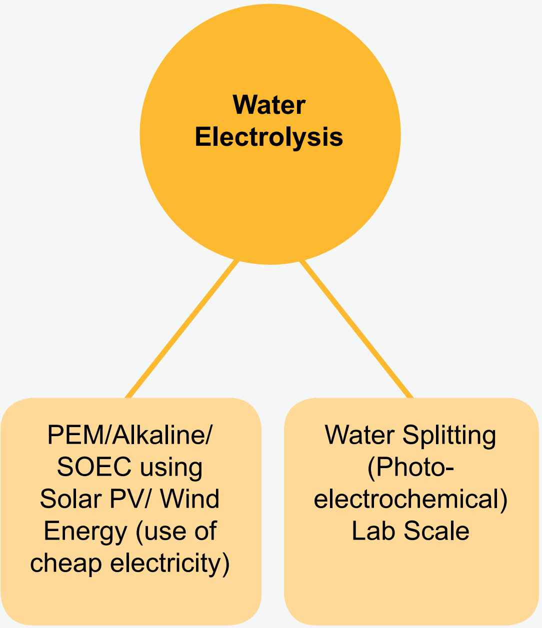
$$CH_4 + H_2O \rightarrow CO + 3H_2CO + H_2O \rightarrow CO_2 + H_2$$

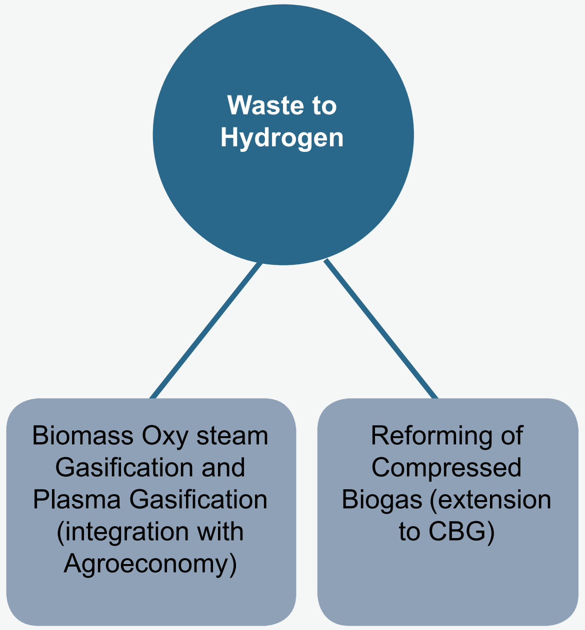
For the SMR process to work efficiently, it is necessary to use a raw material that does not contain any compounds with sulphur as they can damage the catalyst. The process can result in high efficiency of hydrogen production and low levels of carbon monoxide. However, since the process is endothermic, external energy input is required to sustain it.

- Partial Oxidation (POX)
  Partial oxidation is a noncatalytic process, in which the raw material is gasified in the presence of oxygen and possibly steam at temperatures ranging from 1300–1500°C and pressures ranging from 3–8 MPa. In comparison with SMR (H_2:CO :: 3:1), the POX process produces more CO (H_2:CO :: 1:1 or 2:1).
- Autothermal Reforming (ATR)
  ATR is a combination of both steam reforming (endothermic) and partial oxidation (exothermic) reactions. In ATR, steam is added in the catalytic partial oxidation process. ATR has the advantages of not requiring external heat and being simpler and less expensive than SMR.
- Plasma Reforming
  In the case of plasma reforming, the energy and free radicals necessary for the reforming reaction are generated by plasma devices which can produce very high temperatures (>2000°C) with a high degree of control using electricity. Plasma reformers offer several advantages, including compactness and low weight, fast response time, and the ability to operate with a broad range of fuels.

Green Hydrogen

Electrolysis and Gasification of Biomass are the methods used to produce green hydrogen. India, being an agrarian country with ample biomass and access to low-cost renewable power sources like solar, has the potential to emerge as a top producer of green hydrogen, especially with the government's focus on Compressed Biogas (CBG).





Electrolysis

The process of using direct electrical current to split water into hydrogen and oxygen in an electrolyser is called Electrolysis. It is a simple and efficient method for producing hydrogen without any by-products. The oxygen produced can also be used in various industries. However, the cost of the electricity used in the process is a crucial factor in determining the price of the hydrogen produced.

Electrolysis has great potential for producing carbon-free hydrogen from renewable and nuclear sources. The main obstacles facing this technology are the high cost of manufacturing electrolysers and the need to improve process efficiency. It is also important to integrate the compressor into the electrolyser to avoid the expense of a separate compressor for high-pressure hydrogen storage.

In practice, the efficiency of electrolysing water is typically between 50% and 70%. There are three main types of electrolysers: alkaline water electrolysis (AWE), proton exchange membrane (PEM), anion exchange membrane (AEM), and solid oxide electrolysis cell (SOEC). Alkaline systems have been around the longest and have the lowest capital cost, but they are also the least efficient. They have been widely used in the chlor-alkali industry. PEM electrolysers are more compact and have a smaller footprint. SOEC electrolysers are the most electrically efficient due to their high-temperature operation, but they are the least developed. AEM electrolysers are still in the early stages of development but are evolving rapidly.

Photoelectrolysis is a renewable method of generating hydrogen that shows potential for efficient and cost-effective production. However, it is still in the experimental phase. In this process, a semiconducting device called the photoelectrode absorbs solar energy and produces the required voltage to directly split water molecules into hydrogen and oxygen. The photoelectrode is made up of three independent layers – the photovoltaic (semiconductor), catalytic, and protective layers – which collectively affect the overall efficiency of the photoelectrochemical system.

Biomass Gasification

Gasification of organic energy resources from biological sources, such as corn stover, wheat straw, forest residues, witch grass, willow trees, human waste, and animal waste, can be utilised to generate hydrogen and syngas at high temperatures exceeding 700°C and pressures similar to coal gasification.

Biomass gasification presents a more complex challenge than coal gasification, as it produces additional unwanted hydrocarbon compounds. Therefore, additional measures are necessary to convert these hydrocarbons into pure synthesis gas by utilising catalysts. The gasification of biomass generates a substantial amount of tars, a mixture of higher aromatic hydrocarbons, requiring a secondary reactor that employs calcined dolomite and/or nickel catalyst to clean and improve the quality of the product gas to meet the requirements for producing pure hydrogen. Achieving scalability and establishing supply chains for collecting biomass are crucial elements for facilitating the production of low-cost green hydrogen. In an ideal scenario, oxygen would be used in these gasification plants, but the cost of oxygen separation units is too high for small-scale plants, limiting the gasifiers to using air. This results in significant dilution of the product and the production of NOx.

Another promising method of hydrogen production is pyrolysis or copyrolysis. In this process, raw organic material is heated and gasified at a pressure of 0.1-0.5 MPa and a temperature range of 500-900°C in the absence of oxygen and air. As a result, the formation of dioxins is almost eliminated, and no carbon oxides (such as CO or CO_2) are produced, thereby eliminating the need for secondary reactors and reducing emissions. However, if air or water is present, significant COx emissions can occur. This process offers several advantages, such as fuel flexibility, relative simplicity, and compactness, clean carbon by-product, and reduction in COx emissions.

Fast pyrolysis is a modern method for converting organic materials into products with higher energy content, which can also recover a significant amount of solid carbon that can be easily sequestered. Recently, there has been an interest in copyrolysis of a mixture of coal with organic wastes.

Thermochemical Water Splitting

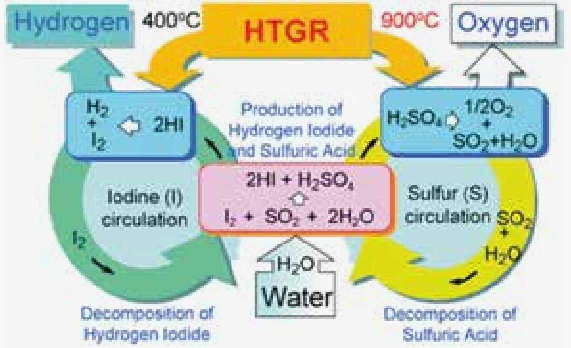
Water typically breaks down at around 2500°C but finding materials that can withstand that temperature and also serve as a sustainable heat source is difficult. However, high temperatures can be achieved through two methods:

- Concentrating sunlight onto a reactor tower using a field of mirror 'heliostats',
- Using waste heat from advanced nuclear reactors.

This technology is well-suited for large-scale, centralised hydrogen production. One advantage of this approach is that it produces pure, clean hydrogen with no GHG emissions. However, it faces challenges in terms of reducing the cost of solar concentrators and heat transfer media, as well as developing nuclear reactor technology that can provide the necessary heat at low temperatures.

Thermochemical cycles are a way to break down water into hydrogen and oxygen through a closed cycle of chemical reactions and heat. They offer advantages over direct one-step thermal water decomposition because they can achieve water splitting at much lower temperatures (usually below 1000°C).

Thermochemical water splitting involves using high temperatures, either from concentrated solar power or from the waste heat of nuclear reactions, to drive a series of chemical reactions that produce hydrogen and oxygen from water. This process operates within a closed loop, using the same chemicals in each cycle and consuming only water while producing hydrogen and oxygen. The copper-chlorine and sulphur-iodine cycles have been extensively studied. Although this technology can produce hydrogen at low cost and high efficiency, it has not yet reached the commercial stage.

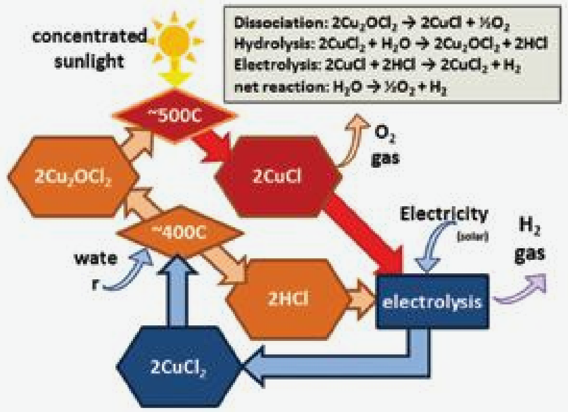


Bio-hydrogen Production

Unlike many other methods, bio-hydrogen is produced as a by-product of various metabolic processes of microorganisms. This makes the bio-hydrogen production method an interesting renewable methodology that requires further technological development to enable efficient and cost-effective hydrogen production.

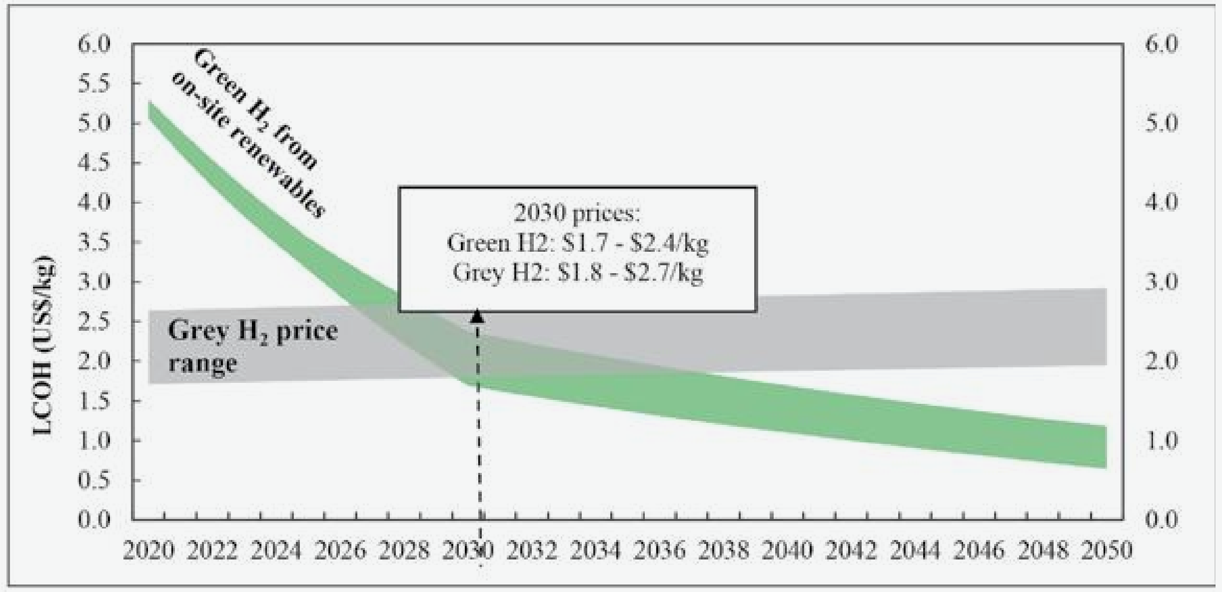
Nuclear

A nuclear fission reactor is a reliable and efficient source of clean energy that can produce power round the clock, regardless of weather conditions. Despite concerns raised by rare accidents like those at Chernobyl and Fukushima, the risks associated with nuclear power are minimal when compared to the amount of energy produced, and modern reactor designs are even safer. Furthermore, improvements in tools and processes have reduced the dangers posed by radioactive waste. For these reasons, nuclear power is an obvious choice for providing the energy needed for hydrogen production.



Copper chloide hybrid cycle

Falling Levelized Cost of Hydrogen (LCOH) for green hydrogen



Source: NITI Aayog

According to a report by NITI Aayog published in June 2022 (Harnessing Green Hydrogen – Opportunities for Deep Decarbonisation in India), the green hydrogen market in India is estimated to be worth $8 billion by 2030 and $340 billion by 2050. The electrolyser market, a key component in green hydrogen production, is expected to be valued at $5 billion by 2030 and $31 billion by 2050. The adoption of green hydrogen will also lead to a significant reduction in CO_2 emissions, with an estimated 3.6 Giga tonnes saved by 2050. This shift towards green hydrogen will result in significant energy import savings, ensure stability in industry input prices, and strengthen foreign exchange reserves in the long run.

The anticipated reduction in the cost of producing green hydrogen is likely to accelerate its availability and use across the country, as well as for export. As the cost of production decreases, green hydrogen will become a more viable and competitive option for various industries and applications, from transportation to energy storage. This increased adoption of green hydrogen will contribute to the decarbonisation of the economy and help reduce GHG emissions. Additionally, the potential for exporting green hydrogen could create new economic opportunities for India, further strengthening its position in the global energy market.

2.5.2 Carbon Capture Utilisation and Sequestration (CCUS)

Currently, the most widely used and cost-effective method for hydrogen production is through the steam reforming of methane or natural gas. This process accounts for about half of the world's hydrogen production. However, GHGs produced during this process must be captured and stored to avoid contributing to climate change.

In India, green hydrogen production costs range from Rs 350-400/kg. However, a KPMG study suggests that these costs could potentially be halved to as low as Rs 170-200/kg by 2030, making green hydrogen as affordable as grey hydrogen and other fossil fuels. In addition to cost, the source of hydrogen generation is crucial for its impact on the environment. Green hydrogen is necessary to achieve a truly low-carbon economy, and it could be used in various applications such

Process	Feed Type	Feed Cost (₹/kg)	Efficiency (%) – Feed to H_2	Tentative H_2 cost -mass production (Rs/kg)
Gasification	**Coal/ Biomass**	4-5	65-68%	~180-220
Bio methanation to H_2	**Agro Residue**	3-4	50%	250-270
Natural gas Reformer (If CCUS is added, then ₹ 35-40/kg) will be additional	**NG**	60-80	75-80%	220-260
Solar/ Wind based Electrolysis	**DI Water (9 litre /kg) Power**	Electricity Cost 50-55 units /kg	65-75 % for Electrolysers	350-400
Aqueous Phase Methanol Reforming	**Coal/NG to methanol to hydrogen**	23-25	~32-40%	250-270
Photoelectrochemical Water Splitting Process (Under Development)	**DI water**	Advantages over other processes: ***Completely green hydrogen. Suitable for both centralised and distributed applications***		

as zero-emissions fuel for maritime shipping and aviation, in high-heat industrial processes, and as feedstock in steel production.

To transition to large-scale low-emissions hydrogen, the deployment of CCUS systems will be significant. Until large-scale storage and transportation solutions become available, hydrogen generation at the point of consumption through distributed reforming can be relied upon.

Reducing costs associated with CO_2 separation and capture, and developing safe and effective sinks are the two main challenges for carbon sequestration from large stationary sources. Safety concerns, particularly regarding storage, are often discussed in the context of carbon capture and storage (CCS) due to the potential for environmental contamination in case of leakages.

Since every country has its unique path towards decarbonisation, India could adopt a public-private partnership model with funding from the government and international climate fund agencies for initial CCS and CCUS projects. This model would align with India's focus on public health, social welfare, and education while also allowing for the development of an economically viable business model for CCS and CCUS.

There are differing opinions on the usefulness of CCUS as a climate mitigation technology. Some believe it is critical, while others see it as a costly subsidy for fossil fuels that could perpetuate reliance on them. Instead, governments should focus on scaling up proven technologies such as renewables and energy efficiency.

Going forward, reducing carbon footprint should be the guiding principle for technology choices, taking into account water availability. This could involve investing in and expanding renewable infrastructure, particularly wind and solar, as well as green hydrogen, while still allowing for a small amount of fossil fuels to ensure flexibility and energy security. Implementing a carbon tax on polluting industries could also encourage the use of green options. The Bureau of Energy Efficiency (BEE) is currently developing a carbon trading scheme for the energy sector.

2.5.3 Storage, Transportation and Distribution

Storing hydrogen is a crucial requirement for the progress of hydrogen and fuel cell technologies in different applications such as stationary power, portable power, and transportation. For hydrogen to become a global energy carrier, it is essential to have large-scale stationary storage. Hydrogen storage can be achieved through physical or material-based methods. Physical methods include storing hydrogen as a gas in high-pressure cylinders or as a liquid at cryogenic temperatures. Hydrogen can also be stored by adsorption on solid surfaces or by absorption within solids like metal hydrides or metal organic frameworks. The Department of Energy (DoE) aims to achieve onboard hydrogen storage targets of 5.5 wt% by 2025, with ultimate targets of 6.5 wt%.

At present, hydrogen is usually generated and consumed in the same location without requiring transportation infrastructure. However, decentralising green hydrogen production would have significant advantages, particularly for reducing the cost and energy required to transport hydrogen to its final destination. Transporting hydrogen over long distances in a gaseous state can be prohibitively expensive, making in-situ production at the point of use necessary for certain applications such as long-haul mobility. By connecting decentralised renewable energy plants to hydrogen refuelling stations in cities and along highways, it would be possible to produce green hydrogen on site.

As the demand for hydrogen grows due to decarbonisation targets and new applications, it's becoming increasingly necessary to develop infrastructure that connects hydrogen production and demand centres. Hydrogen can be transported in gas form via pipelines or in liquid form by ships, similar to liquefied natural gas (LNG). Generally, it's cost-effective to transport hydrogen via pipelines for distances up to 5,000 km. Currently, there are over 2,600 km of hydrogen pipelines in operation in the U.S. and 2,000 km in Europe, mostly used by private companies to connect industrial users. Several countries, particularly Europe, are working on plans to develop new hydrogen infrastructure. The European Hydrogen Backbone initiative, which includes 31 gas infrastructure operators, aims to establish a pan-European hydrogen infrastructure. In June 2022, the Dutch government announced plans to develop a national hydrogen transmission network of 1,400 km, with initial parts to be completed by 2026.

If the distance to be covered is more than 5,000 km, shipping hydrogen or hydrogen carriers is a more cost-effective option than using pipelines. In February 2022, the Hydrogen Energy Supply Chain successfully transported 75 MT of liquefied hydrogen from Australia to Japan, demonstrating the potential for large-scale shipping of hydrogen. However, the extremely low temperatures required to transport liquefied hydrogen (-253°C) makes it challenging and expensive to haul it over long distances, compared to LNG, which only requires a temperature of -162°C.

Currently, compressed gas and liquid hydrogen are the dominant methods for storing hydrogen, but liquid organic molecules have emerged as a favourable alternative due to their low cost and compatibility with existing fuel transport infrastructure. Liquid organic hydrogen carriers (LOHCs) are being developed as a potential option for large-scale hydrogen storage and are being compared with densified storage technologies and circular hydrogen carriers like ammonia and methanol. Although ammonia and methanol can also be used as hydrogen carriers due to their compatibility with existing liquid fuel infrastructure, their synthesis and decomposition processes are more energy and capital-intensive compared to LOHCs. In addition to safety considerations, these factors make LOHCs a potential option for large-scale stationary hydrogen storage.

Using existing natural gas pipelines to transport a blend of hydrogen and natural gas is a cost-effective and time-efficient solution, according to studies. Compared to building new dedicated hydrogen pipelines, converting or repurposing natural gas pipelines for hydrogen transportation can be achieved at a lower cost and in less time. However, there are technical challenges to overcome, particularly in terms of the steel pipeline's susceptibility to Hydrogen Embrittlement (HE). Research is underway to find a solution to this issue in Europe and the U.S., as the transportation of hydrogen blends through high-pressure natural gas networks is not yet feasible. Studies indicate that hydrogen exposure can adversely affect steel's tensile properties and significantly increase fatigue crack growth rate, even at low hydrogen partial pressure. Despite these challenges, it is expected that these issues will be resolved soon.

The risk of HE in low-pressure city gas distribution systems is much lower than in high-pressure gas transmission systems. As a result, trials for transporting hydrogen blends through existing city gas distribution systems are being conducted globally. In India, the Petroleum and Natural Gas Regulatory Board (PNGRB) is responsible for overseeing and authorising projects involving the blending of green hydrogen in city gas distribution networks. In 2022, PNGRB authorised a couple of trial projects involving the blending of up to 2% hydrogen in CGD networks. After the successful completion of these projects, PNGRB recently approved the blending of 5% green hydrogen with PNG, with the ultimate goal of gradually increasing the hydrogen blend limit to 20%.

Hydrogen Compression and Liquefaction

Compared to all other non-nuclear fuels, hydrogen has the highest gravimetric energy density, which is 33 kWh/kg based on its net calorific value. In contrast, gasoline has a gravimetric energy density of 13 kWh/kg, which is three times less than that of hydrogen. However, the density of hydrogen is very low, only 0.089 g/L at 298 K and 1 atm. This means that it would take approximately 11,000 L to store 1 kg of hydrogen or 33 kWh of energy. In comparison, 1 kg of gasoline can be stored in a volume of 1.3 L under the same conditions (considering a density of 775 g/L), which is four orders of magnitude less than the volume required for hydrogen. Hydrogen has a diffusion coefficient in air (0.62 cm^2/g) that is four times higher than that of natural gas, making it dilute very quickly in air, which is a safety advantage. Hydrogen flames are also extinguished faster than those involving gasoline or natural gas. However, the flammable limits for the percentage by volume of hydrogen in air at atmospheric pressure are 4% and 75%, and hydrogen-air mixtures can ignite with a very low energy input, one-tenth that required to ignite a gasoline-air mixture.

At least 5 kg of hydrogen must be stored to cover a distance of 500 km; a density of 42.9 g/L is obtained by compressing hydrogen to 70 MPa and 298 K. Hence, 1 kg of hydrogen can be stored in a volume of approximately 23 L under the above-mentioned conditions. For storage of hydrogen, four different types of high-pressure tanks are currently used. Type III and Type IV tanks are the most widely used to store hydrogen at very high pressure, as they ensure the best performance. These tanks are made of carbon fibre, which reduces the weight of the storage system. Furthermore, an aluminium or polymer inner lining prevents leakages. Although compression has proven to be an efficient solution for the storage of hydrogen, it has to be taken into account that it requires energy to accomplish. Approximately 5% and 15% of the energy of hydrogen is consumed when it is compressed at 35 MPa and 70 MPa, respectively.

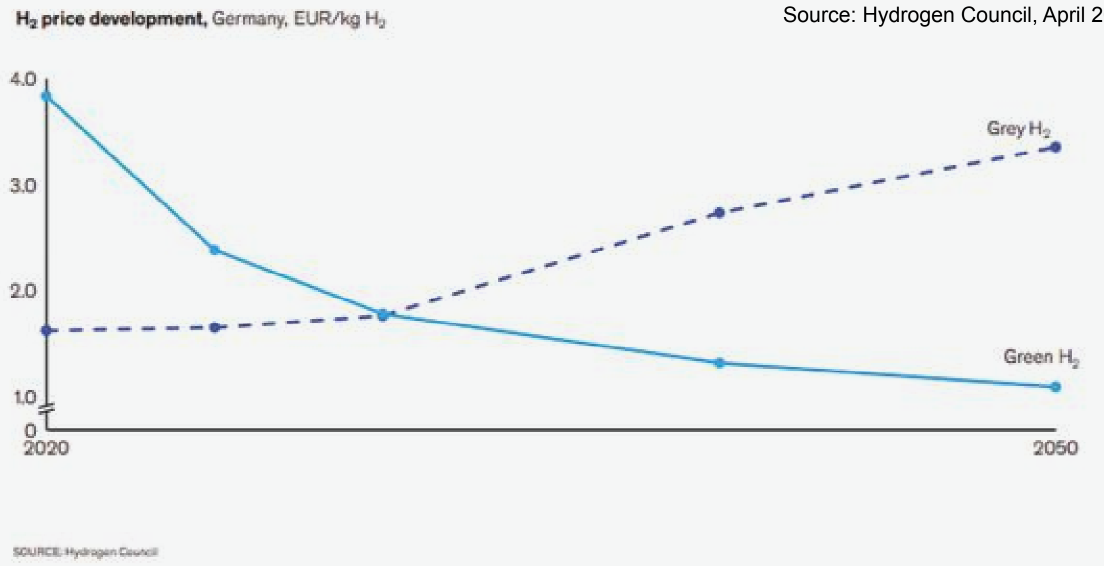
The density of liquid hydrogen, i.e., 70.8 g/L at atmospheric pressure, is 40% higher than compressed gaseous hydrogen at 70 MPa. And 1 kg of liquid hydrogen is stored in a volume of 13.6 L, whereas it takes 23 L to store the same amount of gaseous hydrogen at 70 MPa. The production of liquid hydrogen is quite expensive. Around 10 kWh/kg energy are required to liquefy hydrogen, i.e., 30% of the hydrogen chemical energy. In addition, the CAPEX of industrial plants for hydrogen liquefaction is relatively high. A significant reduction in this cost could be achieved by increasing the production of liquid hydrogen from the current capacity of 5 MT/day to 150 MT/day in the framework of centralised production.

A hydrogen liquefaction system liquefies hydrogen gas by lowering its temperature to -253°C. Liquefaction reduces that volume to approximately 1/800 of the gaseous state, making mass transport far more efficient. A liquefaction system is, therefore, considered the key piece of infrastructure needed to achieve the mass transport of hydrogen. When transported over long distances, liquid hydrogen is more cost-effective than gaseous hydrogen due to the higher capacity of liquid tanker trucks. However, storage tanks for liquid hydrogen must be designed with efficient thermal isolation to prevent losses from hydrogen evaporation at 20 K. Cryogenic tanks consist of an inner and outer lining made up of several aluminium sheets and glass fibres to prevent heat transfer, including radiation. The first-ever shipment of liquefied hydrogen from Australia to Japan in February 2022 marked a significant milestone in the global hydrogen market.

2.5.4 Challenges and Opportunities in Hydrogen Economy

In addition to industrial heating, green hydrogen can also be utilised in the production of chemicals. It makes sense to prioritise the use of green hydrogen in primary products such as green ammonia, in refineries for desulphurisation, in power generation, and in hard-to-decarbonise sectors such as steel production. Large complexes such as airports, commercial centres, and data centres could potentially run entirely on hydrogen. These applications present an opportunity to transition to a hydrogen economy in the near future, as hydrogen could be produced wherever there is water and electricity available. Using hydrogen as a drop-in fuel for internal combustion engines in vehicles is another easily implementable option that can accelerate the growth of the hydrogen economy in India. Many hydrogen filling stations have on-site electrolysers that can produce hydrogen on demand, eliminating the need for transportation. The next logical step would be to develop fuel-cell-based applications for both stationary and mobile use, given their high efficiency. Currently, hydrogen-based applications are being developed and deployed for a variety of uses, including cars, buses, trucks, trains, aircraft, forklifts, ships, drones, stationary power generation, and more.

According to the Paris-based autonomous inter-governmental organisation, the IEA, blue hydrogen production is responsible for emitting around 830 million MT of CO_2 per year, equivalent to the combined CO_2 emissions of the U.K. and Indonesia, even at current levels of demand. This highlights the urgent need to shift to clean energy, particularly green hydrogen. Green hydrogen, which has a zero CO_2 footprint, represents a revolution in the energy sector, and hydrogen is being hailed as the fuel of the future. Many advanced countries have already created hydrogen roadmaps to transition into a hydrogen economy. However, the current cost of green hydrogen is high, so it may be too early to declare the advent of the hydrogen economy. Nonetheless, given its technical advantages and



Source: Hydrogen Council, April 2020

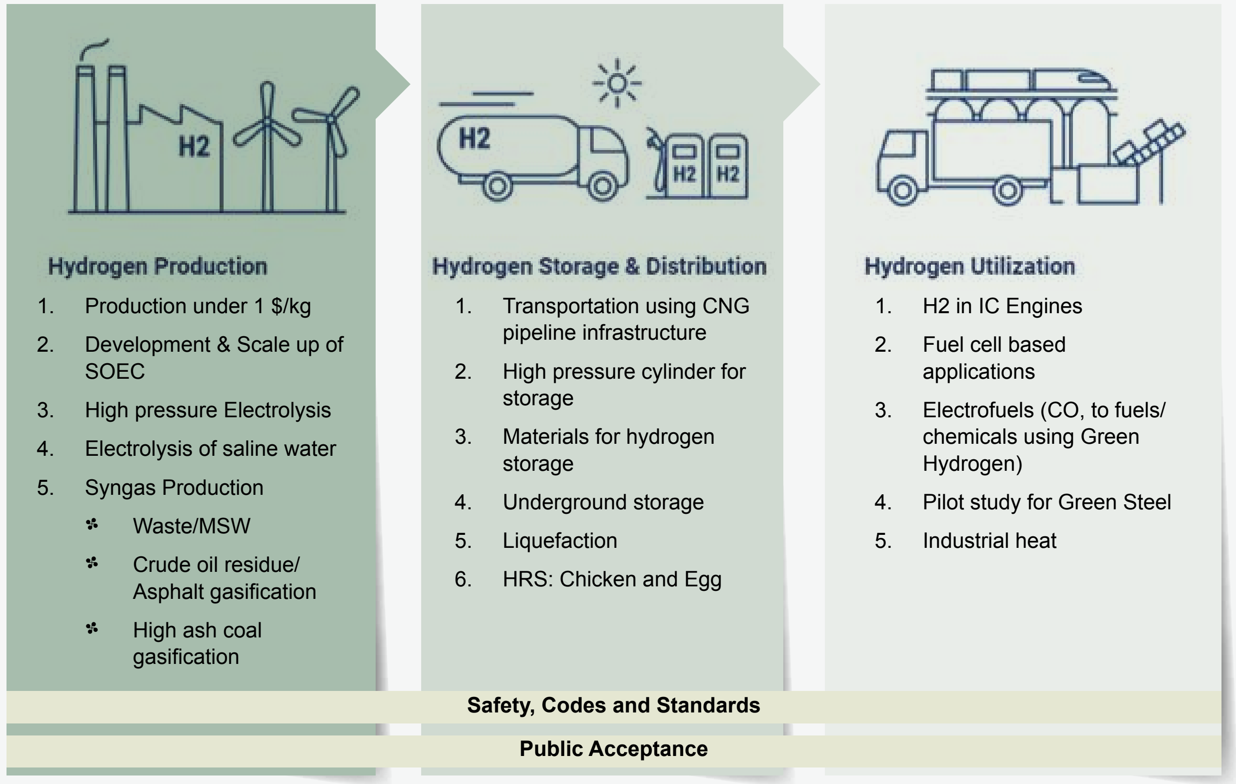
the significant reduction in costs of solar power and batteries over the last decade, Europe, Japan, and other industrialised countries are investing public money to create markets with scale, so that technology can develop and costs can start to come down.

Going forward, India has several options for embracing the hydrogen economy, and it is suggested that multiple strategies should be pursued. While some argue that India should wait for global technological and cost developments to mature, others say that it is the right time to enter the hydrogen market and that India should take ambitious steps to accelerate deployment. Key areas for development include electrolysers, fuel cells, storage, and transportation materials. Collaboration with industry partners is crucial for success in cost reduction and scaling up.

Although the current prices for green hydrogen are high, they are expected to decrease significantly by 2030 due to falling costs for renewable electricity and electrolysers, as well as improved efficiency and larger system sizes.

Industry experts predict that increasing electrolysis capacity will decrease costs by around 70% over the next decade. Additionally, the cost of emitting CO_2 with grey hydrogen is becoming more expensive in many jurisdictions worldwide. The price of blue hydrogen is primarily influenced by natural gas prices, but the cost of capturing and reusing or storing carbon emissions is also a significant factor. India is more interested in green hydrogen because imported LNG costs are high due to the challenges of cryogenic application, transportation, handling, and regasification.

While there are various challenges associated with transitioning to a hydrogen economy, such as the high cost and limited supply of electrolysers, there are also opportunities for organisations and industries in the production and development of hydrogen-related technologies. The biggest challenge in the hydrogen value chain is the storage, transportation, and distribution stages, which increase the cost of hydrogen at the point of use. The development of safe and reliable hydrogen storage and distribution systems is crucial to address these challenges. One challenge in hydrogen storage is the amount of hydrogen required, which poses a challenge for its use in the transportation sector.



Regarding transportation, hydrogen is a promising option. While lithium-ion batteries are mature technology and competitive for light motor vehicles, it is relatively easy to set up charging stations for electric vehicles as they only need connection to the grid. Hydrogen fuel cells can also be used to power automobiles, particularly heavy-duty trucks. However, this requires a full hydrogen supply chain of refuelling stations in cities and on highways. There is currently a chicken-and-egg problem as there are not enough vehicles to fill hydrogen, and auto manufacturers are also waiting for more hydrogen refuelling stations to be established. There is also renewed interest in using hydrogen in internal combustion engines and turbines. Additionally, safety standards and regulations need to be developed to ensure widespread use of hydrogen in various industries.

2.5.5 National Green Hydrogen Mission

The Hon'able Prime Minister of India Narendra Modi launched the National Green Hydrogen Mission on Independence Day in 2021. On January 4 this year, the Union Cabinet approved the National Green Hydrogen Mission, which has an initial budget of Rs 19,744 crore to build the hydrogen ecosystem. The mission aims to develop green hydrogen production capacity of at least 5 million MT/year by 2030, along with renewable energy capacity addition of about 125 GW in the country. The government also earmarked incentives worth Rs 17,490 crore for the production and manufacturing of electrolysers under the Strategic Interventions for Green Hydrogen Transition (SIGHT) programme, Rs 1,466 crore for pilot projects, Rs 400 crore for research and development (R&D), and Rs 388 crore for other mission components.

The National Green Hydrogen Mission aims to lower the cost of renewable energy delivered to electrolyser-based projects by implementing facilitative policies for transmission, connectivity, energy storage, and more. It also plans to increase the production and deployment of high-performance electrolysers in large quantities, as well as establish infrastructure for the storage, delivery, and export of green hydrogen and its derivatives. The development of pipelines for bulk transportation of green hydrogen and the creation of large-scale hydrogen hubs will also be encouraged. Through these targeted interventions, the mission expects that green hydrogen will become cost-competitive with grey hydrogen in the near future.

The Energy Conservation (EC) Act will establish a legal provision to ensure that consumption targets for green hydrogen and its derivatives are enforced. The Central government will have the power to specify the minimum share of energy and feedstock consumption from non-fossil-fuel-based sources that industries must ensure.

2.5.6 Initiatives by Various Organisations

Several public and private sector companies have expressed their interest in contributing to India's green hydrogen mission and have committed to accelerating its development. Some of these companies announced their targets as early as 2021 when the finance minister first announced India's plan to utilise green hydrogen in her budget speech.

INDIAN OIL CORPORATION LTD (IOCL)

IOCL is taking steps towards decarbonisation by starting green hydrogen production and plans to replace some of its grey hydrogen with green hydrogen by 2029-30. Initially, green hydrogen plants are being set up at the Panipat and Mathura refineries. Chennai Petroleum Corporation, a subsidiary of IOCL, has also invited bids for the production of green hydrogen at its Chennai refinery. IOCL, L&T, and ReNew have formed a partnership to establish a green hydrogen business. Additionally, IOCL and L&T have signed an agreement to form a joint venture to manufacture and sell electrolysers used in green hydrogen production. Indian Oil R&D is also working on developing and demonstrating

MISSION IMPLEMENTATION TIMELINE

YEAR	Facilitate	Green Fertilizers	SIGHT	Pilots & Hubs	Regulations & Standards	R&D
2022-23			Consultation and Market Review	Roadmap for key sectors	Procedure for regulatory approval of plot projects	Formulation of R&D Roadmap
2023-24	Notification of targets as may be decided by EG	Notification of Bids Award of Capacity	Notification of Incentive Schemes	Call for Proposals Phase Implementation	Adoption of relevant international standards	Call for Proposals Phase I Implementation
2024-25	Preparatory steps for implementation	Construction			Continuous Review and Monitoring	
2025-26	Implementation	Green Fertilizer Production	Implementation of incentives	Call for proposals		Call for proposals
2026-27				Phase II implementation		Phase II Implementation
2027-28						
2028-29						
2029-30						

15 fuel cell buses with hydrogen infrastructure, using various hydrogen production pathways such as electrolysis, biomass gasification, and biogas reforming.

ADANI GROUP

On June 14, 2022, Adani New Industries Ltd. (ANIL) announced a partnership with Total Energies SE from France to invest $50 billion over the next 10 years in India to produce green hydrogen and create an ecosystem around it. ANIL plans to develop a green hydrogen production capacity of 1 million MT/year before 2030 in the initial phase. Additionally, in December 2022, ANIL signed a development and licensing agreement with Cavendish Renewable Technology (CRT), a hydrogen technology firm from Melbourne, to develop alkaline electrolysers, polymer exchange membranes (PEMs), anion exchange membranes (AEMs), and use CRT's innovative C-Cell technology for mass-scale production.

RELIANCE INDUSTRIES LTD. (RIL)

Mukesh Ambani, the chairman of RIL, announced on August 29, 2022, that the company intends to switch to green hydrogen production by 2025, replacing the current grey hydrogen production. RIL's goal is to decrease the cost of green hydrogen production to less than $1/kg by the end of the decade.

Sources report that RIL is in advanced discussions with Ashok Leyland, a truck and bus manufacturer owned by the Hinduja family, to collaborate on the development and supply chain of hydrogen-powered engines. In 2021, RIL announced plans to invest $75 billion in clean energy projects over the next 15 years, including the construction of giga-factories and blue hydrogen facilities.

ONGC

In July, 2022, ONGC and joint venture partner Greenko inked a pact to spend up to $6.2 billion on renewable energy and green hydrogen projects.

GREENKO-KEPPEL DEAL

Greenko Group revealed in October 2022 that India will begin exporting green energy for the first time in 2025. The first shipments will be sent to a power plant in Singapore after signing an MOU with Keppel Infrastructure. Greenko and Keppel will collaborate to explore green hydrogen opportunities in India, with the goal of securing a contract to supply 250,000 MT/year to Keppel's new 600 MW power plant in Singapore. Greenko Group has invested in a broad range of initiatives, including the storage of carbon-free green hydrogen energy across India, with a total investment of $5 billion.

GAIL INDIA LTD

GAIL announced on May 12, 2022, that it had awarded a contract to establish a large Proton Exchange Membrane (PEM) Electrolyser in India. The installation will be located at GAIL's Vijaipur Complex in the Guna district of Madhya Pradesh and will be powered by renewable energy. The project is expected to produce approximately 4.3 MT of green hydrogen per day, equivalent to a capacity of 10 MW, and is slated to begin operations in November 2023. In January 2022, GAIL began a unique project in India to blend hydrogen with natural gas.

BHARAT PETROLEUM CORPORATION LTD (BPCL)

BPCL invited bids in June 2022 for the installation of a 5 MW electrolyser system, which will gradually establish a green hydrogen production facility within one of its city gas distribution projects.

In April 2022, BPCL entered into a five-year MOU with the Odisha government to assess the possibility of creating a renewable energy and green hydrogen plant for both domestic and export customers, as well as other initiatives.

BPCL has partnered with the Bhabha Atomic Research Centre (BARC) to investigate alkaline electrolyser technology for the production of green hydrogen. It intends to expand the production of this electrolyser for commercial use, particularly in refineries.

NTPC LTD

NTPC intends to allocate approximately 5 GW of its 60 GW green portfolio goal by 2032 towards the green hydrogen and ammonia sector.

NTPC has initiated three pilot projects related to hydrogen. The first involves mixing green hydrogen and natural gas at its Kawas plant in Gujarat. The second involves building a green hydrogen refuelling station with solar plants in Leh, where the company also intends to operate fuel-cell-powered buses. The third is a pilot project for producing hydrogen and capturing carbon at its Vindhyachal plant in Madhya Pradesh.

OIL INDIA LTD (OIL)

In April 2022, OIL made a significant move towards establishing a green hydrogen economy in India by launching the country's first pilot plant for 99.999% pure green hydrogen. The plant, which has a capacity of 10 kg per day, was commissioned at the Jorhat Pump Station in Assam.

LARSEN & TOUBRO LTD (L&T)

In August 2022, L&T established a green hydrogen plant at its AM Naik Heavy Engineering Complex in Hazira, Gujarat. The facility produces 45 kg of green hydrogen daily, which is employed for internal consumption at L&T's Hazira manufacturing complex. L&T has partnered with the Indian Institute of Technology (IIT) Bombay to collaborate on research and development initiatives within the green hydrogen value chain.

In January 2022, L&T signed an MOU with Norway-based electrolyser technology company and manufacturer HydrogenPro AS to establish a gigawatt-scale manufacturing plant for alkaline water electrolysers based on HydrogenPro technology.

In December 2021, L&T teamed up with Nasdaq-listed ReNew Power to collaborate on the development, ownership, execution, and operation of green hydrogen projects in India.

HINDUSTAN PETROLEUM CORPORATION LTD. (HPCL)

HPCL plans to establish a green hydrogen production capacity of 24,000 MT/year. The company intends to begin operations at a green hydrogen plant with a capacity of 370 MT/year at its Vizag refinery.

2.5.7 Summary

The global energy crisis has highlighted the need for policies that align energy security with climate goals. Hydrogen is emerging as a leading option, especially in countries like India, due to falling renewable energy prices and expected decreases in electrolyser costs. Hydrogen has the potential to be a low-cost method for storing renewable energy for long periods and decarbonising heavy-duty transportation and hard-to-abate industrial sectors such as steel, petroleum refining, cement, and fertilisers. Recognising hydrogen's potential, the Indian government has announced a National Green Hydrogen Mission and a PLI scheme for electrolysers to kickstart the hydrogen ecosystem. Blue/grey hydrogen can also be an interim solution until green hydrogen infrastructure is established and its costs come down.

2.6

Hydrogen Fuel Cells

SIDDHARTH R. MAYUR, Founder & MD, h2e Power Systems

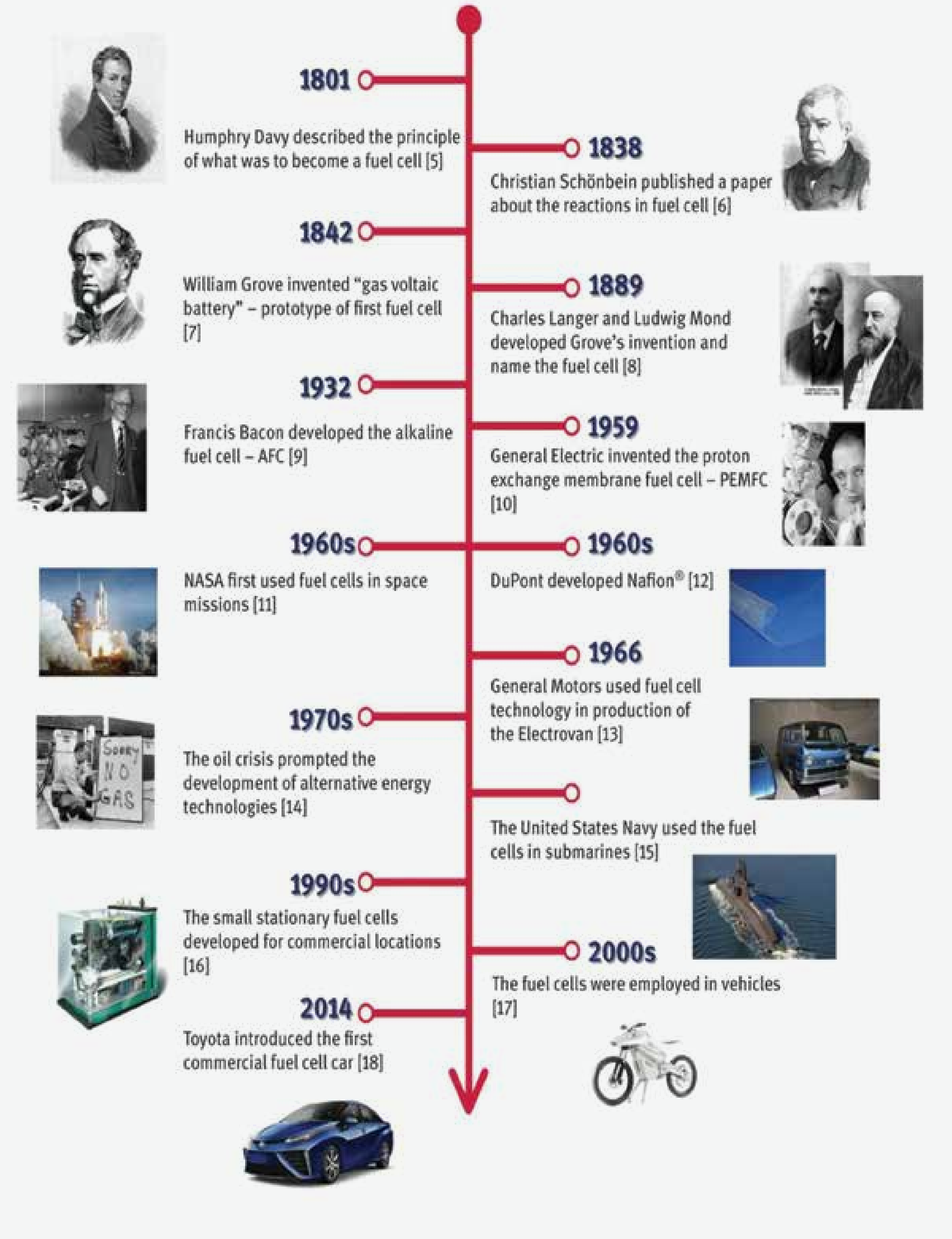
> To cherish what remains of the earth and to foster its renewal is our only legitimate hope of survival.
>
> **Wendell Berry**

2.6.1 Hydrogen Fuel Cells, Ancient Wisdom in Modern Times

The human body can be considered an exemplary and highly efficient fuel cell. At the cellular level, in the mitochondria, oxygen and hydrogen react to generate energy in the form of electricity, heat and water, which sustains human life and movement. Although humans have employed this natural process to create fuel cells, the body's internal fuel cell system, created by a higher power, operates with remarkable efficiency for around 80-90 years. In contrast, human-made fuel cells have a limited lifespan of only 10 years, indicating a significant potential for advancement and innovation in their design and integration.

History of Fuel Cells

The discovery of fuel cells can be traced back to 1801 when Sir Humphry Davy explained the principle that eventually led to the development of fuel cells. Over the past century, several discoveries have established fuel cells as a highly efficient means of generating electricity and heat, both for stationary and mobile applications, including space. In 1932, Francis Bacon's development of the Alkaline Fuel Cell (AFC) marked the beginning of fuel cells' commercial development and deployment worldwide. In 1959, GE invented the Proton Exchange Fuel Cell (PEMFC), which NASA used in its space missions. Fuel cells have since powered several space missions, and with the development of other fuel cell technologies such as Molten Carbonate (MCFC), Solid Oxide (SOFC), Phosphoric Acid (PAFC), and Direct Methanol (DMFC), they have found applications in various industry segments such as data centres, industrial and commercial areas, CHP solutions, automotive sector, and submarines. These fuel cell solutions range from a few kW to several MW and can use both gaseous and liquid hydrocarbons as input fuels, efficiently converting them into electricity and heat.



1801 Humphry Davy described the principle of what was to become a fuel cell [5]

1838 Christian Schönbein published a paper about the reactions in fuel cell [6]

1842 William Grove invented "gas voltaic battery" – prototype of first fuel cell [7]

1889 Charles Langer and Ludwig Mond developed Grove's invention and name the fuel cell [8]

1932 Francis Bacon developed the alkaline fuel cell – AFC [9]

1959 General Electric invented the proton exchange membrane fuel cell – PEMFC [10]

1960s NASA first used fuel cells in space missions [11]

1960s DuPont developed Nafion® [12]

1966 General Motors used fuel cell technology in production of the Electrovan [13]

1970s The oil crisis prompted the development of alternative energy technologies [14]

The United States Navy used the fuel cells in submarines [15]

1990s The small stationary fuel cells developed for commercial locations [16]

2000s The fuel cells were employed in vehicles [17]

2014 Toyota introduced the first commercial fuel cell car [18]

What are Fuel Cells?

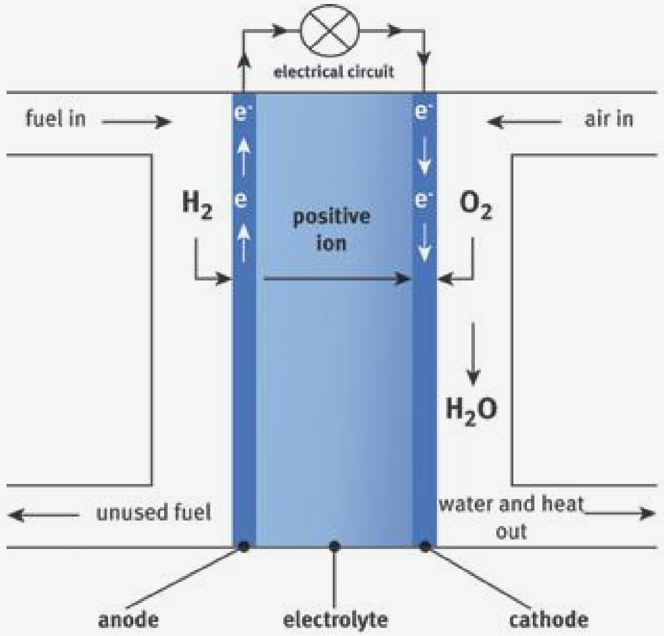
A fuel cell is a device that converts chemical energy directly into electrical energy, along with heat and water as by-products. The cell comprises two electrodes, an anode and a cathode, which are separated by an electrolyte. Typically, all fuel cell technologies require hydrogen and oxygen. Hydrogen gas and oxygen gas from the air are continually supplied to the anode and cathode, respectively. At the anode, the hydrogen fuel reacts with a catalyst, producing positively charged protons (H+) and negatively charged electrons (e−). The electrolyte membrane allows only positive ions to pass through from the anode to the cathode side and serves as an insulator for electrons. The electrons flow through an external electrical circuit to the cathode, where they combine with protons and oxygen to form water, releasing electrical energy in the process. The diagram below illustrates the structure of a simplified fuel cell.

Fuel Cells & India

India is on the brink of a significant energy revolution, driven by the global climate crisis, which presents a unique opportunity for the country to adopt new, green energy technologies to fuel growth without harming the environment. This has led to the development of various product solutions that cater to industries seeking credible energy solutions, including the least-talked-about agriculture sector, which faces significant challenges.

More than 50% of India's population of 1.4 billion suffers from energy poverty, with those in Tier 2 and Tier 3 cities, and rural areas being the most affected. The clarion call of *Amrit Kaal*, commemorating India's 100 years of independence, has increased the opportunity for fuel cells manifold. The vision of *Swadeshi Urja* for a *Swawalambi Bharat*, which the author initiated in 2009, appears to be becoming a reality. Fuel cell technology may emerge as a key solution for the less-talked-about sectors like agriculture, rural villages, and residential areas, enabling those on the ground to be part of this great energy transition from high to zero emissions, from energy poverty to energy independence.

- **Farm to Fork**
  The food value chain originates with the farmer, which also represents the most significant opportunity for fuel cells to provide energy security, enabling farmers to become more prosperous and productive. Fuel cells can be utilised to provide warm and cold storage facilities for seasonal crops, and they



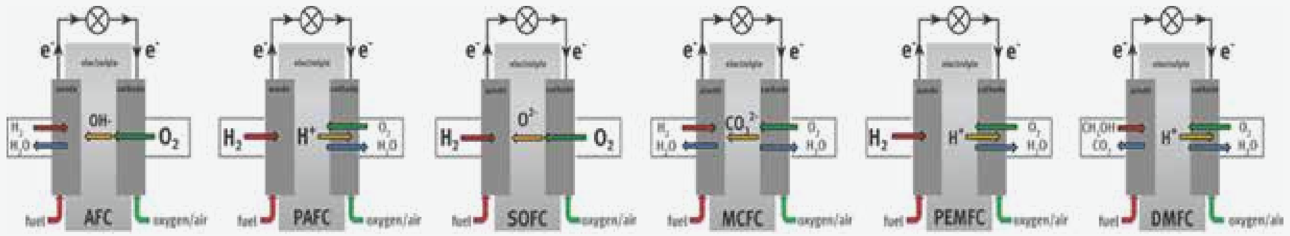
Anode reaction: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode reaction: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Overall reaction: $2H_2 + O_2 \rightarrow 2H_2O$

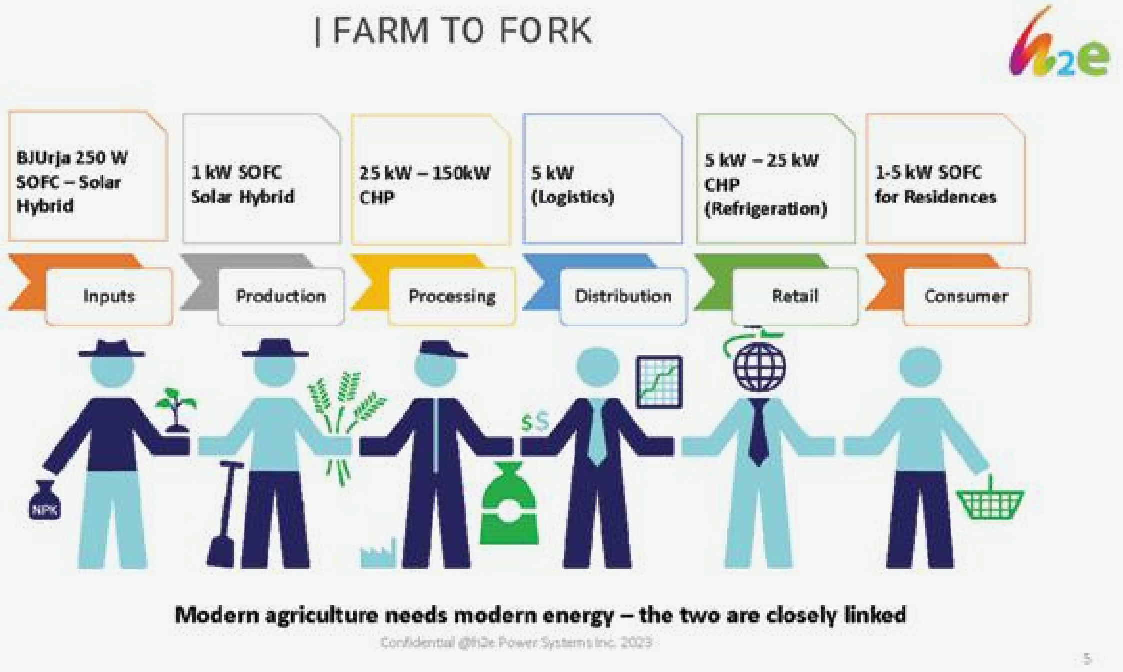
Types of Fuel Cells

Fuel cell type	AFC	PAFC	SOFC	MCFC	PEMFC	DMFC
Common electrolyte	Solution of potassiumhydro	Phospho-ric acid	Solid ceramic inorganico	Molten potassium or lithium carbonate	Solid polymeric protonex	Solid polymer membrane
Anode reaction	$2H_2+4OH- \rightarrow 4H_2O+4e-$	$2H_2 \rightarrow 4H++4e-$	$2O_2-+2H_2 \rightarrow 2H_2O+4e-$	$2H_2+2CO32- \rightarrow 2H_2O+2CO_2+4e-$	$2H_2 \rightarrow 4H++2e-$	$CH_3OH+H_2O \rightarrow CO_2+6H++6e-$
Cathode reaction	$O_2+2H_2O+4e- \rightarrow 4OH-$	$O_2+4H++4e- \rightarrow 2H_2O$	$O_2+4e- \rightarrow 2O2-$	$O_2+2CO_2+4e- \rightarrow 2CO32-$	$O_2+4H++4e- \rightarrow 2H_2O$	$3O_2+12H++12e- \rightarrow 6H_2O$
Fuel	Pure H_2	Pure H_2	H_2,CO,CH_4, other hydro	H_2,CO,CH_4, other hydrocarbons	Pure H_2	CH_3OH
Oxidant	O_2 in air	O_2 in air	O_2 in air	O_2 in air	O_2 in air	O_2 in air
Charge carrier	OH−	H+	O_2−	CO32−	H+	H+
Operating temperature (°C)	60–200	150–250	600–1000	600–700	50–200	60–200
Capacity (kW)	10–100	50–1000	<1–3000	<1–1000	<1–250	0.001–100
Electrical Efficiency (%)	60	>40	50–60	>50–60	35–45	30–40
Power density (Wm−2)	~1.0	0.8–1.9	0–1.5	1.5–2.6	3.8–6.5	1.0–2.0
Installation cost ($kW−1)	1800–1900	2100	3000	2000–3000	<1500	1500–1800



can be employed in the cold chain to transport farm produce to market or processing units. At the food processing unit level, a combined heat and power solution can significantly reduce energy costs and emissions. Fuel cells have the potential to provide distributed generation across the entire farming value chain, ultimately leading to Prosperity Thru Power.

- **BJUrja**
  An innovative mini grid developed by h2e Power Systems, BJUrja is a fuel cell, solar and battery hybrid that uses biogas from farm waste to provide 24x7 energy independence to the farm and the farmer. This system is designed to be mobile and can be easily transported using a trolley. This provides farmers with reliable and uninterrupted power, allowing them to use small scale machinery for level 1 processing of their produce. With the use of BJUrja, a farm can be transformed into a factory and a farmer can become a self-sufficient SME entrepreneur. Considering there are over 118 million small farmers in India, the potential for BJUrja to bring a green revolution to farms is immense.



| FARM TO FORK

BJUrja 250 W SOFC – Solar Hybrid
1 kW SOFC Solar Hybrid
25 kW – 150kW CHP
5 kW (Logistics)
5 kW – 25 kW CHP (Refrigeration)
1-5 kW SOFC for Residences

Inputs
Production
Processing
Distribution
Retail
Consumer

Modern agriculture needs modern energy – the two are closely linked

Confidential @h2e Power Systems Inc. 2023

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- **Rural Micro-Grids Using BioGas**
  The utilisation of mid-range fuel cells (ranging from 50 kW to 250 kW) with biogas as input has immense potential to revolutionise the energy scenario of India's 500,000 villages. Every village, inspired by the ideals of *GramSwaraj* advocated by Gandhiji, must become self-sufficient and independent of the grid, drawing its power from the waste generated within the village. With the reliability that fuel cells offer, the entire rural landscape of India can be transformed, and villages can emerge as the driving force for a NEW INDIA.

- **Energy-Independent Homes**
  The KALAM-FC is a type of micro-combined heat and power fuel cell that is capable of utilising fuel from the natural gas network. As the gas network may include a blend of natural gas and green hydrogen in the future, this fuel cell technology can provide a reliable, affordable, and environmentally friendly power solution for homes. It functions as an independent power plant, eliminating the need for transmission and distribution losses. This technology has the potential to bring about an energy revolution for every household.

- **Fuel Cell for Mobility**
  In industries such as heavy-duty transportation and public transportation, the monetisation of assets is crucial. By utilising fuel cell technology with pure hydrogen as input, these industries can benefit from both increased mileage and zero emissions. This solution also eliminates the hassle and reliance on imports for transportation. As urbanisation continues to rapidly progress and electric power drives become more popular in buses and heavy-duty transportation, hydrogen-based mobility will soon become a reality. India, with its large population of three-wheelers and two-wheelers, has a significant opportunity to transform the transportation of both people

and goods on a large scale.

By utilising a proton exchange membrane fuel cell (PEMFC) with hydrogen, a three-wheeler can achieve a range of up to 200 km, a bus can travel over 600 km, and a heavy-duty truck can reach nearly 1,000 km. This technology has the potential to revolutionise the mobility sector. India has already developed a fuel cell bus that was launched by the prime minister in February 2023. The bus, created by h2e for OIL India, is a testament to India's technological and implementation capabilities.

India is poised to capitalise on the emerging green hydrogen economy by utilising its abundant renewable resources and large population to provide energy solutions both domestically and globally. Fuel cells will play a significant role in India's efforts to achieve its goals of eliminating energy imports, achieving net-zero emissions by 2070, and marking 2047 as the *Amrit Kaal*.

The COVID-19 pandemic of 2020 claimed over 5 million lives, but climate change and energy injustice claim a similar number of lives annually. It is essential for nations and individuals to work together to develop a vaccine for climate change that will protect our planet against this deadly pandemic. Fuel cells are a crucial component in developing such a vaccine.

2.6.2

Fuel Cells Based on Hydrogen

Harshal Agarwal, Vishal M Dhavale, Sreekuttan M U, Santosh Kumar D Bhat
CSIR-Central Electrochemical Research Institute-Madras Unit

Introduction

Globally, a third of oil reserves, half of gas reserves and four-fifths of current coal reserves 'should remain unused' from 2010 to 2050 in order to restrict global average temperature rise to less than 2°C of pre-industrialized value.[1] To mitigate this global disaster, 196 nations including India agreed in December 2015 in Paris to establish a new, legally binding agreement to limit global warming through various measures. The agreement calls for achieving zero anthropogenic GHG emissions during the second half of the 21st century.[2] India has pledged that by 2030 it will (a) reduce the emissions intensity of its GDP by 33-35% from the 2005 level, and (b) achieve about 40% cumulative electric power installed capacity from non-fossil-fuel-based energy resources.[3] For achieving these, we will be chasing a non-fossil-fuel target of about 320 GW by 2030.[4] However, the intermittent availability of solar and wind energy limits its adoption beyond a certain share of total energy without a large and long-term energy storage solution. The battery solution is neither strategically[5] nor economically[6] feasible if India must achieve energy security for its aspiring and growing population.

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[1] https://www.nature.com/articles/nature14016
[2] https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf
[3] https://www.ey.com/Publication/vwLUAssets/ey-the-paris-agreement-what-it-means-for-india/$FILE/ey-the-paris-agreement-what-it-means-for-india.pdf
[4] https://renewablesnow.com/news/cop-21-india-goes-bold-with-40-renewable-power-target-497655/
[5] https://www.mckinsey.com/industries/metals-and-mining/our-insights/lithium-and-cobalt-a-tale-of-two-commodities
[6] https://www.power-eng.com/articles/2018/04/energy-storage-not-at-tipping-point-thoughts-on-why-and-when.html

Therefore, we believe that ultimately the success of clean-and-renewable energy mission of India will depend on a mix of different energy solutions.

We envisage that in the future energy mix, hydrogen and fuel cells will present immense opportunities to address large and long-term renewable energy storage and on-demand reliable generation of electricity for various sectors – commercial, residential, industrial, defence and transportation, in a distributed manner using highly efficient combined-heat/cooling-and-power systems that have zero emissions when using green hydrogen. Of the various types of fuel cells, the Low Temperature Polymer Electrolyte Membrane (LT-PEM) provides a solution that is characterised by high energy density (as much as 3-kWe/L), modular scale-up (few watts to megawatts), silent and vibration-free operation, compatibility with various primary fuel sources, and robustness and safety (solid electrolyte membrane) for both stationary and automotive applications.

Low temperature polymer electrolyte fuel cells (LT-PEFC) for stationary applications

The backup power requirement of telecom towers presents an apt opportunity to deploy reliable and on-demand renewable energy solution. It is estimated that these towers consume about 2 billion litres of diesel per annum amounting to an import cost of about $1 billion and GHG emissions of 5 MTCO$_2$e.[7] There were an estimated 400,000 telecommunication towers in India in 2012 and their numbers are expected to grow at a CAGR of 3% for the next few years.[8] Today there are close to 650,000 towers in India. An estimated 85% of telecom towers require 8 hours or more of backup power because of unreliable grid supply. A significant number of these use diesel generators (DG). Tower companies are exploring cleaner options for cutting their carbon footprint in line with the 'go-green' initiative of the TRAI.[9] For instance, Reliance Industries Ltd. (RIL) has already deployed battery-based backup power systems on several towers. However, batteries become unviable for more than 8 hours of backup time and still depend on unreliable grid for power back-up. In contrast, fuel cell systems generate power continuously if hydrogen is supplied. Hydrogen itself can be generated from multiple and more easily available sources within the country, thereby avoiding import and strategic dependencies.

Realising the limitations of battery and DG-based power back-up solutions as mentioned earlier, RIL has already installed nearly 100 imported LT-PEMFC systems on towers, and the same are being continuously tested since the past three years. RIL's comprehensive on-field experience suggests that PEMFC systems satisfy all technical requirements of a power back-up system for telecom towers. However, the initial capital investment and the Total Cost of Ownership (TCO) of PEMFC systems are still higher than desired, and this limits the wide-spread adoption of fuel-cell-based power back-up solution for telecom towers. The only way to reduce initial capex of PEMFC systems is to develop the technology indigenously and to set up the entire manufacturing ecosystem in India. CSIR, together with RIL, has successfully co-developed LT–PEMFC stack know-how up to 3 kWe and has validated its durability for long hours in its labs and at RIL's Fuel Cell Test Facility (representation in Fig. 1). Local vendors for manufacturing and sourcing of various components as well as a system integrator have been identified. However, large-scale and commercially viable on-field deployment will require further technological developments in two areas: (i) development of stacks of increased power density and increased durability, which also enable reduction in the number of components and simpler system-level operation, and (ii) integrating of stacks with suitable hydrogen generation system.

Globally, there are many companies working in LT-PEM fuel cells and a handful on HTPEM fuel cells. It is not possible to list all of them here; hence only a brief mention of the key players is provided.

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[7] http://www.tsmg.com/download/article/Green%20Telecom%20Towers.pdf

[8] http://trai.gov.in/sites/default/files/presentations_&_cv/Day2_24Aug2017/Session4_Infra%20Sharing/Telecom%20Infrastructure_Umang%20Das_Latest.pdf

[9] http://www.trai.gov.in/sites/default/files/Consultation_Paper_16_jan_2017_0.pdf

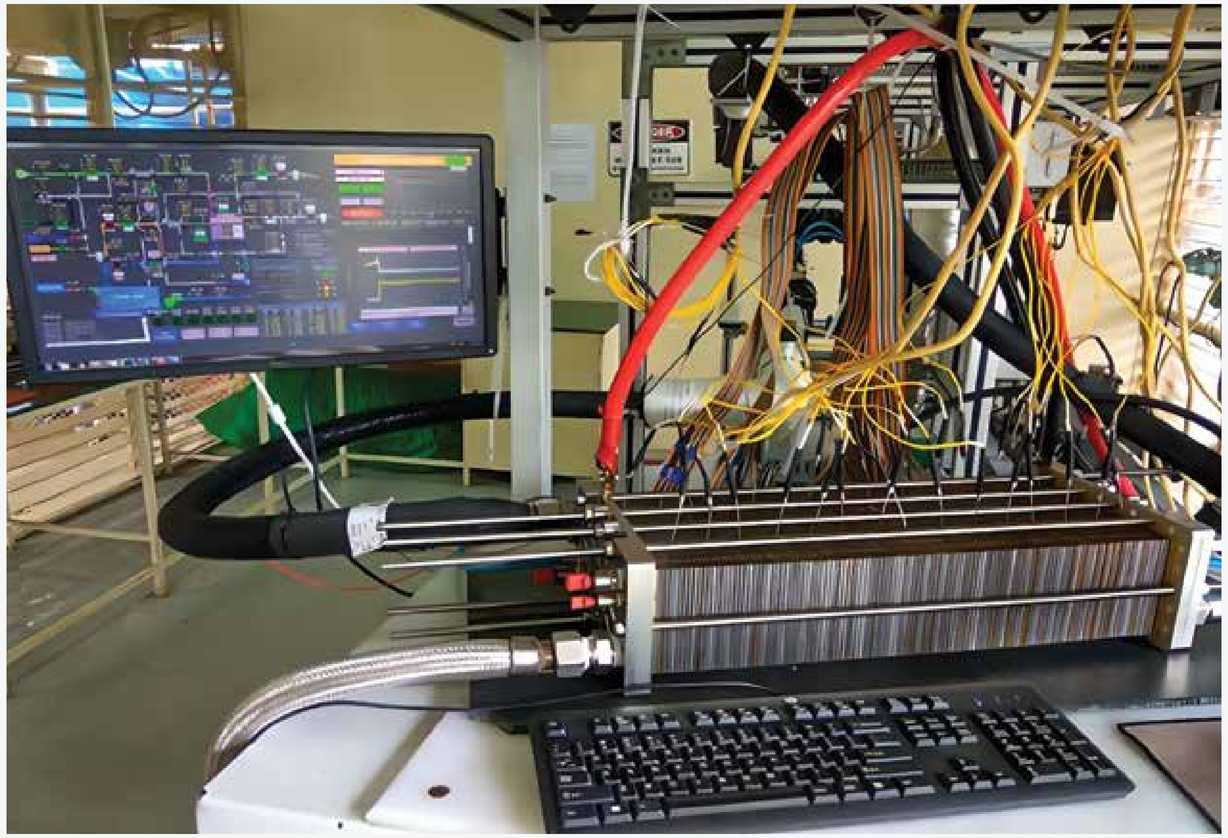


Fig. 1: Testing of 3 kWe LT-Fuel Cell stack at the industry site

- Ballard Power Systems, Canada, manufactures fuel cell stack and systems based on LT-PEMFC technology for stationary power and automotive applications.
- Advent Technologies Inc., USA, supplies components for HT-PEM fuel cells.
- Altergy Systems, USA, manufactures LT-PEMFC systems for stationary power applications.
- EnerFuel, USA, supplies HT-PEMFC systems for stationary power applications.
- FutureE Fuel Cell Solutions GmbH, Germany, manufactures and supplies LT-PEM fuel cell for stationary power applications.
- Horizon Fuel cell Technologies, Singapore, supplies LT-PEM fuel cell stack for portable applications to small (5 kWe) stationary power applications.
- Hydrogenics, Canada, manufactures LT-PEM fuel cell power modules for stationary power applications.
- Johnson Matthey Fuel cells, U.K., supplies Membrane Electrode Assembly (MEA) and catalysts for fuel cells.
- Nedstack PEM Fuel cells, Netherlands, manufactures LT-PEM fuel cell stack for stationary power applications and has set up a power plant of 1-MWe capacity in Belgium.
- Nuvera Fuel Cells, USA, manufactures LT-PEM stack and systems for material handling vehicles.
- Plug Power Inc., USA, manufactures material handling vehicles based on LT-PEM fuel cells.

However, most of the companies mentioned above are still dependent on government interventions such as subsidies and regulations. Further, the capital cost of PEMFC and/or the cost per unit of electricity sold by these companies is high. A plausible way to meet this challenge is to develop indigenous PEMFC technology with on-board hydrogen generation system and to develop indigenous manufacturing ecosystem for PEMFC. This is in line with the 'Innovate in India and Make in India' initiative of the government of India.

Design of Water-cooled Fuel Cell System and Self-humidified Fuel Cell System

Water and thermal management in systems shown in Fig. 2 are critical for achieving maximum performance and durability in PEMFC. For example, excess water generation and accumulation in the stack can create oxygen transport barrier leading to performance reduction. Moreover, the large air handling system and external humidification units increase capital cost and parasitic power consumption thereby reducing system efficiency and hence higher opex. They also increase system complexity, noise and vibration, system weight and footprint. Hence, it is essential to develop a simpler, robust and reliable self-humidified PEMFC system (Fig. 3) which minimises auxiliary balance of plant components.

Compared to externally humidified system, a self-humidified system presents major challenges in terms of lower power density, heat transfer and durability. While optimal flow rate of air is necessary for adequate stack cooling, the drying of the membrane should be minimised to improve power density. The ionic conductivity of the membrane and the ionomeric binder in catalyst depends on the amount of bound water, whereas excessive amounts of water leads fuel and oxidant mass transfer resistance. Hence, the self-humidified system requires a fine play between drying and hydration. To meet these challenges, innovative efforts are required in judicious selection of MEA materials and design of cells and stacks so that the overall efficiency is maintained while at the same time ensuring low capital cost and simplicity of operation. Following key interventions are needed:

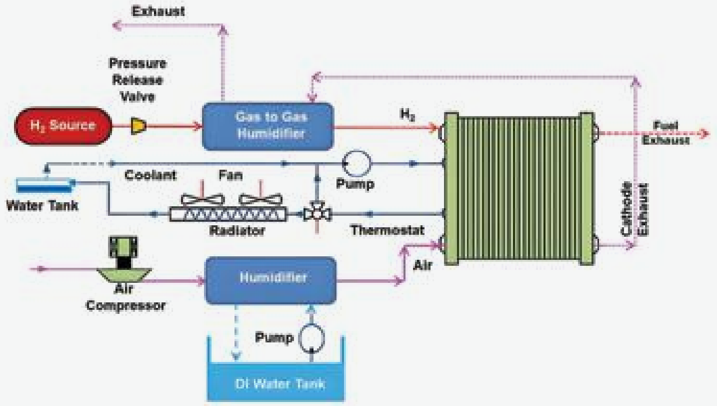


Fig. 2: Conventional externally humidified water-cooled LT-PEMFC system

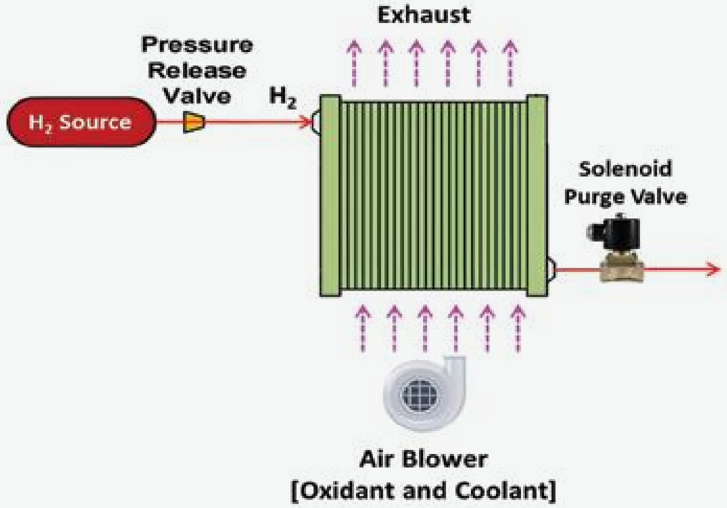


Fig. 3: Self-humidified LT-PEMFC system

- *Optimisation of MEA* materials and manufacturing process to ensure enhanced proton conductivity, water retention ability, adequate porosity, and faster water transport properties.
- *Innovative cell design* to enable adequate oxidant flow for ensuring uniform heat transfer while also minimising drying.
- *Stack design and operational strategy* to ensure uniform cell performance, durability and adequate sealing against hydrogen leakage/cross flow.

Low Temperature PEMFC System for Automobile Applications

As much as 85% of the crude oil is being imported to meet the current energy demand. And transportation sector contributes almost one third of this and road transportation accounts for around 80% of the energy consumption. As India is one of the largest emerging economies of the world, its primary energy consumption is expected to increase by 70% in next 10 years, because of which the gap between local crude oil production and consumption will keep on widening. This requires significant investment of resources in investigating, developing and launching alternative energy systems.

Most prominent amongst automotive alternatives are electric vehicles – specifically, battery electric vehicles and vehicles powered by hydrogen fuel cells. Globally, much effort is focused on lithium ion batteries. India, however, does not possess significant lithium resources. Additionally, lithium ion batteries are bulky. To overcome these limitations, work is ongoing on alternative battery technology. However, for some applications – for instance, where long travel range is required – fuel cells are necessary. Also, battery charging takes significant time whereas refuelling an FCEV is as rapid as conventional fuel-driven vehicles. In general, energy storage technologies such as advanced batteries, super capacitors, and hydrogen fuel cells, complement each other. We therefore believe that a combination of hydrogen fuel cells, advanced batteries and supercapacitors will be key technologies for India in the coming years.

One concern with fuel cell technology has been that of safety, especially associated with hydrogen storage. However, these issues are now getting resolved, and no longer pose a preclusive obstacle. Therefore, this is an opportune time to accelerate the development of hydrogen fuel cell technology. Hydrogen fuel cell technology is being pursued aggressively globally. Almost every single large global automotive company has an FCEV under development, or in the trial stage or even in commercial production. However, FCEVs remain expensive, and importantly, if India ends up in a position of having to import fuel cells, it will be at a significant disadvantage. Therefore, our position is that there is an urgent need for affordable fuel cell technology that is locally developed, technologically competitive, and economically viable in India's context.

CSIR's PEMFC programme, beginning in 2003, was driven under NMITLI and aimed at reducing capital expenditure on fuel cells through localisation, bringing technology readiness, and creating a platform to drive research and development. CSIR-NCL and CSIR-CECRI were involved in most aspects of developing and testing low-temperature PEMFC stacks. Along the way, it helped to successfully localise the development and manufacture of most components of the system, while benchmarking the performance of these components with internationally available components. During 2016-2021, CSIR and KPIT collaborated to develop automotive grade LT-PEMFC using metal bipolar plates, fuel cell system architecture, powertrain integration, control strategy, testing processes, etc. CSIR and KPIT applied this fuel cell expertise specifically to the automotive trials with three-wheeler and four-wheeler demonstration as represented in Fig. 4. MEA performance is the single most important metric that can influence the adoption of fuel cell vehicles. The analysis of current MEA indicates that the MEA fabrication approach adopted is not optimal. Even though we have achieved the maximum current density of 1 A/cm^2 at the single-cell level in an operating cell voltage of 0.6 V with optimised testing parameters, the current density lies between 0.5 and 1 A/cm^2 at cell voltage of

Fig. 4: Testing of CSIR-10 kWe fuel cell stack for vehicular platform in collaboration with industry (CSIR-NMITLI programme)

0.6 V in multi-cell fuel cell stack. Secondly, a performance of >1.5 A/cm^2 as well as durability of the stack is crucial. It is important to achieve the desired power output in minimum fuel cell stack size for the successful deployment of the fuel cell in the automotive sector.

For applications like residential and small/ medium capacity commercial distributed power requirements, high temperature polymer electrolyte membrane fuel cell (HT-PEMFC) would be a better candidate owing to the advantage that the system can be conveniently coupled with a reformer unit.
The better CO tolerance expected from the system due to his high operating temperature gives HT-PEMFC a clear edge over its LT counterpart. Also, an HT-PEMFC integrated with the thermal system would be the right choice for realising better energy efficient installations to simultaneously take care of space cooling and electrical power supply. While high temperature SOFC systems can also enable excellent thermal integration at the system level, these systems are difficult to run in start-stop modes due to thermal shocks in cycling between operating temperature (> 600°C) and ambient temperature. Since the phosphoric acid in HT-PEMFC is confined in the matrix of the PBI membrane, the system (Fig. 5) retains clear technological advantage compared to PAFC, which is based on liquid phosphoric acid. Hence, installations and maintenance will be relatively easy in the case of HT-PEMFCs.

HT-PEMFC has relatively simple BoP compared to LT-PEMFC due to the absence of the humidifier and associated components. This makes the HT system more compact and adaptable to many niche applications where size and weight are going to be the important governing factors. Like other fuel cells and alternate energy systems, HT-PEMFC can also play a vital role in establishing hybrid and decentralised energy generation systems. The increased attention by many telecom companies in India to deploy PEMFC-based back-up power supply systems for telecommunication towers is going to open huge opportunities in this rapidly growing sector in the country.

Fig. 5: Development of CSIR-5 kW HT-PEMFC system for stationary application in collaboration with Industry

Conclusion

Self-humidified stack configuration will enable reduced capital cost and operational simplicity by using our advanced understanding of electrochemistry, catalysis, chemical engineering, mechanical design and system integration. The self-humidified configuration eliminates the need for expensive and complex humidification and air handling sub-systems. Development of advanced membrane electrode assemblies with current density of 2.5 A/cm^2 at 0.65 V and thin bipolar plate (1 mm) for the LT-PEFC stack must be developed for automotive application. High temperature polymer electrolyte fuel cells with indigenous components must be developed for stationary applications.

2.7

Hydrogen – Storage Technologies

RAVINDRA VASISHT, Principal Consultant, Global Outreach & Strategy Consulting

Man shapes himself
through decisions that
shapes his environment.

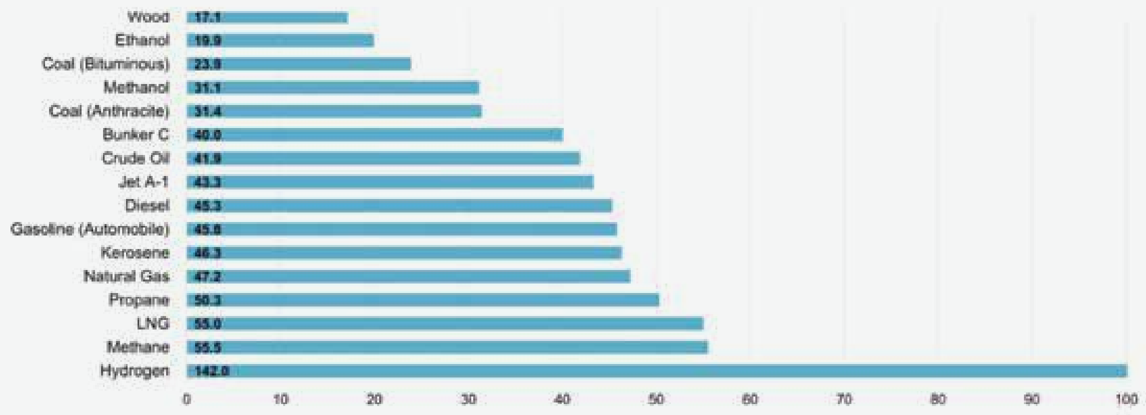
Rene Dubos

Since 2020, hydrogen has emerged as the favoured energy source worldwide, often referred to as green, clean, and even zero-emission resource. This sector has gained traction, policy, and investments across the globe, which presents its own set of challenges. Resources may become scarce, established supply chains may come under pressure, and technology throughout the value chain is still in the developmental stages.

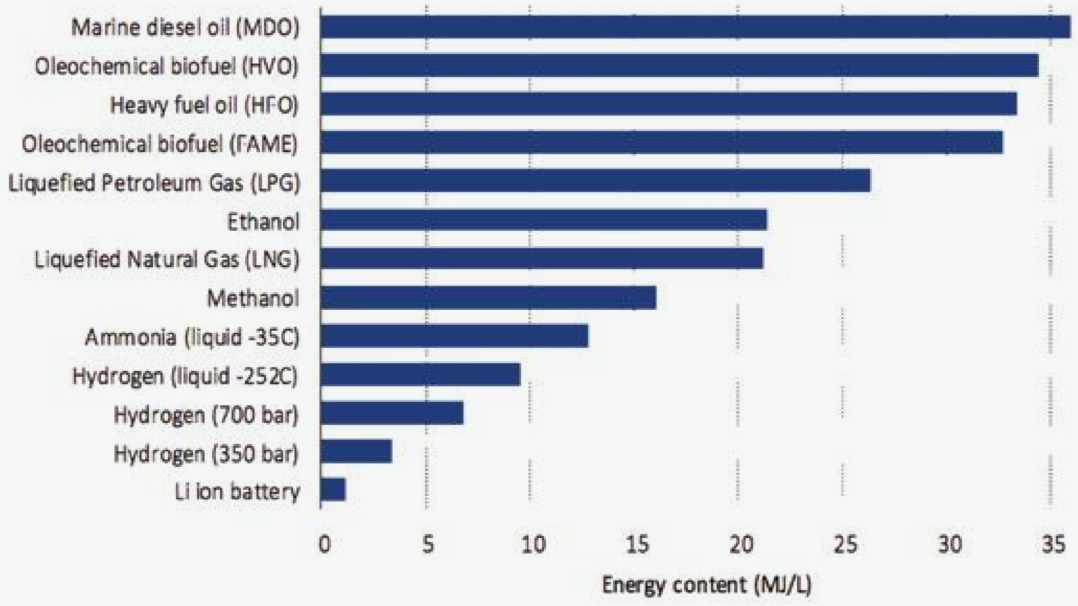
The high level of interest in hydrogen can be attributed to its potential to provide energy security for nations, as it boasts one of the highest energy content available, although this is offset by its low energy density.

The world faces a significant challenge when it comes to energy sources, namely the need for practical, cost-effective storage that meets specific requirements. Hydrogen, which has one of the highest energy content, is no exception to this rule, and its low energy density presents an added challenge. For many years, hydrogen has been stored as either high-pressure compressed gas or cryogenic liquid, each with its own set of difficulties. This article seeks to outline some of the available options and their features.

When it comes to fuel or energy sources, there are typically two storage/delivery applications: on-board/on-site storage, where the fuel is used for a specific application such as transportation or power generation, or on-site use in process industries. The second application involves the transport of the fuel to a distant location via mobile pipelines for delivery to the end-user.



Chemical Energy Content of some Fuels (in MJ/kg)



Energy density of different fuel options (MJ/L)

In all cases, storage is critical, and hydrogen presents unique techno-commercial challenges compared to other gases, such as natural gas. Each situation must be analysed independently, and decisions made based on a comprehensive system cost approach. The cost of storage or gas dispensing must consider all stages of the supply chain to determine the best cost efficiency rather than looking at storage efficiencies in isolation to determine the best option.

The available storage options are as follows:

2.7.1 High Pressure Storage

This method is widely used across various industries worldwide and considered the most common and prevalent solution. Despite the high costs involved, it remains an attractive option for many due to its effectiveness.

The technical options regarding type of tanks are as follows:

Table 1

Tank Type	Description
Type 1	Steel tank, the oldest and proven technology across sizes and applications technically.
Type 2	An interim solution where a steel tank has a composite hoop wrap. Not used in any nation except possibly China.
Type 3	The first generation of low-weight composite cylinders. An aluminium liner is used with carbon fibre winding to make the tank.
Type 4	The latest generation tank where a plastic liner is used with carbon fibre winding to make the tank.

Whenever the term composite is mentioned in this article, it will specifically refer to either T3 or T4 technology. As shown in the figures below, the only difference between the two options is the liner material, while the rest of the system remains the same.


Fig. 1: (a)

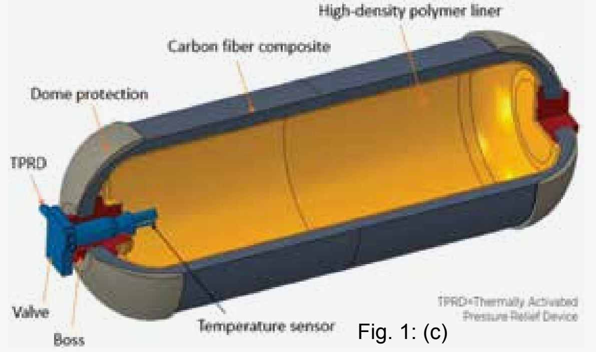


Fig. 1: (c)


Fig. 1: (b)

From the perspective of pressure ratings, the following storage options are currently deployed and utilised globally:

Table 2

Pressure in Bar	Comments
200 bar	Usually, steel tanks where smaller quantities and distance are involved or when there is a lack of economical options. Used in all applications.
250 bar	Steel tanks continue to be used but usually with special grade steel for stationary storage. However, for mobile pipelines T3/T4 composites start becoming viable. Used only in mobile pipeline applications.
350 bar	Composite cylinders preferred since these are used mainly for mobility applications like buses, trucks and rail.
300 & 380 bar	Interim solutions created due to industry requirement or change in design safety requirements. Invariably used for storage options.
450 & 500 bar	Used for storage applications. Invariably used with composite tanks though there are steel tank options used in ground storage. For mobile pipeline applications, invariably T3 or T4 composites are used.
700 bar	At this operating pressure only T4 tanks are used globally, irrespective of application. However, predominantly used in mobility solutions like trucks where space is a constraint and range is a key requirement.
950 bar	Here again only T4 tanks used and used for ground storage.

Benefits of Using Composite Tanks vs Steel

The main challenge when using steel tanks, irrespective of the gas or application, is the problem of rust and corrosion, as well as their heavy weight. If the environment is humid or salty, such as a coastal area, then steel tanks corrode more quickly. Apart from safety concerns, the rust or corrosion can also be carried with the gas, leading to operational and maintenance issues downstream. By using a composite tank, this risk can be practically eliminated, particularly when using it with fuel cells, which require high-quality hydrogen.

The weight of steel tanks is their biggest challenge, and they are typically three times heavier than composite tanks. This weight difference is leveraged by mobility applications to achieve greater range with lower weight. In theory, a bus or truck can achieve nearly double the range with the same size of composite tank. In mobile pipeline applications, a given truck can carry almost three times the gas with reduced weight, resulting in a 40-50% reduction in unit transportation costs. The more gas delivered daily and the longer the range, the more economically attractive composite tanks become.

Using steel tanks for hydrogen poses a significant risk of metal embrittlement, unless the steel used is of a special grade that can withstand hydrogen's aggression. This risk is particularly high at higher operating pressures, making steel tanks unsafe. Even at lower operating pressures, proper maintenance is essential to prevent metal embrittlement from becoming a safety hazard. Additionally, if the ambient temperature drops below -25°C, a combination of low temperature and hydrogen can create an unacceptable risk, making steel tanks unsuitable. In such cases, composite tanks are the only viable option.

The Type 3 vs Type 4 Debate

The debate on whether to use Type 3 or Type 4 technology is artificial and has little practical impact as both are equally good and acceptable. Decisions should be based on factors such as delivery, price and service. While each technology has its own talking points, they do not significantly affect performance.

Type 4 technology becomes the preferred choice, and sometimes the only option, when manufacturing large-sized tanks as it is easier and more cost-effective. Tanks with a water capacity of up to 8,500 litres have been manufactured using T4 technology for a long time.

When using hydrogen and operating at pressures exceeding 450 bar, T4 tanks become popular mainly because they do not contain metal and offer longer lifetime duty.

Therefore, for applications with pressures not exceeding 350 bar, there should not be a debate on which technology to choose based on technology, performance and safety.

Conclusion

In conclusion, high pressure composite cylinders have gained popularity due to their cost-effectiveness, availability in different sizes, and preference in most applications. However, the use of carbon fibre, which is a costly raw material mainly used in the defence and aerospace sectors, limits the widespread use of composite tanks for commercial purposes. Despite this, composite tanks are expected to remain the dominant option in the future unless other technologies rapidly emerge and change the status quo.

2.7.2 Cavern Storage

An alternative option that is not often discussed is geological hydrogen storage, which may be suitable in cases where large quantities of hydrogen need to be stored on-site. This involves using giant salt caverns located deep underground or other geological formations.

Adsorption

Another technology that has been considered is adsorption, where special materials are used to store large quantities of hydrogen in a container by adsorbing it and then releasing it as needed. However, current research on nano particles does not suggest that a commercial solution will be available anytime soon.

2.7.3 Material-based Storage

Another option for hydrogen storage is materials-based storage, where materials that can chemically absorb or react with hydrogen are used. For example, metal hydrides can be created from elements like magnesium, aluminium, palladium, etc. Another option is using ammonia as a storage and transportation medium, which has significant potential due to the doubled energy density. However, at the user end, the ammonia needs to be converted back into hydrogen, and this technology is still evolving and inefficient.

Liquid Hydrogen

Liquid hydrogen is a proven solution for storage and transport of hydrogen, similar to cryogenic LNG developed for natural gas. However, while it is technically efficient, it has not been widely adopted due to operational and commercial challenges. Liquid hydrogen is primarily used for rockets and other applications that require extremely low temperatures (minus 253 °C), and the storage process is complex and expensive.

The energy loss during storage and transportation is higher compared to high-pressure compression technology, and there is a risk of product loss through evaporation over time. This method is not used for mobility applications but for bulk transport, especially for extremely large quantities. It can also be considered for stationary storage, but the technology requires complex engineering and manufacturing using a combination of super insulation and vacuum in metal containers.

2.7.4 Cryo-compressed Storage

A new technology has emerged that seeks to address the limitations of both high-pressure and low-temperature storage options by combining their benefits, resulting in a highly efficient storage solution suitable for mobility, stationary storage, and bulk transport applications.

This technology is called Cryomotive and it is promoted by a German company led by experienced technocrats who have worked with top companies in this field. The company's brief introduction is included at the end of this publication as a gesture of appreciation for their support.

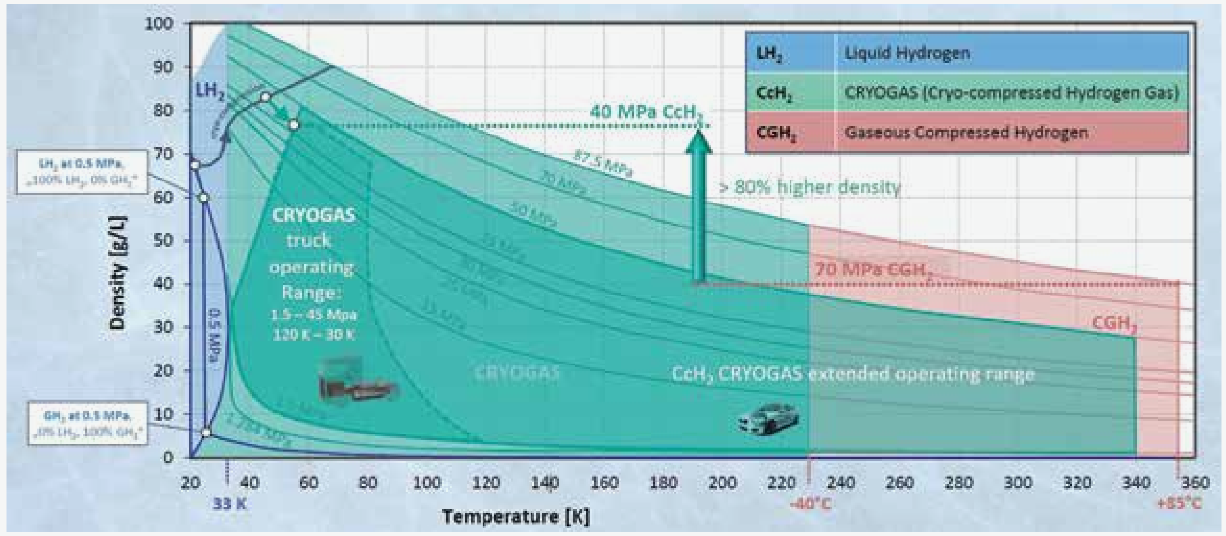
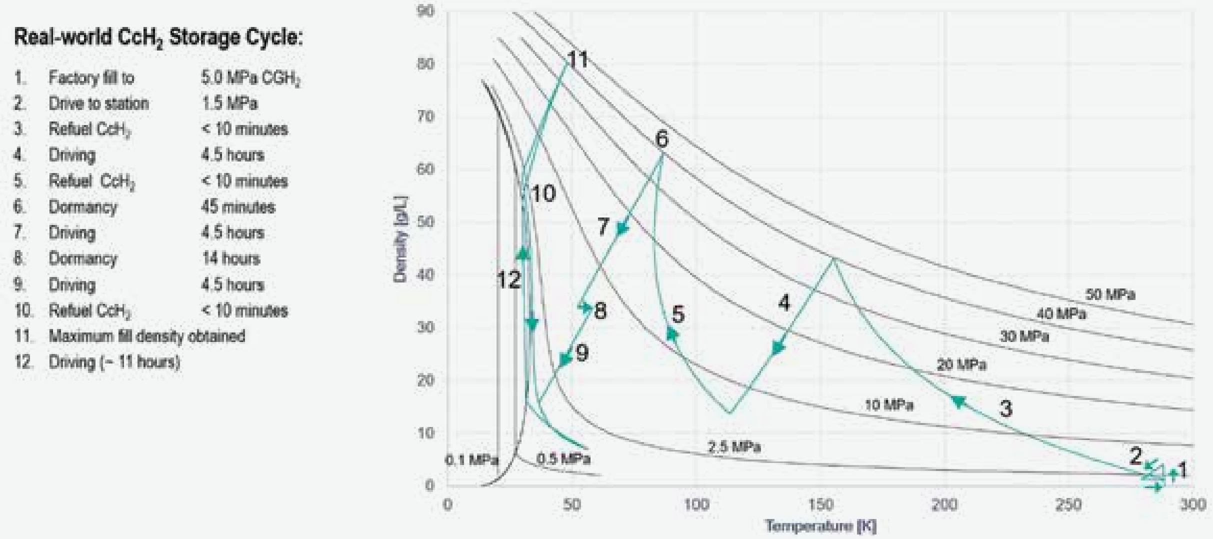


Fig. 2: Thermodynamic classification of CRYOGAS in a density-pressure diagram: CRYOGAS is a gas at pressure levels above 1.5 MPa and cryogenic temperature. It can be generated from liquid hydrogen by compression via a cryo-pump or by cryo-cooling a high-pressure gas.


Real-world CcH_2 Storage Cycle:

1.	Factory fill to	5.0 MPa CGH_2
2.	Drive to station	1.5 MPa
3.	Refuel CcH_2	< 10 minutes
4.	Driving	4.5 hours
5.	Refuel CcH_2	< 10 minutes
6.	Dormancy	45 minutes
7.	Driving	4.5 hours
8.	Dormancy	14 hours
9.	Driving	4.5 hours
10.	Refuel CcH_2	< 10 minutes
11.	Maximum fill density obtained	
12.	Driving (~ 11 hours)	

Fig. 3: Loss-free cool-down and self-cooling of CRYOGAS is a major advantage over liquid hydrogen (LH2), since no evaporation losses occur. CRYOGAS storage can start with a gas fill (1, 2) at ambient pressure & cools down during discharge operation (4, 7, 9, 10) & consecutive CRYOGAS refills (3, 5, 12)

CcH_2 CRYOGAS – Cryomotive's Cryogenic Hydrogen Gas Refuelling and Storage Technology

CRYOGAS, also known as cryo-compressed hydrogen gas (CcH2), is a form of high-density hydrogen gas that is compressed cryogenically. This process can achieve densities of up to 80 kg/m³ at pressure levels ranging from 300-400 bar. CRYOGAS is always in a gaseous state, and its pressure can be adjusted between 1.5 and 3 bar to supply hydrogen internal combustion engines and fuel cells with flow rates of up to 7 g/s at their operating pressure.

CRYOGAS has a higher physical density than liquid hydrogen and is thermally stable since it cannot evaporate. CRYOGAS can be stored in insulated pressure vessels with simplified superinsulation. It can be produced on an industrial scale at a lower cost than current high-pressure gaseous storage systems (CGH_2 350 and 700 bar) since it requires less carbon fibre and has a lower material footprint, volume and weight. CRYOGAS can be generated by compressing liquid hydrogen (LH_2) cryogenically or by cooling compressed hydrogen gas (GH_2) cryogenically.

The thermal robustness of CRYOGAS is one of its main advantages, as it cannot evaporate and has better self-cooling properties compared to liquid hydrogen. While CRYOGAS can achieve higher physical density than liquid hydrogen using pressure and temperature, it does not have the same evaporation issues.

Additionally, CRYOGAS can remain dormant for several days or weeks, which eliminates concerns about evaporation during storage. Furthermore, unlike liquid hydrogen, there is no need to pre-cool lines or dispensers before filling with CRYOGAS.

Advantages of CcH_2 CRYOGAS Onboard Storage for Trucks and Buses

The use of CRYOGAS for onboard storage in trucks and buses offers several advantages compared to existing solutions for compressed gas and liquid hydrogen storage:-

Using CRYOGAS hydrogen storage vessels in truck and bus platforms provides greater adaptability compared to liquid hydrogen storage vessels. The latter needs to limit heat transfer to prevent loss due to evaporation. CRYOGAS hydrogen technology enables long-haul heavy-duty commercial vehicles to travel up to 1,000 km and refuel in just 10 to 15 minutes, which offers numerous benefits in terms of performance and versatility.

Advantages of CcH_2 CRYOGAS Refuelling for Trucks and Buses

The primary obstacle to the widespread adoption of hydrogen in various types of mobility, including long-distance transportation, is the hydrogen refuelling infrastructure. However, by utilising this technology, a CRYOGAS station capable of producing 3 MT/day is anticipated to exceed other established refuelling technologies in terms of performance, cost, efficiency, and space requirements. The primary characteristics include:

- 500 kg/h reciprocating cryogenic LH_2 pump
- 400 bar CRYOGAS dispenser (500 kg/h)
- 3 MT LH_2 bulk tank with return gas line
- Unlimited back-to-back refuelling's with direct feed from the cryo-pump
- No high-pressure buffers, heat exchangers or communication
- < 0,5 kWh/kg energy consumption
- < 350 m^2 footprint (station alone without delivery and vehicle fill area < 100 m^2)

Cryomotive and their partners have set their sights on creating the initial batch of public and depot truck and bus refuelling stations by 2025. The critical elements, such as the nozzle, have already been designed to support high flow rates of up to 900 kg/h, which is suitable for boat and rail applications.

Conclusion

The use of CcH2 CRYOGAS refuelling and storage technology can bring innovation to hydrogen transportation by reducing the cost of high-flow refuelling and enabling high-density onboard storage for long-range travel more effectively than any other existing technology. A product that combines CRYOGAS onboard storage and refuelling station is being developed and is anticipated to be available for use by 2024/25.

Table 3

Storage capacity per vessel	10 – 100 kg CcH_2
Storage system gravimetric density in typical truck configurations	8 – 10 wt-%
Storage system volumetric density in typical truck configurations	1.2 – 1.5* kWh/L system
Allowable heat leak for loss-free operation in typical truck configurations	20 – 50 W
Minimum holding time before vent (@ 100% capacity)	2 - 3 days
Average holding time before vent (@ 50% capacity)	10 – 30 days
Pressure supply level for fuel cell or hydrogen internal combustion engine	1 – 3 MPa

There are also plans to conduct joint demonstrations with truck manufacturers and infrastructure partners in Europe, with future plans to expand to the U.S. and Asia. The first commercially available onboard storage and refuelling product for trucks and buses is expected to be launched by 2025, followed by applications for boats and rail.

Fig. 4: CRYOGAS onboard storage allows up to 40 kg of hydrogen being stored in one vessel. A two-vessel package allows storing up to 80 kg in a typical truck platform, sufficient to reach a 1,000 km range. Three-vessel packages or more enable even higher ranges and energy supply in special heavy-duty applications.

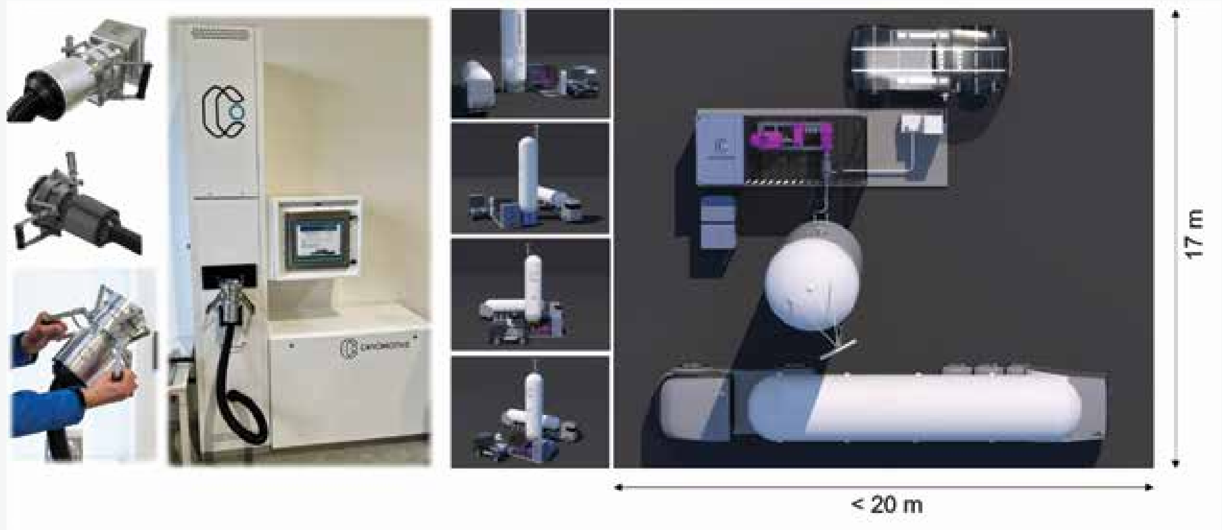


Fig. 5: CRYOGAS 3 MT/day refuelling station with high-flow dispenser and compact robust CRYOGAS nozzle-receptacle for very high flow rates up to 900 kg/h (15 kg/min). CRYOGAS stations have the lowest footprint and cost of all known hydrogen refuelling stations for truck and bus applications.

Cryomotive
Cryomotive is a well-known German start-up that focuses on hydrogen mobility. It was established in October 2020 and plans to enter the market by 2025 with its high-density hydrogen onboard storage and refuelling technology. Cryomotive concentrates on its unique CRYOGAS hydrogen storage technology, which was previously demonstrated in BMW cars and was based on one of the company's founder's concepts. Cryomotive is part of the CryoTRUCK consortium and will work with MAN Truck & Bus to develop a CRYOGAS hydrogen storage system and core components.
The project is supported by the German Federal Ministry for Digital and Transport (BMDV). In May 2021, Cryomotive formed a strategic partnership with Chart Industries, Inc. ("Chart", NYSE: GTLS), which included investment, in-kind contribution, and a commercial agreement.

To conclude, cryogenic and high-pressure compressed storage are currently the most mature hydrogen storage technologies. Newer solutions, such as cryo-compressed gases and hydrides, are still being developed. The feasibility of these mature technologies is known based on their applications, and the world is currently developing standards and regulations to adapt to changing conditions. Infrastructure and periodic inspection systems are also under development, with a focus on ensuring suitably trained and knowledgeable manpower across the supply chain. As the world focuses on hydrogen, there is abnormal pressure on resources, manpower, investments, regulations, suppliers, and infrastructure. However, this pressure is expected to ease over the next decade.

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2.8

Lifestyle for Environment: An Industrial Perspective for CCUS

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A society grows great
when old men plant trees
whose shade they know
they shall never sit in.

Greek Proverb

Abstract

India has achieved self-reliance in many industrial sectors and is on track to become a developed nation soon, surpassing the need to depend on developed countries for critical needs. Industrial and infrastructural changes in developed nations have led to technological advancements and boosted research and development and innovation in developing countries, especially India. However, this growth has occurred without much concern for the environment. This presents a significant opportunity for developing countries to use existing technologies and expertise while doing environmental impact assessment, lifecycle analysis, and implementing environmental control and requisite protocols.

Carbon, the basic building block for life, becomes a significant agent for heat-trapping in the atmosphere when it is in gaseous form, especially as CO_2. Technological innovations are now being rewarded worldwide for cutting CO_2 emissions to meet the Paris Agreement's goals and combat climate change. The CCUS mission aims to capture, transport, and store GHGs back into the earth. Achieving the 2030 targets requires fast-track adoption of commercially available CCUS technologies, with a need to prioritise and sectorise different sectors' needs to achieve zero emissions stage-wise. This report envisions a bouquet of solutions to reduce carbon footprints across various industrial sectors and suggests changes in the lifestyles of individuals and industries.

Introduction

India's progress in infrastructure over the past few decades has brought it closer to becoming a developed nation. The developed countries have made significant advancements in infrastructure and technology, which developing countries like India are embracing to become developed as well. This provides an opportunity for India to implement these technologies in a way that prioritises zero emissions, a goal that is important not only for becoming a developed nation but also for combatting global carbon emissions. Carbon emissions are a worldwide concern, and a coordinated effort is needed to tackle this issue.

The Indian government's goal of proposing five elixirs (*Panchamrit*) is considered ambitious and requires the participation of stakeholders to enhance the environment by making lifestyle modifications. This initiative is not only relevant to India but to the whole world, as lifestyle changes need to be embraced by individuals, industries and sectors to reduce emissions while considering the energy penalty. Low-cost and sustainable solutions need to be developed across all industries to combat climate change, as significant investments in new technologies may not yield the desired impact. The focus should be on developing incremental solutions that can be integrated for a significant overall impact.

The world has undergone four major industrial revolutions that have significantly impacted people's lifestyles. However, these advancements have come at the cost of environmental degradation, and the replacement of traditional fuels with cleaner alternatives has not been a priority. This has led to a substantial increase in CO_2 emissions and GHGs, which continue to rise despite efforts to reduce them.

Environmental damage is an unavoidable consequence of development, and it affects the global population. Therefore, industries such as manufacturing, food processing, mining, and energy production must adopt technologies to reduce GHG emissions. The direct emissions from other industries, such as fossil fuel combustion for generating heat and electricity, as well as chemical processes in industries such as cement and ores, must be decarbonised by implementing effective solutions. These industries must also be willing to adapt to available technologies to promote a cleaner environment. Achieving this goal will require cooperation and support not only from relevant industries but also from researchers in various interdisciplinary fields and governments that must establish policies to monitor and implement progress.

Thus, in order to address the challenges of sustainability, innovative approaches are needed across all industries and academic fields. The impact of GHG emissions on the environment and climate change is affecting the entire world, leading to significant health issues for populations. This is a global environmental crisis that requires the cooperation of all stakeholders. The current decade is critical in terms of taking action, just like how the world joined hands to combat the COVID pandemic by developing vaccines, implementing policies, and individuals taking personal responsibility. Decisions made today will have historical significance and impact future generations. Everyone from individuals to industries to governments must take responsibility for making lifestyle changes to address this environmental crisis. The industry should adopt new technologies and adapt to the changing needs of the end-users in Industry 4.0.

Industries face a complex challenge in implementing CCUS technologies due to their varied operations, energy usage, and process development. Therefore, a multidimensional approach is necessary to achieve net-zero emissions within a reasonable timeline. India, with its diverse climate and corresponding lifestyle variations, has a significant role to play in fulfilling its environmental responsibilities. Country-specific standards for GHG emissions and technologies must be established to curb emissions as per Indian standards. Furthermore, a roadmap for industry-specific decarbonisation is necessary to provide specific solutions for all industries.

To limit global temperature rise to 1.5°C, it is not only necessary to reduce emissions but also to adopt technologies to remove carbon from the atmosphere. CCUS should be a global mission that all countries undertake together, with open-source technologies available to smaller countries.

To effectively implement CCUS technologies and meet global energy and climate goals, it's important for the IPRs generated under CCUS to be made available on an open platform, encouraging collaboration among industries, the academia and governments. These technologies can help trap and remove CO2 from large industrial sources, such as power generation plants and industries that use traditional sources of fuel like fossil fuels or biomass fuels, resulting in a cleaner environment with reduced climatic warming. The captured CO_2 can then be used as an input for various value-added products through chemical and biological processes, including solvents, fertilisers, fuels like methane and methanol, and building materials like cement and concrete.

Human activities that involve the use of fossil fuels have been the main contributor to the rise in atmospheric CO_2. As the demand for energy and resources continues to grow due to the increasing population, sectors such as energy, agriculture and food, construction, and transport need to undergo significant transformations by utilising technological advancements to reduce CO_2 emissions at the point source.

The need to decarbonise residential buildings around the world has become urgent due to the increasing demand for household energy. While existing buildings cannot be rebuilt, they can be retrofitted to maintain a comfortable indoor temperature without emitting GHGs. In India, the growing energy demand from households has led to significant emissions, which can be reduced through design modifications such as installing photovoltaic panels on roofs and using reflective coatings and paints to reduce thermal heat.

Given the severity of the climate crisis, it is crucial for industries to adopt new technologies and work towards achieving zero emissions. This requires a shift away from conventional energy sources and the adoption of innovative solutions like CCUS. Alternative sources of energy, such as low-carbon electricity, solar photovoltaics, bioenergy/biofuels, hydrogen, and hydrogen-based fuels, can be combined to reduce dependence on fossil fuels. Additionally, technologies with low or zero thermal loss processes should be implemented to further reduce emissions. Industries must invest in these technologies and allocate a portion of their revenue towards their adoption.

The sustainability of infrastructure is a crucial sector that needs to be addressed worldwide. The construction and operation of buildings and infrastructure require a significant amount of energy, which contributes to GHG emissions. Therefore, the adoption of water-saving and water-harvesting technologies, LED lighting, and solar rooftops can help reduce energy consumption. Additionally, green infrastructure, such as smart transportation, suburban developments, and flood defences in coastal areas, can mitigate GHG emissions and provide leverage against global warming.

Plants and soil are effective components for carbon sequestration, and they offer several benefits, such as increased organic content in soil, soil fertility, nutrient retention, and pollution attenuation. Vegetative growth and biodiversity are essential for ecosystem health and carbon sequestration, but urbanisation and industrialisation are disrupting natural processes. Boosting biodiversity can enhance ecosystems and make them more resilient to environmental disturbances. Industries and governments need to develop strategies to minimise the impact of urbanisation on biodiversity loss by promoting green infrastructure.

Implementing CCUS technology in industrial centres through shared transport and storage infrastructure can help promote a clean and green environment and accelerate the deployment of such technologies while reducing duplication and enhancing efficiency.

The transportation sector has significant potential to reduce emissions and promote a cleaner climate, and immediate steps can be taken to improve infrastructure and connectivity in public transportation, including last-mile connections, good roads, and intelligent traffic management systems. The adoption of such systems can significantly reduce the environmental burden in urban areas, and small incremental changes in the transportation sector can provide integrated opportunities to create a cleaner environment for future generations.

In order to address various environmental problems and provide comfortable and efficient transportation of people and goods, it is necessary to make incremental improvements in the transport sector towards decarbonisation. This can be achieved by deploying clean-energy technologies such as electric vehicles, which will require charging and battery-swapping infrastructure, and using hydrogen as a fuel for clean transportation. The adoption of these technologies will also create new business opportunities and employment in all related segments of the transportation sector and strengthen the country's energy independence. As India becomes a manufacturing hub, timely transportation of materials and goods is crucial. Therefore, the connectivity between airports and seaports via highways is also essential.

Adopt New Technologies to Mitigate Carbon Emissions

The majority of emissions in industries and transportation are caused by post-combustion processes. To address this issue, it is important to capture the emissions at their source and transform them into useful products, particularly in coal and oil combustion for energy production and transport. While there are numerous solutions and technologies for capturing carbon after combustion, they tend to be expensive and result in high energy penalties for industries. Many of these technologies require high pressure and compressed gases, which are energy intensive. Therefore, there is a need for the development of methods that capture emissions with reduced adsorption and desorption energies and fewer thermal gradients. One potential solution is the use of solid adsorbents and aqueous amines, which are currently available.

Additionally, the storage of the emitted CO_2 is a crucial aspect that requires attention. Establishing infrastructure for transporting the CO_2 from the source to the storage site demands proper identification of suitable locations and land resources. Thus, capturing and storing or using the CO_2 should occur near the emissions source to minimise transportation costs. For instance, CO_2 emitted from cement industries can be buried permanently in building materials and concrete. One sustainable solution that requires comparably less cost is the utilisation of marine algae.

Algae ponds can be built near emission sources of various industries like coal, steel, petroleum, and so on. Different CCUS technologies can be employed in various industries such as coal, refineries, transportation, chemical manufacturing, iron and steel plants, food and beverage manufacturing, cement, and others. Effectively capturing the carbon and utilising/sequestering it near the emissions source is a viable solution for reducing GHG emissions and transitioning to zero or low emissions.

The use of CCUS technology for post-combustion CO_2 capture in commercial settings has its limitations, such as high energy and cost requirements, low rates of absorption and desorption in various materials, as well as issues with corrosion and material loss. This presents a challenge to finding an energy-efficient approach to capturing CO_2.

In some industries like oil and gas, processes can produce highly concentrated CO_2 which can be easily stored and transported for use in value-added products at a low cost of capture and utilisation. However, gas reservoirs can also contain impurities such as SOx and NOx, which must be separated before transportation. This can be achieved using gas membrane separations, functionalised molecular sieves, and other available technologies. Separating the impurities can increase yield and reduce corrosion in pipelines, while also emitting fewer toxic gases into the environment.

Another area of focus is recycling. The mining sector is not effectively mining useful metals and materials, which are limited resources. Therefore, recycling these materials should be prioritised to reuse them and reduce the environmental burden. An unorganised sector is already involved in recycling, but if we can develop a good incentive-based mechanism to organize it, we can save money and reduce import costs by more than 30%. This will also ensure sustainable availability of metals and materials in the country.

By promoting the recycling and remanufacturing industry, we can reduce energy utilisation and emissions, achieving cost and energy parity. Domestic biomass, another significant source of emissions, can be converted into affordable biofuel and bioproducts, overcoming the barriers to syngas conversion. Biocatalysts can play a vital role in this process, providing a green solution for decarbonisation of chemical industries.

Industry-Academia Collaboration

Researchers and industry experts worldwide are currently focused on exploring CCUS technologies to mitigate the global carbon footprint and promote a cleaner environment. The Paris Agreement, which has been endorsed by nearly 197 countries, requires the reduction of GHG emissions to prevent the global temperature from rising by more than 2°C by the end of the century. As a result, it is imperative for research communities to continuously seek innovative solutions for CCUS, including negative emissions strategies. Universities, funding agencies, and research institutes are actively engaged in developing sustainable CCUS solutions.

Government Support for PPP Model

It is necessary to establish a robust network of partners that includes industry, the academia, national laboratories, and all government agencies. This will reduce the effort, time, and resources required. We need to develop a platform to share current research on a single platform so that repeatable work can be avoided, and complementary knowledge and resources can be utilised. This will also help early-stage start-ups to move promising clean energy technologies out of the lab and into manufacturing, and with the support of R&D labs, industries can adopt innovative manufacturing materials, technologies, and processes. A few national hubs should be created to develop the technologies available in R&D labs that can be taken up to the factory level of manufacturing.

In recent years, the public-private partnership (PPP) model has emerged as an effective way to support investments in green infrastructure. The PPP model offers several benefits, such as sharing the high costs of investment between the government agencies and private sector organisations, reducing the burden on public funds, and providing high-quality public services with the private sector's expertise. By collaborating through research and development in laboratories, this partnership can increase efficiency and save time and money for both parties.

CCUS technology is still in its early stages of implementation and requires significant scientific and technological research and development efforts. The high cost of implementation has discouraged industries from adopting it, but cost-effective solutions need to be developed to improve storage capacity and transportation while reducing uncertainties.

Therefore, it is essential to encourage public and private sectors to collaborate on a single platform to reduce socio-economic disparities and work towards the public good. This collaboration can help bring together the two sectors, encouraging them to share their expertise and resources to develop cost-effective solutions for CCUS.

Infrastructure projects such as roads, energy generation, and water treatment have a significant impact on the environment, and thus, require substantial investments in research and development. This will lead to sustainable, long-term solutions that can help alleviate environmental burdens. It is important to create awareness about environmental concerns and encourage industries to adopt existing R&D technologies before embarking on new projects, as well as during the implementation of ongoing projects.

Adopting CCUS as a Mission across Industry, Academia and Government

Electricity has become a basic necessity in today's world, and a major portion of it is generated through fossil fuels. This trend is expected to continue until a breakthrough or disruptive technology is developed and implemented. Therefore, energy producers should consider adopting hybrid modes of energy generation. This would not only result in cost savings, but also provide better control over fuel prices and reduce associated uncertainties. Furthermore, it would help control capital and operational expenditures while simultaneously enhancing the efficiency of usable energy.

The adoption and deployment of CCUS technologies should be a priority for industries to include in their energy consumption portfolio. Collaboration between government, private, and public entities can establish CCUS hubs in various industries with shared transport and storage infrastructure to lower the costs of implementing CCUS. The government should create policies to incentivise industries to significantly reduce their emissions while promoting competitiveness among them to adopt CCUS technologies. Industries need to assess the impact of their infrastructure projects on climate change and utilise available tools and models to redesign their infrastructure. This can be achieved by using forecasting models that provide estimations based on historic data and trends.

The small percentage of plastics that are recycled leads to waste and pollution. Some researchers have shown that recycled plastics can be used in tiles and pavements to reuse plastic through reprocessing and reduce reliance on fossil fuel-derived materials.

Researchers globally are currently engaged in a research effort aimed at recycling industrial emissions into methanol, a high-value product with potential to lower GHG emissions. To convert emissions efficiently and selectively into value-added products like methanol, it is essential to develop new materials and catalysts. Methanol has several applications, including as a heating fuel for boilers, blended fuel for transportation, aviation fuel, and for generating electricity, making it a promising candidate for GHG-reduction efforts. By using affordable and low-cost solutions for renewable methanol conversion from CO_2, it is possible to create innovative steps towards generating useful and value-added products without causing environmental harm.

Innovations for Next-Generation Technologies

To achieve environmentally friendly goals, substantial investments are necessary to research and develop next-generation technologies that can offer end-to-end solutions in terms of supply chain, sustainability, and competitive environments to foster the development of new technologies. Cost-effective manufacturing processes and the development of novel materials with enhanced properties under harsh conditions, with an emphasis on recycling and reverse supply chain logistics, can be one type of solution that requires government initiatives and researchers' knowledge. In the recycling industry, there is tremendous potential for recovering rare materials and metals, preventing precious and rare materials from ending up in landfills.

Biomass or non-recyclable materials have been used to generate power for a long time. However, ensuring a sustainable and consistent supply of biomass, addressing storage and transportation issues, and ensuring resistance to moisture are a few of the challenges that must be addressed. The key to the process is torrefaction, a thermal process that converts biomass into a coal-like material. Torrefaction involves the mild application of heat, typically between 200°C and 320°C, to homogenise and make biomass materials more consistent while also eliminating other compounds that can become harmful gases during combustion.

There is an expectation that the solutions to reduce emissions over the next few decades will largely come from technologies that are currently being researched, prototyped, or demonstrated. However, there are multiple efforts happening simultaneously in various locations, and these innovations need to be accelerated to avoid duplication of efforts.

The success of using CO_2 capture, transportation, utilisation, or storage to mitigate climate change depends on having the necessary technology at every stage of the process, as well as building and expanding networks for transporting and storing CO_2. For CCUS to expand, all stages of the value chain must achieve a level of technical readiness and development simultaneously.

Concentrating solar-thermal power: The development of next-generation concentrating solar thermal power (CSP) facilities is a crucial step towards achieving 100% clean energy. Unlike other technologies, CSP only requires a one-time investment, making it a cost-effective solution. To achieve this goal, it is necessary to develop new materials such as metal halides that can be used to transport and store heat or at power stations and generate effective electricity at a reasonable cost while allowing for heat recycling. CSPs can be integrated with photovoltaics (PVs) at the community level, where CSPs can be used for community kitchens while solar PVs can meet energy demands. By deploying CSPs and solar PVs at the community level, affordable and clean energy can be made available whenever and wherever it is needed, benefiting multiple households in a particular region. This is more beneficial than individual rooftop installations, which can be expensive.

Biofuels: The promising technology of biofuels has the potential to bring about immediate benefits to the environment. Biofuels can power a range of vehicles, from trains to airplanes, which can greatly reduce carbon emissions. These energy-dense fuels can contribute to lowering GHG emissions in the transportation sector. Currently, there is a significant need to improve biorefineries, which can create employment opportunities while also having a positive impact on the environment. Biofuels can be a transformative technology that can rapidly reduce our reliance on fossil fuels and stimulate economic growth, ultimately leading to a cleaner and greener environment.

Solid state cooling and power generation: Using a hybrid refrigerator based on Peltier cooling technology could be an effective way to reduce GHG emissions and decrease dependence on grid power. This technology has been around for a long time and is reliable, making it a good option for long-term cooling solutions. Solid-state cooling systems can be used in medical facilities or small households where large refrigerators are not necessary. Additionally, thermoelectric generators can be used to generate useful power from waste heat sources with significant temperature differences. This is an easy-to-use and simple technology that can be commercialised with minimal effort. A typical solid-state cooling refrigerator with a capacity of 30-35 litres can potentially reduce GHG emissions by 1 MT CO_2 per year.

In terms of water management, desalination and wastewater reuse systems can be used in unconventional water sources such as brackish water, seawater, and wastewater. These technologies have a significant impact on the environment because they reduce reliance on underground water supplies, which are already being depleted in various areas. They can also help reduce the amount of potable water waste.

Batteries for energy storage: Solid-state batteries have the potential to replace lithium-based batteries, which are currently the main contributors to economic growth in the industry 4.0 era. India currently holds the majority of economic power over lithium batteries, making it necessary to explore alternative approaches. Solid-state batteries have higher energy density and better safety compared to lithium-ion or lithium-polymer batteries, and investing in research to develop them can make a significant impact on environmental control and GHG reductions. Additionally, there is a need to create strong recycling plans for lithium-ion battery recycling and extracting potential materials. These steps are crucial to achieving a clean energy future, reducing reliance on fossil fuels, and protecting the climate. Therefore, battery storage using new and available technologies is crucial towards the clean energy transition.

Clean hydrogen: Hydrogen as a fuel is a cutting-edge technology that has the potential to play a crucial role in reducing emissions in various sectors, such as road and rail transport, chemical and processing units, and steel industries. However, there are challenges that need to be overcome, such as safety and cost concerns, to fully realise its potential. The use of environmentally sustainable feedstocks for bioenergy and new agricultural technologies should be encouraged. Marine algae and mangrove plantations are natural ways of tackling carbon emissions and can have a long-term impact on the environment. Utilising crop residues as biomass can also help farmers earn more money during off-seasons, while also controlling soil erosion and improving soil fertility.

Building industry: The building industry is another area where zero-energy homes can be utilised with self-sustaining plans for all energy needs and recycling. Building materials can be designed to sequester CO_2 and used in residential, commercial, and government buildings. Additionally, there is potential to explore the use of materials in the construction of roads and highways for carbon storage.

Other key points: Key sectors such as energy, transport, construction, and food have the potential to make a positive impact on the world by adopting more sustainable and renewable sources and reducing waste. Two crucial steps that can help emit less CO_2 are avoiding wastage and spoilage of food products from farm to plate and shifting to a plant-rich diet. Halting deforestation and ecosystem degradation and restoring ecosystems are also essential factors in addressing the current state.

Conclusion

The current era prioritises environmental concerns and requires support from various individuals, industries, governments, researchers and technologists. There is a need to identify and adopt available and upcoming technologies to make the environment green. This report highlights several gaps that need to be filled by all stakeholders, and it is essential for every individual to adopt new lifestyles to reduce their carbon footprint. While government initiatives are important, individuals must also be cautious to achieve clean climate goals. Implementation of CCUS technologies in various industries is crucial to accelerate the clean and green climate, and there are significant investment opportunities at this time of global concern. Strong collaborations and partnerships are needed between stakeholders, with intercountry and intercontinental cooperation. Researchers must work collaboratively, and all research and technological output should be considered public goods to benefit current and future generations.

2.9

Green Hydrogen Applications – Ammonia, Ceramic, Steel, Cement, Etc

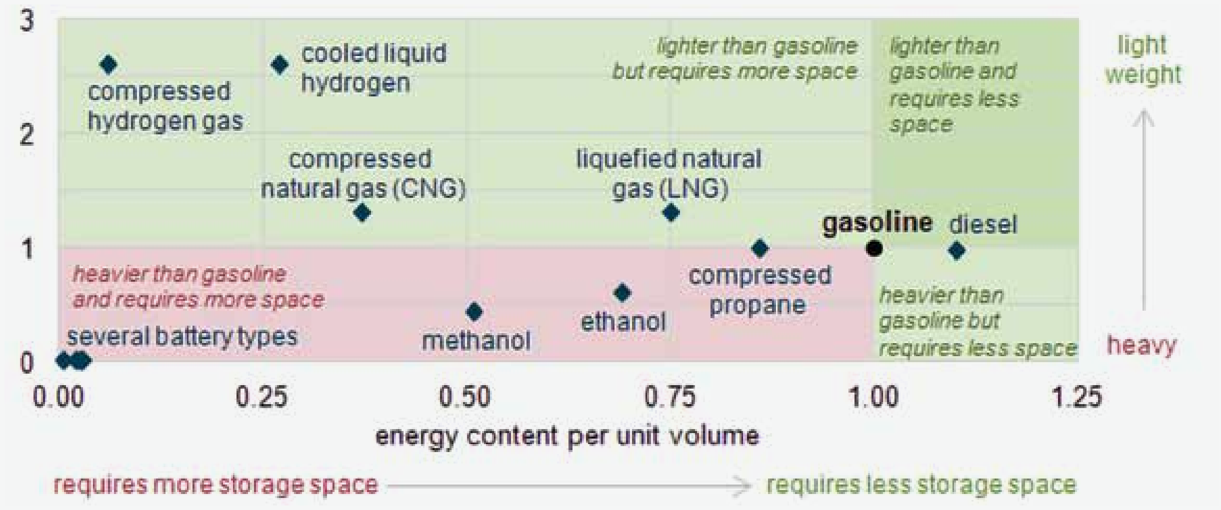
DR J P GUPTA, MD, Greenstat Hydrogen India Pvt. Ltd.

> Everything in Nature contains all the powers of Nature. Everything is made of hidden stuff.
>
> **Ralph Waldo Emerson**

2.9.1 Ammonia as a Hydrogen Carrier

Hydrogen is currently transported globally in compressed gas and liquid forms, with different supply chain methods depending on the distance between production and end-users, demand scale, and road-weight restrictions. For short-distance transportation (less than 60 miles or 100 km), compressed hydrogen is carried in bundles of long cylindrical tubes on trailers, with each trailer containing up to 250 kg of hydrogen. However, the weight of the steel tubes and gross vehicle weight limits the amount of hydrogen that can be transported. This method is commonly used in Europe. Recently developed composite storage elements can transport larger quantities of hydrogen of up to 1,100 kg at a pressure of 500 bar, and further developments in composite technology may allow for trailers up to 700 bar in the future. This will increase load-carrying capacity and extend the range of compressed hydrogen transportation.

In North America, hydrogen is usually transported in liquid form for longer distance deliveries, typically ranging from 200-300 miles. The production of liquid hydrogen is supported by several fully depreciated liquefaction plants originally developed for NASA programmes in the 1970s. Specially constructed and well-insulated cryogenic tanks are used to transport the liquid hydrogen by road, with typical capacities of 2,000 kg, but even up to 4,300 kg. However, handling liquid hydrogen poses challenges such as boil-off losses and transfer losses, with some studies estimating up to 25% hydrogen loss throughout



Energy density comparison of selected fuels (indexed to gasoline = 1).

the service chain. To address the low energy density problem of hydrogen, various options have been explored, including transporting it in liquid form. Although liquid hydrogen has higher energy density than compressed hydrogen gas, it is still low compared to conventional fuels used for long-distance transport. Liquefying hydrogen requires a significant amount of energy, with around 30-40% of the hydrogen's energy content needed to maintain it in a liquid state during storage and transportation to minimise losses.

Many complexities are inherent in the production and storage of liquid hydrogen at -253°C (energy density of 9.98 MJ/l). Specifically, to liquefy hydrogen, it must first be pre-cooled to -195°C using liquid nitrogen, and then expanded to atmospheric pressure to reach the required temperature. This two-step process is necessary to ensure the hydrogen cools upon expansion and falls below the inversion temperature of -71°C. As a result, liquefying hydrogen requires an intricate and costly cooling system that involves compressors, pumps, heat exchangers, and a liquid nitrogen system.

The Need for an Effective Hydrogen Carrier
Considering the difficulties in storing and transporting hydrogen in its natural gaseous or liquid form, alternative methods have been explored to convert it into a form that has higher energy density and is more convenient for storage and transportation. Among the main options are liquid organic hydrogen carriers (LOHCs), which consist of organic hydrocarbons, other organic molecules such as methanol, metal alloy hydrides, and liquid ammonia. It is worth noting that, except for metal alloy hydrides and ammonia, all these alternatives contain carbon.

Ammonia as a Hydrogen Carrier
Ammonia stands out from other hydrogen carriers because it does not contain carbon in the non-hydrogen part of its molecule (nitrogen) and does not require direct recovery and recycling after hydrogen extraction. Nitrogen comes from the atmosphere and is returned after hydrogen release, making ammonia a zero-carbon hydrogen carrier if generated from renewable hydrogen. Ammonia production using atmospheric nitrogen is highly efficient and easier than carbon capture. Liquid ammonia has many advantages, including its high hydrogen content, ease of liquefaction, and physical properties similar to LPG, allowing for the use of existing storage and transport equipment. Ammonia is widely used as a fertiliser, chemical raw material, and refrigerant, and can be transported economically over long distances.

Zero/Low-Carbon Ammonia Production Routes
The cost of low-carbon hydrogen in Europe is significantly higher at approximately £1.90/kg H_2 (£57/MWh H_2 LHV). This means that Middle East low-carbon hydrogen could be cost-competitive in Europe if it can be transformed into ammonia, transported, and converted back into hydrogen of similar purity for less than £0.69/kg H_2 (£20/MWh H_2 LHV).

Ammonia from Green Hydrogen
Renewable hydrogen can be used for ammonia production by electrolysing water using electricity generated by wind or solar power. This method produces high-purity hydrogen, simplifying the ammonia production process by avoiding the need to remove CO and CO2 from the hydrogen produced by steam methane reforming.

Both wind and solar energy are suitable for hydrogen generation through electrolysis, with solar being particularly advantageous for locations with consistent sunshine, as it allows for direct current power transmission, reducing the cost of power electronics and AC-DC conversion. With the help of energy and hydrogen storage, along with wind power to supplement in the absence of sunshine, the production of hydrogen and ammonia can be economically feasible.

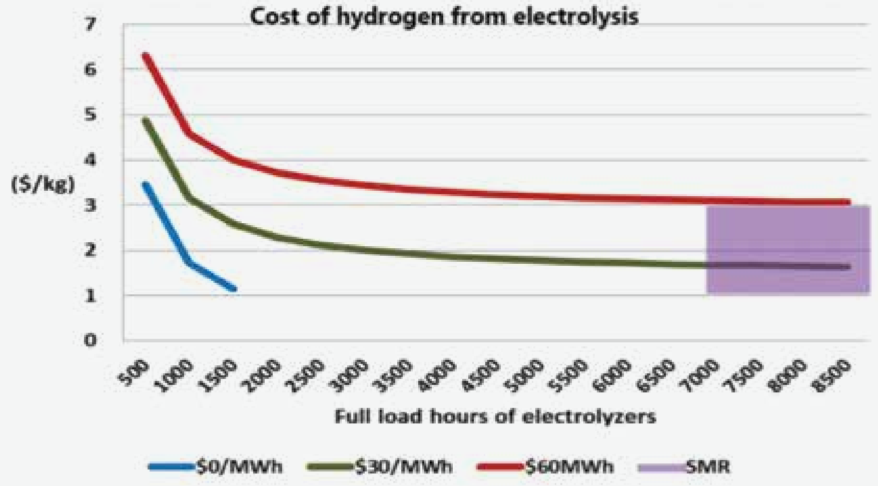
Shipping and storing ammonia are easier than hydrogen, so ammonia synthesis plants are best located near hydrogen-generating plants. These integrated plants, currently using H_2 from steam methane reforming or electrolysis in the future, benefit from economies of scale and are usually very large, producing over 500,000 MT/year.

2.9.2 Use of Ceramic

The ceramics industry utilises clay to create a variety of products, including bricks, ceramics, glass, heavy clay items, tiles, aggregates, and refractory goods. Ceramic materials are typically non-metallic and inorganic, such as oxides, nitrides, or carbides, and may contain elements like carbon or silicon. These materials are strong in compression but weak in tension and shearing and have a high tolerance for chemical erosion in acidic or caustic environments. They can also withstand very high temperatures, ranging from 1,000-1,600°C .

After cutting the clay to the correct dimensions, the drying process begins by utilising the hot air from kilns. The dried clay is then fired in the oven, with the kilns being fuelled by natural gas. The process involves starting at a high temperature and gradually cooling the bricks down using fresh air towards the end of the kiln, where the air is heated by the burning fuel in the middle.

However, the ceramic industry can be highly



Cost of hydrogen from electrolysers at $450/kW Capex for different electricity costs and load factors. Note: Exchange rate = $1.11/£ (27/8/19).

polluting, with CO_2 emissions from ceramic tile production reaching about 180,000 MT/year. The CO_2 emission per unit of product is approximately 10% more than the global advanced level, with around 80% of the total CO_2 emissions occurring during the drying and firing processes.

The ceramic industry is particularly difficult to decarbonise as the kilns are energy-intensive and are generally operated on natural gas. Substituting green hydrogen as an alternative fuel would help achieve decarbonisation of this hard-to-abate industry.

Green Hydrogen and Ceramic Industries – Global Scenario

- **The World's First Green Hydrogen Ceramic Industry—Iris Ceramica Group**

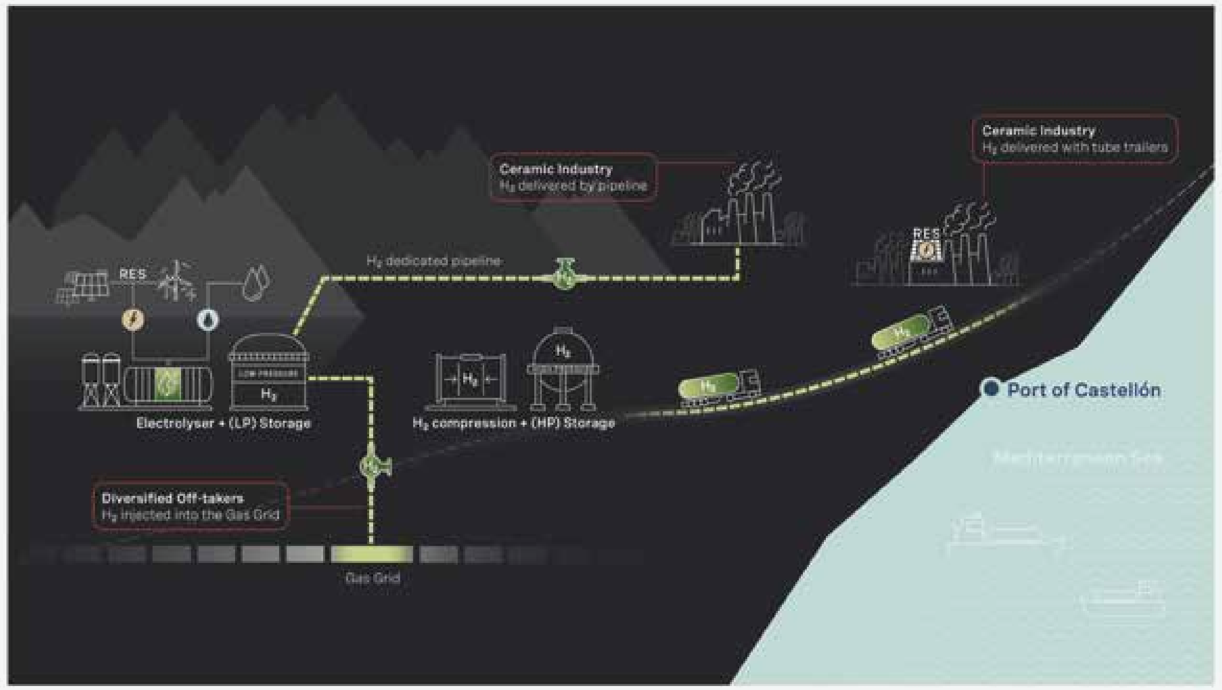
The Iris Ceramica Group, which includes Ariostea, has signed an MOU with Snam to develop the world's first ceramics factory powered by green hydrogen. By early 2023, the new production site in Castellarano (RE) will be equipped with native technologies that allow the use of green hydrogen as an energy source. The solution will combine green hydrogen, produced from solar energy, and natural gas to immediately reduce CO_2 emissions.

A photovoltaic plant, electrolyser, and hydrogen storage system will be installed on the factory roof to produce and store renewable hydrogen on-site. The plant is designed to run on 100% hydrogen, paving the way for zero-emissions production using only renewable energy. The use of rainwater as a source of water for the electrolyser is being studied by a university research team to save water resources. The introduction of green hydrogen into the production processes will contribute to achieving the European goal of carbon neutrality by 2050.

https://www.ariostea-high-tech.com/news-2021/the-worlds-first-green-hydrogen-ceramic-industry-is-born

- **European Decarbonisation Action Plan—ORANGE.BAT**

A consortium is leading a new green hydrogen project that aims to reduce the carbon footprint of the entire value chain of a major European ceramic cluster. The project, known as ORANGE.BAT, is driven by 26 industrial end-users from the Regional Ceramic Cluster of the Comunitat Valenciana, as well as the two associations representing the whole sector, ASCER and ANFFECC. The goal is to replace natural gas with green hydrogen as the combustion fuel, which will fully decarbonise the energy- and CO_2-intensive industry sector.



[Image: Iberdrola]

The project has secured funding from the EU's Green Deal Call to overcome the financial challenges faced by pioneering industrial-scale projects in the current ramp-up phase of the green hydrogen economy. The electrolyser is expected to be operational by early 2024, enabling ORANGE.BAT to cover the full value chain, from the generation and storage of green hydrogen to its consumption and distribution to end-consumers.

The ORANGE.BAT project adheres to the principles of the circular economy by making use of the by-products generated or consumed in the industrial process of the electrolyser. This includes replacing natural gas consumption with green hydrogen to avoid CO_2 emissions, using the generated oxygen to improve the kiln process, and utilising the generated heat for industrial and residential heating to achieve maximum energy efficiency throughout the entire value chain.

https://www.climateaction.org/news/100mw-green-hydrogen-project-to-decarbonise-value-chain-of-major-european-c

- **Iberdola and Porcelanosa**

Iberdrola and Porcelanosa launched their first project to electrify ceramic production by combining renewables, green hydrogen, and heat pump technology.

The GREENH2SKER project is a joint initiative between the two companies that recently agreed to promote the decarbonisation of the industrial ceramic production process. This project will develop a system that uses both green hydrogen and a heat pump to improve energy use and reduce CO_2 emissions in an oven at a Porcelanosa factory in Vila-real. The solution will replace up to half of the natural gas used as fuel with green hydrogen by optimising residual thermal energy.

The project will include installing an electrolyser on the Porcelanosa site, powered by a photovoltaic plant to produce green hydrogen. Additionally, it will utilise high-efficiency systems to extract excess waste heat and heat from the production lines. By integrating green hydrogen generation with a heat pump, the project aims to reduce the release of 2,351 MT of CO_2/equivalent per year and reduce the energy impact from Porcelanosa's industrial activity, in line with the Decarbonisation Objectives set by the EU. This is the first joint project between the two companies after signing the agreement to promote decarbonisation.

- **CarburosMetálicos pioneered initiative to accompany ceramic and glass industries towards decarbonisation**

The Institute of Ceramic Technology (ITC-AICE) is leading a study as part of the experimental study at laboratory scale of ceramic firing using hydrogen as fuel (Hidroker) project. This study is funded by the GeneralitatValenciana through the Valencian Institute of Business Competitiveness (IVACE) and aims to explore the use of hydrogen as a direct source of thermal energy in the drying and firing processes of ceramic tile firing kilns and frit melting kilns. CarburosMetálicos, responsible for the combustion team, provided the mixing panel and a precise combination of natural gas and hydrogen to achieve controlled combustion with conventional burners and up to 20% hydrogen. They have successfully developed and tested burners that use up to 100% hydrogen, with both air and oxygen as oxidants. Their experience in hydrogen production, handling and distribution, coupled with these developments, contributed to the success of the tests conducted at the ITC. This transition to natural gas and hydrogen mixtures in the ceramic industry will help to reduce CO_2 emissions and move towards decarbonisation.

The Air Products group also has a significant portfolio of technologies and operational expertise in oxygen-enhanced combustion, which can be advantageous for various industries. This process uses oxyfuel or oxygen enrichment to enhance the efficiency and productivity of heating and melting furnaces. The transition from the traditional air-fuel combustion system to an oxy-fuel system can result in up to a 40% reduction in energy usage, leading to a similar decrease in direct CO_2 emissions and other pollutants generated by these processes. The reason for this is that pure oxygen reacts faster with fuel, increasing the flame temperature up to approximately 1,000°C, which results in greater efficiency.

Air Products' oxy-fuel burners are also designed to support the combustion of natural gas and hydrogen mixtures, offering a direct path towards reducing the carbon footprint without generating higher temperatures in ceramic kiln walls, elevated nitrogen oxide emissions, or inefficiencies in glass melting processes. Additionally, the company is working to reduce CO_2 emissions associated with oxygen production and transportation to create a green or renewable oxygen.

'The ceramic sector is intensive in the use of thermal energy and the margin for reducing direct emissions from its production processes is certainly limited if it does not substantially modify the technologies and energy sources it uses. The research led by the Institute of Ceramic Technology represents a first step to incorporate hydrogen to this industry, a molecule of great interest to achieve the planned decarbonization goals,' explains Dr Salvador Ferrer, from the ITC Sustainability Area.

https://energynews.biz/carburos-metalicos-successfully-tests-its-hydrogen-technology-in-the-ceramics-industry/

- **UK funds hydrogen-enabled decarbonisation of the ceramic industry – Ryze Hydrogen (Pink Hydrogen)**

The UK's £26 million Industrial Hydrogen Accelerator Programme is run by the Department for Business, Energy, and Industrial Strategy. Nine projects were awarded £2.95 million by Stream 2A to showcase the full process of switching to hydrogen as an industrial fuel, and to further develop their concepts. One of the winning projects, the Hydrogen4Hanson project by the Bay Hydrogen Hub, aims to decarbonise the asphalt and cement industry by developing nuclear hydrogen production. EDF Energy R&D UK Centre Ltd. intends to demonstrate the integration of solid oxide electrolysis with nuclear heat and electricity to provide low-cost, low-carbon hydrogen to asphalt and cement sites near the Heysham nuclear power station.

Learnings from the project, which received more than £399,000, will be shared with more than 250 Hanson sites across the U.K. and potentially within the wider mineral products industry.

Other awardees included Nanomox Ltd., which received £173,000 for OISH, a project to produce hydrogen from steelmaking waste, to be used as a fuel for steel production.

Nanomox Oxidative Ionothermal Synthesis (OIS) is a new metal-rich waste treatment process that uses green catalytic solvents at low temperatures to complete the direct oxidation of metals and produces hydrogen that can be used in steel manufacturing, with potentially large energy efficiency improvements over existing technologies.

The Centre for Process Innovation was awarded £370,000 to explore the use of hydrogen as a fuel for kiln firing in the ceramics industry, replacing natural gas. Its PRO-GREEN H_2 aims to produce green ammonia made from renewable electricity and low-energy feedstocks, including seawater and nitrogen.

The project will also ascertain the feasibility of a switch to 100% hydrogen in ceramic manufacturing kilns and its effect on products.

https://hydrogen-central.com/uk-funds-hydrogen-enabled-decarbonisation-steel-cement-ceramics-production-ryze-hydrogen/

- **HECO2®: Green hydrogen in the ceramics sector**

HECO2® enables the use of hydrogen for firing ceramic products. The system includes four parts:

  - Electrolyser/s
  - System for supplying H_2 and O_2
  - Burner/s
  - Management panel

The electrolyser produces H_2 and O_2 from water. If the electricity used is derived from renewable energy sources, it is referred to as green hydrogen.

- For Italforni, this represents the main gateway towards a true ecological transition. The electrolyser produces extremely pure H_2 (> 99.5%) and O_2, which are both used for combustion, exploiting the energy in both reaction products.
- The supply system is designed to enrich the comburent (usually air) with O_2, which is input into the same pipe, and to enrich the fossil fuel (usually natural gas) with H_2, which is fed into the burner as required.
- The burners are designed to optimise the simultaneous use of H_2, O2, air, and fossil fuel.
- The production of H_2 on site enables the use of the generated oxygen, which otherwise would be lost, reducing total air emission volumes from flues, while also reducing NOx emissions, since the H2 component substituting the carbon-based fuel reacts stoichiometrically with the oxygen separated during electrolysis.
- On-site production offers other important advantages:
  - all the hydrogen produced is used without storage.
  - if the plant has an adequately sized solar panel array, it can produce hydrogen for free.
- HECO2® can be used on existing firing kilns.
- The system is designed to independently use both fuels. If hydrogen is input into the burner the flow of the second fuel is automatically reduced, and vice-versa.
- This new technology can be scaled according to the kiln and type of ceramic products. The supply of HECO2® from 200 to 800 m3/h of H2.
- The degree of decarbonisation can range from 15% to a theoretical 100%.

https://www.italforni.com/wp-content/uploads/2022/09/HECO2%C2%AE-1.pdf

Points of Consideration for Ceramic Industries

- To reduce CO_2 emissions and eventually achieve zero-emission production through renewable energy sources, a combination of green hydrogen and natural gas can be used instead of natural gas alone. In order to increase sustainability and achieve energy independence, it would be beneficial to construct a plant that runs on 100% hydrogen.
- By building the hydrogen plant near the source of renewable energy generation, costs associated with energy transportation for the electrolyser can be avoided. Some ceramic industries have already installed their electrolyser units on their factory rooftops to avoid energy transportation costs. To further improve efficiency, a technological structure that utilises excess waste heat and heat from production lines should also be implemented.
- Research on the use of rainwater as a source of water to be used in the electrolyser can be taken into consideration, provided there is an existing rainwater harvesting system in place and the proper data from the study.
- In order to use green hydrogen to fuel kilns in the ceramic industry, modifications to the burners are necessary to accommodate hydrogen as fuel. Traditional burners can handle flames fuelled with a mix of 20% hydrogen and natural gas, and this can be a viable strategy to reduce CO_2 emissions.
- The oxygen produced from the electrolysis process can improve the kiln process and the heat generated from combustion can be utilised for industrial and residential heating to achieve maximum energy efficiency, a process known as oxygen-enhanced combustion by Air Products. The reason for this is that pure oxygen is more efficient than air, as it reacts faster with fuel, increasing the flame temperature up to approximately 1,000°C.
- The firing and drying processes in ceramic industries are highly energy-intensive, making the substitution of a hydrogen-blended fuel a suitable solution to reduce dependence on fossil fuels.
- However, the use of hydrogen as an energy carrier requires a revision of the safety procedures on the ceramic production site. Safety is already a crucial issue with the use of natural gas, but hydrogen has different properties that may require additional or different types of safety precautions, detection systems, and installations.

2.9.3 Green Steel Plants

There are two main pathways for reducing the carbon footprint for the steel sector: Innovative DRI and the so-called Smart Carbon (which refers to CCUS). A third technology pathway, direct iron ore electrolysis, is still far from being commercially viable.

The Innovative DRI pathway focuses on using hydrogen in the direct reduced iron (DRI) process. DRI technology, based on natural gas, is a well-established one, and new DRI installations that will use green hydrogen to produce low-emissions steel are now under development. The Smart Carbon pathway is not yet ready for commercial deployment, and there is no clear indication as to when it will be.

Innovative DRI

The Sestao project in Spain, Bremen, Eisenhüttenstadt, and Hamburg H_2 projects in Germany, Dunkirk in France, and Contrecoeur in Canada are among the most significant H_2DRI-EAF (electric arc furnace) projects.

Smart Carbon

Smart Carbon comprises a range of technologies that can contribute to achieving the net-zero emissions target. The key technology included is CCUS, but it also involves powering blast furnace operations with renewable energy and using biomass and hydrogen in blast furnaces to replace some coal consumption.

India: The Key Global Steel Growth Market

India's National Steel Policy 2017 aims to achieve 300 MT of crude steel capacity and production of 255 MT by FY2030-31 (Fig. 5). India needs to double its capacity by the end of this decade to meet this target, and Indian steel producers have aligned their growth strategy with this policy.

Indian crude steel capacity reached 154Mt in FY2021-22. To achieve the National Steel Policy's 2031 target, a compound annual growth rate (CAGR) of 7.7% in steel capacity is needed. In 2021-22, India produced 120.29Mt of crude steel with a growth rate of 8.9% compared to the previous year. To reach the target production of 255Mt by 2031, an additional 135Mt of steel above 2021-22 production levels would be needed, or a CAGR of 8.7%.

In addition to these high growth rate targets for steel capacity and production, the government is targeting India's low steel consumption. According to the World Steel Association, India's apparent steel use per capita in 2021 was only 76 kg, while the average in Asia was 306 kg (Fig. 2). The National Steel Policy 2017 aims to increase per capita steel consumption to 160 kg by 2030-31.

According to the IEA, Indian steel production will double by the end of this decade and quadruple by 2050. While China may be at or close to peak steel production, India, the second-largest steel producer with a high economic growth rate, is an attractive market for steel investors.

India's National Steel Policy limits the share of the blast furnace-blast oxygen furnace (BF-BOF) route process to 60-65% of total crude steel production by 2030-31. However, the expansion plans of large steelmakers in India, including AM/NS India, are dominated by BF-BOF projects, so there is a likelihood of India going over the 60-65% cap.

With steel demand and steel sector emissions in China, the world's largest producer, perhaps already in permanent decline, India is the key growth market globally. Europe is already starting to shift away from reliance on coal-based steelmaking[31], but efforts to bring the global steel sector towards net-zero emissions will not be achieved if India relies on coal-based steelmaking to meet demand growth. The technology pathway that India chooses for its capacity expansion will, to a large extent, define the success or failure in achieving net zero emissions in the steel sector worldwide.

Increasing Risks Associated with Coal-based Technologies

A report released in 2021 by think tank E3G and the U.S. Department of Energy's Pacific Northwest National Laboratory stated that all blast furnaces without CCUS must be phased out by 2045 for the global steel sector to remain on a 1.5°C pathway. Additionally, no new blast furnaces without CCUS should be brought online after 2025 to avoid stranded assets. However, AM/NS India plans to bring two new blast furnaces online in 2025 and 2026 without CCUS. The company also has plans for further expansion at Hazira and, in the longer term, a greenfield plant at Kendrapara, Odisha, with a capacity of 24 MT/year and a 6 MT/year integrated steel plant at Paradip, Odisha. Feasibility studies for both Kendrapara and Paradip are currently underway.

Carbon Capture Technology has a Long History of Failure

The major iron ore miner BHP noted in October 2022 that 'there are no full-scale operational CCUS facilities in blast furnace steelmaking operations at present, with only a limited number of small-capacity carbon capture or utilisation pilots underway or in the planning phases globally'.

In its second Climate Action Report released in 2021, ArcelorMittal stated: 'In many respects, the challenges confronting steelmaking today resemble those faced by renewable energy over a decade ago. In that case, the importance of solar and wind power was widely acknowledged yet the technology remained economically prohibitive.' What happened over the following decade was that the declining cost of renewable energy left CCUS in the power sector far behind. Today, CCUS is making virtually no contribution to emissions reduction in the power sector while the roll-out of renewable energy accelerates.

With hydrogen-based DRI projects now shifting from announcements to investment decisions and construction, CCUS in the steel industry faces being left behind in the same way it was in the power sector as wind and solar power became ever cheaper, increasingly widespread, and far more financially viable.

Future Coking Coal: Availability and Costing Question

Australia, the world's largest coking coal exporter, is not investing enough in future mine capacity. Imports make up 85-90% of India's coking coal supply, with Australia being its main supplier.

South32, another major Australian coking coal exporter, also made it clear in 2022 that it will not be investing in new coking coal projects and will wind down its coal business as existing mines are depleted. The company will instead focus on 'metals critical to a low carbon future'.

At the same time, mining coal in Australia is becoming more difficult. Starting new mine projects will become harder going forward as more financial institutions cease providing funding for coal. This process is now well advanced in the thermal coal sector, but will undoubtedly spread to coking coal as pressure on climate action tightens.

India's steel ministry is already concerned about a lack of coking coal supply and has reportedly requested that import taxes be waived. Short supply also leads to higher prices; the Indian steel industry has been hit by extra raw material costs during 2022 thanks to high coking coal prices. The steel industry has low margins and is sensitive to the market fluctuations of key input prices. Coking coal comprises 40% of the production cost and prices surged 70% in the second half of 2022. Given the energy security concerns that result from this, it is no surprise that the Indian government is keen to try to diversify its coking coal import sources.

India's steelmaking capacity is clearly set for expansion. If that expansion is based on blast furnaces, it faces a risk that sufficient coking coal supply is not available. This could lead to shortages and/or frequent periods of very high prices. We've seen the outlook for thermal coal decline significantly over the past decade as financiers increasingly rule out funding. Technology transitions have a habit of occurring faster than expected, and it is likely that coking coal will suffer a similar fate to thermal coal over the rest of this decade.

Steelmakers are coming under increasing pressure to decarbonise their operations. This pressure will only escalate if they start to increase their own investment in coking coal mines as incumbent miners and financiers exit the sector.

Green Hydrogen: A Promising Alternative

The reliance on coking coal has the potential to cause India a further energy security problem on top of oil and gas imports. However, green hydrogen could conceivably provide a solution for a nation highly dependent on fossil fuel imports.

A June 2022 report by Indian public policy think tank NITI Aayog and RMI found that growing global momentum towards the transition towards green hydrogen is a good fit for India given its energy security, emissions reduction, and development concerns. The report found that a major adoption of domestically produced green hydrogen in India could save between $246 billion and $348 billion in energy imports, reduce price volatility for inputs into Indian industries, and provide a foreign exchange advantage.

NITI Aayog and RMI report that India's hydrogen demand could be four times bigger by 2050 with the country representing 10% of global demand. Indian demand growth would initially come from existing uses such as industrial feedstock and chemical processes, but in the long-term, steel will become a major source of new demand. By 2050, green hydrogen would account for 94% of India's hydrogen supply.

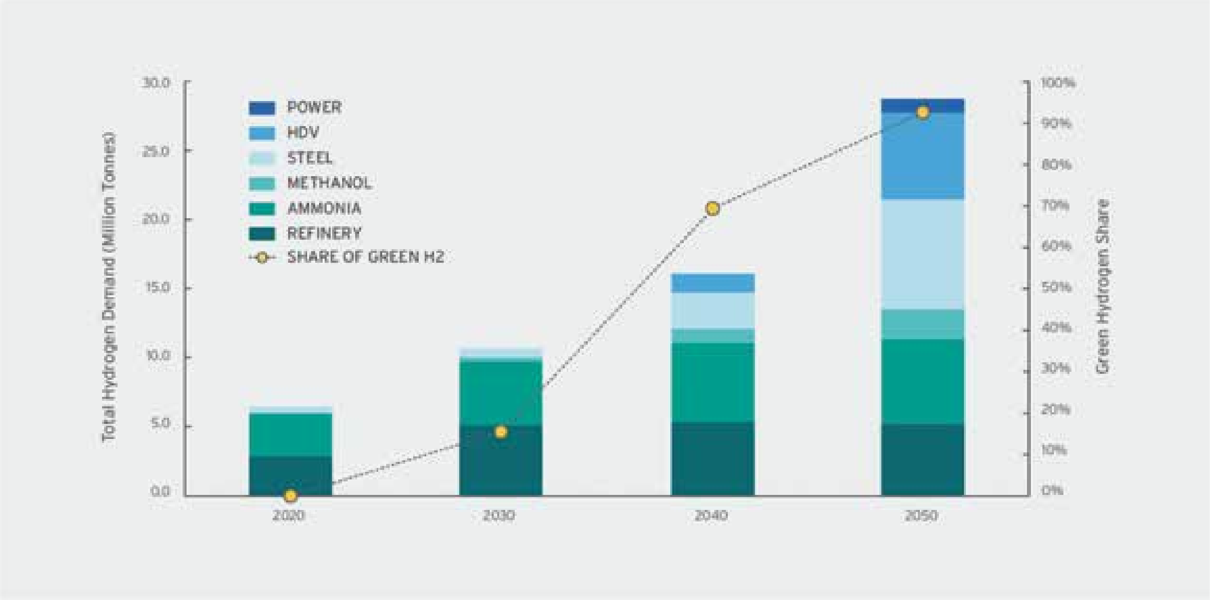
The Indian government is now reportedly eyeing a huge increase in green hydrogen production to 25 MT by 2047 to reduce energy imports. The National Green Hydrogen Mission was launched on August 15, 2021, Independence Day, and the government revealed the first part of its hydrogen roadmap in February 2022, which included free interstate transmission of renewable energy as it seeks to become a global green hydrogen hub.

In January 2023, India approved a $2 billion incentive plan to support green hydrogen production. The government is aiming to produce 5 Mt of green hydrogen annually by the end of this decade, reducing fossil fuel imports by Rs 1 trillion. The government expects Indian investment in green hydrogen will reach almost $100 billion by 2030.

The growing interest in green hydrogen worldwide matches India's aspirations. According to a report by the IEA in October 2022, at least 43 countries have completed or are in the process of creating hydrogen roadmaps. The report also indicates that the shift towards low-carbon hydrogen has gained momentum due to the Russian invasion of Ukraine. The IEA predicts that global low-emissions hydrogen production will increase significantly from 1 MTPA produced today to 30 MTPA under its Announced Pledges Scenario. Low-emissions hydrogen includes both green and blue hydrogen, with the latter being produced from fossil fuels, but with the potential for carbon emissions to be captured. However, the IEA report also highlights that blue hydrogen production had made little progress in 2021, remaining at the same level as in the previous year. There are still uncertainties about the practicality of using green hydrogen for long-distance shipping. The IEEFA believes that it is more likely that domestically produced green hydrogen will be used in sectors like iron/steel and fertiliser production rather than exported for seaborne transport.

The IEA reported in November 2022 that the use of hydrogen in steelmaking had gained significant momentum. The number of steelmakers announcing their plans to use this technology has tripled over the last 12 months, with several moving from pilot projects and green steel announcements towards commercial-scale investment decisions and construction. As a result, new low-carbon installations will be operational in just 3-4 years, using green hydrogen to further reduce emissions.

Salzgitter AG's board approved funding for its switch to hydrogen-based DRI in July 2022,



Indian Hydrogen Demand Outlook and Potential Green Hydrogen Share at Cost Parity (Without Policy Intervention)

Source: NITI Aayog and RMI, Harnessing Green Hydrogen, p.14.

with orders for central components placed in August. ThyssenKrupp also announced a €2 billion investment in its decarbonisation plan in September 2022, intending to replace the first of four blast furnaces using hydrogen-based DRI technology. By 2026, the first new DRI plant is set to produce 2.5 MTPA. The remaining blast furnaces will be replaced progressively.

Most recently, Blast, a Norwegian company, announced its plans to invest €4 billion in Finland to establish a 2.5 MT integrated hydrogen-based steelmaking facility, with production expected to start by 2026.

India has a competitive edge in producing green hydrogen due to its established low-cost renewable energy sources. According to NITI Aayog and RMI, Indian green hydrogen could achieve cost parity with gas-based hydrogen by 2030. The two main cost drivers for green hydrogen production are the cost of renewable electricity and the cost of the electrolyser. With the costs of both expected to decline, green hydrogen could cost around $1.60/kg by 2030 and $0.70/kg by 2050, making it cost-competitive with natural gas-based DRI by 2027. By 2030, green hydrogen-based DRI could become the most cost-competitive steelmaking route in India, even cheaper than blast-furnace-based operations.

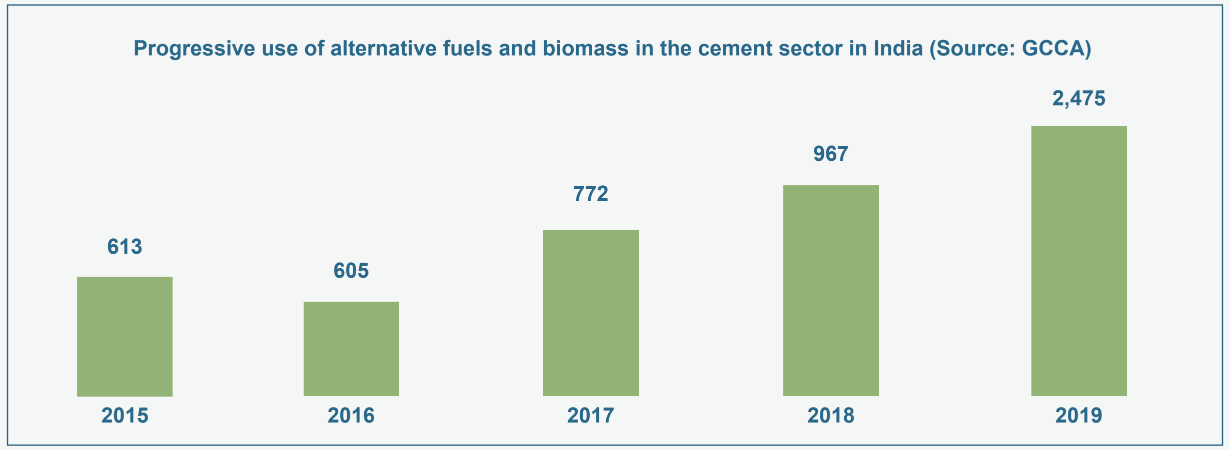
The Climate Action 100+ initiative, led by investors, aims to ensure that the world's largest corporate carbon emitters take action to reduce emissions. The number of global investors who have signed up for the initiative has reached 700, with assets under management totalling $68 trillion. It is now the world's largest investor engagement initiative focused on climate change.

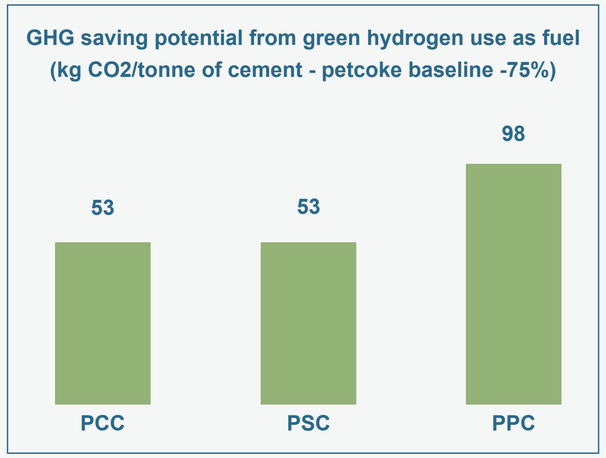
2.9.4 Green Hydrogen in the Cement Industry

Electrolyser manufacturers in India are working towards reducing the cost of green hydrogen to around $1/kg by 2025. The decreasing cost of green hydrogen is encouraging, and it is widely believed that hydrogen will be the future of clean, uninterrupted energy supply worldwide. Green hydrogen could be highly beneficial for industries that are considered difficult to decarbonise, such as the cement industry. India's cement sector is the world's second largest, producing low-carbon cement. Cement manufacturers have committed to reaching net-zero emissions in three decades by adopting the 1.5-degree ambition. In the cement manufacturing process, there are two GHG emission attributes: energy-related emissions, which account for about 45% of GHG emissions, and process-related emissions, which account for the remaining 55%. Green hydrogen has the potential to reduce GHG emissions in both cases. However, this evaluation is limited to the use of green hydrogen as fuel in the pyro-processing of the cement industry, which has the highest thermal energy consumption.

According to the latest data from the Global Cement and Concrete Association (GCCA), the average thermal energy consumption of clinker in India is 3,098 MJ/MT, and the thermal energy intensity of cement from pyro-processing, excluding mineral drying in HAGs, is 2,076 MJ/MT of cement when applying the average clinker factor of 67%. Petroleum coke is currently the main fuel used in the cement industry, with a high calorific value of around 33 MJ/kg. Moreover, cement kilns are highly effective in waste disposal due to their high temperatures exceeding 1,400°C and extended residence time. This feature makes the cement industry a crucial player in the circular economy and scientific waste management in India, especially given the increasing consumption trends that contribute to higher waste generation.

The cement industry can transition to green fuels by replacing 25-30% of its pyro heat input currently supplied by petroleum coke. This means that only 70-75% of the fossil energy would need to be replaced by other fuels such as green hydrogen. It takes approximately 47 kg of petroleum coke to deliver the remaining 75% of energy required to produce 1 MT of cement, which could be replaced by 12 kg of green hydrogen. However, currently, there is a mismatch between the economics of green hydrogen and petroleum coke.


Progressive use of alternative fuels and biomass in the cement sector in India (Source: GCCA)


GHG saving potential from green hydrogen use as fuel (kg CO2/tonne of cement - petcoke baseline -75%)

According to the analysis, the energy delivered from green hydrogen at a price of $1/kg would cost $7,692/million MJ, compared to $2,803/million MJ for petcoke. The analysis takes into account the price volatility of petcoke over the past two years. This shows that the energy delivered from petcoke is only 36% of that from green hydrogen in order to reach the $1/kg target by 2025. Therefore, there is still a long way to go for green hydrogen to become a dominant fuel in the cement industry until its price comes down to around $0.37/kg. However, the use of green hydrogen can result in significant CO_2 savings of approximately 144 kg/MT of cement, based on a 75% petcoke baseline and the country's average clinker factor. Carbon markets may also play a role in changing the situation to some extent.

Green hydrogen has several advantages for reducing the carbon emissions associated with cement production. First, it can be used as a replacement for fossil fuels like petroleum coke, which are currently the dominant source of energy in cement kilns. By replacing 25-30% of petcoke with green hydrogen, the cement industry can significantly reduce its reliance on fossil fuels. Second, green hydrogen can help reduce GHG emissions associated with cement production. Cement production is responsible for a large amount of CO_2 emissions, and green hydrogen can reduce these emissions by up to 144 kg CO_2 per MT of cement. Finally, green hydrogen is a renewable and sustainable source of energy, which can help the cement industry transition to a more circular and sustainable economy. Overall, green hydrogen has great potential for decarbonising cement production and reducing the environmental impact of this important industry.

The cement industry is facing increasing pressure from the public to address climate change, leading to a faster pace of energy transition within the sector. This shift is being facilitated by various technological advancements, including the use of alternative fuels, the recovery of waste heat, a lower use of clinker, reduced costs of renewable energy, advancements in electrical storage systems, and the adoption of CCSU techniques. Additionally, the potential benefits of green hydrogen are being considered as a possible solution.

The increased use of renewable energy is a positive step towards reducing the effects of climate change. However, as we move towards a low-

carbon future with more renewable energy, there are concerns about energy storage. Currently, the fluctuations in renewable energy are balanced by feeding back to national power grids where renewables are only a part of the total energy mix. While current energy storage solutions can handle these fluctuations, larger capacities will be needed as the proportion of renewables increases. Storage times will need to increase from 2-4 hours to days, weeks, or months, and discharge times will also need to be extended to fully utilise renewable sources.

As a result, extensive research is ongoing to find effective storage solutions, which will be essential for decarbonising the economy, including the cement sector. To address the intermediate storage problem, various solutions have been proposed so far, including:

- Batteries of various sizes and chemistries;
- Gravity storage: A heavy object (or water) is winched (or pumped) upwards using electrical power and then lowered in a controlled fashion to regenerate power when required;
- Thermal batteries: Heat is transferred to high-capacity concrete blocks, ceramic blocks, pebbles or aluminium ingots;
- Kinetic storage, including flywheels.

Hydrogen as a Storage Solution

As the lightest and simplest chemical element, hydrogen is highly reactive and is not found on Earth in its molecular form. Instead, it exists in more complex chemicals, such as water or methane. However, molecular hydrogen can be produced through the process of electrolysis, which involves separating water molecules into hydrogen and oxygen molecules.

$$2H_2O \text{ (+ electrical energy)} \rightarrow 2\ H_2 + O_2$$

Both hydrogen and oxygen are extremely reactive and can potentially be used as fuels/oxidants in rockets, fuel cells and other applications:

$$2H_2 + O_2 \rightarrow 2H_2O \text{ (+ heat energy)}$$

The process of electrolysis used to produce molecular hydrogen from water requires a large amount of energy, making it unsustainable when using fossil-derived electricity. On the other hand, using renewable electricity to generate hydrogen, also known as green hydrogen, is a sustainable method to store and move energy without emitting CO_2. There was a significant effort to promote green hydrogen in 2019, as well as hydrogen produced from existing industrial processes. Some emerging technologies include thermal splitting of water using solar concentrators or nuclear energy. Despite being used as a thermal fuel, hydrogen is advantageous because it already has an existing infrastructure. In 2019, the U.S. produced 10 MT of hydrogen, mainly from steam/methane reformers fuelled by fossil fuels, which produce large amounts of CO_2. Alkaline electrolysis is also used to produce hydrogen.

Although there is already established technology for producing molecular hydrogen from water via electrolysis, ongoing research is exploring alternative methods, such as replacing the water with steam. This could potentially enable the utilisation of waste heat from industrial processes, including cement plants, to improve the current conversion efficiency of 70%. Assuming that the conversion efficiency of a fuel cell is also about 70%, the overall efficiency of the electrolyser/fuel cell pair is approximately 50%. However, the overall efficiency of an electrolyser/combustion process depends on various factors, such as the specific parameters of the combustion equipment utilised and the proportion of hydrogen in the fuel mixture.

Firing Cement Kilns with Hydrogen

A multinational corporation is testing the use of green hydrogen as a replacement for fossil fuels in a cement plant in Europe, with the goal of achieving 100% substitution of fossil fuels. The use of hydrogen as a fuel source to replace all or part of fossil fuels is gaining popularity in Europe, where natural gas is expensive and CO_2 emissions come with a cost. The combination of green hydrogen and natural gas is being seen as a method to decarbonise heat and electricity production. Major Original Equipment Manufacturers (OEMs) are already offering gas turbines that can burn a mixture of hydrogen and natural gas, and are working towards hydrogen-only combustion. Similar to oxygen, hydrogen can be mixed with natural gas at up to 10% with minimal impact on combustion equipment.

Managing Hydrogen

It is important to take precautions when handling hydrogen because it is highly flammable and buoyant, and material for pipes and valves must be selected to resist hydrogen-induced embrittlement. Major burner manufacturers have some experience with firing pure hydrogen or mixtures of it with other fuels. Although it is easy to handle, the high flame propagation speed and temperature peak issues need to be properly understood and dealt with. In rotary kilns, hydrogen injection can lead to refractory damage and higher NOx levels, depending on the injection location and local oxygen concentration.

Interestingly, in the 19th century, gas produced from coal (known as town gas) contained about 40% hydrogen. Nowadays, coke oven gas and non-condensable gas, which have high hydrogen content (50-60%), are commonly used as fuels for rotary kilns in lime production at pulp and paper plants, as well as in lime kilns used in steel plants.

Don't Forget About the Oxygen

While the focus in electrolysers is on hydrogen production, one important advantage of co-locating these electrolysers within cement or lime plants is the 'free' oxygen that would be available. In fact, some cement manufacturers currently pay a premium to receive oxygen in tanks from third parties due to the numerous benefits it brings to the process, including a shorter and more stable flame, higher quality clinker, greater use of alternative fuels (including lower-quality alternatives), increased production rates (or lower electrical use by the ID fan at the same rate), and finally, a reduction in CO_2 emissions. When oxygen is currently vented at some electrolysers due to a lack of immediate practical use, it presents a clear opportunity.

Conclusion

The cement industry has made significant progress in reducing the clinker factor, increasing the use of alternative fuels, improving process efficiency, and enhancing other production parameters. Nonetheless, the journey toward completely decarbonising the industry remains gradual and lengthy. Nonetheless, it is evident that a solution can be attained using existing mature technologies and green hydrogen created from renewable sources. This approach can provide opportunities for storing and regenerating electrical power and for directly powering the cement-making process.

Hydrogen Economy Data

Density: 1 kg H_2 = 11 Nm^3
Mass energy density: 1 kg H_2 = 3.2 kg of petrol
Volumetric energy density: 1 Nm^3 H_2 = 0.25 L of petrol
1 MW electrolyser produces:
H_2: 200 Nm^3/hr / 18 kg/hr / 0.43 MT/day
O_2: 100 Nm^3/hr / 144 kg/hr / 2.45 MT/day
Conversion efficiency: ~70%
Water use: Production of 1 kg of H_2 requires at least 10 L of demineralised water.

Use of Hydrogen in the Cement Sector

All of the mentioned companies are actively exploring ways to decarbonise their cement production processes, with a focus on using green hydrogen generated from renewable sources. For example, VICAT is exploring the possibility of converting the CO_2 emitted during the production process into usable biofuels or chemical intermediates. In addition, it plans to use waste heat from cement production to increase the yield of hydrogen and use the oxygen generated to improve efficiency in its kiln.

Similarly, the Hanson Ribblesdale plant in the U.K. is trialling the use of hydrogen and biomass in its kiln, with results to be shared across the industry.

Lafarge Zementwerke, OMV, Verbund, and Borealis are also collaborating to build a full-scale unit at a cement plant in Austria to capture CO_2 and process it with hydrogen into synthetic fuels, plastics, or other chemicals. While the path to fully decarbonising the cement industry is long and incremental, these companies are actively seeking ways to use existing mature technologies and green hydrogen to achieve their goals.*

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* Anupam Badola, Assistant General Manager at Dalmia Cement (Bharat) Ltd. Published Dec 27, 2021

2.10

Production of Green Hydrogen from Agro-Waste: Thermo Chemical Conversion of Biomass

K K PANT, Director, IIT Roorkee

An education isn't how much you know. It's being able to differentiate between what you know and what you don't.

Anatole France

Currently, the majority of hydrogen production in the world is used by the petrochemical, fertiliser, and chemical processing industries. However, as the hydrogen economy grows, there will be an increased need for hydrogen as a fuel in the automobile sector. Despite hydrogen being the most abundant element in nature, it is not freely available and must be produced from renewable energy sources rather than fossil fuels. The most common technique for hydrogen production today is hydrocarbon-steam reforming or coal gasification for industrial processes, which require steam and hydrocarbons. However, hydrogen produced through these methods cannot be considered a renewable or clean gas, as it is produced from hydrocarbon fuels and generates similar CO_2 emissions. With reducing the greenhouse effect and reducing dependence on fossil fuels being a top priority globally, new sustainable methods of hydrogen gas production must be explored. Biomass gasification offers a solution for producing hydrogen, as it allows for energy recovery from waste biomass and the production of not only hydrogen but also fuels and other value-added chemicals. This process offers flexibility in input feedstocks and output products.

Biomass is a significant source of energy, accounting for approximately 10-14% of the global energy supply. In addition, it is responsible for fulfilling up to 90% of the total energy demand in rural and remote areas of developing countries worldwide [1]. It is projected that biomass will continue to be the primary source of energy for developing countries in the future as over 80% of the world's population is expected to reside in rural and remote areas of developing countries by 2050 [2-3].

There are numerous techniques for biomass waste to hydrogen conversion, but currently, most of these methods are only being tested on a small scale in laboratories or pilot projects. One such method is gasification, which has been used for over 100 years to produce syngas and biochar using various types of gasifiers. Among these gasification systems, the downdraft gasifier with throat has been found to be the most effective for producing high-quality syngas. However, gas cooling and cleaning are also critical for achieving the desired output in a gasifier reactor system. Additionally, the conversion of unwanted gas streams and the utilisation of waste heat can lead to higher energy efficiency in the system.

The gasification process requires high temperatures (>700°C) and a gasifying agent to convert waste biomass into syngas, which is a mixture of carbon monoxide (CO), CO_2, CH4 and hydrogen. Tar and biochar are also produced during the gasification process. Thermal cracking in the presence of oxygen can be used to convert the tar, and a water gas shift reactor can be used to increase the production of hydrogen. Separation techniques like pressure swing adsorption or membrane separation can be used to extract hydrogen from syngas. The yield of hydrogen from gasification depends on the physical and chemical properties of the biomass. Therefore, the production of hydrogen from waste biomass requires optimisation of the process and the identification and characterisation of biomass to achieve optimum yields of hydrogen gas.

To improve the techno-economic feasibility of gasification systems, it is necessary to identify and optimise the various process parameters involved at different stages of the process, such as feedstock preparation and characterisation, gasification, tar cracking, gas cooling and clean-up, shift conversion, and purification. Computational tools can also be used to enhance the process parameters for better output variables.

Current Status of Hydrogen: Global as well as Indian Demand

The utilisation of hydrogen is anticipated to rise significantly in the near future to address the issue of CO_2 emissions and create a carbon-neutral environment worldwide. By 2050, it is projected that the demand for hydrogen in India may quadruple, representing nearly 10% of the global hydrogen demand. Fig. 1 and 2 provide the current worldwide hydrogen demand and hydrogen demand in India by different sectors, respectively [5]. Based on a cost parity analysis without policy intervention, Fig. 3 presents the future forecast for hydrogen demand and the proportion of green hydrogen by 2050 [6]. The following are some of the significant findings regarding global hydrogen demand:

- Global hydrogen demand was around 115 Mt in 2020, having grown 50% since the turn of the millennium.
- Expected annual demand of hydrogen will increase to 200 Mt in 2030 and 530 Mt in 2050.
- The annual demand for hydrogen in India was 6 MT in 2020, primarily for petro refining, ammonia, and methanol production. Currently, these two applications account for more than 80% of hydrogen consumption, which is primarily derived from natural gas using steam methane reforming.
- Direct reduction of iron (DRI) in steel production also has major demand for hydrogen. As per the report of Ministry of Steel, around 35% of the steel production in India is produced from DRI-based plants.
- It is expected that the hydrogen demand of India will increase from 6 MT as of 2020 to more than 11 MT by the end of 2030.
- In India, currently all the hydrogen production is done using natural gas which results in emission of CO_2 into the environment. SMR produces around 11 kg CO_2 per kg of H_2 while coal gasification produces around 20 kg CO_2 per kg of H_2. However, if up to 5 MT of green hydrogen is used per year, it could reduce the consumption of natural gas by 11 MT per year or around 25 MT of coal per year. This would also lead to a reduction in CO_2 emissions, from natural gas by 34 million MT per year or from coal gasification by 57 million MT per year by 2030.

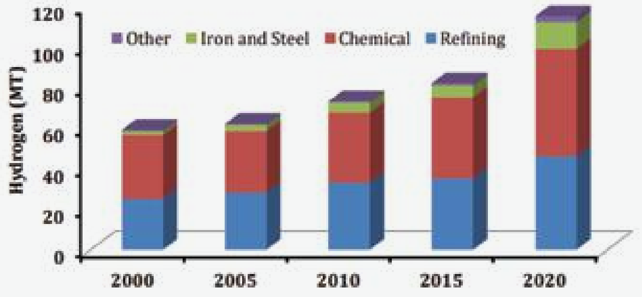


Fig. 1: Global hydrogen demand in million tonnes by sector, 2000-2020 [5].

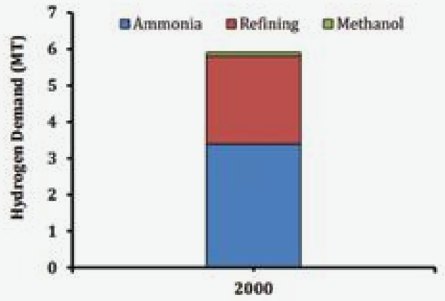


Fig. 2: Hydrogen demand in million tonne for various sectors in India [6].

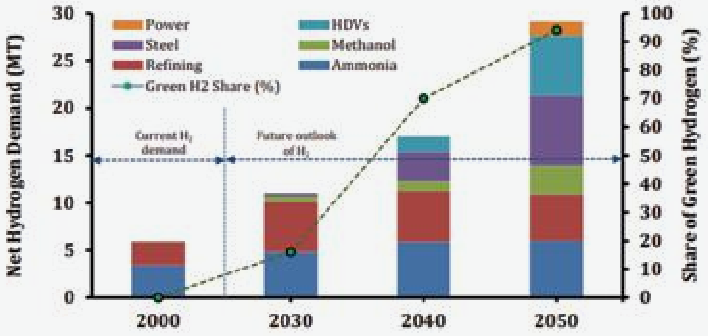


Fig. 3: Current demand and future outlook of hydrogen and potential green hydrogen share at cost parity [6].

Hydrogen Energy Carrier

The hydrogen economy is rapidly gaining importance worldwide, and India is taking significant steps towards its development. With its high energy content (33.2 kWh/kg), hydrogen is an ideal non-carbon energy carrier for various applications, including thermal, electrical, cooking, and mobility. As a result, it is a universal energy source for nearly all end-users, ranging from industry (across all segments) and commercial centres to residential habitats and the transport sector. The development of hydrogen fuel cells (HFCs) or on-board reformed hydrogen fuel cells (ORHFCs) with the possibility of adding a combined heating and cooling (CHP) system has made HFCs highly efficient, making hydrogen a potent clean energy option.

While one pathway to producing green hydrogen is through water electrolysis using renewable energy, it is equally critical for India to build a hydrogen economy using solid fuels such as coal, petcoke, and solid waste, including MSW and biomass. This approach would generate hydrogen based on a preliminary analysis and the proposed technology route outlined in this chapter at a reasonable cost (under Rs 200/kg compared to nearly twice the cost from renewable energy and water electrolysis using today's state-of-the-art technology). Fig. 4 provides a comparison of the energy-carrying capacity of hydrogen with other energy sources, while Table 1 illustrates the colour code of hydrogen with GHG emissions from the production process and the acceptance level of different processes.

Advantages of Green Hydrogen Economy

There are many advantages of green hydrogen economy, including:

- Hydrogen produces energy and water when it is used as fuel.
- It has a high energy density (on a mass basis).
- It produces no carbon emissions or any toxic gas.

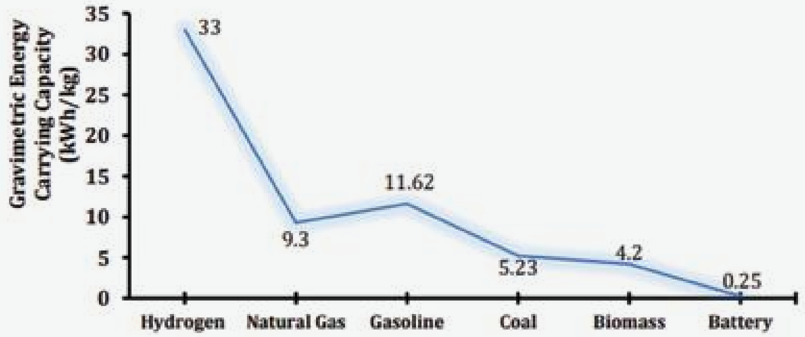


Fig. 4: Comparison of energy carrying capacity hydrogen with other.

Table 1: Colour code of hydrogen with greenhouse gas emission and acceptance level of different process

Colour Code	**Brown**	**Grey**	**Blue**	**Turquoise**	**Green**
Energy Source	Coal or lignite	Natural gas	Any non-renewable energy source	Methane	Any renewable energy source
Process of getting hydrogen	Gasification	Steam methane reforming	Steam methane reforming and carbon capture & storage	Pyrolysis	Electrolysis of water and biomass gasification
Highest to lowest greenhouse gas emission	↔				
Lowest to highest acceptable level	↔				

- Hydrogen can be used to produce fuels of lower C/H ratios which can also moderate the CO_2 emission intensity, while utilising the existing infrastructure.
- It can be produced in central as well as decentralised facility using various methods like gasification and electrolysis.
- Due to its low density, it is a safer fuel than LPG, NG, gasoline and diesel. If hydrogen leaks, it rises up quickly.
- The simpler chemistry and small molecular size of hydrogen allow for higher activities, and therefore, clean combustion of hydrogen is possible with little or no NOx emissions.
- It reduces dependency on fossil fuels.

Market Demand and Application

As can be seen from Table 2, if all the current demand for fossil fuels, including crude oil, coal, and natural gas, were hypothetically replaced by hydrogen, approximately 276 million MT/year of hydrogen would be required. Additionally, if the hydrogen is green, there would be a corresponding decrease in CO_2 emissions by about 2,725 MT/year. Therefore, there is a strong need to replace fossil fuels with hydrogen in current applications.

2.10.1 Agro-waste Feedstock Potential

For hydrogen production, agricultural waste such as crop residue waste, rice straw, wheat straw, sugarcane bagasse/trash, cotton stalk, sorghum stover, etc., which are abundantly available and have low commercial value, can be effectively utilised. By using these materials as feedstock for hydrogen production, waste management problems or stubble burning of agro residue in rural areas can be addressed, thereby reducing pollution and other environmental hazards. These feedstocks are abundantly available throughout the year in the country, without any supply obstacles.

Table 2: Market demand of green hydrogen and equivalent CO2 saving per annum

Fossil Fuel type	**Annual Indian Demand**	**Green H2 requirement for replacement**	**Equivalent CO2 saving due to replacement**
Coal	430 MTPA oil equivalent	143 MTPA	1625 MTPA
Crude Oil	250 MTPA	83 MTPA	740 MTPA
Natural Gas	130 MTPA	50 MTPA	360 MTPA
Total		**276 MTPA**	**2725 MTPA**

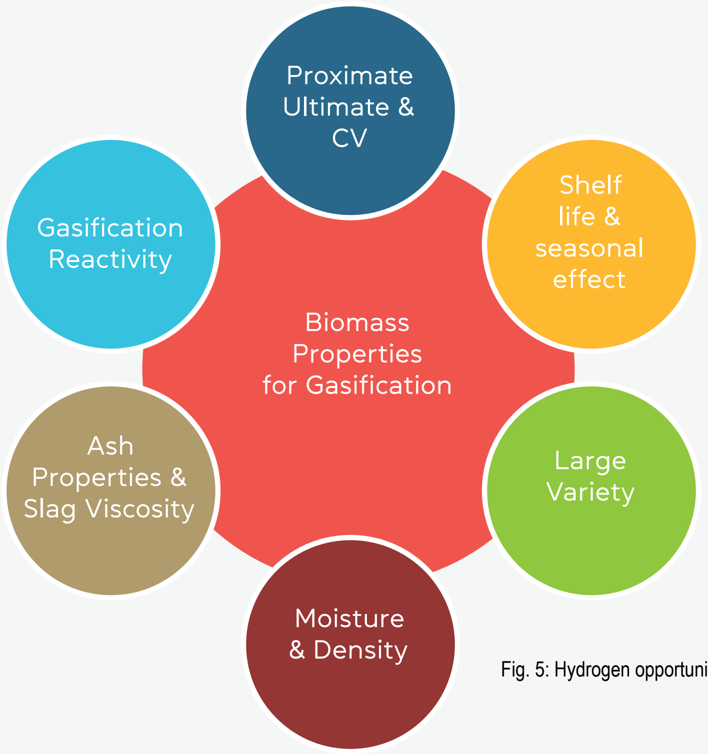


Fig. 5: Hydrogen opportunity from agro-waste

India, being a major agrarian society, generates a lot of agro residues. Overall, approximately 686 million MT of crop residue biomass in the form of stacks, roots, trashes, husks, and yard trimmings are produced on an annual basis, of which 234 million MT (34% of gross) are estimated as surplus for bioenergy generation and available in distributed form [8]. According to the MNRE report, it is estimated that 750 million MT of agricultural and forestry biomass is generated in India per year. The surplus biomass available in India is around 230 million MT out of the total available, which has the potential for 28 GW of energy production (MNRE, 2023) [9].

Based on the survey data from 2010–11 to 2015–16 covering production statistics of main selected crops such as wheat straw, rice straw and husk, sugarcane leaf and bagasse, gram, soyabean, groundnut, castor, etc., it is estimated that the annual averaged biomass generation from these crops was around 683 million MT. It was also found that more than 80% of biomass is generally produced from rice straw and husk (33%), wheat straw (22%), sugarcane tops and bagasse (17%), and cotton (8%). The majority of biomass was produced in Uttar Pradesh, Maharashtra, Madhya Pradesh, Punjab and Gujarat, the top five states in India in generating biomass [10].

Agricultural biomass is normally used for cooking and has heating applications in rural households, and sometimes it is burnt in the open air or combusted (incineration systems) after making briquettes/pellets. The traditional/open field burning of biomass adds to the pollution load and causes serious health problems. Besides, the energy conversion efficiencies of such traditional burning systems are very poor, normally in the range of 10-20%, making such conversion technologies less viable.

2.10.2 Agro-waste Gasification Process

It is a thermo-chemical process involving multiple chemical reactions wherein a carbon-containing feedstock, such as agro waste, is converted into synthetic gas in partial supply of air, oxygen or steam [6,7]. The process operates at a sufficiently high temperature (>600–1000°C) in order to thermally degrade the biomass waste to yield the hydrogen-rich syngas [13]. Several advantages are associated with gasification such as an increased heating value of fuel by the rejection of non-combustibles like nitrogen and water, a reduction in oxygen content of fuel, exposure to H_2 at high pressure or exposure to steam at high temperatures and pressures where H_2 is added to the product will raise the product's relative hydrogen content (H/C ratio).

Biomass feedstock has varying moisture content during different seasons as well as in different parts of the country. Many researchers have reported the problems associated with moisture content during the gasification process. The feedstock quality, especially the moisture content, plays a significant role in the quality of the product after gasification, and less than 20% moisture content generally seems good for good quality product [14]. An overview of different production processes, types of hydrogen storage, various modes of hydrogen transportation, and end applications can be seen in Fig. 6.

Gasifying Medium

One of the important parameters to consider during the gasification of agro waste is the gasifying process's environment. Biomass gasification can be carried out in different media such as steam, air, CO_2, or oxygen, or a combination of these gases [4, 14-15]. The gasifying medium plays a significant role in converting solid carbon and heavier hydrocarbons into low molecular weight gases like CO and H_2. Oxygen is mainly used as a gasifying medium, either in pure form or via air. The products include CO and CO_2 when subjected to low and high oxygen levels, respectively [16-18]. Gasification proceeds towards combustion when oxygen is supplied over a threshold limit, resulting in the formation of flue gas instead of synthesis/producer gas. The formed combustion product or flue gases possess no residual heating value.

Similarly, when steam is utilised as a gasifying medium, the H/C ratio of the resulting product increases due to the higher amount of hydrogen per unit of carbon. Conversely, if air is used directly instead of oxygen, the nitrogen in the air dilutes the product, causing a decrease in the heating value of the gas produced in comparison to the heating value of the gas generated through oxygen/steam gasification [4,19]. Consequently, it can be inferred that the use of oxygen as a gasifying medium results in the highest heating value, followed by steam and air. The gas produced after air gasification is generally referred to as producer gas, while the gas produced through oxygen/steam gasification is known as synthesis gas.

Classification of Gasifier

The classification of gasifiers is mainly based on two criteria, namely the gas-solid contacting mechanism and the gasification medium. The gasifiers are broadly categorised into three types, namely fixed or moving bed gasifiers, fluidised bed gasifiers, and entrained-flow bed gasifiers. The gasifying medium flow direction further categorises each type of gasifier.

However, a particular gasifier type may not be suitable for all gasifier capacities. For instance, moving bed (updraft and downdraft) types are typically used for smaller units (under 10 MWth), whereas fluidised bed types are more appropriate for intermediate units (between 5 and 100 MWth). Entrained flow reactors, on the other hand, are utilised for larger capacity units (above 50 MWth) [4]. The key differences between these three gasifier types are presented in Table 3.

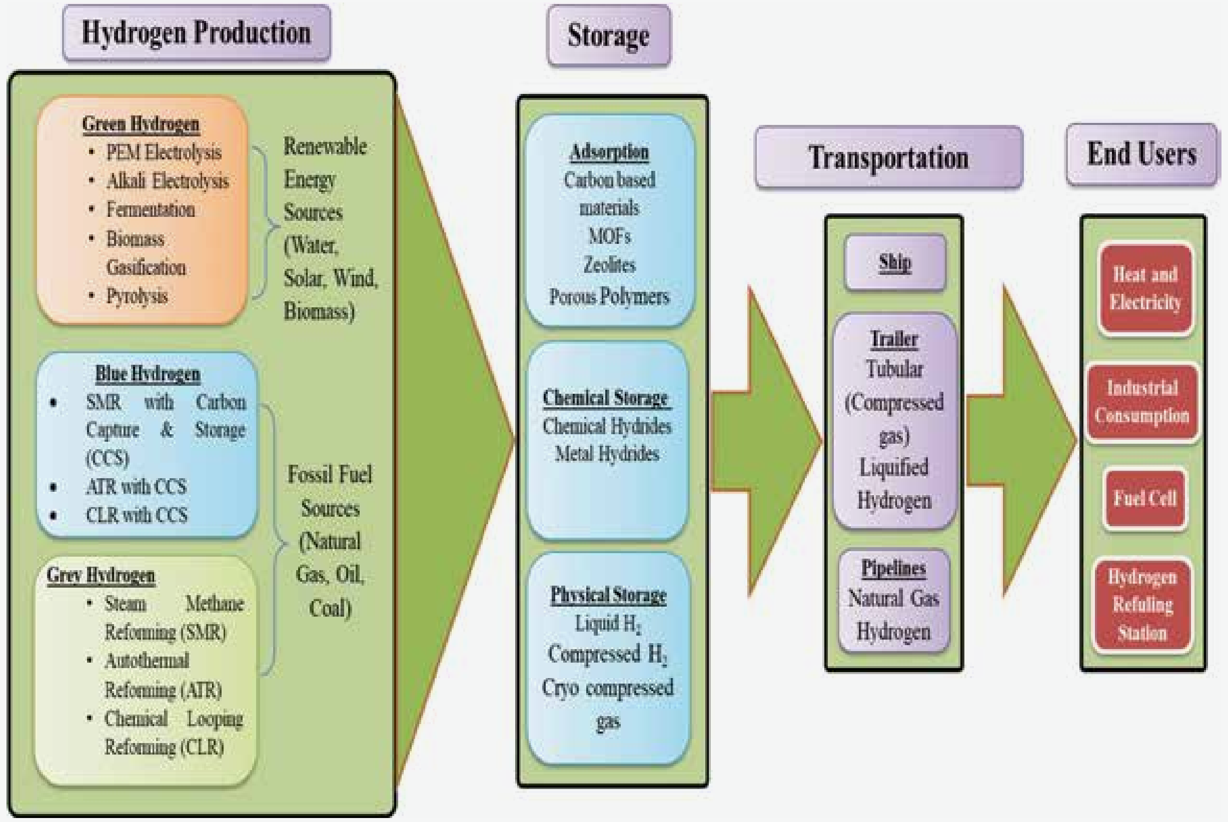


Fig.6: Overview of hydrogen production to end use.

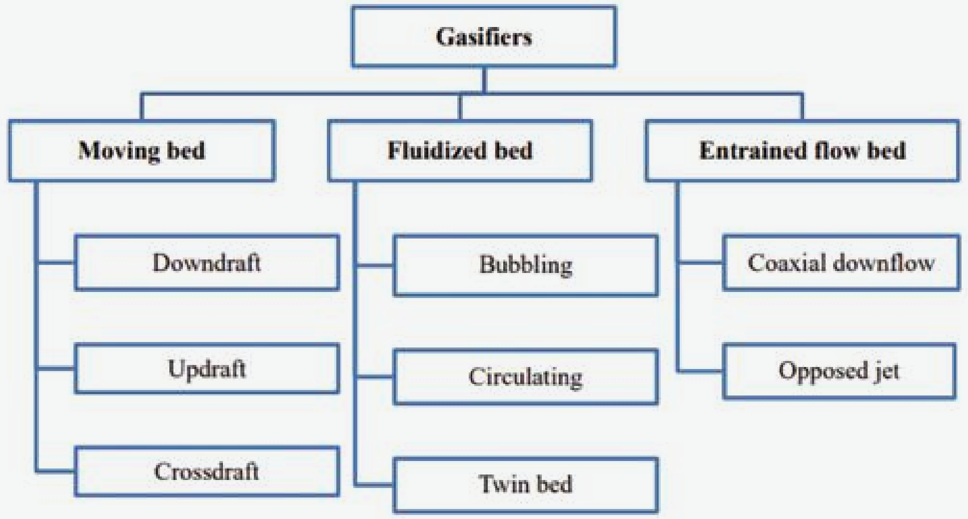


Fig.7: Classification of gasifier

Table 3: Major differences between the gasifier types

S. No.	Parameter	Fixed or Moving Bed	Fluidized Bed	Entrained Bed
1.	Feed size	Less than 51 mm	Less than 6 mm	Less than 0.15 mm
2.	Tolerance for fines	Limited	Good	Excellent
3.	Tolerance for coarse	Very good	Good	Poor
4.	Gas exit temperature	450-650 °C	800-1000 °C	Greater than 1200 °C
5.	Feedstock tolerance	Low rank coal	Low rank coal and excellent for biomass	Any coal including caking but unsuitable for biomass
6.	Oxidant requirements	Low	Moderate	High
7.	Reaction zone temperature	1090 °C	800-1000 °C	1990 °C
8.	Steam requirement	High	Moderate	Low
9.	Nature of ash produced	Dry	Dry	Slagging
10.	Cold-gas efficiency	80%	89%	80%
11.	Application	Small capacities	Medium size units	Large capacities
12.	Problem areas	Tar production and utilization of fines	Carbon conversion	Raw-gas cooling

Chemical Reactions During Gasification

In a typical gasifier system, biomass conversion takes place through four different stages, which are drying, pyrolysis, gasification, and combustion. During these stages, various reactions of different types, including endothermic and exothermic, take place simultaneously. The reactions that occur inside the gasifier are complex and can be found from reaction number R1 to R8. These reactions are usually classified into five types: i) carbon reactions, ii) oxidation reactions, iii) shift reactions, iv) methanation reactions, and v) steam reforming reactions.

Scheme for Hydrogen from Agro-Waste

High-purity and near-green hydrogen with a higher production rate can be obtained from advanced biomass gasification systems, as shown in Fig. 8. The syngas produced after the gasification of biomass typically contains a high amount of tar, which can be converted into more syngas by increasing the temperature. This process is called thermal/catalytic cracking of tar. Oxygen can be added to the gas leaving the gasifier during the thermal cracking stage to facilitate this process. After the thermal cracking operation, the temperature of the gas stream is lowered to around 250°C by water quenching, and solid particles are removed using a bag-house filter.

Combustion reaction

$C + ½ O_2 \leftrightarrow CO$ *Heat of Reaction*= -122(kJ/mol) (R1)

$CO + ½ O_2 \leftrightarrow CO_2$ *Heat of Reaction*= -283 (kJ/mol) (R2)

$H_2 + ½ O_2 \leftrightarrow H_2O$ *Heat of Reaction*= -248 (kJ/mol) (R3)

Water gas shift reaction

$C + H_2O \leftrightarrow CO + H_2$ *Heat of Reaction*= +136 (kJ/mol) (R4)

$CO + H_2O \leftrightarrow CO_2 + H_2$ *Heat of Reaction*= -35 (kJ/mol) (R5)

Steam reforming of methane

$CH_4 + H_2O \leftrightarrow CO + 3H_2$ *Heat of Reaction*= +206 (kJ/mol) (R6)

Boudouard reaction

$C + CO_2 \leftrightarrow 2CO$ *Heat of Reaction*= +171 (kJ/mol) (R7)

Hydrogasification

$C + 2H_2 \leftrightarrow CH_4$ *Heat of Reaction*= -74.8 (kJ/mol) (R8)

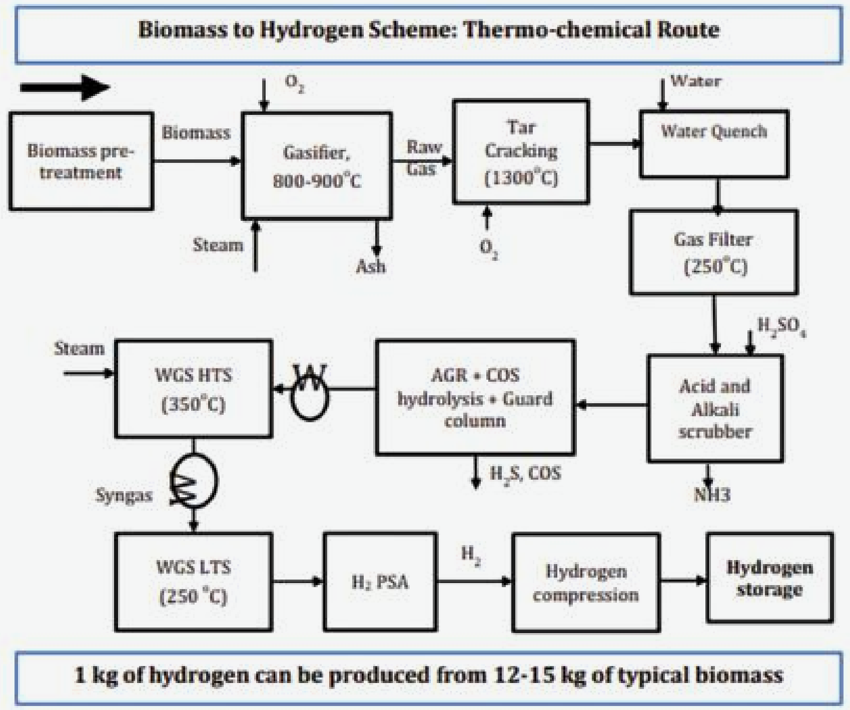


Fig.8: Proposed route for biomass to hydrogen production.

To increase the production of hydrogen, the water gas shift (WGS) conversion process is necessary. This process converts carbon monoxide (CO) in the syngas to CO_2 and additional hydrogen (H_2) through the reaction ($CO + H_2O = CO_2 + H_2$), which is exothermic and known as the water gas shift reaction (WGSR). Typically, 1 kg of biomass feed requires 1 kg of steam during the WGSR. The WGSR can be categorised based on temperature conditions, including High Temperature Shift Conversion (HTSC), Medium Temperature Shift Conversion (MTSC), Low Temperature Shift Conversion (LTSC), and Sour Gas Shift Conversion (SGS), with each shift reaction having different temperature requirements for maximum efficiency.

Depending on the syngas characteristics or final product quality requirements, one or more shift conversion reactions can be used. The SGS conversion process usually involves using a bed of cobalt-molybdenum catalyst and a temperature range of 230-260°C. A high-temperature shift reaction is generally carried out at a temperature range of 350-450°C, while a low-temperature shift can be carried out at a temperature of 250°C.

After the WGSR process, Pressure Swing Adsorption (PSA) is used to recover and purify the hydrogen from the hydrogen-rich gas stream produced by WGSR. Currently, PSA is an effective tool used to produce pure hydrogen from syngas. The PSA process relies on the differences in the adsorption properties of different gases to separate them under pressure. The tail-gas from the PSA process, which contains impurities, can then be sent into a burner for process heating and steam generation. The crude hydrogen obtained from the gasifier is a complex mixture of hydrocarbons, heavy chemicals, and moisture. Removing such impurities from hydrogen is an essential part of hydrogen energy utilisation.

Other separation processes such as low-temperature separation methods (cryogenic distillation and low-temperature adsorption) and membrane separation methods (inorganic membrane and organic membrane) could also be employed for hydrogen purification and separation. The application of a specific purification method depends upon the types and amounts of impurities. Impurities such as sulphide, HCHO, and HCOOH can be effectively eliminated by using low-temperature adsorption. However, this is a complex method that requires high energy consumption suitable for small-scale operations. Metal hydride separation and palladium membrane separation methods are feasible when separation of a gas source with a high content of inert components is required, but the purification efficiency is low.

Recently, new membrane technologies such as carbon molecular sieve membranes, ionic liquid membranes, and electrochemical hydrogen pump membranes have been developed, but their industrial implementation is limited. The Pressure Swing Adsorption (PSA) technique is the most common and frequently adopted hydrogen purification technology widely used in coal gasification and natural gas reforming processes because of its long service life and economic feasibility. In most PSA processes, activated carbon and zeolite are used as adsorbents to remove critical impurities such as CO_2 and CO from the crude hydrogen.

2.10.3 Hydrogen Storage and Dispensing

The pure hydrogen stream obtained from the PSA can be compressed using booster pumps to reach typical dispensing pressures of 350 or 700 bar and then filled into cylinders or storage tanks for dispatch to customers. If a gas grid is available, the hydrogen can be boosted to the appropriate pressure and injected into the gas grid. Hydrogen, either in molecular form or combined form (such as methanol, ammonia, or DME), can be used to power fuel-cell-based vehicles. However, this would require suitable infrastructure for the storage, distribution, and dispensing of hydrogen (in both molecular and combined form).

Storage of hydrogen can be done either in the form of compressed gas or in the form of liquid. A high pressure of the order of 350–700 bar is required to store hydrogen in the gaseous state. On the other hand, cryogenic temperatures are required to store hydrogen in the liquid state because hydrogen has a boiling point of -252.8°C at atmospheric pressure. Other options to store hydrogen include adsorption on the solid surface or absorption within the solid [24-25]. Different methods of hydrogen storage can be seen in Fig. 9. The basic features and requirements of different types of hydrogen storage are as follows:

Mechanical Storage Tanks
Hydrogen needs to be compressed under high pressure, such as 700 bars, due to its low density. Tanks and pumping systems need to be designed specifically for hydrogen, and high pressure means higher compression work.

Storage in Materials
Hydrogen can be stored in solid-state materials, such as metal and chemical hydrides. This can potentially enable even greater densities of H_2 to be stored at atmospheric pressure and avoids compression work penalty. During filling and releasing the gas, heat is released and absorbed, respectively, hence efficient thermal management is essential.

Liquefied Storage Tanks
Pure hydrogen can be liquefied before it is transported to increase its density. However, liquefaction requires hydrogen to be cooled to minus 253°C, which incurs an energy penalty equivalent to 25-35% (10% for natural gas) of the initial quantity of hydrogen. High levels of insulation will incur further cost.

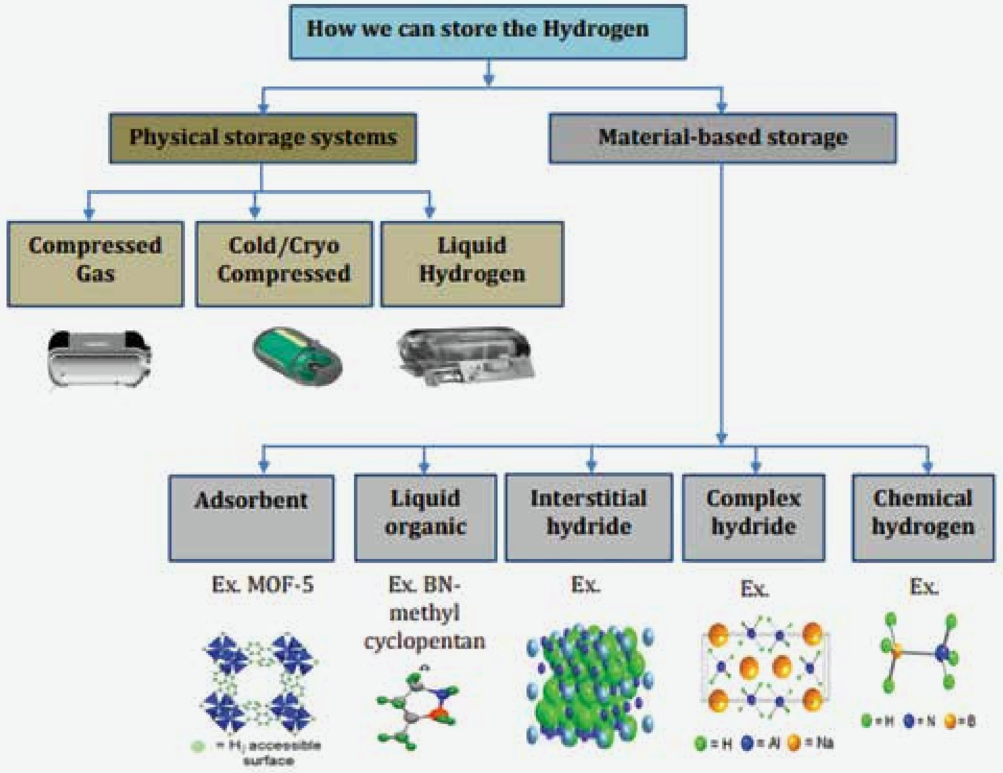


Fig.9: Various methods of hydrogen storage [24].

2.10.4 Hydrogen Safety

Biomass gasification is a complex technology and hydrogen production plants based on biomass gasification must comply with various guidelines and national laws.

Each process step must be carefully considered for its health, safety, and environmental constituents during the planning, engineering, construction, and operation stages. Identification of process safety and risk assessment is an important activity during biomass gasification. Globally, it is gaining interest as the most cost-effective tool to identify safety requirements and reduce risks during operation.

People dealing with gasification plant construction and operation generally recognise the requirements of risk assessment, but due to a lack of experience and resources, they may not assess the risk quantitatively. By using advanced safety techniques and tools during gasification plant design and operation, many key safety issues can be easily identified.

Implementation and incorporation of important safety features during the initialisation step of plant design will result in safe operation during the production process. This will not only meet the necessary legislative standards but also satisfy the criteria of ALARP (As Low As Reasonably Practicable) while handling various raw materials in the proper way. Although several hazardous events may occur with various consequences, the most critical issues are (i) fire and explosion hazards during operation, (ii) operational failures due to various reasons, and (iii) unplanned release of hazardous liquids, chemicals, and gases.

2.10.5 Production Cost of Hydrogen Using Major Methods

The cost of hydrogen production from different methods was analysed based on various assumptions and market surveys, and the results are summarised in Table 4. It is possible to produce 1 kg of hydrogen from 12-15 kg of raw biomass through the thermochemical conversion route.

The proposed technology (shown in Fig. 8) for biomass waste gasification has some unique features. It has the capacity to produce 100 kg of hydrogen from 1.2-1.5 TPD of MWS/biomass with 85-95% conversion efficiency. With this high efficiency, the proposed pathway can be used to convert all available agricultural biomass to hydrogen energy. One kilogram of biomass is capable of producing approximately 85 grams of hydrogen. While 1 kg of biomass may yield a maximum revenue of Rs 3 by producing 0.6 kWh of energy, converting it to hydrogen using the proposed technology can yield approximately 0.093 kg of hydrogen and a revenue of Rs 15, which is five times higher revenue. The total cost works out to be approximately Rs 150/kg after the successful demonstration of the indigenised technology.

2.10.6 Major Challenges for Green Hydrogen Economy

To develop the indigenous technology for low-cost hydrogen production from biomass/agro-waste, there are many challenges, and some of which are summarised as follows:

Challenge of safety is the first and the foremost to be addressed since:

- High flame speed, wide flammability limit of hydrogen, need extra safe approach for handling.
- Little study on its safety and hydrogen-related disaster mitigation with regards to its handling by the general public.
- No research on long-term adverse health effects on people or animals in case of chronic or persistent exposure.
- In the future, with the scale-up, there will be associated waste generation and its management will be highly critical.

Biomass feedstock:

- Biomass characteristics and availability play an important role in the economy of the process.
- To overcome these issues in different seasons throughout the year, an appropriate amount of biomass needs to be stored in advance.

Table 4: Cost of hydrogen production

S. No.	Water splitting (high pressure electrolyzer)	Steam-Methane reformation (SMR)	Methane Pyrolysis (The new process)	Coal gasification (high ash India coal)	Biomass waste to hydrogen
Yield (kg of H_2)	1 kg of hydrogen/ 55 - 60 kWh_e	1 kg of hydrogen /3 kg of Methane	1 kg of hydrogen/ 4,2 kg of Methane	1 kg of hydrogen/19.2 kg of HAIC	1 kg of hydrogen/15 kg of biomass
Primary energy cost	At Rs 3/kWhr	18-41.4 Rs/kg of natural gas	18-41.4 Rs/ kg of natural gas	1.8-3.5 Rs/kg of HAIC Imported is nearly the same on eq. cal. Basis	If MSW cost is zero. Others is governed by policy
Energy costs/MJ	Rs 0.83 / MJ_e	0.836-0.36 Rs/MJ	0.836-0.36 Rs/MJ	0.11-0.239 Rs/MJ	0 - 0.2 Rs/MJ
Cost of hydrogen	240-300 Rs/kg	200 - 300Rs / kg	200 Rs/kg	120-160 Rs/kg	120-160 Rs/kg
CO_2 emission	Associated with electrolyzer manufacturing	8.07 kg of CO_2 Kg	1.67 kg of CO_2 / kg of hydrogen	21 kg of CO_2 per kg	Carbon neutral and hence zero

Biomass supply chain:

- For the large-scale plants, the required amount of biomass will be huge, which may not be accessible through a solitary source, and may require collection which may increase the transportation charges. This can be overcome by setting up small-scale plants in a decentralised manner.

2.10.7 Approach for Green Hydrogen Economy in Indian Scenario

Some of the key points on the economical approach for green hydrogen production in the Indian scenario are summarised in Table 5.

- It is important to pursue the two approaches shown in Table 5 in a decentralised manner and using existing infrastructure. Both renewable electricity and biomass/waste can be generated/sourced in a decentralised manner.
- Decentralised manufacturing and consumption can eliminate or reduce the transportation and storage challenge.
- Injection of excess hydrogen into existing natural gas lines will result in hythane (mixture of H_2 and natural gas).
- The use of hythane is proven and can be promoted on a large scale for domestic, industrial and transport applications in the future.

2.10.8 Conclusion

To conclude, this chapter covered several topics related to hydrogen, including its demand, the potential for using biomass as a source for hydrogen production, the process of biomass gasification, and the challenges involved in hydrogen enrichment, purification, and storage. The chapter also outlined an approach for achieving a green hydrogen economy in India, emphasising the significance of biomass as a source of energy that can help meet global energy demands. While there are several hydrogen production technologies available, biomass gasification is expected to be the most cost-effective option in the near future. India, with its abundant supply of biomass and waste, has the potential to generate hydrogen at a low cost through gasification. However, challenges such as biomass collection and high production costs need to be addressed for the technology to be commercially viable on a larger scale. In the future, advancements in agro-waste gasification technology may help overcome these challenges and make the process more accessible for widespread use.

2.10.9 Future Direction and Recommendations

- Agro-waste gasification demonstration units should be established for the production of hydrogen from renewable sources.

Table 5: Key points of green hydrogen production from renewable electricity water electrolysis process or via using the biomass waste gasification

Green hydrogen using renewable electricity	Green hydrogen using biomass and waste
✤ Renewable energy installation and usage picking up, especially in solar and wind. ✤ Excess electricity generation curtailment is a big challenge. ✤ H_2 production by using excess electricity is an attractive option as the cost of hydrogen will reduce drastically. ✤ For solar wind hybrid based commercial electrolysis based hydrogen cost, for India, can be about Rs 150-240 /kg hydrogen in future.	✤ Availability of water is a constraint if hydrogen is to be produced via electrolysis. ✤ With the availability of large amounts of biomass and wastes, India has large potential to generate hydrogen by the means of gasification at a low cost. ✤ Cost target of Rs 120-160/kg of hydrogen (or lower) can be achieved by using biomass.

- India needs to create its own unique path for renewable fuels. This path should involve blending all types of hydrogen and incorporating CO_2 capture and fuel-cell-based end-use patterns.
- Our target should be to produce 25 million MT of hydrogen by the end of this decade, which is equivalent to 75 million MT of crude oil or 100 GW of electricity.
- Additionally, it means a saving of 800 million MT of CO_2, and this can come equally from renewable, biomass, coal, and natural gas for India.
- It is crucial to capture and utilise CO_2 in the case of biomass to make the process carbon neutral.
- The gasifier may be integrated with CCUS units to produce green hydrogen, and it is important to ascertain the economics before deciding on the location of the plant.
- We need to develop CCUS technologies for net-zero carbon by 2070.

2.11

Biomass to Chemicals and Energy

YOGENDRA (YOGI) SARIN, Founder/ President/ CEO, Patron Scientech Inc. USA

We make the world we live in and shape our own environment.

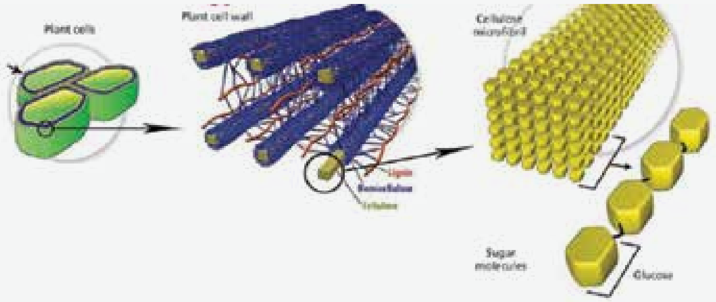
Orison Swett Marden

Major agricultural countries with ample land mass, including the U.S., Canada, Australia, China, India, Brazil, France, Germany, Japan, South Africa, and others, possess enough renewable biomass to reduce their dependence on petroleum refineries for fuels and petrochemicals used in the production of everyday chemicals and consumer products. Shifting away from crude oil imports could lead to a reduction in carbon emissions, energy security, and empowering farmers.

Using sustainable solutions from biomass waste could create a negative carbon emission future for biofuels and help combat climate change. This could be one of the best pathways to improve the lifestyle of the 60% of the Indian population who are involved in farming.

Below are brief descriptions of some biofuel options, including ethanol, synthetic aviation fuel, bio-naphtha, renewable diesel, green methanol, green ammonia/urea, boiler/bunker fuel, and clean bio-cogeneration.

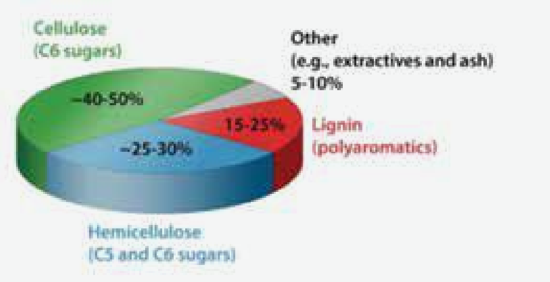
2.11.1 Basic Structure of Biomass



2.11.2 Feedstock Flexibility – Global Opportunities for Deployment

Technology well suited for agricultural residues, energy crops, woody biomass, and forestry residue.

2.11.3 Typical Biomass Composition Source: Office of Biological and Environmental Research of the US



2.11.4 Biomass to Chemicals to Biofuels

- **Biomass to ethanol:** Biogenic CO_2 is produced as a by-product in fermentation in the same amount as Ethanol, produced in a 1:1 ratio. Ethanol is used for biofuels, gasoline blending (E20, E85), downstream industrial, pharma and other applications.
- **Ethanol to ethylene:** Ethylene is the heart of a trillion-dollar global petrochemical industry, and this bio-ethylene is of higher quality than petroleum-based ethylene. It is a drop-in and all ethylene derivatives such as polyethylene, ethylene oxide/glycols, PVC, and others can be produced.
- **Ethanol and water mixture to green hydrogen:** No energy is required, unlike electrolysis, which needs an average of 50 MW/MT of hydrogen. Biogenic CO_2 is produced as a by-product. The hydrogen produced is suitable to make green ammonia, bio-methanol, fuel cell for automobiles, power turbines, blend with natural gas, and for all industrial hydrogenation applications.
- **Ethylene to SAF and renewable diesel and naphtha:** Using ethylene and a small amount of green hydrogen.
- **Bio- methanol production using all the CO_2 by-product and hydrogen:** Complete CO_2 sequestration. Methanol is suitable for all biofuels and industrial applications.

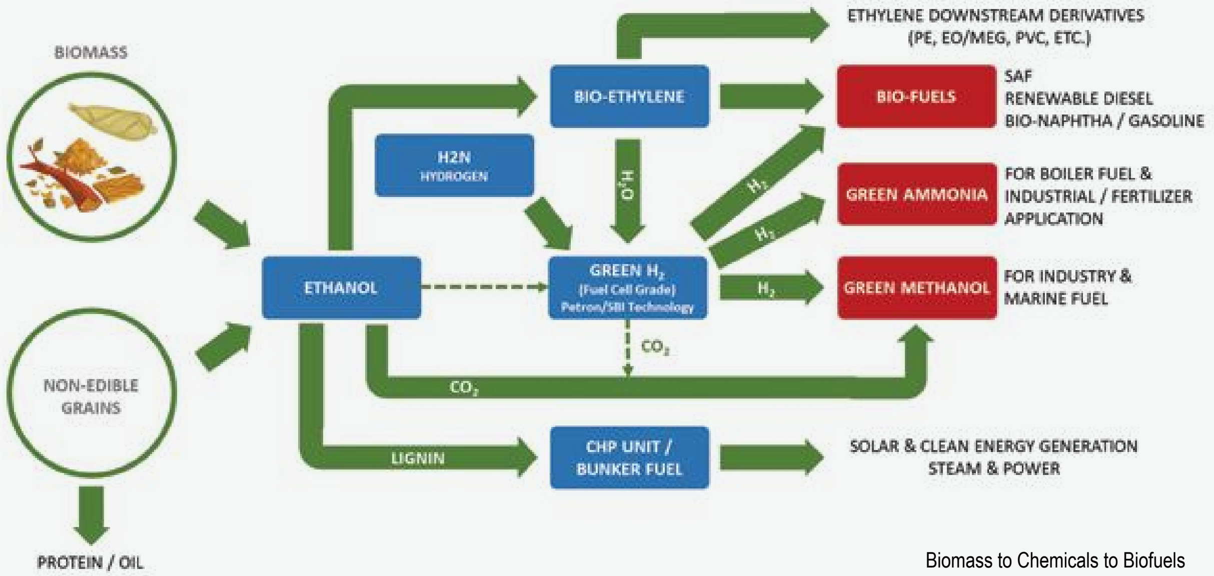
2.11.5 From Biomass to Biofuels

G20 Technology Cellulosic Ethanol from Biomass

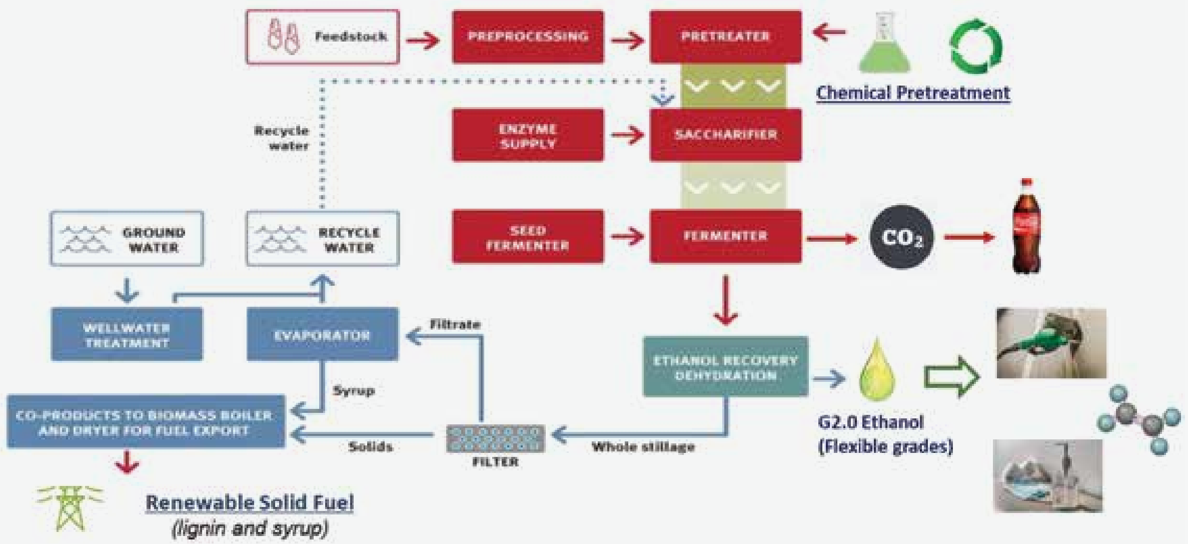
The process involves separating biomass lignin from cellulose and hemicellulose, with Petron having the most efficient pre-treatment technology available. The next step is breaking down cellulose and hemicellulose into simple C5/C6 sugars through the action of enzymes (hydrolysis/saccharification), followed by fermentation of those sugars to produce ethanol using yeast or bacteria. The resulting ethanol product is then distilled/purified and dried, with valuable co-products such as CO_2 and co-gen biofuel also obtained.

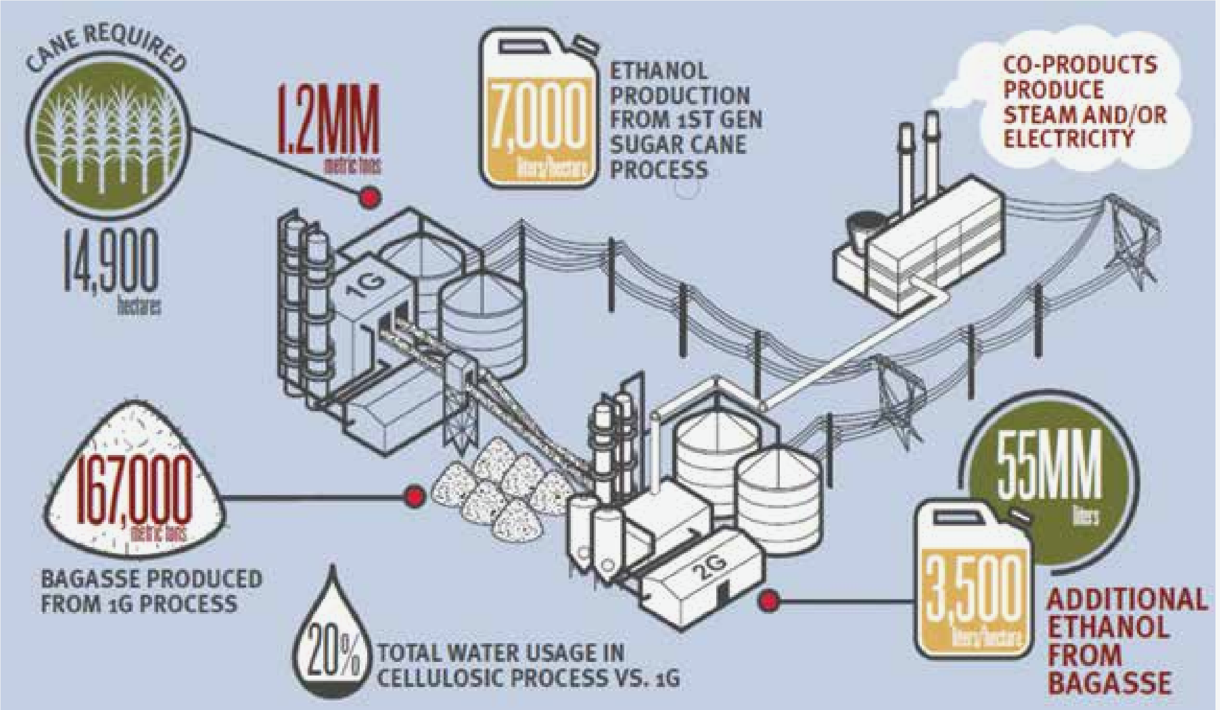
This is a highly integrated process that features extensive heat integration, water recycling, CO_2 capture, and co-product usage as a renewable fuel for the production of steam and power.

- **Pre-processing:** Reduce the size of the biomass particles to enhance pre-treatment effectiveness and increase enzyme access.
- **Pre-treatment:** Efficiently separate lignin from cellulose and hemicellulose using a highly efficient, patented proprietary process.
- **Enzymatic hydrolysis:** Use enzymes and water to break down the cellulose and hemicellulose into C5/C6 sugars.
- **Fermentation:** Utilise proprietary zymomonas bacteria to convert C5/C6 sugars into ethanol.
- **Lignin separation:** Separate lignin-rich solids



Biomass to Chemicals to Biofuels





from the ethanol solution and use them for steam and power production.

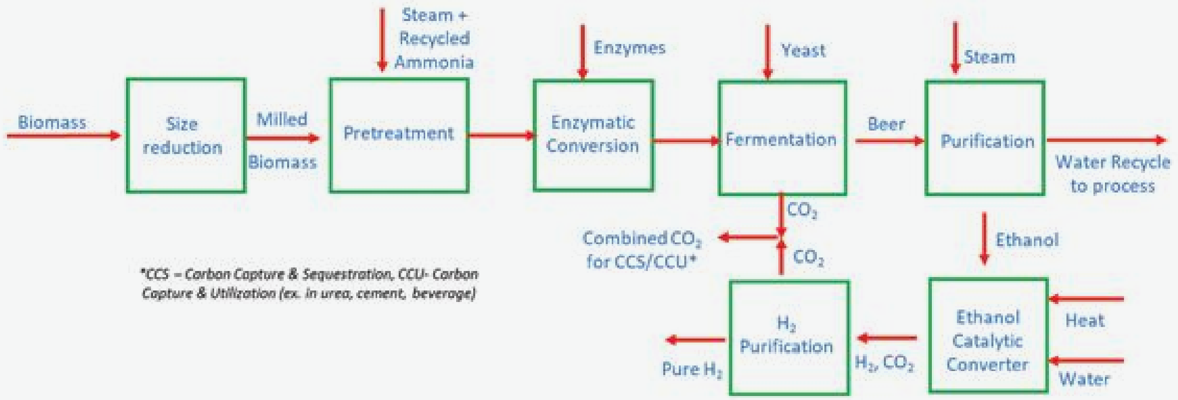
- **Distillation and drying:** Purify and dry the ethanol product to meet desired applications, whether they be fuel, industrial, or pharmaceutical.

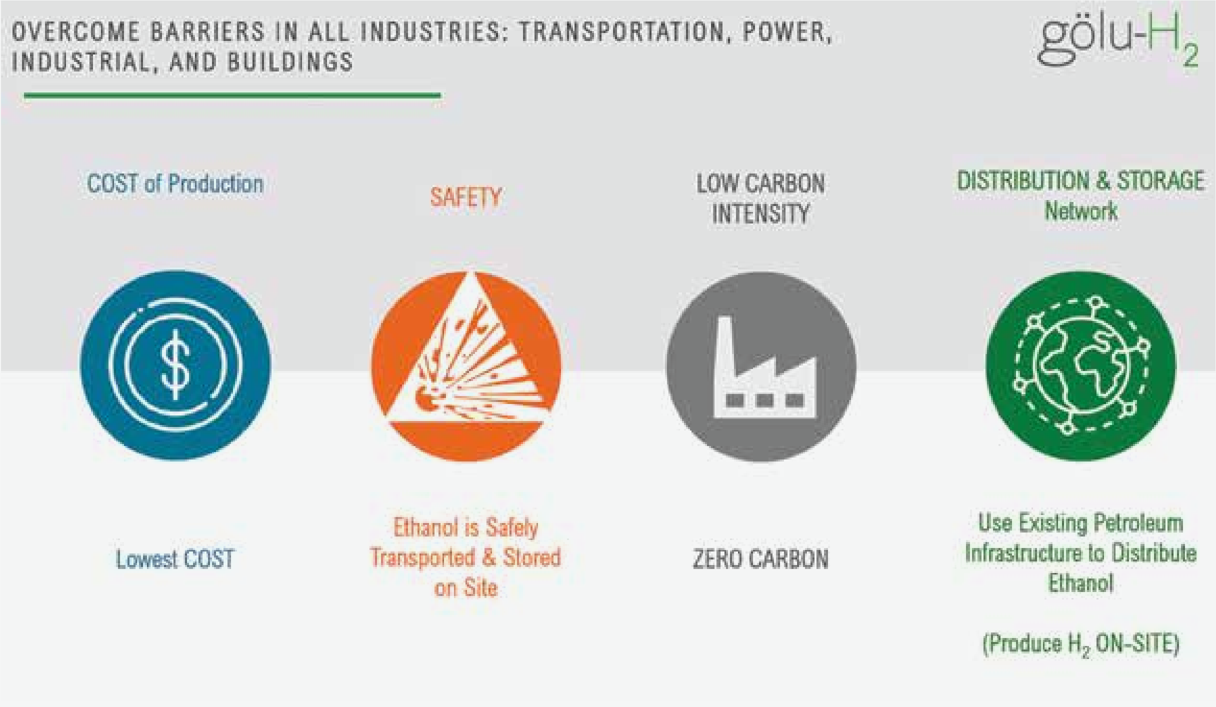
2.11.6 Potential of Bagasse for Cellulosic Ethanol

Cellulosic ethanol technology can process multiple feedstocks, including sugarcane bagasse. This process enables sugarcane mill owners to unlock additional value by producing approximately 50% more ethanol from bagasse, while also generating power from cellulosic ethanol co-products.

2.11.7 Biomass/ Non-Edible Grains/Sugar to Green Hydrogen (End-to-End Solution)

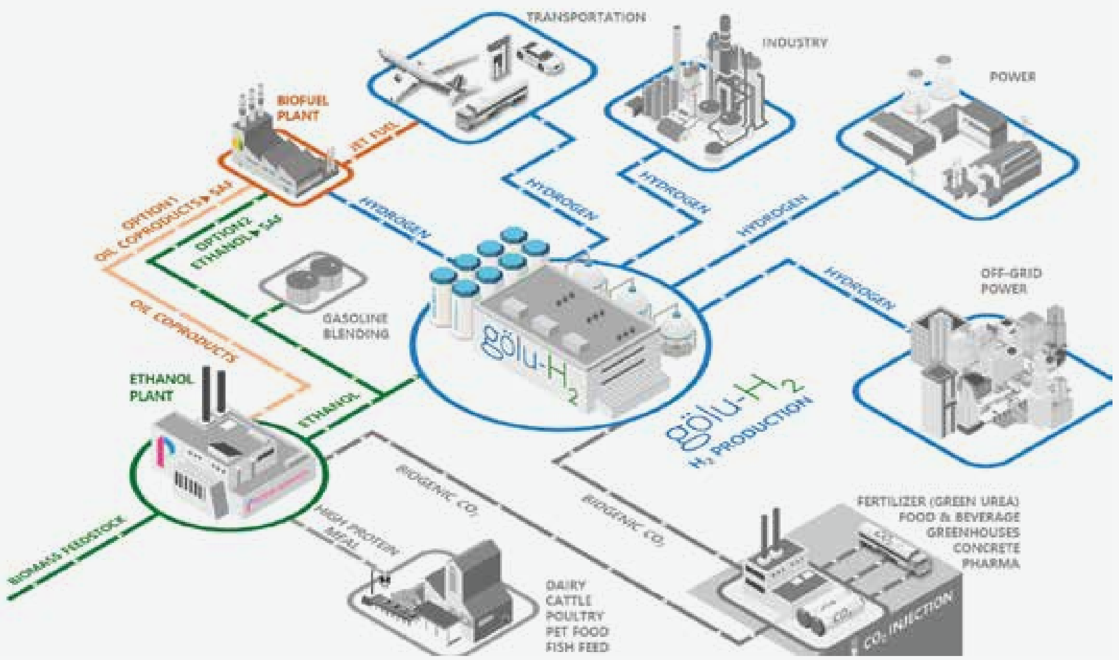
The process is Ethanol agnostic, meaning it is flexible in terms of ethanol production from multiple feedstocks, including both 1st and 2nd generation sources. Petron offers a complete integrated solution from feedstocks to green H2 via the ethanol intermediate, resulting in better economics.



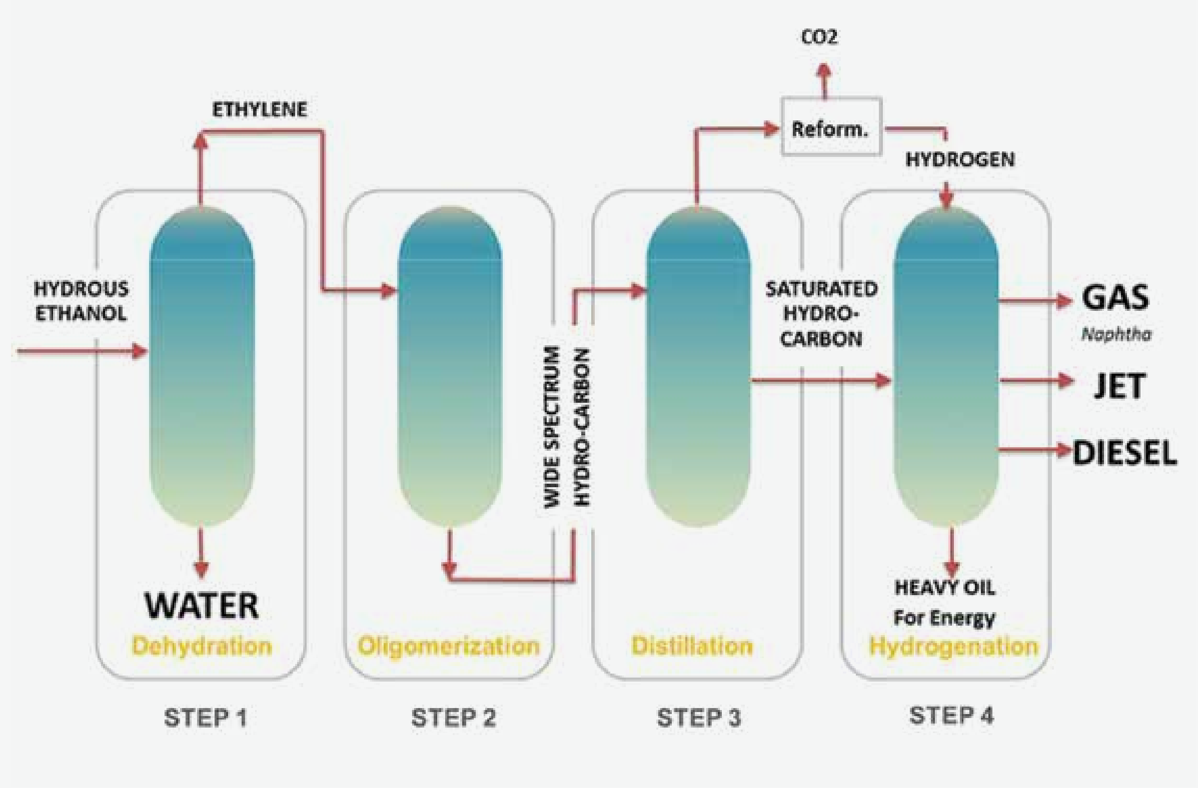


2.11.8 Biomass Hydrogen Driving Defossilisation

SBI's ethanol-to-hydrogen technology and Petron's biomass-to-ethanol technology are utilised to convert biomass into carbon-negative hydrogen, which can replace conventional grey hydrogen to decarbonise transportation, fuel production, power generation, and the production of everyday goods. Additionally, the project offers an optional alternative: production of oil-based SAF.



A >$500 million CAD Project in the Alberta Industrial Heartland



2.11.9 SAF/ Renewable Diesel/ Bio-naphtha from Bioethanol

STEP 1
Alcohol is catalytically dehydrated into its associated alkene/olefin (ethylene, butane, etc.). A co-product of this process is the creation of pure water, which can be used for boiler feed, electrolysed hydrogen production, or irrigation.

STEP 2
The olefin gas (such as bio-ethylene or bio-butene) is then converted into a wide spectrum hydrocarbon liquid in a dual multi-tube catalytic reactor. This process, known as oligomerisation, has been used since the 1960s on a refinery scale.

STEP 3
The wide spectrum hydrocarbon is separated into a fuel distribution of light carbon end products, naphtha, gasoline, jet fuel, diesel, and heavy oils using a standard distillation column, which is used throughout the petrochemical industry.

STEP 4
A mild hydrogenation with an industry-standard catalytic hydrogenation reactor is required to remove the small amount of olefinic edge conditions of the branched carbon chains of the jet fuel cut. The hydrogen demand is minimal, with sufficient production of internal hydrogen to adequately produce the exact fuel quality needed.

2.11.10 Efficient & Commercially Proven Production of Bio-Ethylene from Natural Agriculture Resources/Biomass

A foundation for building a chemical industry with sustainable solutions, helping the environment by reducing global warming and climate change.

Commercial Experience of Ethanol to Bio-Ethylene

The technology to convert ethanol (from any source) to ethylene has been around since before World War 2, but it was eventually overtaken by naphtha- and ethane-fuelled steam crackers, which rely on fossil and petroleum feedstocks and produce carbon emissions.

However, in the past 30 years, there have been significant developments in commercially proven and energy-efficient ethanol-to-bio-ethylene technologies. These technologies have been implemented in large-scale commercial plants and continue to improve in terms of reducing the carbon footprint and energy consumption.

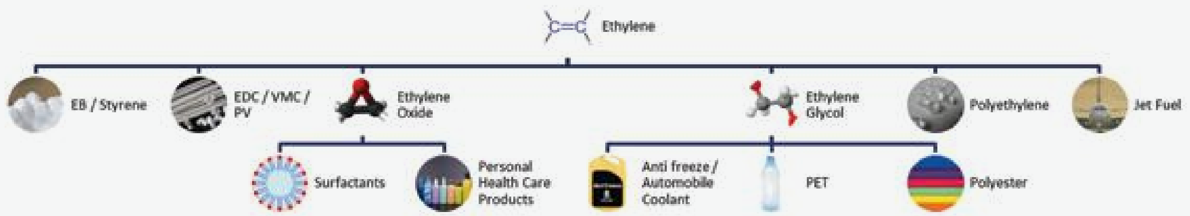
Numerous projects are currently underway, including several large multinational and downstream initiatives around the world. Compared to petroleum-based crackers, this technology can reduce CO_2 emissions by over 3 MT per MT of ethylene.

Diverse Applications

- Polymerisation: LLDPE/LDPE/HDPE
- Oxidation: VAM/EO/Glycols/Polyester
- Halogenation: EDC/PCV
- Alkylation: Styrene/Polystyrene/Rubber
- Oligomerization: Aviation JET Fuels
- Hydroformylation: Detergents

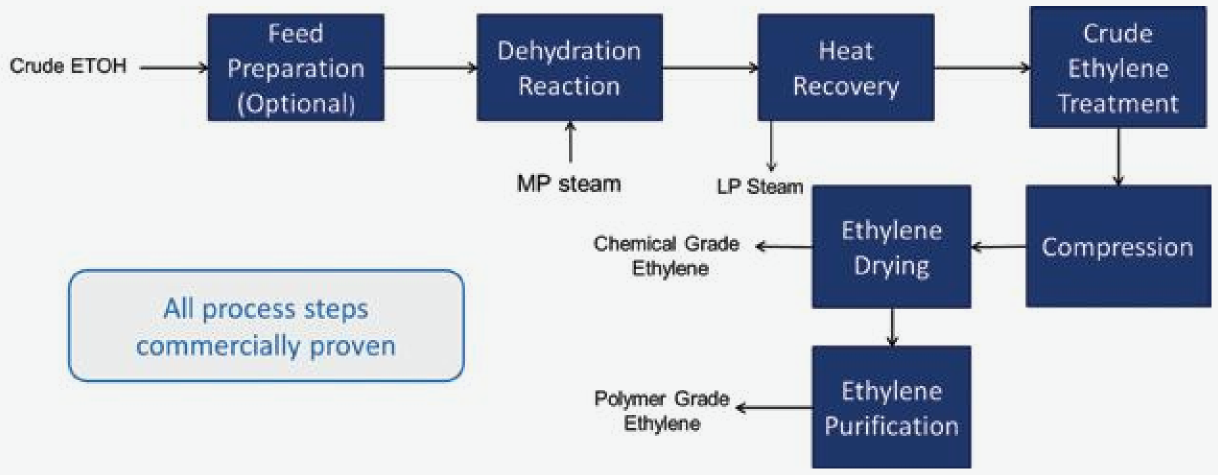
And Other Information

- Global Production: Circa 200 million MT/year, growing @CARG of 4.5%.
- Manufactured by 130 companies in 60 countries.
- >99% produced from petroleum.



2.11.11 Bio- Ethylene from Ethanol is Drop-in Solution and Provides Sustainable Feedback Option to Petroleum Ethylene

ETE Schematic Flow Diagram



Preliminary Capex Investment

Unit Size, KTA	ISBL Requirement
100	50-60 Million $
100	10,000 sq. meters
250	100-110 Million $
250	15,000 sq. meters
500	180-200 Million $
500	20,000 sq. meters
1000	340-360 Million $
1000	25,000 sq. meters

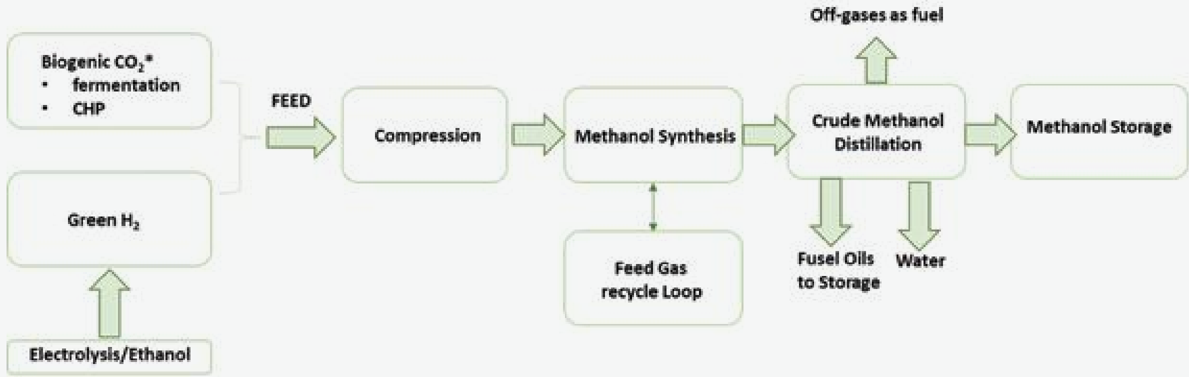
Example Plants Using Our ETE Technology


India


China

CO_2 And Hydrogen Conversion to Bio-Methanol

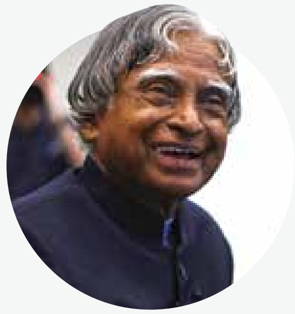
The technology for converting CO_2 and hydrogen to bio-methanol has been proven commercially. The CO_2 produced from the ethanol process is of high purity, which minimises the need for purification. Green hydrogen can be obtained from bioethanol, by electrolysis, or from other sources.



2.12

Synthetic Paraffinic Kerosene (Sustainable Aviation Fuel)

AMOL NISAL, Assistant Vice President, Praj Industries Ltd., India



Adversity always presents opportunities for introspection.

Dr A P J Abdul Kalam

While highlighting India's stride in the area of energy transition at India Energy Week on February 6, 2023[1], the Prime Minister Shri Narendra Modi emphasised the need for commercialisation of Sustainable Aviation Fuel (SAF) in India to decarbonise the aviation sector.

'We are making efforts towards the commercial utility of Sustainable Aviation Fuel.'

The announcement of India's Nationally Determined Contributions (NDCs), which include the goal of achieving net-zero emissions by 2070, is a pivotal moment in the country's fight against climate change. Today, India is one of the most prominent voices in the world advocating for energy transition, and alternative energy sources such as biofuels are one of the four major pillars of India's energy strategy, along with exploration and production, diversification, and de-fossilisation[1].

Indeed, India has made significant advances in the area of renewable energy, particularly in the biofuels sector. Ethanol blending of 10% with gasoline has already been achieved, and the 20% ethanol blending mandate is likely to be achieved soon in India's road transport sector [1]. Given India's ambitious NDCs, it is imperative to extend the success story of biofuels in the road transportation sector to the 'hard to abate' aviation sector.

The civil aviation sector in India consumed around 8 million MT of ATF and emitted around 20 million MT of GHGs in 2019 (pre-COVID)[2-3]. Globally, the civil aviation industry consumes around 250 million MT of fossil-based (conventional) ATF, generating approximately 1 billion MT of GHG emissions, accounting for around 2-3% of total emissions or around 10-12% of transportation emissions[4-5]. As per recent research, additional non-CO_2 pollutants, such as particulate matter, nitrous oxide, CO, water vapour, etc., from the exhaust of aircraft engines, also impact climate change and global warming[6].

Recently, at its 41st assembly, the International Civil Aviation Organisation (ICAO) announced the Long-Term Aspirational Goal (LTAG) to achieve net zero by 2050[7]. The use of SAF is considered as the only imminent solution for energy transition and decarbonisation of the aviation sector globally. The International Air Transport Association (IATA) has estimated that SAF will contribute to the reduction of around 65% of emissions required, to achieve net zero by 2050 globally and expected SAF requirement to achieve this is around 449 billion litres (350 million MT) per year[8]. Apart from the Carbon Offsetting & Reduction Scheme in International Aviation (CORSIA), established by the ICAO, various other policies and market drivers are already in place in the U.S. and EU to create demand and promote production of SAF.

This chapter will examine the current state of the SAF market, policy drivers in various countries, the role of government, feedstock sustainability and availability, technology pathways approved by ASTM, the readiness level of various technologies, the cost economics of SAF produced from various technologies and feedstocks, and ecosystem development.

The overall aim of this chapter is to provide a comprehensive overview of SAF, with the goal of making India a hub for SAF production and supply to decarbonise the global aviation sector. The chapter will also discuss the challenges and opportunities that lie ahead in achieving this goal.

2.12.1 About SAF

The conventional Aviation Turbine Fuel or ATF, produced from fossil sources such as crude oil, natural gas, shale oil etc., is used to power aircrafts with gas-turbine engines. There are various types of ATF, which are produced as per standardised international specifications (such as ASTM D1655). However, the most commonly used ATF in commercial aviation are of type Jet A and Jet A1.

ATF is a complex mixture of hydrocarbons, including aromatics, cycloalkanes, iso-alkanes, and n-alkanes, composed of molecules that range in size from 7 to 18 carbon atoms, with an average of 12 carbon atoms[4]. The composition of ATF is difficult to define precisely since it varies depending on the source of crude oil and the refining process. Therefore, ATF is defined in terms of its performance specifications rather than as a specific chemical compound[9]. Some of the performance specifications for ATF include specific energy, thermal stability, viscosity, density, freeze point, flash point, and distillate temperature[4].

SAF is a type of aviation fuel made from renewable or waste-derived sources. SAF has a composition similar to that of ATF and meets the sustainability criteria defined by the ICAO under CORSIA guidelines[10]. Certain types of SAF that contain lower levels of aromatics burn more cleanly and emit less SOx and particulate matter than conventional ATF.

In general, SAF is characterised as follows:

- A fuel derived from feedstock that is either biogenic in nature, a hybrid of biogenic and fossil fuels, green liquid hydrogen, recycled carbon-based fuels (e.g., off-gases of fossil origin), CO_2 from a biogenic source, or captured directly from the air.
- A drop-in fuel that is identical to conventional ATF at the molecular level, fully compatible with existing aviation infrastructure, and within the standard range of ATF properties.
- Complying with the specifications defined under ASTM D7566 or IS 17081-2019 published by the Bureau of Indian Standards.
- Produced using a technology pathway approved under ASTM D7566.
- Achieving a significant reduction in lifecycle GHG emissions compared to conventional ATF (ICAO requires a minimum reduction of 10%).
- Meeting various sustainability criteria as defined by ICAO, such as land use for growing feedstock and permanence of GHG emission reduction.

The ASTM D7566 standard approves blending of SAF with ATF in blend ratios ranging from 10% to 50%. However, aircraft engines are currently being designed to use 100% SAF[10].

2.12.2 SAF Policy Landscape

Policies are crucial in facilitating the supply and demand of SAF, given its considerably higher cost than conventional jet fuel (see the section on SAF cost economics). The ICAO, a United Nations agency with over 190 member countries, has developed an international framework for SAF policy under CORSIA to address this issue. In addition to the global framework, the U.S., EU, and some European countries have implemented their own national policies.

CORSIA (Carbon Offsetting & Reduction Scheme in International Aviation) [11]:

In October 2016, ICAO established CORSIA as a means of limiting the carbon emissions produced by international flights. CORSIA is a global environmental policy instrument that caps the net CO_2 emissions of international flights between participating countries at the average of 2019-2020 levels for the years 2021-2035, making it the first market-based policy of its kind. Airlines have several options to meet their cap, including reducing emissions through operational and maintenance improvements, purchasing ICAO-approved carbon offsets, or using CORSIA-eligible fuels like SAF. The implementation of CORSIA will occur in three phases: Phase 1 from 2021 to 2023, Phase 2 from 2024 to 2026, and Phase 3 from 2027 to 2035. While the first two phases are voluntary for participants, the determination of member participation in Phase 3 will be based on 2018 RTK (Revenue Ton Kilometre) data.

U.S. SAF Policy[12-13]

The U.S. government has introduced the SAF Grand Challenge, which involves collaborating with the SAF industry to reduce costs, increase sustainability, and expand production to achieve a minimum of 3 billion gal/year of domestic SAF production by 2030. The SAF produced must achieve at least a 50% reduction in lifecycle GHG emissions compared to conventional fuel. By 2050, the goal is to produce 100% of projected aviation jet fuel use, or 35 billion gal/year. The plan involves partnering with private companies and addressing areas such as feedstock, technology, and supply chain. Policy support will also be provided to achieve this target.

Currently, there are various policy instruments at the national and sub-national level in the US.

- National / Federal Policy:
    - Renewable Fuel Standard (RFS): RFS allows SAF to generate compliance units (Renewable Identification Number or RINs) that becomes usable as credit once SAF is blended with jet fuel. These credits can be traded, generating revenue.
    - Blender's Tax Credit (BTC): BTC incentives SAF producers with minimum $1.25 per gallon credit for each gallon of SAF sold as part of a qualified fuel mixture with a demonstrated lifecycle greenhouse gas (GHG) reduction of at least 50% compared to conventional jet fuel.

- Sub-national/State level Policy: SAF can benefit from sub-national or state-level policies such as the Low Carbon Fuel Standard (LCFS) programme, which allows SAF producers to sell credits for the GHG emission reductions achieved through their fuel compared to conventional jet fuel. These credits can be sold to other obligated parties, providing an incentive for SAF production. The calculation of these credits is done through lifecycle assessment modelling that quantifies the avoided emissions.

SAF Policy in European Union[13]
The European Commission has put forward a policy called RefuelEU that requires aviation fuel suppliers to blend their products with a certain amount of SAF and synthetic fuel. The policy will be mandatory for suppliers operating at EU airports, and the percentage of SAF required in the blend will increase every five years. The initial target in 2025 is a minimum of 2%, with a goal of reaching a minimum of 63% by 2050, of which 28% will be synthetic aviation fuels.

2.12.3 Sustainability of SAF

Sustainability Criteria[14]
The ICAO has established a set of specific sustainability criteria that will apply to aviation fuels that are eligible under CORSIA, and these criteria are set to take effect from January 1, 2024[3]. These criteria comprehensively consider the various aspects of sustainability.

Lifecycle Analysis[15-16]
To qualify as a CORSIA-eligible fuel, SAF must have a Carbon Intensity (CI) that is at least 10% lower than that of conventional jet fuel, according to one of the sustainability criteria set by ICAO. To calculate the carbon emissions of SAF, Lifecycle Analysis (LCA) methodology specified by CORSIA is used, which accounts for all emissions throughout the value chain, including direct and indirect effects like Induced Land Use Change (ILUC) caused by feedstock production.

ICAO has authorised two sustainability certification schemes, namely International Sustainability & Carbon Certification (ISCC) and Roundtable on Sustainable Biomaterials (RSB), to certify CORSIA-eligible SAF. SAF producers must choose one of these schemes to audit their supply chain and certify their SAF as CORSIA-eligible fuel. They must meet the CORSIA Methodology for Calculating Actual Lifecycle Emission Values during the audit process.

Table 1: Sustainability Criteria for CORSIA-Eligible Fuels/SAF

Theme	Criterion
Greenhouse Gases (GHG) Principle:	SAF must produce at least a 10% reduction in carbon emissions over the lifecycle of the fuel in comparison to traditional jet fuel.
Carbon Stock	SAF should not be made from biomass obtained from land/aquatic systems with high biogenic carbon stock.
GHG Reduction Permanence	Emissions reductions attributed to SAF should be permanent.
Water	Production of SAF should maintain or enhance water quality and availability.
Soil	Production of SAF should maintain or enhance soil health.
Air	Production of SAF should minimize negative effects on air quality.
Conservation	Production of SAF should maintain biodiversity, conservation value, and ecosystem services.
Waste & Chemicals	Production of SAF should promote responsible management of waste and use of chemicals.
Human and Labour Rights	Production of SAF should respect human and labour rights.
Land Rights	Production of SAF should respect land rights and land use rights including indigenous and/or customary rights.
Water Use Rights	Production of SAF should respect prior formal or customary water use rights.
Social Development	Production of SAF should contribute to social and economic development in regions of poverty.
Food Security	Production of SAF should promote food security in food insecure regions.

In general, the emissions at the following stages of SAF value chain are calculated:

- Emissions during feedstock production
- Emissions during collection, logistics and transportation of feedstock to the location of conversion unit
- Emissions during conversion of feedstock into SAF
- Emissions during transportation of SAF from conversion unit to blending facility.

Among the four stages mentioned earlier, the emissions from feedstock production have a significant impact on the CI of SAF. The emissions associated with feedstock production are determined based on the classification of feedstock by ICAO. Chart 1 below shows that the GHG emission savings are highest for SAF produced from municipal solid waste (around 95%) and lowest for SAF produced from corn grain (almost zero). However, it is important to note that the CI of Corn-based SAF can be reduced by using de-fossilised energy for production or by capturing carbon and storing it underground through the CCUS system.

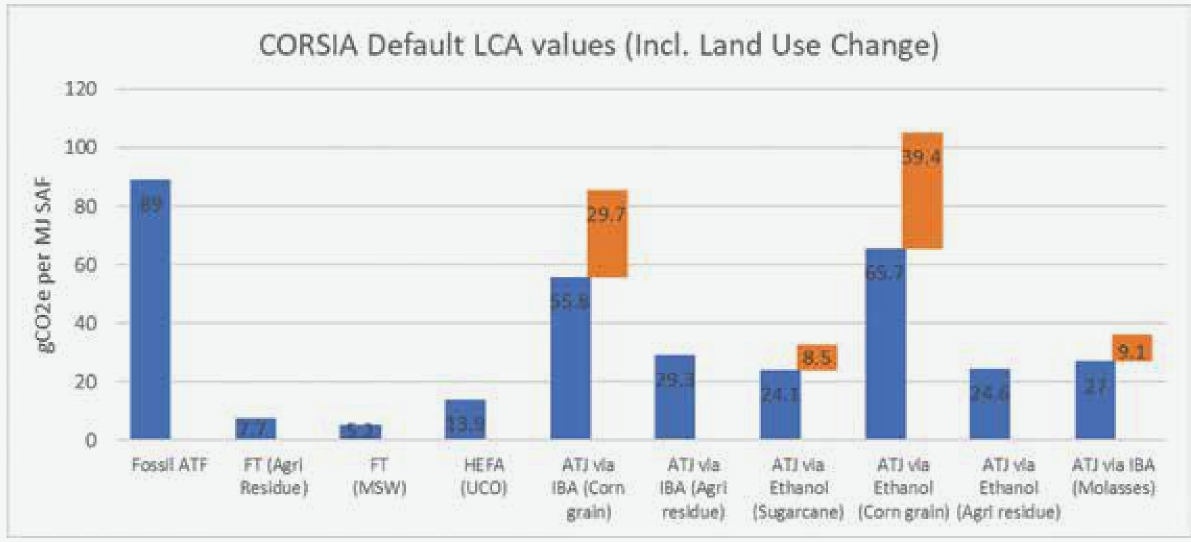


Chart 1: Typical/Default Carbon Intensity of SAF produced from variety of feedstock and based on some of ASTM approved technology pathways as provided by ICAO [15]

Table 2: Classification of feedstock for SAF

Primary & Co-Products	Main products of production process having significant economic value & elastic supply Example: First Generation (1G) feedstock such as Corn, Cane Molasses etc. **High emissions** associated with production of feedstock and Land Use Change
By-Products	Secondary products with inelastic supply and some economic value. Example: Palm Fatty Acid Distillate, Technical Corn Oil etc. **Zero emissions** associated with production of feedstock and Land Use Change
Waste	Material with inelastic supply and no economic value Example: Municipal Solid Waste, Waste Gases, Used Cooking Oil etc. **Zero emissions** associated with production of feedstock and Land Use Change
Residues	Secondary material with inelastic supply and little economic value Example: Agricultural residues, forest residues etc. **Zero emissions** associated with production of feedstock and Land Use Change

Feedstock Classification[16]
ICAO has classified feedstock for production of SAF under the following four categories.

SAF produced from feedstocks categorised as by-products, waste and residues have low lifecycle emissions since the emissions associated with their feedstock production are zero. This is because these feedstocks are considered to be waste products that would have been emitted as GHGs if not utilised for SAF production. Therefore, SAF produced from these feedstocks can result in higher GHG emission savings compared to SAF produced from other feedstocks such as crops or forestry products.

2.12.4 Technologies for SAF Production

Technology Landscape
The world of SAF production technology is rapidly evolving, as new technologies and pathways are being developed and commercialised. Currently, there are nine technology pathways that have been approved by ASTM International, which was previously known as the American Society for Testing and Materials, for synthesising hydrocarbons, including SAF, from different types of feedstocks as of October 2021.

Table 3: ASTM-approved pathways[17]

ASTM reference	Conversion process	Abbreviation	Possible Feedstocks	Blending ratio by volume
ASTM D7566 Annex 1	Fischer-Tropsch hydroprocessed synthesised paraffinic kerosene	FT-SPK	Coal, natural gas, biomass	50%
ASTM D7566 Annex 2	Synthesised paraffinic kerosene from hydroprocessed esters and fatty acids	HEFA	Bio-oils, animal fat, recycled oils	50%
ASTM D7566 Annex 3	Synthesised iso-paraffins from hydroprocessed fermented sugars	SIP	Biomass used for sugar production	10%
ASTM D7566 Annex 4	Synthesised kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources	FT-SKA	Coal, natural gas, biomass	50%
ASTM D7566 Annex 5	Alcohol to jet synthetic paraffinic kerosene	ATJ-SPK	Biomass for ethanol or Isobutanol production	50%
ASTM D7566 Annex 6	Catalytic hydrothermolysis jet fuel	CHJ	Triglycerides such as soybean oil, jatropha oil, camelina oil, carinata oil, and tung oil	50%
ASTM D7566 Annex 7	Synthesised paraffinic kerosene from hydrocarbon-hydroprocessed esters and fatty acids	HC-HEFA-SPK	Algae	10%
ASTM D1655 Annex A1	Co-hydroprocessing of esters and fatty acids in a conventional petroleum refinery	co-processed HEFA	Fats, oils, and greases (FOG) co-processed with petroleum	5%
ASTM D1655 Annex A1	Co-hydroprocessing of Fischer-Tropsch hydrocarbons in a conventional petroleum refinery	co-processed FT	Fischer-Tropsch hydrocarbons co-processed with petroleum	5%

Key Technologies & Pathways
Of the above, the following three pathways have high technology readiness level and show enormous potential for commercialisation, particularly in India[18-20]

- Hydroprocessed Esters and Fatty Acids (HEFA): This pathway is considered technologically mature and has already been commercialised in the U.S. and Europe. It was approved by ASTM in 2011, and most of the demonstration flights that use SAF blends are based on SAF produced from the HEFA pathway. HEFA refines lipids such as vegetable oils, waste oils, or fats into SAF and other valuable co-products such as renewable diesel. This process involves hydrotreatment and isomerisation to convert triglycerides into hydrocarbons within the ATF range.
- Alcohol-to-Jet (ATJ): This pathway utilises alcohol as a source (either Isobutanol or Ethanol) for SAF production. Alcohol can be produced from sugary, starchy, and biomass feedstocks. ATJ converts alcohols into SAF by removing oxygen (dehydration) and linking molecules together to achieve the desired carbon chain length (oligomerisation). Further processing includes hydrogenation and fractionation to obtain SAF and co-products such as renewable gasoline (isooctane) and green diesel. The technology of this pathway is rapidly maturing, and many commercial-scale plants based on ATJ pathway have already been announced across the globe.
- Fischer Tropsch (FT): In this process, syngas produced from biomass gasification is synthesised and catalytically cracked to produce SAF. Two different FT processes have been certified by ASTM so far, one that produces a straight paraffinic jet fuel (SPK) and one that also produces additional aromatic compounds (SAK).

Apart from the above-mentioned technologies, the 'Power to Liquid' pathway for producing SAF is quickly gaining prominence as a more sustainable alternative to other pathways. This technology involves synthesising CO_2, captured from either the air or waste/flue gases, with green hydrogen produced through water electrolysis using solar energy to create hydrocarbons, including SAF. However, it may take at least a couple of decades for this pathway to become commercially viable, despite its high environmental sustainability.[19]

Efforts of SAF Technology Development in India
While the initial development of SAF technology has primarily taken place in the U.S. and Europe, some Indian organisations and research labs are also taking the lead in developing technological solutions for SAF production using feedstock available in India.

The Indian Institute of Petroleum (IIP), a constituent laboratory under the Council of Scientific & Industrial Research (CSIR), has developed an indigenous single-step catalytic technology for producing SAF based on hydro-processing of waste lipids, such as used cooking oil and tree-borne oils. CSIR-IIP has also established a pilot-scale testing facility with a capacity to process up to 50 kg of feed per day. In 2018, SpiceJet operated India's first SAF-powered test flight from Dehradun to Delhi, using SAF produced by CSIR-IIP. One of the two engines of SpiceJet's Bombardier Q400 turboprop aircraft was powered by a blend of 25% SAF (based on CSIR-IIP's HEFA technology) and conventional Jet A1 fuel [20].

Praj Industries Ltd., a global leader from India for around four decades in providing bio-process solutions in the area of agro-processing, energy, and environment, has collaborated with a partner to develop technology for SAF production based on the ASTM-approved ATJ pathway. The commonly available feedstock in India, such as cane molasses, cane syrup, and agricultural residues, are first converted into isobutanol, which is then processed into SAF. The process of converting isobutanol into SAF also yields premium high-octane gasoline as a co-product.
In a significant development towards decarbonizing of the aviation sector, India's first commercial passenger flight using indigenously

produced Sustainable Aviation Fuel (SAF) blend was successfully flown on Friday, 19th May 2023. Air Asia flight (I5 767) flew from Pune to New Delhi powered by the blend of conventional Jet Fuel and SAF produced by Praj in India using indigenous feedstock. The fuel was tested, blended and distributed by Indian Oil Corporation Ltd.[23]

Sustainable Feedstock

The successful commercialisation of SAF largely depends on the availability of low-cost sustainable feedstock. Currently, most of the SAF produced in the world is based on lipid feedstock such as used cooking oil, animal tallow, etc. However, SAF plant facilities based on corn, sugarcane, and second-generation (2G) lignocellulosic biomass (such as agricultural or forest residues) are either in the planning stage or under construction in various parts of the world.

Here is an overview of various prominent feedstocks available in India for SAF production:

Agricultural Residues/Second Generation (2G) Feedstock[21-22]

Every year, India produces around 500 million MT of agricultural residues, of which about 100 million MT are burnt in fields, leading to widespread pollution. In response, the government of India has launched an ambitious programme to set up 12 ethanol plants that operate using agricultural residues as feedstock. India's first second-generation (2G) ethanol plant was inaugurated by the Honourable Prime Minister in August 2022 in Haryana and is now producing 100,000 litres of bioethanol per day from rice straw.

Ethanol produced from agricultural residues can be converted into SAF using ASTM-approved ATJ pathway. Even converting just 10% of the total available agricultural residues, which is around 50 million MT, could yield 4 to 5 million MT of SAF per year and save around 10 to 15 million MT of GHG emissions annually. The refining process can also yield high-value, low-carbon renewable fuels as co-products, leading to further carbon emission savings. With the demand for ATF in India expected to be around 9 to 10 million MT/year by 2025, just 10% of the total available agricultural residues in India could potentially replace 50% of ATF and halve the emissions of India's civil aviation sector.

SAF produced from agricultural residues will not only contribute to environmental solutions but also improve the rural economy. Collecting agricultural residue as feedstock for biofuel production could create employment in the rural areas and provide farmers with an alternative, sustainable revenue stream.

First Generation (1G) Feedstock for Alcohols Production

Although India currently blends 20% ethanol into the gasoline pool, it is possible that there may be an excess of ethanol or available feedstock for the production of other alcohols, like isobutanol or ethanol, from sources such as sugary streams (cane syrup, cane molasses, etc.) and grains that are not suitable for human consumption. The supply chain for producing alcohols from first-generation feedstock is already established, and any excess ethanol or isobutanol can be transformed into SAF by constructing plants that use the ATJ pathway.

Lipids (Used Cooking Oil or Tree Borne Oil) [21]

India produces a substantial amount of Used Cooking Oil (UCO) every year, as the country consumes about 22 to 27 million MT of vegetable oil annually. However, almost 40% of UCO is disposed of illegally, and the remaining UCO is utilised for various other purposes. If the collection and logistics system for UCO is made more efficient, there is potential availability of 2 to 5 million MT of UCO per year. This could lead to the production of almost 2 million MT of SAF per year, based on the HEFA pathway. In addition, Tree Borne Oil (TBO) from plants like jatropha and pongamia, cultivated on degraded land, is another potential feedstock for SAF production in India.

2.12.6 Cost Economics of SAF

At present, the cost of producing SAF through approved pathways is much higher, ranging from 2 to 9 times more expensive than conventional fossil-based aviation fuel. It will likely take several decades before SAF becomes cost-competitive with traditional aviation fuel. Therefore, policy interventions are necessary to ensure the successful commercialisation of SAF.

Among the various pathways, the HEFA pathway is the most commercially viable and technologically advanced, resulting in the lowest cost of SAF production compared to other pathways. However, given the surplus feedstock available in India, SAF produced through the ATJ pathway in India is likely to have lower costs than or be on par with the cost of SAF produced through the HEFA pathway.

Note: Given the broad variety of existing feedstocks (within a particular pathway), SAF production processes, and the regional differences in the feedstock & processing costs, the SAF cost range shown below is indicative in nature.

2.12.7 Socio-Economic Benefits of SAF

In addition to the environmental advantages, SAF production and utilisation will bring about noteworthy social and economic advantages to the country. According to an estimate, the production and utilisation of roughly 360,000 MT of SAF per year would have a beneficial impact of approximately $2.8 billion on India's GDP. This would ensure an additional source of income for farmers, strengthen energy security, create new job opportunities that would boost the rural economy, enhance waste management, and contribute to cleaner skies with reduced open-air burning.

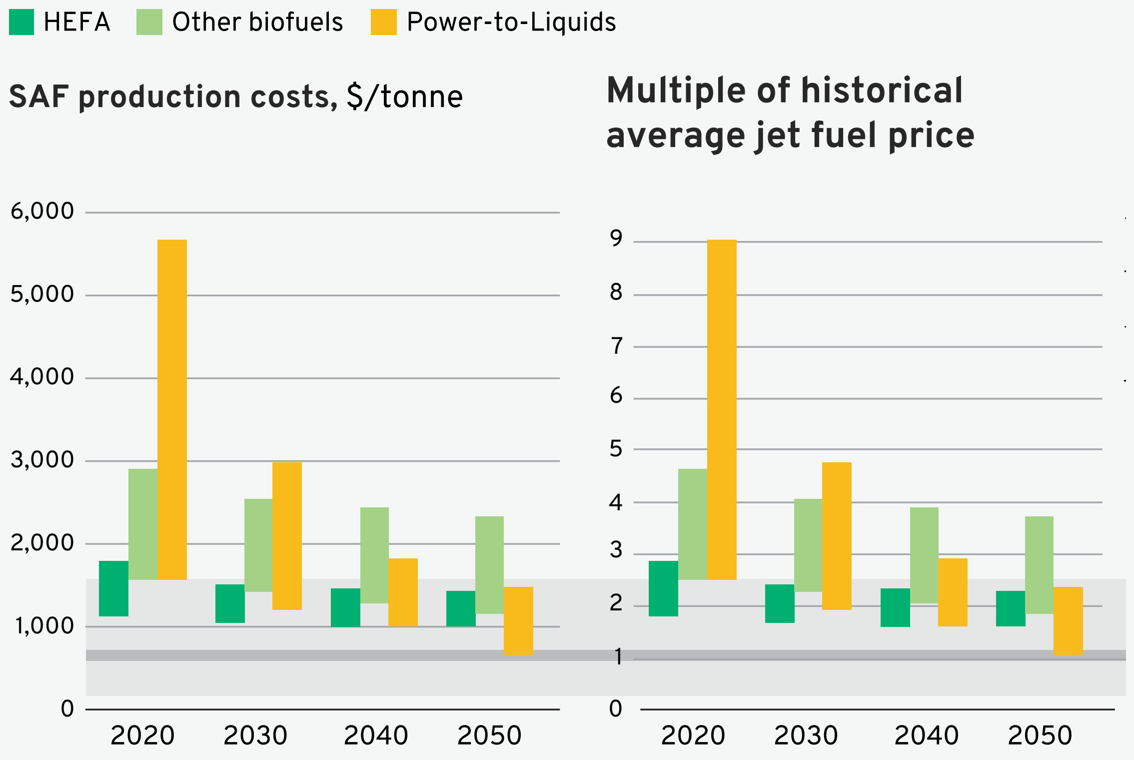
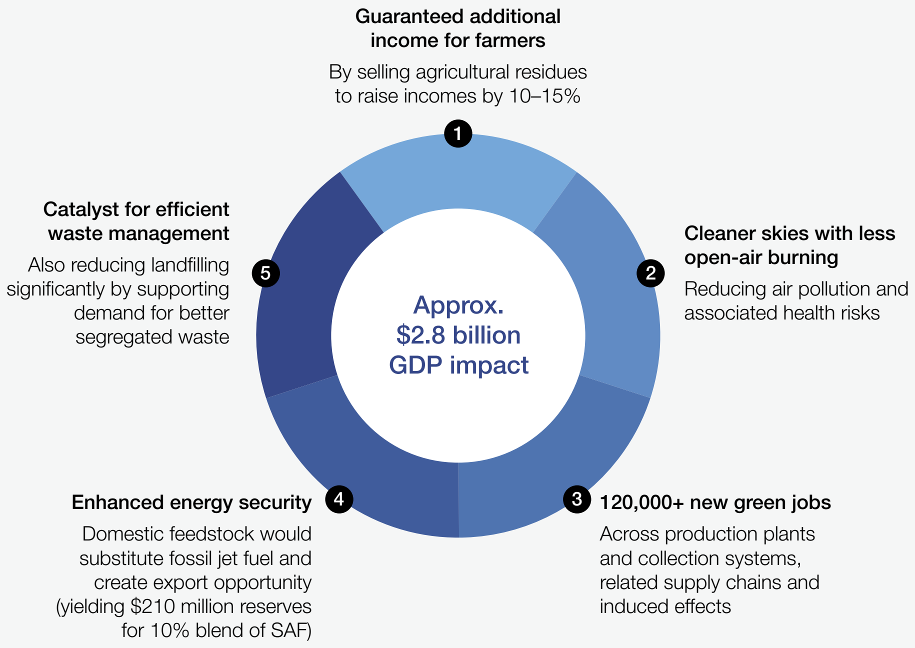


Chart 2: Current and projected cost of SAF produced from HEFA, ATJ (mentioned as Other Biofuels) and Electro-Fuel pathway[19]



Source: United Nations; Shyamsundar et. al., 2019; expert interviews; McKinsey Global Institute

Chart 3: Socio-Economic benefits of achieving 360,000 MT/year of SAF capacity by 2030 in India[5]

2.12.8 Turning India into an International SAF Hub[5, 21-22]

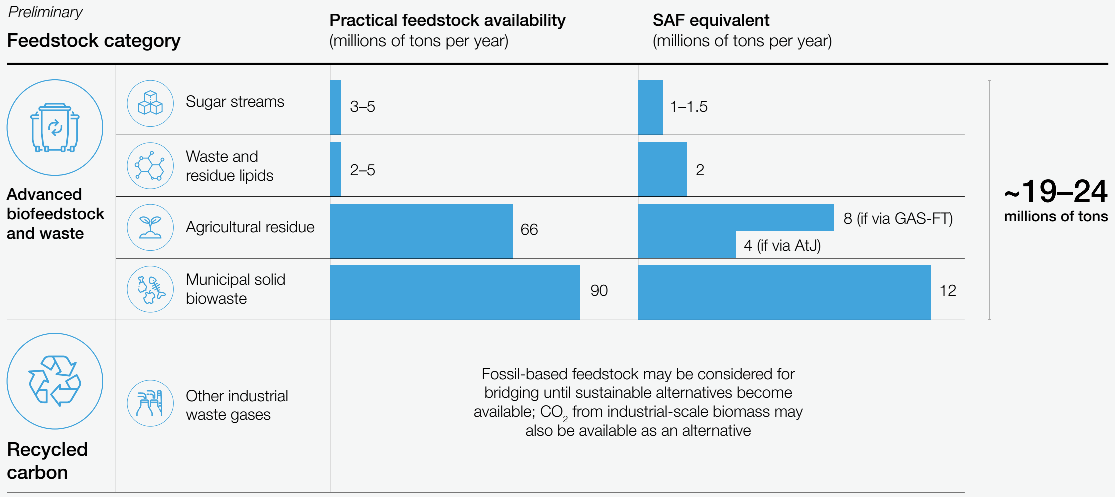
India has an abundance of surplus feedstock such as agricultural residue, sugary streams (cane molasses, cane syrup), and grains that are unfit for human consumption. As per one estimate, India has feedstock for potential production of 19 to 24 million MT of SAF per year [5], whereas the estimated maximum requirement of SAF in India, considering 50% blend, is around 8 to 10 million MT/year by 2030.

As technologies for SAF production continue to improve, the cost of production is decreasing, but policy interventions are still necessary until the cost of SAF becomes competitive with conventional ATF. While CORSIA has policies that promote the use of SAF for international aviation, the Indian government must also implement policies to support the commercial use of SAF, including regulations and incentives throughout the value chain.

The Indian government has already established various policies to promote biofuels, such as the National Policy on Biofuels 2018, Ethanol Blending Mandate, PM-JiVan Yojana, Sustainable Alternative Towards Affordable Transportation (SATAT), and national solar and hydrogen missions. The government can also develop policies for SAF in India based on these existing policies.

The following government interventions can accelerate the commercialisation of SAF in India:

- Incentivising SAF Producers: Since SAF production plants are highly capital-intensive, the government could assist SAF producers in mitigating risks through financial measures such as:
  - Viability Gap Funding, similar to that of the PM-JiVan Yojana.
  - Differential premium pricing, similar to that of ethanol.
  - Tax incentives, similar to the Blender's Tax Credit in the U.S., which is based on the carbon intensity of SAF.
  - Grants and funding support, as well as loan guarantees through financial institutions for the development of demonstration and commercial plants.
  - Supporting the establishment of an efficient feedstock collection and logistics system throughout India, particularly for agricultural residue and UCO.



Source: ACRE McKinsey solution based on e.g. GLADA, Bai et al., 2008, Gibbs et al., FAO, Mapspam, FAO 2015 FRA, ESA CCI Land Cover, FAOstat, USDA, World Bank, Greenea, Ecofys, Fischer Solve, Statistik der Verarbeitung Tierischer Nebenprodukte 2016, WRI, press search

Chart 4: Feedstock availability and potential of SAF production in India[5]

- Blending Mandate: The government could institute a blending mandate starting with either 0.5% or 1%, with plans to gradually ramp it up. The blending mandate would create local demand for SAF.
- Developing a Local Carbon Market: A local Carbon market in India could help SAF producers generate additional revenue through the trading of Carbon Credits. The carbon market in the U.S., such as the LCFS, plays a crucial role in improving the viability of SAF projects.
- Developing or Adapting Various Standards for SAF Ecosystem and Infrastructure: This includes SAF certification, testing, storage, blending and distribution.

Given the surplus feedstock availability, access to rapidly maturing technologies, and development of indigenous technologies, India has many positive factors that could make it an international hub for SAF supply. With the right policies in place and the establishment of an appropriate ecosystem and infrastructure, India could not only fulfil the domestic SAF demand but also cater to the international demand for SAF.

2.13

Biofuels: Status Today and Outlook for the Future

DR ANJAN RAY, Director & BHAVYA B KRISHNA, JAYATI TRIVEDI, NEERAJ ATRAY
CSIR-Indian Institute of Petroleum (IIP), Dehradun, India

The man has reached immortality, who is disturbed by nothing material.

Swami Vivekananda

2.13.1 The Discovery of Fire; Fuels Before Fossil Fuels

It is believed that the discovery of fire occurred approximately 1.5 million years ago during the Palaeolithic era. Early humans probably discovered fire by natural means like lightning or volcanic eruptions. Later, they learned how to make and manage fire using techniques like using rocks to make sparks or creating friction to produce sparks. Once humans learned to create and control fire, they used it for various purposes like cooking food, providing warmth and light, and for protection against predators. Fire also played an important role in the development of early human societies by allowing them to extend their day beyond daylight hours and settle in colder regions.

Before the discovery of fossil fuels, humans used various types of fuels to create and maintain fire. These fuels were usually burned in simple hearths or open fires, which were constructed in the centre of dwellings or at dwelling area perimeters for protection against enemies or predators. Early humans used fallen branches and other plant materials for fuel, and later learned to cut down trees and use wood for cooking and heating. For thousands of years, wood remained the primary fuel, and it is still widely used in many parts of the world. Animal dung was another fuel used before the discovery of fossil fuels. It was dried and burned for cooking and heating, particularly in areas where wood was scarce, like arid regions or areas with few trees. In some regions, peat was used as fuel. Peat is created from partially decomposed plant material and can be burned like wood to produce heat. It was significant in areas with a high-water table where wood was scarce or difficult to obtain.

Charcoal was another important fuel for humans before the discovery of coal. It is created by heating wood in the absence of oxygen, which causes it to break down into carbon and other compounds. Charcoal burns hotter and more efficiently than wood, making it ideal for metalworking and other industrial processes. It was widely used in ancient civilisations like Greece and Rome and remained a crucial fuel until the discovery of coal.

The use of various fuels before the discovery of coal underwent a gradual progression from basic biomass fuels such as wood and dung to more advanced fuels such as charcoal. These fuels allowed early humans to carry out essential activities such as cooking and heating, which helped in the development of more complex societies and technologies.

As human societies became more complex, the demand for more efficient and sophisticated fuel production and methods of use increased. The discovery of fire played a vital role in the evolution of human society by enabling early man to survive and thrive in different environments, paving the way for the development of more advanced technologies and social structures.

However, the significance of fuel evolution in enhancing the quality of human life and advancement is often overlooked. An interesting example is the surge in the whaling industry during the 18th and 19th centuries when newly established American colonies relied mainly on whale oil for lighting lamps. The discovery of petroleum and the subsequent development of petroleum refining eventually put an end to this practice and saved marine mammals from being hunted extensively.

2.13.2 The Ascent of Coal

Coal is a sedimentary rock that is black or brownish black in colour and is mainly composed of carbon, along with varying proportions of other elements like hydrogen, sulphur, oxygen, and nitrogen. It is a fossil fuel formed over millions of years from decomposing plant matter that turned into peat and then coal under the heat and pressure of deep burial. Coal forests were the primary source of huge coal reserves that date back to the late Carboniferous and Permian periods (Cleal & Thomas, 2005). Several important coal deposits that date back to the Mesozoic and Cenozoic eras are older than this (Sahney et al., 2010). While coal has been used for thousands of years, it was not until the Industrial Revolution that its use significantly increased with the development of the steam engine. Coal has mainly been used as a fuel source, particularly in industrial processes like iron and steel production. However, with the advent of the petroleum industry, oil became the primary energy source, leading to a decline in the use of coal.
(https://www.britannica.com/technology/coal-mining/Coal-deposits).

Coal exploration involves various activities and assessments that gather information for decisions related to the technical and economic viability of mining, coal quality assessment, marketability, and preparation of mined coal for market requirements.

It is predicted that the world's energy consumption will increase by 25% by 2040, with non-OECD countries accounting for 70% of the increase. China's energy demand is also expected to match that of the U.S., Europe, and other OECD countries by 2040. Fig. 1 shows the forecasts for the world's energy demand in terms of fuel source and demographics up to 2040.

Renewable and nuclear energy sources will play a major role in meeting the growing energy demand, while natural gas demand is expected to rise significantly by 2040. Coal is projected to remain a significant energy source, accounting for around 20% of the total, even though much of the high-quality coal has already been mined. As a result, the use of sustainable technologies for coal is essential for future use. Coal is formed through a process known as coalification, which begins with dead vegetation turning into peat when shielded from biodegradation and oxidation by acidic water or mud in wetlands.
(http://www.fe.doe.gov/education/energylessons/coal/gen_howformed.html).

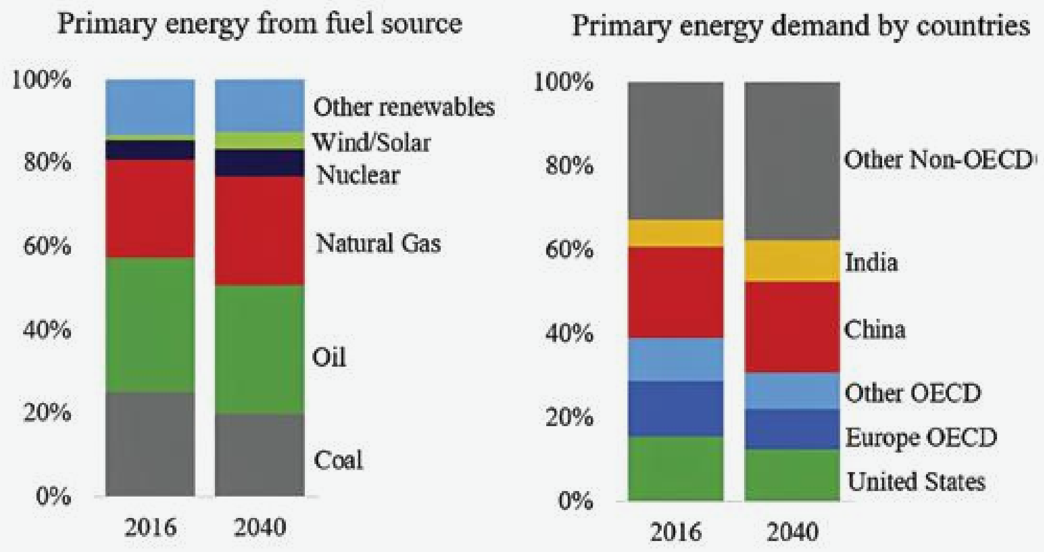


Fig. 1: Global energy demand projections in terms of fuel source and by country till 2040 (adapted from ExxonMobil 2018 Outlook for Energy: A View to 2040. ExxonMobil; 2018)

Over time, the heat and pressure of deep burial cause the release of water, methane, and CO_2, and the carbon content increases, leading to the formation of lignite, sub-bituminous coal, bituminous coal, or anthracite coal depending on the temperature and pressure reached.

(Taylor et al., 2009; https://www.eia.gov/energyexplained/coal/).

Types of Cleaning and Coal Preparation

Initially, the primary aim of coal preparation was to create a consistent-sized product and to diminish the quantity of unreactive rock materials present in the raw coal. This reduction of impurities not only elevated the heating potential of the purified coal but also decreased the accumulation of waste in the furnace, decreased the burden on the particle-removal system, and boosted the furnace's overall operational efficiency. Broadly, the coal preparation procedure consists of four main phases, namely characterisation, liberation, separation, and disposal.

Coal Resources

In sedimentary rock basins, coal deposits can be discovered as a series of layers, or seams, wedged between layers of sandstone and shale. Sedimentary basins, containing coal, can be found in more than 2,000 locations worldwide. The total amount of coal globally, or the world's coal resources, is roughly 11 trillion MT.

The term 'coal reserves' denotes the coal resources that are currently technically and commercially feasible for mining. The world has around 760 billion MT of feasible coal reserves, and these reserves are distributed across continents in the following manner: Europe (44%), North America (28%), Asia (17%), Australia (5%), Africa (5%), and South America (1%).

(https://www.britannica.com/technology/coal-mining/Coal-deposits).

Coal mining, which includes mapping, different mining techniques, and photogrammetric approaches, is a wonderful way to improve the carbon resource for coal production.

A global study on coal production has found that surface mining and underground mining contribute almost equally to the production of coal worldwide. Only a small percentage of the world's coal production, less than 10%, comes from anthracite seams, which are usually mined underground, while about 25% of the world's lignite seams are typically surface mined. Both methods are used to mine almost equal amounts of bituminous seams, which account for approximately 65% of global coal production.

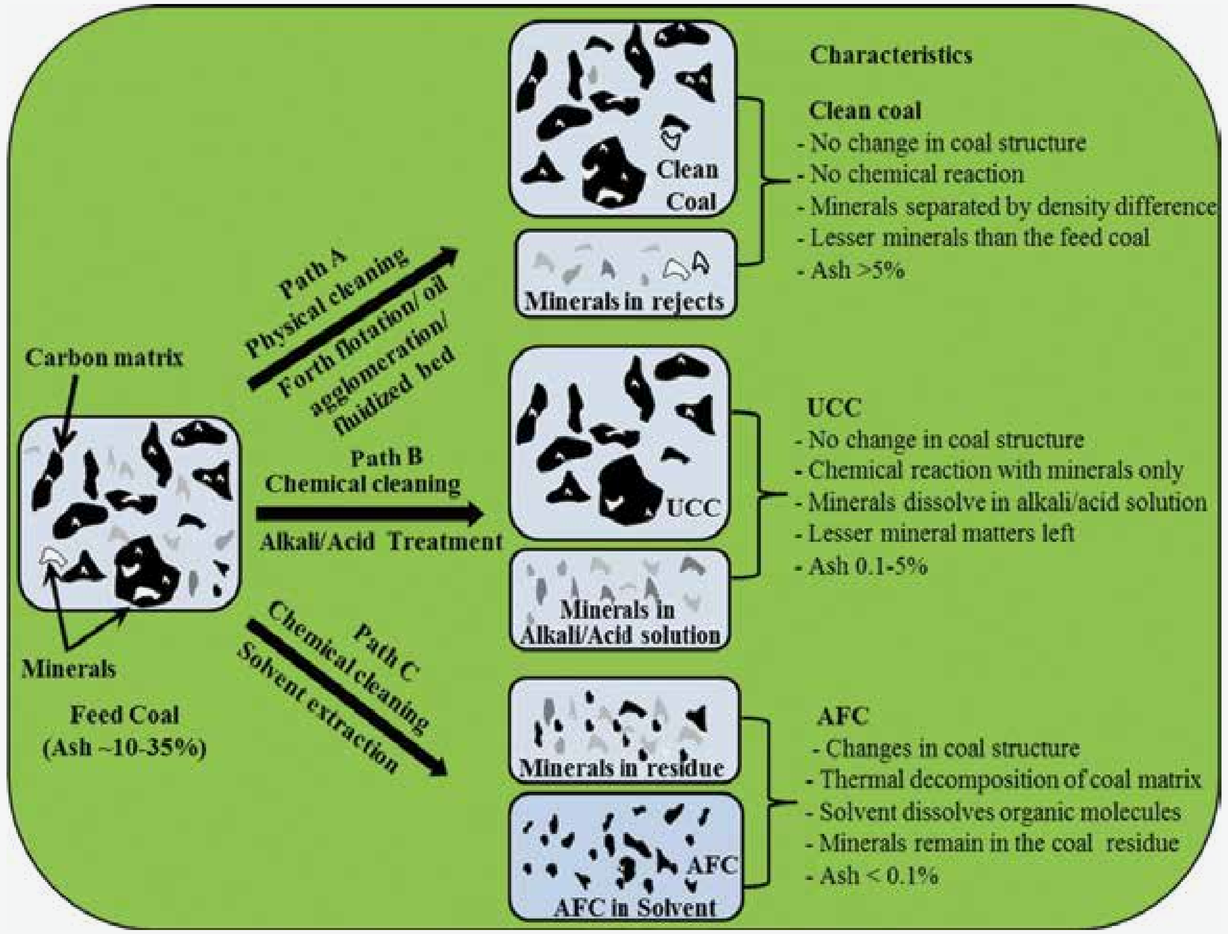


Fig. 2: Types of coal cleaning

In the United States, coal is mainly used to generate energy, accounting for about 92% of its usage. The remaining coal is utilised as a primary energy source in various industries such as steel, cement, and paper, with only a small amount being exported.

(https://ei.lehigh.edu/learners/energy/readings/coal.pdf).

About half of the electricity produced in the U.S. comes from coal, which is burned in power plants to generate steam that drives turbines to produce power. Coal is also used by various industries for its heat and by-products, which are used to create products such as plastics, tar, synthetic fibres, fertilisers, and pharmaceuticals. Additionally, coke made from coal is used to smelt iron ore into steel, which is used in bridges, buildings, and automobiles due to its strength and flexibility.

In 2006, the U.S. exported 49.6 million short tons of coal to other countries, with the majority of the coal used for steel production. However, over the past decade, coal imports have increased while exports have decreased, with around 36.2 million short tons imported in 2006 from countries like Colombia, Venezuela and Indonesia.

India is also a significant player in the coal industry, with its thermal power plants and other sectors relying on the country's coal production of 780 million MT (provisional) in 2022. This production level is expected to lead to policy changes that will improve India's energy security. India's coal production has been increasing in recent years, with a total production of 778.19 million MT in 2021-2022, up from 716.083 million MT in the previous fiscal year. Until November 2022, the

country's coal supply was 558.24 million MT (provisional), up from 521.08 million MT during the same period the previous year. Coal India Limited (CIL) and Singareni Collieries Company Limited (SCCL) have increased their coal supply to meet the growing demand of the power industry over 2022-2023.
(https://pib.gov.in/PressReleasePage.aspx?PRID=1887132#:~:text=During%202022%2C%20eight%20coal%20mines,MT%20during%20last%20year%202021).

Disadvantages of Coal

Coal mining and consumption result in early mortality and disease (https://www.env-health.org/wp-content/uploads/2018/12/HEAL-Lignite-Briefing-en_web.pdf). Coal is the biggest contributor to human-made CO_2 emissions that cause climate change, and it has a significant negative impact on the environment. In the year 2020 alone, burning coal produced a staggering 14 billion MT of CO_2 (Ritchie & Roser, 2020), which is 40% of all fossil-fuel emissions (https://phys.org/news/2018-12-china-unbridled-export-coal-power_1.html) and more than 25% of all GHG emissions worldwide (https://www.resilience.org/stories/2020-01-24/dethroning-king-coal-how-a-once-dominant-fuel-source-is-falling-rapidly-from-favour/). Many nations have decreased or completely stopped using coal as part of the global energy shift (https://www.carbonbrief.org/analysis-the-global-coal-fleet-shrank-for-first-time-on-record-in-2020/; Simon, 2020). The UN secretary-general had urged governments to stop constructing new coal-fired power facilities by 2020.
(https://www.theguardian.com/environment/2019/may/15/tax-carbon-not-people-un-chief-issues-climate-plea-from-pacific-frontline). The year 2013 saw the peak of the world's coal utilisation (Coal Information Overview, 2019).

The Glasgow Climate Pact included an agreement to phase out coal, as part of efforts to achieve the goals of the Paris Agreement, which aims to limit global warming to below 2°C (3.6°F). To achieve this, there is a target to reduce coal use by 50% from 2020 levels by the year 2030.
(https://www.carbonbrief.org/analysis-why-coal-use-must-plummet-this-decade-to-keep-global-warming-below-1-5c/).

Technologies for Sustainable Coal Utilisation

The process of transforming coal into energy involves various stages such as extraction, storage, processing, and combustion, which have a significant impact on efficiency and the environment. Sustainable use of coal requires improvements in each of these stages, beginning with coal preparation, combustion, and the implementation of technology that minimises GHG emissions.

To achieve cleaner coal technologies, it is recommended to use methods such as demineralisation, dewatering, and sulphur removal from coal before combustion. Moreover, the use of modern, efficient technology, as well as efficient coal boilers such as USC, can improve efficiency. Advanced technology such as SCR and SNCR for NOx, FGD for SOx, and ESP, FF, and BF for particulates are examples of efficient pollution control.

High-tech, high-efficiency equipment such as SC or USC boilers, IGCCs, and IGFCs can improve conversion efficiency while reducing fuel consumption and emissions per unit of electricity.

Carbon capture technologies, including pre-combustion, post-combustion, oxy-firing combustion, and CLC, show promise in cutting or completely eliminating CO_2 emissions. IGCC, which integrates coal gasification technology with gas and steam turbine generation to produce syngas, is a high-efficiency and low-pollution method, although it is expensive and requires further research for commercialisation.

2.13.3 The Discovery of Petroleum, the Emergence of Refineries and the Dominance of the Fossil Fuel Industry in the 20th Century

The origin of non-renewable alternative fuels like petroleum has significantly improved the quality of life in day-to-day scenarios. Petroleum, or crude or simply oil, is a simple yet complex mixture of hydrocarbons, alkene, aromatics and metal/non-metal impurities produced under great geological transformations (www.eia.gov). Petroleum includes raw unprocessed crude oil, as well as refined oil and petroleum products and gases produced during the refining process.

A study by Anjan Ray revealed that in 2017, India imported 212 million MT of crude oil, which is a concern as it shows the country's increasing reliance on imported carbon-based fuels and depletion of fossil fuel reserves globally. The study also indicated that India imported 180 million MT of coal or petroleum coke and about 20 million MT of natural gas.

Most of the fuels produced from crude oil are from conventional deposits using traditional methods. However, unconventional crude, such as extra-heavy oil, oil sands, and oil shale, can be processed to produce upgraded or synthetic crude and could help improve India's energy security by increasing local supply to meet the growing demand.

Petroleum is primarily recovered by oil drilling. After structural geology, sedimentary basin analysis, and reservoir characterisation studies, drilling is carried out. A summary of crude oil refining is outlined in Fig. 3.

The Emergence of Refineries and the Dominance of the Fossil Fuel Industry in the 20th Century

In 1908, Austria-Hungary became the third-largest oil-producing country in the world with a 5% share of the global oil production, surpassing the United States and the Russian empire. Other countries, such as the Dutch East Indies, Persia, Peru, Venezuela and Mexico, also had significant oil resources being produced on an industrial scale by the early 20th century. The loss of Austria and Hungary's leadership in oil production led to the 1910 Petroleum War. Alberta, Canada, began developing significant oil reserves in 1947, and the offshore oil drilling site, Oil Rocks (NeftDashlari), in the Caspian Sea near Azerbaijan, led to the construction of a city on pylons in 1949. After World War I, the availability and access to oil became crucial for military capability, especially for fleets that switched from coal, and for the development of motorised transportation, tanks, and aircraft. Oil refineries were a significant strategic asset and heavily targeted during World War II. Large oil deposits were discovered in the al-Ahsa region of Saudi Arabia in 1938, and oil gradually replaced coal as the most popular fuel globally by the mid-1950s.

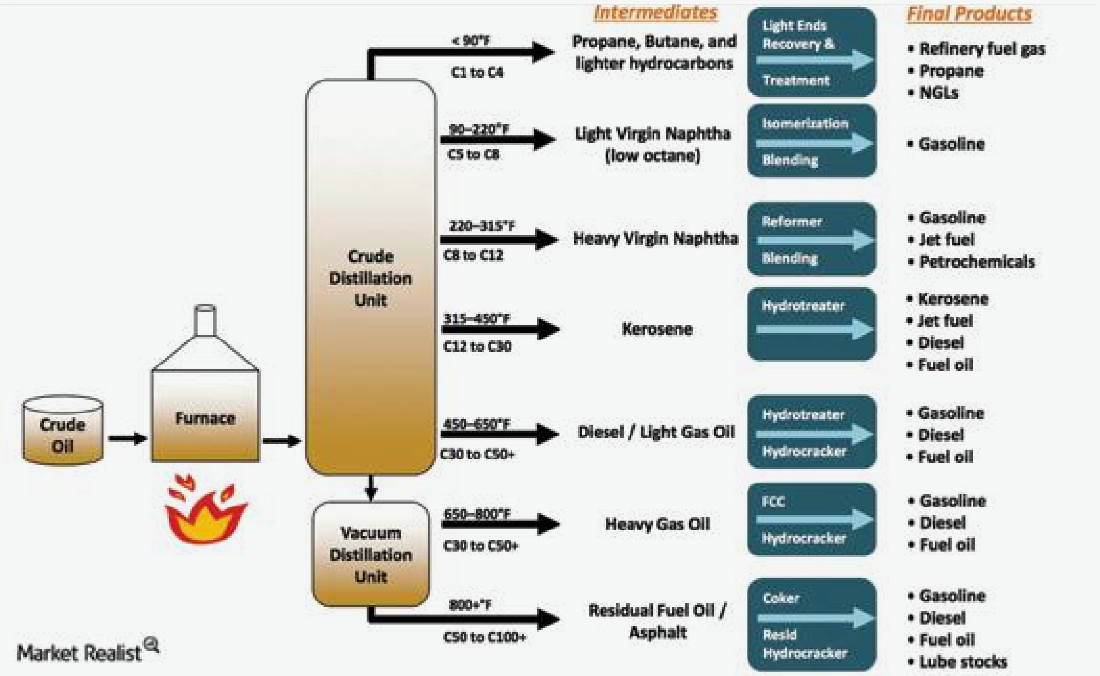


Fig. 3: Overall schematic of crude oil refining (Adapted from https://marketrealist.com/2016/11/crude-oil-refining/)

After the energy crises of 1973 and 1979, the media brought attention to the limited supply of oil as an economically viable energy source. Despite initial pessimistic projections, an oil surplus occurred in the 1980s due to increased production and decreased demand. However, concerns about peak oil resurfaced in the early 21st century. Currently, oil is used for 90% of vehicle fuel and accounts for 40% of overall energy consumption but only 2% of electrical production. As a highly valuable and transportable energy source, petroleum is crucial for powering vehicles and industrial chemicals. Hydraulic fracturing is now widely used in the United States, Canada, and China to extract shale oil.

The Emergence of Refineries in India

India has been operating refineries for a considerable time and has made a mark for itself as a significant contender in this field. India holds the fourth position globally and second position in Asia, after China, with a refining capacity of 251.2 million MT/year as of January 1, 2022, according to the Snapshot of India's Oil & Gas data 2022. The locations of the different refineries in India are depicted in Fig. 4.

Applications of Petroleum

Oil played a crucial role in the 20th century and will continue to do so in the first half of the 21st century. Besides serving as a significant source of energy, it is also a crucial starting material for producing numerous synthetic products and chemicals. Oil is necessary for the production of natural gas, which is used to manufacture fertilisers, among other things. The global food production industry relies heavily on oil and gas for various purposes, such as transportation, insecticides, and cultivation. In pre-modern times, crude oil had multiple applications, including caulking boats, lubricating cartwheels, and manufacturing torches. Natural gas was used both as an illuminant and an energy source. The modern oil industry was established in the 19th century when engineers and businessmen began drilling for petroleum. At that time, kerosene was produced from crude oil to replace the increasingly scarce whale oil used for lighting. With the invention of vehicles, the industry's focus shifted to producing gasoline and other transportation fuels.

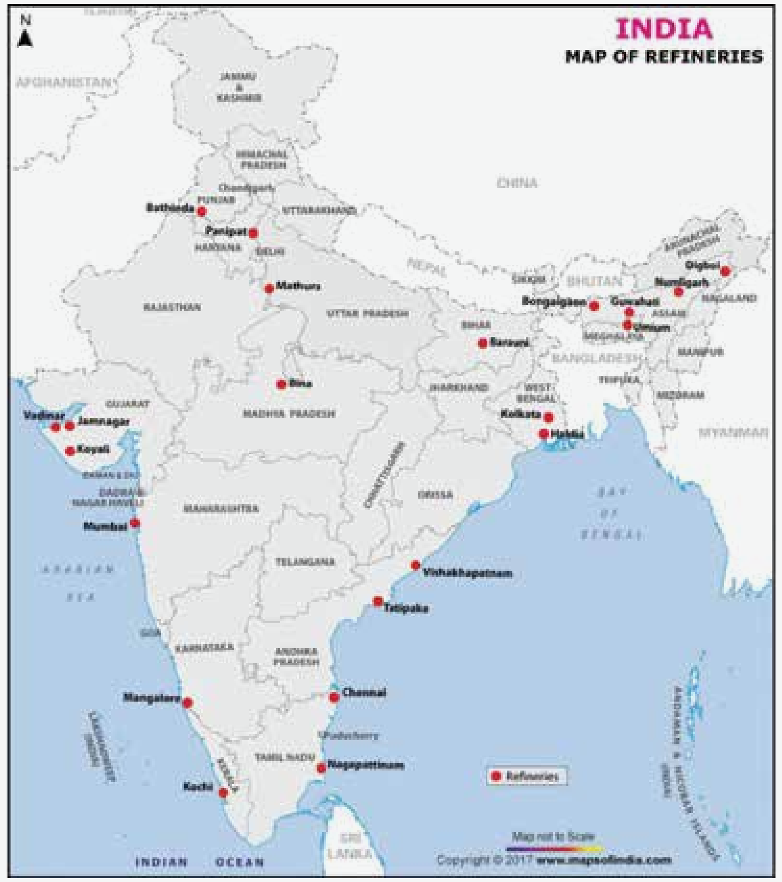


Fig. 4: Refineries in India

The use of petroleum has revolutionised not only the energy sector but also the manufacturing of a wide range of petrochemicals and synthetic products, such as plastics, textiles, rubber, insecticides, explosives, and more. Refining methods developed in the early 20th century was critical in making petrochemical production possible, and by the 1930s, during World War 2, these products, including synthetic rubber for tires, were being widely used.

India's domestic crude oil production has decreased over time, leading to a greater reliance on imported oil. Data released in December 2022 shows that there was a 1.1% decline in the production of indigenous crude oil and condensate compared to December 2021. However, the amount of crude oil processed during this period increased by 3.7%. There was also a 3% decline in crude oil imports compared to the same period in the previous year, followed by a 9.9% increase in refining.

From Fig. 5, it can be seen that the production of petroleum products saw a growth of 3.7% during December 2022 compared with December 2021. At 164.87 million MT consumed from April to December 2022, that figure represents a 10.5% increase over the 149.16 million MT consumed during the same period in 2021. In addition to furnace oil/low sulphur heavy stock (FO/LSHS), pet coke, bitumen, lubes and greases, LPG, and other items over time, this increase was driven by a 14.6% growth in motor spirit (MS) consumption, 14% rise in high-speed diesel (HSD), and 50% hike in ATF use. In comparison to the same month in 2021, the consumption of petroleum products in December 2022 increased by 3.1% to 19.6 million MT.

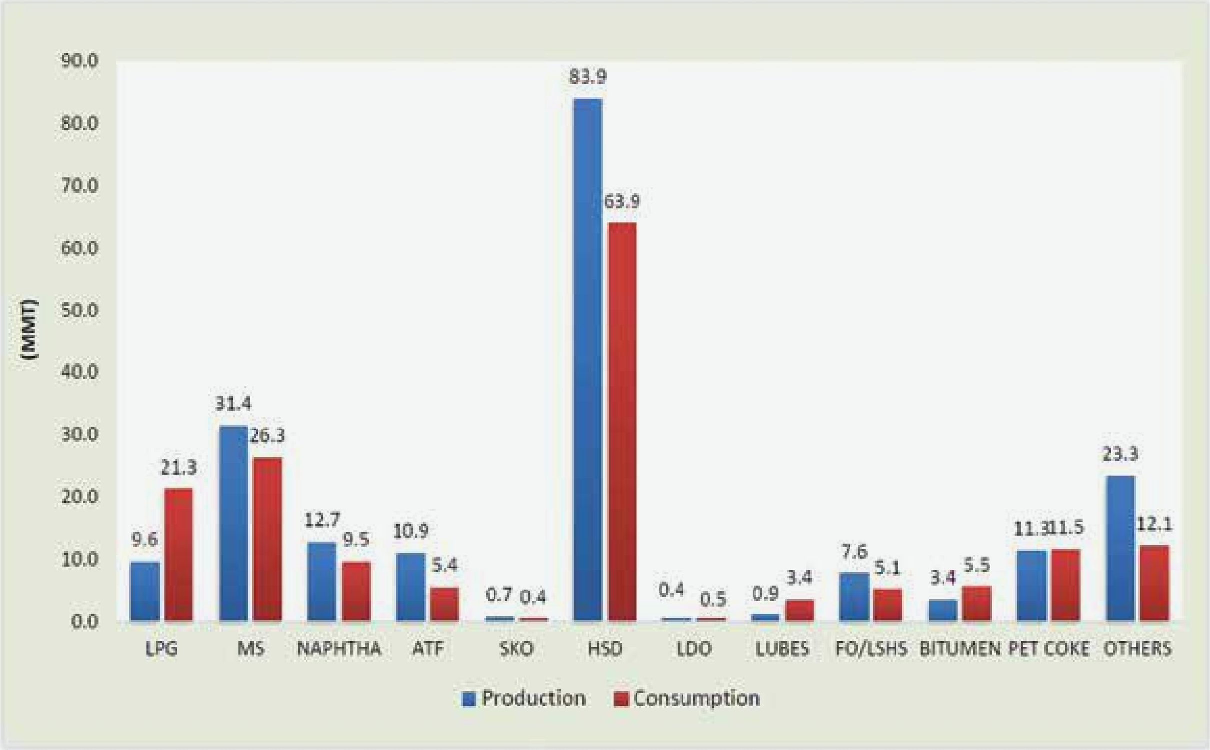


Fig. 5: Production and Consumption of Petroleum Products (million MT)

2.13.4 Alternative Fuels: World War 2, Apartheid Sanctions and The First Oil Crisis

Alternative fuels, also referred to as non-conventional and advanced fuels, are any substances or materials that can be used as fuels in place of conventional fuels, such as fossil fuels (petroleum, coal, and natural gas), nuclear materials like uranium and thorium, as well as synthetic radioisotope fuels produced in nuclear reactors.

Biodiesel, bio-alcohol (methanol, ethanol, butane), refuse-derived fuel, chemically stored electricity (batteries, fuel cells), hydrogen, non-fossil methane, non-fossil natural gas, vegetable oil, propane, and other biomass sources are a few well-known alternative fuels (U.S. EPA, 2015).

The First Oil Crisis

The oil crisis of 1973 was caused by the decision of Arab OPEC members to triple oil prices and stop oil shipments to several nations, including Western Europe and the United States. This had significant economic and political consequences for many countries, leading them to search for alternatives to overcome the crisis.
(https://www.rapidtransition.org/stories/from-oil-crisis-to-energy-revolution-how-nations-once-before-planned-to-kick-the-oil-habit/).

- **The United States**

The U.S. government joined forces with the industry to improve wind turbine technology and facilitate the construction of larger commercial wind turbines. They also conducted research on sustainable and alternative energy sources such as solar, geothermal, and wind energy. In response to the oil crisis, the U.S. government began to subsidise the production of corn-based ethanol as another solution. This crisis also resulted in a decrease in demand for gas-guzzling cars, and automakers began producing smaller and more fuel-efficient vehicles. Brazil blended ethanol with gasoline for use as car fuel, while natural gas and nuclear energy were utilised for electricity production, and natural gas was used for home heating applications.

- **Brazil**

The Brazilian government mixed ethanol with gasoline to create fuel for cars, while natural gas and nuclear energy were utilised to generate electricity, and natural gas was employed for domestic heating purposes.

- **Sweden**

Due to the oil crisis, Sweden's wood pulp sector reduced its reliance on fossil fuels by 70%. This is accomplished by producing biofuels.

As much as 90% of Sweden's biomass is produced by the forestry industry, which uses several types of wood (www.greenfacts.org). These contain tree pieces that can't be used to make paper or lumber. Recycled wood is often regarded as a form of biofuel. The remaining 10% of biomass comprises garbage, by-products of industry, biogas, and farmable fuel.

Alternative Fuel During World War 2

World War 2, which lasted from 1939 to 1945, was fought between two military coalitions: the Allied powers, led by the Soviet Union, the U.K., the U.S., and China, and the Axis powers, led by Germany, Japan, and Italy. The majority of the world's nations, including all of the great powers, were involved in this war. Both sides sought alternative energy sources because the available fuels were limited.

The Axis nations faced a significant shortage of petroleum to produce liquid fuel, whereas the Allied powers had access to more petroleum. Germany (part of the Axis bloc) developed a method to convert coal into synthetic fuel. The primary objective of the World War 2 oil campaign was to target the synthesis factories.

During World War 2, the U.S. supplied Britain and other Allied countries with aviation gasoline that contained tetraethyl lead as an additive. This additive improved the octane rating of the fuel, which allowed for higher compression ratios and increased the efficiency of Allied aircraft. As a result, the planes were able to achieve higher speeds and ranges, while also decreasing the cooling load. (https://en.wikipedia.org/wiki/Technology_during_World_War_II). During the interwar period, researchers explored potential alternative fuel sources for gasoline, leading to the decision to equip all motor vehicles with wood-gas generators in case of emergency. Wood gas was used to power gasoline engines, and vehicles, also known as wood gas or producer gas cars, converted wood into a flammable gas that could be used in place of gasoline. During World War 2, Belgium used liquid ammonia to power its buses. (https://alternative-fuels-observatory.ec.europa.eu/general-information/alternative-fuels).

2.13.5 Rediscovering Ethanol: Brazil's Great Leap

Ethanol, chemically known as ethyl alcohol (C_2H_5OH), is produced through the fermentation process when biomass serves as the feedstock. During this process, microorganisms such as yeast convert fermentable sugars into bioethanol. It is a colourless liquid that is safe for human consumption in small amounts.

The history of ethanol production dates back to ancient times when our ancestors noticed the fruity taste in ripe fruits and attempted to replicate it in a crude way. The use of ethanol by neolithic people was observed in dried residue found in northern mainland China, dating back to over 9,000 years ago. Ethanol was first synthetically prepared in 1826 by Henry Hennel in the U.K. and independently by S.G. Sérullas in France. Michael Faraday reported the first industrial synthesis of ethanol in 1828 through acid-catalysed hydration of ethylene. Ethanol was used as fuel in the U.S. before the Civil War and in early Model T automobiles. (https://kimia.co.uk/blog/the-history-of-how-ethanol-was-first-isolated/). Ethanol could not compete with the evolving petroleum industry, which revolutionised living in every way possible. The low cost and easy availability of fossil-derived sources led to the fading of ethanol use for fuel purposes.

The alcohol-producing industries are based on the following chemical reaction (Levey, 2004):

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

During the 1920s and 1930s, ethanol was primarily used as an octane booster in the fossil fuel industry. However, the potential of ethanol as an alternative fuel began to emerge in the 1970s due to the health risks associated with leaded petrol, which resulted in a need for an alternative octane booster. This led to the emergence of the modern ethanol industry, which was aided by the abundance of corn and its easy conversion into ethanol.
(https://www.ag.ndsu.edu/energy/biofuels/energy-briefs/history-of-ethanol-production-and-policy).

The Minnesota model proposed in the U.S. made it all the more popular, where the farmer-owned co-operatives received money for producing ethanol using the corn they grew. Here, a producer payment programme of $0.20/gal on up to 15 million gallons of ethanol per year for a maximum of 10 years was said to be provided.
(https://ilsr.org/rule/ethanol-and-biodiesel/2040-2/).

This introduced the concept of decentralised biomass processing, where the feedstocks available in a particular area is used to produce fuel that could be consumed in the same vicinity. It also helps to create local employment and business opportunities. The phasing out of methyl tertiary butyl ether (MTBE) was another critical step in fuelling the ethanol production business as its demand increased considerably.

The laws in different countries promoting the use of ethanol have been different and at varied timelines.

For instance, in the U.S., the Energy Policy Act of 2005 mandated an increase in the proportion of renewable fuel or ethanol blended with gasoline. The Energy Independence and Security Act of 2007 further increased its blending limits and widened the feedstocks' scope in terms of cellulosic ethanol.
(https://www.iea.org/policies/1492-energy-policy-act-of-2005-energy-bill).

Brazil has been at the forefront of blending biofuels with gasoline. The oil crisis in the 1970s prompted Brazil to look for domestic resources, leading to

the launch of the Proálcool programme in 1975 to support the ethanol-based transport industry. At that time, Brazil was importing around 70% of its petroleum requirement. Since then, ethanol production in Brazil has increased by 45 times, and the production cost has decreased by 70%. Brazil's RenovaBio programme aims to increase the share of bioethanol to 45% by 2030 as part of its decarbonisation efforts.
(https://energy.economictimes.indiatimes.com/news/oil-and-gas/brazils-ethanol-journey-from-a-fuel-of-the-future-to-the-future-of-fuel/90941877).

India has also been actively involved in blending bioethanol with petrol and has provided the necessary policy support for a 20% blending. The National Biofuel Policy of 2009 was the first step in this direction, followed by several amendments to address implementation challenges. The current policy, established in 2022, aims to achieve 20% ethanol blending in petrol by 2025. The Ethanol Blending Programme (EBP) has expanded the range of feedstocks that can be used.
(https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1826266).

The studies conducted in various countries indicate that utilising domestic resources for energy production has greater advantages such as achieving energy self-sufficiency and reducing GHG emissions compared to using fossil fuels for transportation. This approach also helps to establish a local supply chain to cater to local needs, leading to increased employment opportunities in rural areas.

2.13.6 Biodiesel and the Palm Revolution of Southeast Asia

Ascent of the Palm Oil Industry in Southeast Asia

The oil palm tree, scientifically known as Laeisguineensis, is a significant source of oilseeds worldwide. Initially, in West Africa, manual processing of oil palm was done to produce palm oil. However, during the industrial revolution in Europe, palm oil gained importance as an industrial lubricant for engine parts and wheels, leading to a surge in demand. The existing plantations in West Africa could not meet this demand, which prompted European colonialists to establish large-scale plantations in other parts of the world (Henson, 2012).

Adrien Hallet, a Belgian entrepreneur who had prior experience working in the industrial plantation of rubber in Congo, is credited with the development of oil palm in Southeast Asia. Hallet noticed that the palm tree in Indonesia produced more seeds than the African plants and was inspired to initiate a large-scale plantation in Sumatra in 1911. This was followed by a commercial-scale plantation in Selangor, Malaysia, by French investors in 1917 (Awalludin et al., 2015). After World War 1, the demand for natural rubber declined, rendering the land unutilised. Giant plantation companies, such as Guthrie and Socfin, repurposed the land for the plantation of palm oil. Subsequently, Southeast Asia's palm industry expanded rapidly, and by 1939-40, around 100,000 hectares of land were used for palm cultivation in Indonesia and Malaysia (https://chinadialogue.net/). By the 1980s, Malaysia and Indonesia had become the world's largest palm oil producers.

With the rise of the palm oil industry, evidence of its detrimental environmental consequences emerged, including deforestation of rainforests, disruption of food chains, loss of habitat and biodiversity, soil erosion, and negative social impact (Ayompe et al., 2021; Szulczyk & Khan, 2018). Since 1970, the expansion of oil palm plantations has led to the deforestation of tropical forests, resulting in a significant impact on biodiversity and ecosystem functions (Qaim et al., 2020). According to reports by the IUCN in 2018, industrial palm oil plantations were responsible for around 47% and 16% of deforestation in Malaysia and Indonesia, respectively, over the last 40 years.

Moreover, large-scale deforestation has devastated the biodiversity of tropical forests and raised issues of human-wildlife conflict. On the other hand, the expansion of palm oil has led to significant income gains for farmers and has generated employment through involvement in the supply chain and trade intermediaries. However, the extent of benefit gained by landholders and communities has varied significantly, causing adverse social effects such as conflicts over land rights and forced labour (Santika et al., 2019). Due to controversies surrounding palm oil cultivation, palm oil producers and buyers established the Roundtable on Sustainable Palm Oil (RSPO) in 2004 to create an ethical certification system aimed at promoting sustainable industry practices and implementing global palm oil standards (Hinkes, 2020).

Biodiesel Industry – Present Scenario

Palm oil is grown extensively in different regions of the world, including tropical Asia, Africa, and America. The oil, the meal, and its derivatives are exported worldwide, but it is especially important to the economies of Southeast Asian countries like Indonesia and Malaysia, which account for 83% of global production. Table 1 provides a breakdown of production capacity by country. Over 2022-23, the global production of palm oil reached nearly 77 million MT. The cultivation of palm trees is particularly attractive because it has a high oil yield of around 4-4.5 MT per hectare, which is significantly more than other oil-bearing crops such as soyabean (1-3.5 MT/hectare), sunflower (1-1.5 MT/hectare), or rapeseed (1.57 MT/hectare) (Mutsaers, 2019).

The leading sustainable palm oil players worldwide in 2023 (based on market capitalisation) include IOI Corporation Berhad, Sime Derby Plantation, Wilmer International Limited, Cargill, and Kuala Lumpur Kepong.
(https://www.researchandmarkets.com/).

Over the last decade, despite low fossil fuel prices, the global biodiesel market has experienced a remarkable growth of 20% per year, driven by international and national policies that promote biodiesel production. During this period, a significant portion of palm oil was utilised in the production of biodiesel. The process of producing biodiesel involves the transesterification reaction of oil, in which fatty acid methyl esters are generated from the oil. Transesterification occurs when the oil's triglycerides react with short-chain alcohols like methanol or ethanol in the presence of an alkali to produce biodiesel, along with glycerol as a by-product. Palm oil is more suitable for biodiesel production than other abundant vegetable oils due to its high content of palmitic and oleic acids. However, despite its benefits, the cultivation of palm oil has negative environmental impact, including deforestation, soil erosion, loss of habitat and biodiversity, and social issues (Ayompe et al., 2021; Szulczyk& Khan, 2018).

The increasing concerns with palm oil conjugated with the research on other sources of environment-friendly, locally available oils has given impetus to the use of non-edible oils for biodiesel production. Examples of non-edible oils extensively explored during the past decade include jatropha, madhuca, pongamia, azadirachta, jojoba and others. (Ogunkunle & Ahmed, 2019). Oil extraction from short-rotation crops such as Brassica *carinata*, castor and hibiscus has recently gained much attention (Basili & Rossi, 2018; Chidambaranathan et al., 2020). During the last decade, photosynthetic algae have attracted much attention, owing to their carbon sequestration capabilities, wastewater utilisation for biomass production, and fast biomass growth rate compared to other plants. Lipids extracted from biomass of oleaginous microalgae can be upgraded to fatty acid methyl esters suitable for use as biodiesel (Trivedi et al., 2022).

Another feedstock considered as a low-hanging fruit, due to its abundant availability and low cost, is used cooking oil (UCO). The conversion of UCO presents the dual benefit of waste valorisation and diverting the harmful-to-health waste cooking oil from the food chain to produce biodiesel (Bhonsle et al., 2022).

2.13.7 Biomass Energy: Coal Phase-out in East Asia

Coal usage has not yet reached its highest point in many countries and is expected to do so soon in order to achieve the goal of net zero by 2070. Power generation in the Asia Pacific region relies heavily on coal, which is the most carbon-intensive fossil fuel. As a result, phasing

Table 1: Global production of palm oil and the key locations of production (https://ipad.fas.usda.gov/ (Jan 2023))

Global rank	Country of Production	Oil production capacity (mil MT)	% of world production	Main Locations
1	Indonesia	45.5	59	Riau, Sumatra Utara, Sumatra Selatan, Jambi
2	Malaysia	18.8	24	Sabah, Sarawak, Johor, Pahang
3	Thailand	3.2	4	South and central Plain
4	Colombia	1.8	2	Meta, Santander, Cesar, Magdalena
5	Nigeria	1.4	2	South Nigeria
	Others	6.5	9	
	Total	77.2		

out coal is critical to achieving decarbonisation targets. Countries like India, China, Indonesia, the Philippines, and Vietnam depend on coal for more than 50% of their primary energy mix, which leads to significant greenhouse gas emissions.
(https://www.reuters.com/business/energy/asias-coal-phase-out-must-be-gradual-says-mitsubishi-heavy-head-2022-11-14/).

The failure to meet the coal phase-out targets can be attributed to various factors. The foremost reason is the insufficient availability of renewable energy sources, both in terms of intensity and quantity, to meet the growing electricity demand. The increase in industrialisation and digitalisation has led to a steep rise in energy requirements, and heavy-duty machines in energy-intensive industries cannot operate on intermittent energy sources. Another reason is the underutilisation of large-scale infrastructure, which can continue to operate for an optimal lifetime. The transition to a greener economy is often deemed economically unfeasible for newly established facilities with existing power purchase agreements.
(https://www.aljazeera.com/economy/2022/2/7/southeast-asias-no-1-hurdle-to-dumping-coal-decades-long-deals).

If power plants that run on coal were retired early in favour of cleaner energy sources, it will mean wasting a substantial amount of capital expenditure that went into building the infrastructure for electricity production, storage and transmission. Another major issue with coal phase-out is the socio-economic impact, particularly the loss of jobs for those whose livelihoods depend on coal. This includes many poor and vulnerable individuals.

To address these challenges, the Asian Development Bank recently announced the establishment of an Energy Transition Mechanism (ETM) during COP26. The ETM aims to identify barriers to early coal retirement and provide effective solutions. It will also serve as a funding vehicle to facilitate the phase-out of coal and the scaling-up of renewable energy production.
(https://www.spglobal.com/commodityinsights/en/ci/research-analysis/asias-pledge-on-coal-phaseout-a-thorny-problem-of-retiring-you.html).

After the COP26 conference, it has become clear that the world needs to explore alternative energy sources, particularly renewable ones. India has negotiated a coal phase-down plan instead of a coal phase-out plan, allowing the country to utilise newly built coal plants that still have 20-30 years of lifetime left. Currently, India has a coal-based electricity generation capacity of approximately 200 GW, whereas its renewable energy capacity is only around 100 GW. By phasing down coal, India can gradually transition to renewable energy by installing cost-effective renewable electricity generation and storage units.
(https://www.cnbctv18.com/energy/explained-why-india-negotiated-coal-phase-down-instead-of-phase-out-at-cop26-11495092.htm).

India has introduced the *Panchamrit* initiative as a means to achieve the goal of decarbonisation and reach net zero by 2070. The initiative aims to increase India’s non-fossil energy capacity to 500 GW by 2030, with the goal of meeting 50% of its energy requirements through renewable energy sources by that year. India also plans to reduce projected carbon emissions by 1 billion MT by 2030 and lower the carbon intensity of its economy to less than 45% by then. Ultimately, India aims to reach the net zero target by 2070.
(https://pib.gov.in/PressReleseDetail.aspx?PRID=1768712).

Renewable electricity costs have decreased due to advances in solar, wind, and other energy systems through R&D. While this electricity can power buildings and light vehicles, heavy vehicles and chemical industries still require carbon-based fuels/chemicals. Biomass is the only renewable source of organic carbon that can be used to produce valuable hydrocarbons.

Although humans have used biomass for centuries, it has only recently become popular for its conversion processes. India has been a leader in policymaking for biomass and formulated the National Biofuel Policy in 2009. The policy focused on fuels derived from non-edible plants, waste, and degraded or marginal lands to avoid the food versus fuel debate. In 2018, a gazette notification was issued with a target of 20% blending of ethanol in petrol and 5% blending of biodiesel in diesel by 2030.
This target aimed to reinforce ongoing ethanol/biodiesel supplies through increasing domestic production, setting up Second Generation (2G) biorefineries, developing new feedstock for biofuels, developing new technologies for conversion to biofuels, and creating a suitable environment for biofuels and its integration with primary fuels.
(https://mopng.gov.in/files/uploads/NATIONAL_POLICY_ON_BIOFUELS-2018.pdf).

The National Policy on Biofuels underwent several amendments to expand the range of feedstocks for biofuel production and encourage their production within the country, specifically within Special Economic Zones (SEZ) and Export Oriented Units (EoUs) as part of the Make in India initiative.
(https://mopng.gov.in/files/article/articlefiles/Notification-15-06-2022-Amendments-in-NPB-2018.pdf).

The amendments also included the addition of new members to the NBCC and granting permission for specific cases of biofuel exports. Additionally, certain phrases in the policy were deleted or amended to align with decisions taken during meetings of the National Biofuel Coordination Committee. These changes are expected to contribute to the Make in India campaign and decrease the imports of petroleum products through increased biofuel production.
(https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1826266).

Furthermore, the Indian government has implemented the SATAT scheme, which aims to promote the use of compressed biogas (CBG) by encouraging entrepreneurs to establish CBG plants and supply the fuel to Oil Marketing Companies (OMCs) for use in the automotive and industrial sectors.
(https://satat.co.in/satat/).
(https://rpo.gov.in/Home/Objective).

In addition, co-firing biomass in thermal power plants and co-generation in sugarcane mills is encouraged by the government of India through various schemes, including the SAMARTH scheme.

2.13.8 21st Century Green Diesel – the First True Drop-in Fuel

Biofuels such as biodiesel and bioethanol have higher oxygen content and moderate dissolution capabilities compared with conventional petroleum-based fuels.

They also possess corrosive properties. Reports indicate that blends of biodiesel in diesel above a 20% ratio can cause harm to engine parts, metal parts, rubber gaskets, and dispensers (DOE, 2016). This issue could be resolved by creating a drop-in fuel that is fully compatible with existing machinery. Drop-in fuels are similar to petroleum fuels in terms of their characteristics and chemical properties and do not necessitate any modifications to fuel storage, supply, and distribution infrastructure (Scaldaferri & Pasa, 2019).

Green diesel, or renewable diesel, has become a promising drop-in fuel that is non-oxygenated and, therefore, can be used in existing diesel engines (Guo, 2020). At the commercial level, green diesel can be produced using the following chemical routes: hydrodeoxygenation, deoxygenation, decarboxylation, decarbonylation, catalytic cracking, isomerisation, and hydroprocessing (Gerpen& He, 2014). The majority of green diesel is produced through hydroprocessing, in which biomass-based feed is transformed into a blend of paraffins and their branched isomers with a carbon range of C15-C18. Green diesel has a higher cetane number than biodiesel, ranging from 70-90 compared to biodiesel's range of 50-65, signifying faster and more complete ignition. Additionally, it offers advantages such as a higher calorific value, better oxidation stability, and superior performance in cold weather (isomerisation results in a cloud point of -20 to 20°C) (Fivga et al.,2019).

The renewable diesel industry is experiencing an increase in popularity and is expected to grow at a rate of 21.33% annually from 2020 to 2024, with the possibility of reaching an annual production of around 15 million MT by 2024. Table 2 provides information on the main industrial companies, their production capabilities, and the technology they employ.

Table 2: Global status of industrial players and technologies used for green diesel production (Farooqui et al.,2022; Zhang et al., 2018)

Company	Technology used	Location	Production capacity (tons/year)	Process details
Neste	NExBTL™	Netherland	10,00,000	Step 1: Single stage hydroprocessing Step 2: Isomerisation
		Singapore	10,00,000	
		Finland	380,000	
Axens IFP	Vegan®	France	540,820	Step 1: Single stage hydroprocessing Step 2: Isomerisation
Honeywell UOP/ENI	Ecofining™	Italy	780,000	Step 1: Single stage hydroprocessing Step 2: Isomerisation
AltAir Fuels		USA	780,000	
Diamond Green Diesel		USA	900,000	
Renewable Energy Group Inc	Dynamic fuels LLC	USA	250,000	Step 1: Two-stage hydroprocessing, Step 2: Isomerisation
UPM biofuels	UPM Bio Verno	Finland	100,000	Step 1: Single stage hydroprocessing, Step 2: hydrocracking/isomerisation

2.13.9 Sustainable Aviation Fuel and the Quest for a Drop-in SAF

The aviation industry has grown rapidly due to increased economic activities, trade, and travel on a global scale. Despite the slowdown in travel caused by the COVID-19 pandemic, passenger miles are expected to double by 2050 compared to 2010. Although aviation has played a significant role in enhancing global trade, its environmental impact is substantial. In 2021, the aviation industry alone emitted about 1 billion MT of CO$_2$, which is equivalent to approximately 2% of global CO$_2$ emissions (Gonzalez-Garay et al., 2022).

The aviation industry, along with the ICAO members, has developed a system to evaluate the lifecycle carbon footprint of different environmental and social risks. They have adopted CORSIA guidelines as an efficient way to decrease net emissions, in order to reinforce their efforts towards decarbonisation (Zhang et al., 2020). The aviation fuels certified by this agency are termed sustainable aviation fuels (SAF) (ICAO, 2021). The IATA, an alliance of over 300 airlines, made a significant commitment in October 2021 to reach net zero emissions by 2050.

At present, the aviation sector primarily uses Jet A-1 Kerosene that is derived from fossil fuels for its operations. The shift to SAF has emerged as the most promising approach to decarbonise the aviation industry in the near- and medium-term. The development of alternatives such as electric flight and energy-dense fuels like hydrogen is still in the early stages of technological advancement (Wolff &Riefer, 2020).

Chemically, SAF is synthesised paraffinic kerosene (SPK), which can be blended with fossil-fuel-derived jet fuel and can be used as a drop-in alternative fuel in existing aircraft engines seamlessly (Yang et al., 2019). SAF, sometimes also cited as bio-jet fuel or renewable jet fuel, is synthesised from renewable and sustainable bio-resources such as lignocellulosic biomass, agriculture residue, oils (vegetable oil, non-edible oil, algae oil, waste cooking oil), and industrial carbonaceous emissions (Farooqui et al., 2022).

SAF as a drop-in is much cleaner, and the lifecycle well-to-wake CO$_2$ equivalent (CO$_2$e) emissions of SAF vary from 5.2-73.4 gCO$_2$e MJ–1, depending on the type of feedstock used and the technology pathway. The numbers are significantly lower (94%) than for conventional fossil-based jet fuel, with emissions of 88-89 gCO$_2$e MJ-1 (Teoh et al., 2022).

The American Society for Testing Materials (ASTM) Subcommittee on Aviation Fuels has established the properties of aviation fuels in the U.S., according to IEA Bioenergy (2021). The ASTM certification (D7566) has approved seven alternative pathways for producing jet fuel, including Fischer-Tropsch Hydroprocessed Synthesised Paraffinic Kerosene (FT SPK), Synthesised Paraffinic Kerosene from Hydroprocessed Esters and Fatty Acids (HEFA SPK), Synthesised Iso-Paraffins from Hydroprocessed Fermented Sugars, Synthesised kerosene with aromatics derived by alkylation of light aromatics from non-petroleum (SPK/A), Alcohol-to-jet Synthetic Paraffinic kerosene (ATJ-SPK), Catalytic Hydrothermolysis jet (CHJ-SPK), and production of paraffin derived from hydrogenation and deoxygenation of fatty acid esters, and free fatty acids (HC-HEFA) (Białecki et al.,2020).

SAF has faced challenges in terms of commercial production due to its economic feasibility. Despite being priced at 2-4 times that of fossil-based jet fuel, the aviation industry has shown interest in it. In 2021, airlines globally purchased 125 million litres of SAF, and forward-purchasing agreements worth $17 billion have been signed as of 2022. (https://www.iata.org/).

A favourable and consistent policy environment and stable investments for bio-jet fuel production will incentivise its production and accelerate the commercialisation of SAF technologies in the future (Wang et al., 2019). A coordinated effort from governments, airlines, biofuel manufacturers and the private sector can pave the way towards achieving the long-term goal of net-zero emissions.

2.13.10 Today's biofuels – Lifecycle Analysis and Pathways to Evidence-based Sustainability

As mentioned earlier, biofuels are predominantly produced from non-edible sources, such as lipid biomass or non-lipid biomass. The shift towards renewable energy sources has been driven by the high carbon emissions and other GHGs associated with traditional energy sources. Consequently, new processes must be carbon-neutral or carbon-negative to avoid contributing to climate change. Biomass has an advantage in this regard since emissions resulting from biofuel combustion are typically absorbed during biomass growth. To determine whether a process is carbon positive or negative, a lifecycle analysis study is conducted. This analysis assesses the environmental emissions of a process from cradle to grave. The study involves several steps, including goal and scope definition, inventory analysis, and stage-wise impact assessment. By conducting a detailed analysis, it is possible to identify the unit operations or processes that are the major contributors to emissions, the energy efficiency of the process, and the possible trade-offs for the technology under study (Reijnders, 2021).

Bioethanol is produced mainly through the fermentation of 1G or 2G feedstocks. The bioconversion step is usually the major contributor to emissions, followed by feedstock harvesting. In the U.S., the study on bioethanol production using poplar was found to be carbon-negative (Morales-Vera et al., 2022).

Net energy gain has been observed in studies on bioethanol production from unutilised rice straw, from production to purification and wastewater treatment (Jayasundara et al., 2022). As mentioned earlier, the choice of feedstock used in the process also plays a significant role in the lifecycle results. Some feedstocks require more fertilisers during the growth phase than others making the latter set of feedstocks attractive for bioethanol production.

Before the major bioconversion step, the pre-treatment step is crucial as it enables the release of sugars for fermentation from the macromolecular structure of the biomass. It is important to take into account the feedstock growth factors before moving on to this step (Hassan et al., 2021). Therefore, in order to improve the energy efficiency of the process, a suitable pre-treatment step is necessary. When renewable grid electricity is utilised during production, the emissions during bioethanol production are further reduced (Parascanu et al., 2021).

Another approach being explored is fermenting the syngas or carbon-rich gases that are generated during the production process. This method is currently being tested in a few production units. A specific process that uses this approach for producing ethanol from biomass has shown nearly 90% reduction in emissions (Handler et al., 2016).

Renewable biomass-derived biogas is gaining attention due to the increased awareness about natural gas utilisation. It can be produced using the domestic carbon resources of any country. The production of biogas involves the anaerobic digestion of carbon substrates by microorganisms (archaea), resulting in a gas rich in methane. The produced biogas has to undergo purification and compression before use.

Studies have shown that biogas derived from municipal sewage sludge has negative GHG emissions when compared to coal-based electricity plants (Singh et al., 2020). In a case study in China, dry anaerobic digestion followed by digestate incineration was found to have better environmental benefits than wet anaerobic digestion (Xiao et al., 2022). Co-digestion of suitable substrates also helps increase the process's sustainability as it enables increased feedstock flexibility and reduces pressure on a single feedstock supply chain (Mosquera et al., 2021).

Biodiesel, another biofuel, is being considered for sustainability analysis based on lifecycle emissions. It can be produced by transesterification of seed oils, including both edible and non-edible, algal-derived oil, and UCO. In recent years, waste cooking oil or reused cooking oil has been the most preferred feedstock for biodiesel production as continuous utilisation of UCO can lead to health hazards and needs to be removed from the cooking supply chain. The transesterification process can be carried out using solid-phase or liquid-phase catalysts.

The major sources of GHG emissions in the biodiesel production process are the catalysts/acids and methanol used in the process, as well as feedstock production, as noted by Yung et al. (2021). Lifecycle analysis studies conducted by the CSIR-Indian Institute of Petroleum on their low-temperature biodiesel production process indicates that reduced temperature requirements during the conversion process result in lower emissions (Bhonsle et al., 2022).

In another study, Longati et al. (2022) used oleaginous yeast grown on sugarcane bagasse derived C5 sugars to produce microbial oil, which was then converted to biodiesel in an integrated biorefinery with lower environmental impact than the usual sugarcane ethanol production process. Studies on biodiesel production from non-edible oils such as palm and rapeseed oils indicate that a significant portion of the environmental load comes from the feedstock production stage (Gupta et al., 2022; Phuang et al., 2021). In the case of microalgal biodiesel production, the type and amount of solvent used in the process are the primary contributors to the environmental impact (Huang et al., 2022).

Another approach to producing diesel involves hydroprocessing esters and fatty acids to generate green diesel and bio-ATF (aviation fuel derived from biomass). Research indicates that this method results in lower GH emissions compared to traditional diesel production from fossil fuels (Antonio et al., 2021).

The next type of biofuel being explored is biomass-based aviation turbine fuel. There are various ways to produce aviation fuel from biomass, including hydroprocessed esters, bio-derived alcohol, and the Fischer-Tropsch method. One of the easiest

ways to produce this fuel is through co-processing studies in conventional refinery models. However, more research and development are necessary before it can be implemented on a commercial scale. Co-hydroprocessing is believed to be more effective than co-processing via the FCC method (Cruz et al., 2019).

Bioconversion of poplar biomass has been carried out to produce jet fuel. The emissions were lower than the conventional fossil-derived jet fuel (Budsberg et al., 2016). The step that was the major contributor to GHG emissions was the feedstock production stage (Budsberg et al., 2022). Brassica *carinata* has been found to be a suitable feedstock for SAF production due to its high yield and lower fertiliser requirement during the growth stage.

Significant carbon savings of around 65% has been observed in this case (Alam et al., 2021). The Fischer-Tropsch Jet process shows significant reduction in emissions compared to the other methods of bio-ATF or SAF (Han et al., 2013; Guimarães et al., 2023; Ahmad et al., 2021). The multitude of available options or pathways for producing SAF requires further research to identify the optimal process for each country's specific situation.

Upon examining the lifecycle assessments of the aforementioned biofuels, it is apparent that the emissions from feedstock production and transportation are significant contributors to process emissions. Therefore, there is a need for future studies to better understand the availability and characteristics of biomass in various locations to efficiently plan the production process. It is well-established that biofuels derived from biomass have lower environmental impact compared to fossil fuels. The focus now should be on identifying the most suitable biofuel to complement fossil fuels during the transition to a net-zero scenario.

2.13.11 Future Outlook

Most human activities involve the use of machines that cannot convert 100% of the input energy into output work, leading to GHG emissions when fossil fuels are used. The growing demand from stakeholders for sustainability has made it imperative to transition from non-renewable carbon sources extracted from the earth to alternative sources of energy. There are three main ways to achieve this.

On the demand side, improving energy efficiency is a key approach to reducing the carbon demand of machines. Energy efficiency trends are moving towards customising lubricants for each machine, which is the first line of defence for decarbonisation. Digital tracking and optimisation of energy use at every source and load point is also crucial to identify inefficiencies and suboptimal system elements. Waste heat recovery, pinch analysis in thermal energy networks, and variable nozzle turbines in fuel combustion systems are other emerging options for improving energy efficiency.

On the supply side, there are two approaches to decarbonisation: replacing carbon-based energy with non-carbon sources such as solar, wind or geothermal, or replacing carbon-based energy with lower-carbon-footprint sources such as biofuels.

To achieve the net-zero goals, a combination of the above options will be necessary, as there is no single solution. However, it's also important to provide affordable energy access for everyone, and the pace of decarbonisation may vary depending on the region and the emergence of affordable non-fossil alternatives. Unexpected events such as the COVID-19 pandemic, which caused a significant reduction in energy demand, or conflicts like the Ukraine War that create artificial scarcity of natural gas, may delay the global transition to non-fossil alternatives for a few more decades.

SECTION -3

NUCLEAR FISSION AS A SOURCE OF CLEAN ENERGY

Nuclear Fission as a Source of Clean Energy

3

Nuclear Fission as a Source of Clean Energy

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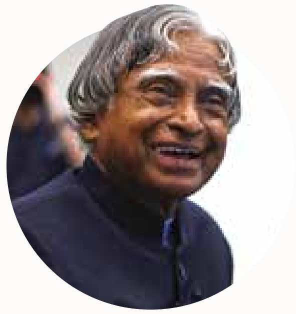


We are all born with a divine fire in us. Our efforts should be to give wings to this fire and fill the world with the glow of its goodness.

Dr A P J Abdul Kalam

Our society relies heavily on the energy we generate, but this production often comes at a cost to the environment. However, clean energy production offers a way to generate the energy we need without the harmful GHG emissions associated with fossil fuels. GHGs trap heat in the earth's atmosphere and are a major contributor to the increasing levels of CO_2. Fossil fuel combustion is one of the primary sources of these emissions [1]. By shifting towards clean energy sources, we can help slow down the pace of climate change.

In India, electricity is generated using conventional sources such as thermal, nuclear, and hydro, as well as renewable sources such as wind, solar, and biomass. However, around 75% of the total power generated comes from coal-fired thermal power plants, which are also the main sources of electricity in India. According to the Central Electricity Authority, India generated 103.66 billion units of electricity in December 2020[1].

If we can reduce our carbon footprint and rely more on clean, renewable energy sources, we will have a better chance of limiting the effects of climate change and protecting our world for future generations. Clean energy refers to the generation of electricity without the direct production of greenhouse gases such as CO_2. This type of energy can be produced through the use of sunlight, wind, nuclear resources, and even water.

There are several examples of clean energy sources[2] that can be used to generate electricity, including nuclear energy, solar energy, hydroelectric energy, wind energy, and geothermal energy. Nuclear energy is produced through nuclear fission, where the nucleus of an atom is split into smaller segments, releasing a large amount of heat energy that can be used to generate electricity. Solar energy involves converting the sun's light energy into electrical energy using solar panels. Hydroelectric energy uses the potential energy of running water to spin turbines and generate electricity. Wind energy is generated by the movement of wind turbine blades, which capture the kinetic energy of wind and convert it into electricity. Geothermal energy uses heat from the earth's core to generate electricity by drilling holes into the earth, allowing water and steam to ascend to the surface, and then using the water to drive electricity-producing turbines.

Fig. 1: Clean energy sources save the environment. ref [10].

Clean energy offers several advantages, with the main two being economic and environmental. From an environmental perspective, producing clean energy generates fewer pollutants compared to the process of generating energy from fossil fuels. Reducing these harmful emissions is crucial for mitigating climate change. From a financial standpoint, as the renewable energy sector expands, it can support the creation of new jobs and drive economic growth[2].

The nucleus is primarily composed of protons and neutrons, collectively called nucleons. Similar to the Coulombic force that holds electrons outside the nucleus, it is the nuclear force that binds nucleons together. In comparison to electronic transition energy, nuclear transition energy is several orders of magnitude larger (see figure 2). Therefore, a significant amount of energy is released during nuclear fission and fusion processes. Nuclear fusion refers to the combination of nuclei, while fission is the splitting of nuclei.

As shown in Fig. 3, when an incident neutron hits a fissile nucleus, such as 235U, it will break into two smaller nuclei, such as a krypton nucleus and a barium nucleus, and two or three neutrons with a large amount of energy in the form of heat and radiation. The extra produced neutrons will then incident on the surrounding uranium nucleus, which will again split and generate more neutrons. This will create a chain reaction in a fraction of a

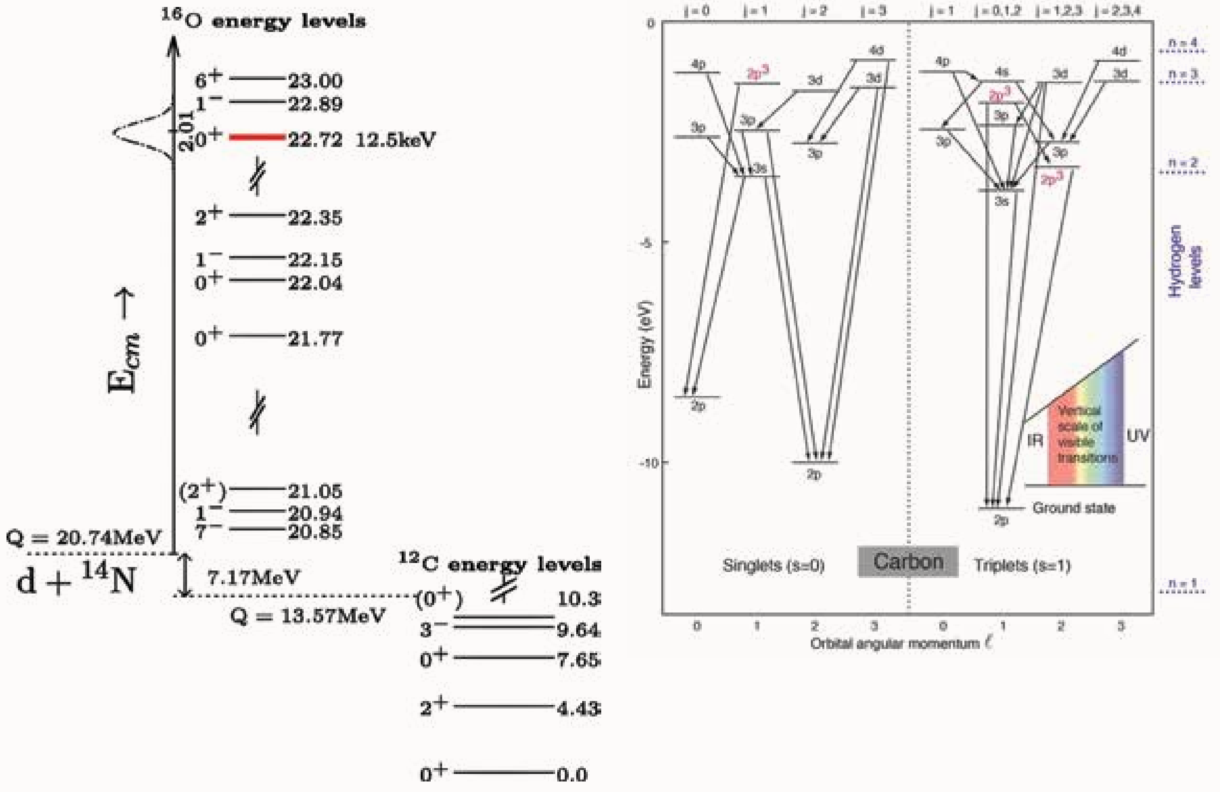


Fig. 2: Comparison between electronic (a) and nuclear transitions (b) of 12C. The order of electronic and nuclear transitions is in eV and MeV respectively. Figure (a) and (b) ref. [3] and [4].

second. In a controlled chain reaction, the energy released in the nuclear fission process can be converted into electrical energy.

A typical nuclear reactor consists of fuel rods, a moderator, control rods, and spin turbines. The fuel, uranium, is converted into small ceramic pellets, which are then placed into sealed metal tubes called fuel rods. To create a fuel rod, the fuel pellets – which are typically 1.5 cm long and 1 cm in diameter – are often placed in a long zirconium alloy (zircaloy) tube. Zirconium is a robust, corrosion-resistant metal that is also neutron transparent. It is a crucial mineral for nuclear energy, which is where it is mostly used. As a result, trade controls are in place. The zircaloy is made of about 98% Zr plus around 1.5% tin, iron, chromium, and occasionally nickel to increase its strength because it is typically contaminated with hafnium, a neutron absorber [6]. These fuel rods are bundled, with over 200 rods in each assembly. The reactor core consists of several hundred of these assemblies, which can vary depending on the power output required from the reactor [7].

The fuel rods are immersed in the moderator and coolant inside the reactor vessel, with water or heavy water being the common choices. The purpose of the moderator is to slow down the neutrons produced during the reaction to sustain the nuclear reaction. The selection of moderator/coolant depends on whether the fuel rods are enriched in 235U or not. Heavy water makes a good moderator due to its high moderating ratio and low neutron absorption cross-section. Although the use of heavy water is expensive, the cheaper cost of natural uranium more than makes up for it. Heavy water (D2O) is used for natural uranium fuel while water is used for enriched uranium fuel.

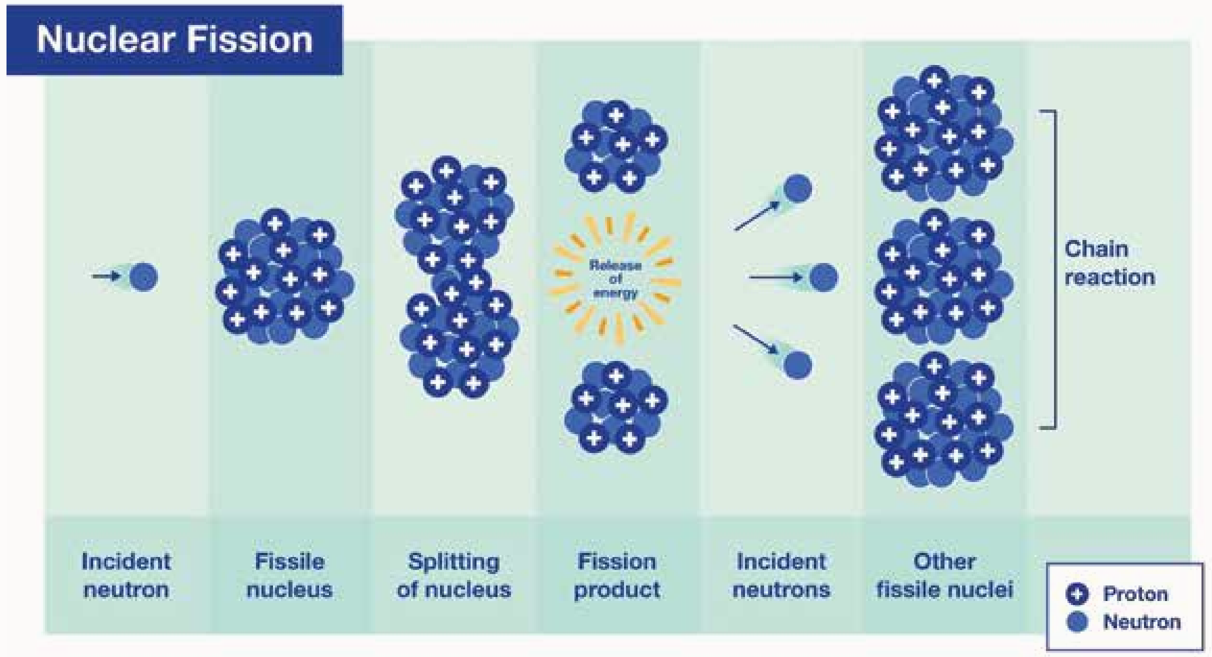


Fig. 3: Typical fission reaction in nuclear reactor. Image adopted from reference [5].

Control rods made from boron can be inserted or withdrawn from the reactor core to decrease or increase the reaction rate, respectively. The heat generated by the fission reaction can be used to vapourise water, which then spins the turbines to produce electricity.

In India, there are currently 22 operational reactors with a combined operating capacity of 6780 MW, and one reactor, KAPP-3 (700 MW), was linked to the grid on January 10, 2021. Additionally, there are eight reactors with a combined capacity of 6,000 MW that are in different stages of construction. The most common type of reactor in India is the Pressurised Heavy Water Reactor (PWHR).

3.1 Types of Nuclear reactors[6]:

- Pressurised water reactors (PWRs) are the most prevalent type of reactors for electricity generation with around 300 operational reactors and several hundred more used for marine propulsion. Initially conceptualized as a submerged power plant, PWRs use ordinary water as a moderator and coolant. This design is characterised by a primary cooling circuit that travels through the reactor core under extremely high pressure and a secondary circuit where steam is produced to power the turbine.

A big reactor would typically have approximately 150-250 fuel assemblies containing 80-100 MT of uranium. In contrast, a PWR contains fuel assemblies with 200-300 rods each that are vertically placed in the core. The water in the reactor core reaches a temperature of around 325°C, which means it must be kept under a pressure of almost 150 times that of the atmosphere to prevent boiling. A pressuriser is used to maintain the pressure, as shown in the diagram. Water serves as a moderator in the primary cooling circuit, and if any of it were to turn to steam, the fission reaction would slow down. One of the safety features of this type of reactor is the negative feedback effect. The primary circuit of the secondary shutdown mechanism is supplemented with boron. As there is less pressure in the secondary circuit, water boils in the heat exchangers, which act as steam generators. The steam then condenses and returns to the heat exchangers in contact with the primary circuit after powering the turbine to generate electricity.

- Boiling water reactor (BWR): This type of

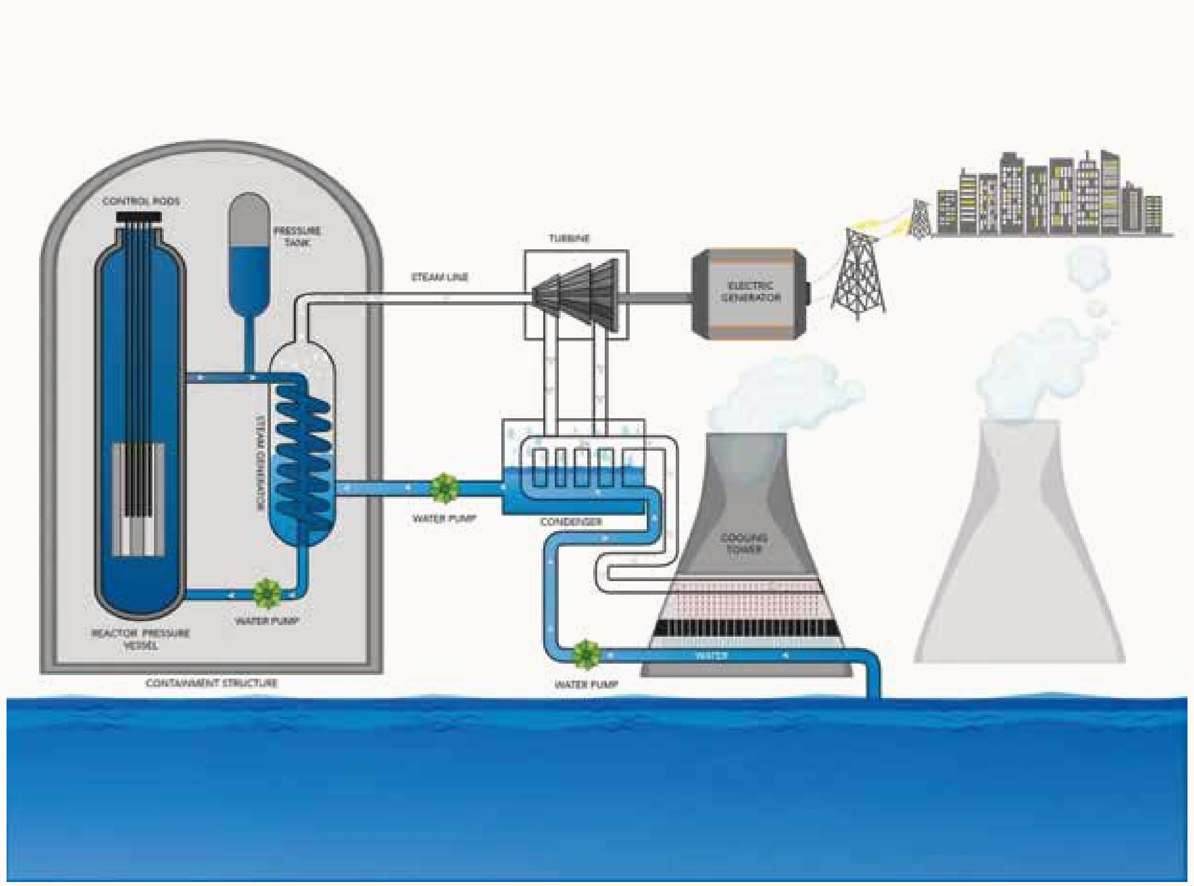


Fig. 4: Pressurised Water Reactor. Image Adopted from Reference [5].

reactor resembles the PWR in many ways, but it only has one circuit where the water is at reduced pressure (about 75 times air pressure), and it boils at around 285°C in the core. The reactor is designed to operate with 12-15% of the water in the top of the core being steam, which results in a less efficient moderating effect. Compared to PWRs, BWR units can operate in load-following mode more easily. The turbines, which are a part of the reactor circuit, receive the steam directly after passing through steam separators above the core.

- As traces of radionuclides are always present in the water around a reactor's core, the turbine needs to be protected, and radiation protection must be provided while it is being maintained. This tends to be more expensive than having a simpler design. As the majority of radioactivity in the water is extremely transient, the turbine hall can be used shortly after the reactor is turned off. There are up to 750 BWR fuel assemblies in a reactor core, each carrying up to 140 MT of uranium. A BWR fuel assembly consists of 90-100 fuel rods. In order to reduce moderation, the secondary control system restricts water flow through the core and increases the amount of steam in the upper section.
- Pressurised heavy water reactors (PHWR): The PHWR reactor, often known as the CANDU, has been developed since the 1950s in Canada and since the 1980s in India. Since PHWRs typically burn natural uranium oxide (0.7% U-235) as fuel, a more effective moderator is required. In this case, heavy water (D2O) is used. Compared to other designs, the PHWR produces more energy per kg of extracted uranium, but it also uses a lot more fuel per unit of output.

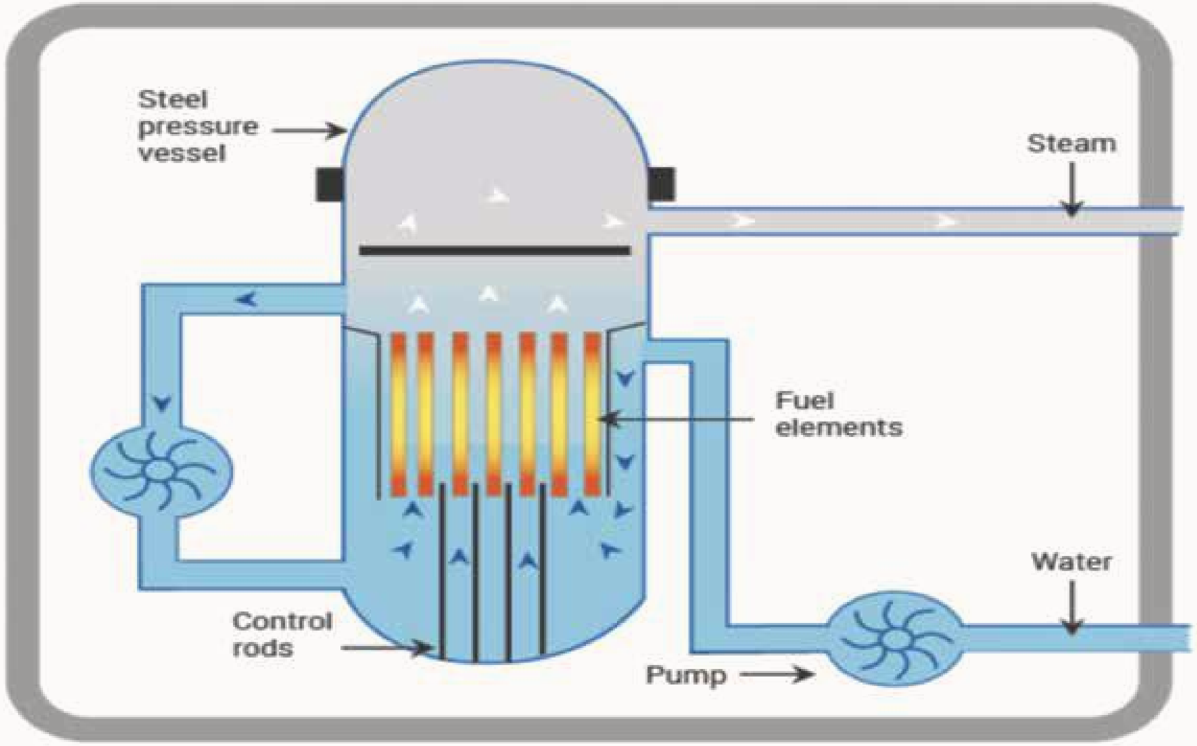


Fig. 5: Boiling Water Reactor. Image Adopted from Reference [6].

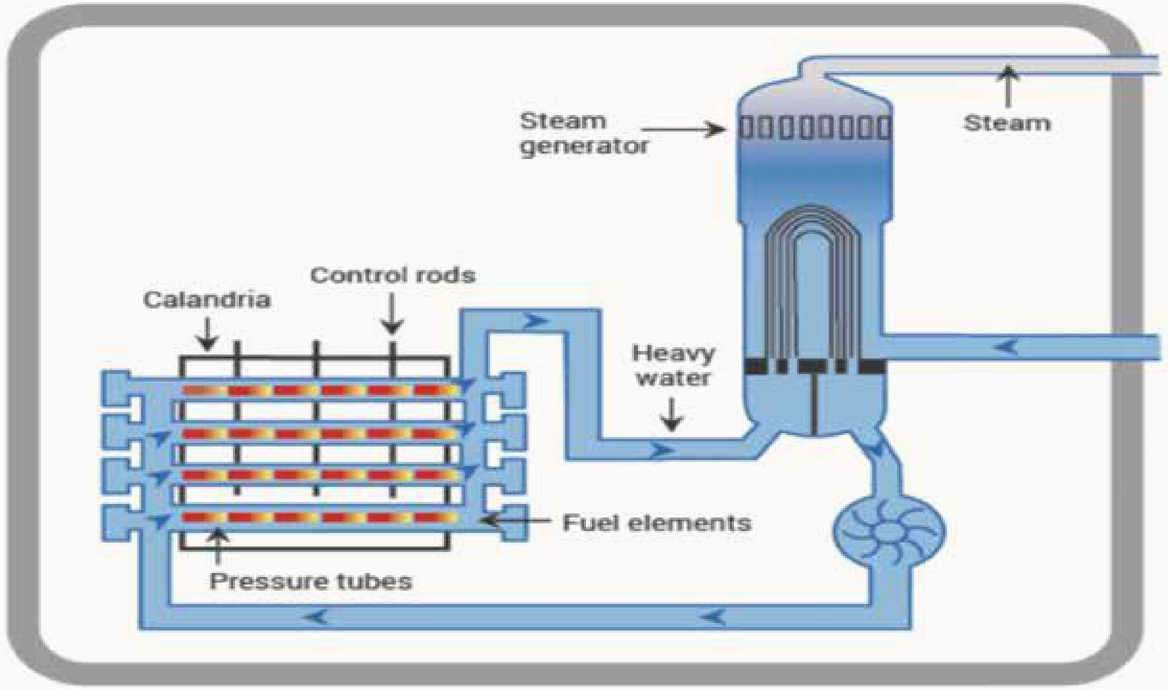


Fig. 6: Pressurised heavy water reactor. Image adopted from ref [6].

- The moderator is situated within a sizable tank called a calandria, which is perforated by several hundred horizontal pressure tubes that serve as channels for the fuel. The primary cooling circuit uses a flow of heavy water under high pressure, typically reaching 290°C, roughly 100 times atmospheric pressure. Like in the PWR, the primary coolant generates steam in a secondary circuit to power the turbines. Due to the pressure tube architecture, the reactor can be refuelled gradually without shutting down if each pressure tube is isolated from the cooling circuit. Although the tubes have not proven to be as durable, it is also less expensive to construct than designs with a big pressure vessel.
- Advanced gas-cooled reactors use CO2 as the main coolant and graphite as the moderator. The fuel consists of uranium oxide pellets in stainless steel tubes enriched to 2.5-3.5%. After reaching a temperature of 650°C, the CO2 circulates within the steam generator tubes outside the core, still inside the concrete and steel pressure vessel. Control rods enter the moderator, and nitrogen is injected into the coolant as part of a secondary shutdown mechanism.
- Fast neutron reactors: Some reactors use fast neutrons instead of a moderator to generate electricity from plutonium while producing more of the radioactive isotope 238U in or around the fuel. Although they produce more than 60 times as much energy from the original uranium as conventional reactors do, they cost more to develop. They are predicted to undergo further development in the upcoming ten years, with FNRs being the primary designs anticipated to be constructed in that time. They are known as fast breeder reactors if they are set up to create more fissile material (plutonium) than they consume (FBR).

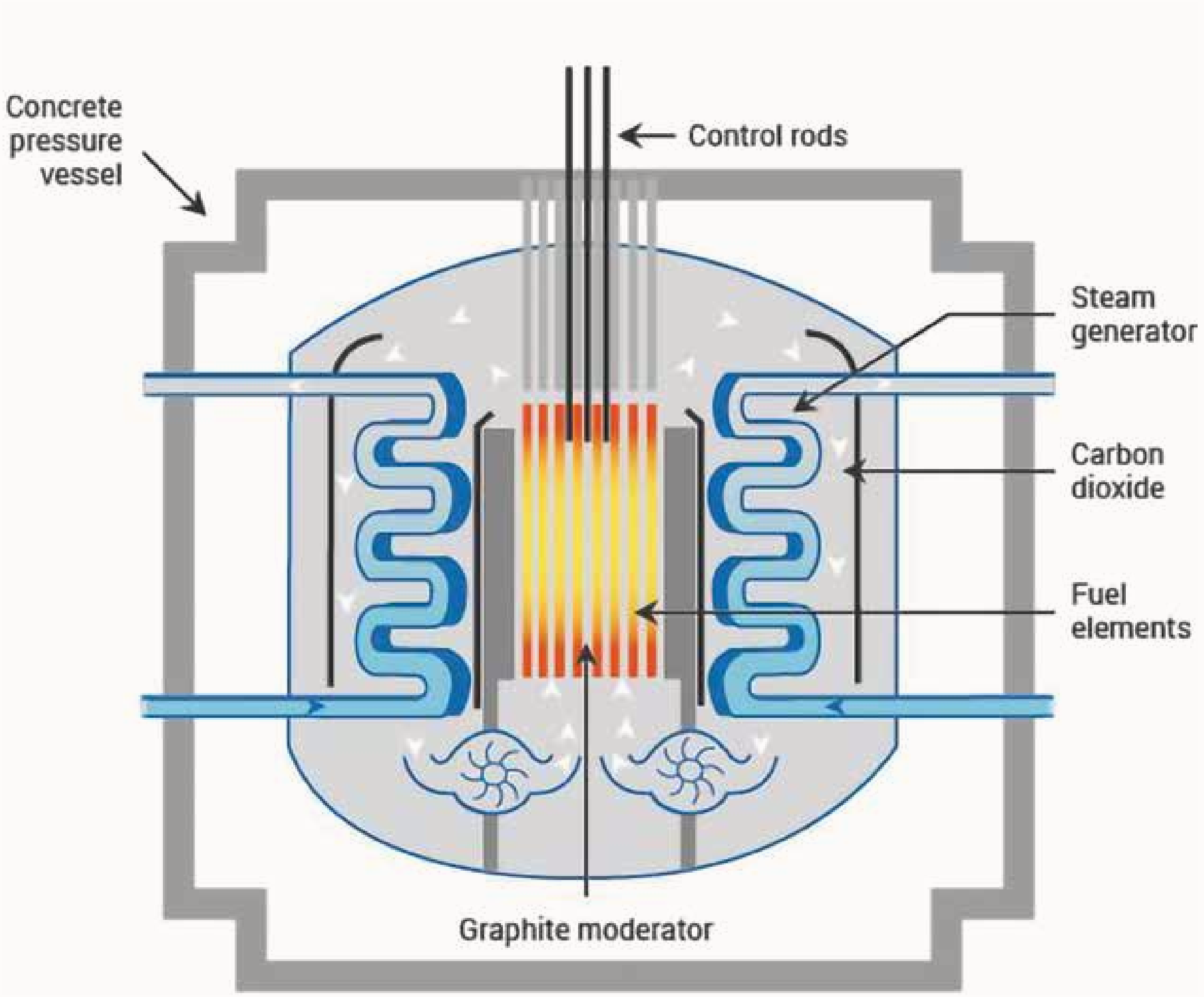


Fig. 7: Advanced gas cooled reactor. Image Adopted From Ref [6].

- Nuclear microreactors: Nuclear technology is becoming more compact, providing the industry with significant new opportunities. In the next ten years, some microreactor designs currently being developed in the US may become available. These small, truck-transportable compact reactors could assist in addressing energy issues in various settings, including military posts and isolated commercial or residential areas. To reliably heat and power various locations, from residential and isolated areas to military outposts, some microreactors can be set up in days rather than years. Despite their diminutive size, microreactors have a lot of power. Typically, a single unit produces 1 to 10 MW of electricity.

3.2 Disposal Of Nuclear Material [11]:

The protection of people and the environment is the primary goal of nuclear waste disposal. Practically all wastes are contained and controlled to ensure that they do not emit hazardous radiation. However, some wastes obviously require deep and permanent burial. Deep geologic storage and recycling are two general possibilities for properly disposing of nuclear waste.

The four primary categories of nuclear waste are as follows [11]:

- High-level waste: This is the waste that is left over after producing energy using nuclear fuel in a nuclear reactor. Little pellets and fuel rods make up the waste because the fuel has been utilised.

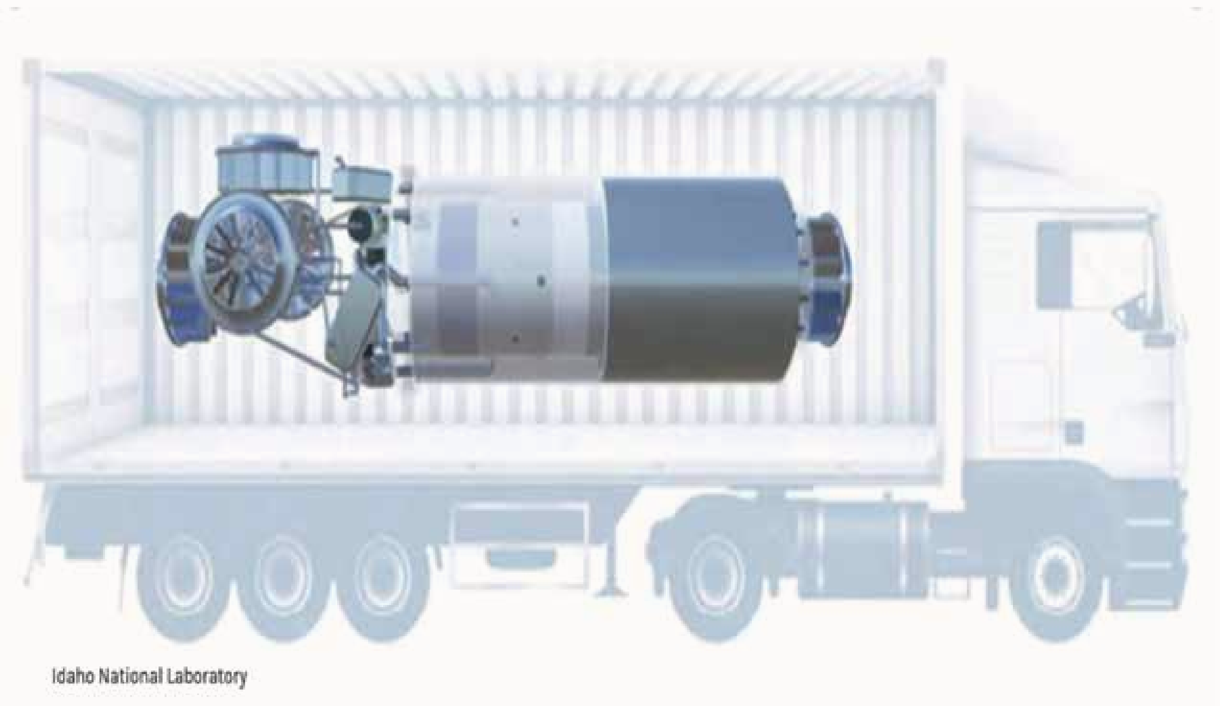


Fig. 8: A cartoon depicting micro-reactors that can be placed inside a truck for the purpose of electricity generation. ref [9].

- Intermediate-level waste: An intermediate class of radioactive waste often includes substances that must be safely kept away from people or the environment but do not need to be cooled first. This degree of radioactivity is frequently present at decommissioned nuclear facilities, and how waste is managed depends on how long it takes for the radioactivity to decay.
- Low-level waste: Often, they are items that were used in a nuclear operation and are now contaminated, such as cloths for cleaning up, tubes for storing materials, or even clothing and tools.
- Mill tailings waste: The residue generated during the extraction process of nuclear materials is called mill tailings and must be disposed of.

There are several conventional methods used for handling and disposing of nuclear waste [11]:

- Incineration: Low-level waste, such as contaminated clothing and common objects, are typically incinerated.
- Storage: Radioactive waste with a short half-life is stored until it is no longer radioactive.
- Shallow burial: Mill tailings, which are less radioactive, can be buried in designated areas close to the mill by building a mound of tailings and covering it with an impermeable material like clay.
- Deep burial: High-level waste is disposed of in deep burial pits underground, which requires the construction of underground laboratories to monitor the materials.
- Recycling: Certain radioactive elements like uranium and plutonium can be separated and reprocessed for reuse from specific radioactive materials, including old fuel.

SECTION -4

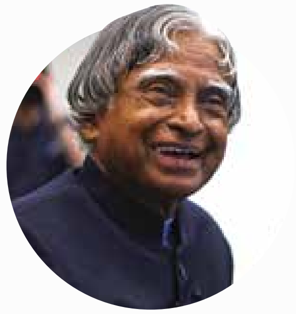
RESEARCH AND DEVELOPMENT

Hydrogen for Clean Cooking | Coal Gasification | Indian Coal Gasification Strategy: Current Status and the Way Forward | H2 in SOLID – The “Missing Piece” in the Net-Zero Logistics Ecosystem

4.1

Hydrogen for Clean Cooking

Dr J P GUPTA, MD Greenstat & G. HARI BALAMURALI, Scientist,
Shriram Institute for Industrial Research



It is very easy to defeat someone, but it is very hard to win.

Dr A P J Abdul Kalam

4.1.1 Hydrogen as Fuel

Hydrogen has been a well-known gas since 1766, but due to its low density and flammability, it has not been commonly used as a fuel for domestic purposes. However, the Shriram Institute of Industrial Research has successfully developed a solution for utilizing hydrogen gas safely at low pressures for domestic use. They have named this solution GUI-WOSH, which stands for Generate Utilise Instantly Without Storage & Hold-up.

The GUI-WOSH should be implemented using the following steps:

- Instantly generate green hydrogen gas using a PEM electrolyser from de-ionised water. The electrolysis process will be powered by solar panels.
- Immediately combust the generated hydrogen gas passing through a wet-liquid flashback arrestor to produce a flame for cooking. The combustion will occur via a precisely designed burner while maintaining a certain fuel-to-oxygen ratio.
- There will be no storage or hold-up in the stove, even in the event of power unavailability during cooking, solar power fluctuation, or any other breakdown scenario.
- The design practices have been followed as per the following standards:
    - NFPA 2 is the Hydrogen Technologies Code.
    - CGA H-5-2014 is the Installation Standard for Bulk Hydrogen Supply Systems.

4.1.2 Globally Used Domestic Fuel Today

LPG cylinders are widely used by people as the primary source of fuel for cooking in households worldwide, and people are generally well-versed in the safe handling and usage of LPG cylinders. In addition to LPG, many major cities have City Gas pipelines that provide Piped Natural Gas connections. In rural areas, biogas is produced through anaerobic digestion of cow dung, while in cities, some people use anaerobic digestion of decayed plant and household organic matter to produce biogas. Some individuals use kerosene for cooking, while others use electric induction stoves as an alternative to LPG when it is unavailable or while traveling. Propane is also used for room heating purposes.

4.1.3 Hydrogen for Clean Cooking

Penetration of Hydrogen in LPG Market

To successfully introduce hydrogen into the current LPG market, the following criteria need to be met:

- The hydrogen fuel must be user-friendly in a closed kitchen environment, with safe handling measures similar or even safer than those of other fuels.
- The price of cooking with hydrogen per day should be comparable or lower than LPG currently.
- Hydrogen fuel should have low emissions of CO_2 into the ambient air and low heat radiation into the surrounding area, compared to all other existing fuels.
- There should be leak protection alarms and automatic shutdowns in case of any leaks, which is not currently available in most gas cooking stoves.
- Efficient and healthy cooking should be possible using hydrogen, while minimising the amount of fuel consumed.

Practical Observation of Hydrogen Gas by Shriram Institute of Industrial Research Team

Our team has observed the following impressive results:

- Hydrogen can be safely burned like other fuels, provided it is handled with care.
- Safe handling can be achieved by avoiding storage and immediately burning the generated hydrogen.
- An auto-ignition system should be used to ignite the hydrogen, and a flame detector should be in place to prevent any accidental fires.
- By following our "GUI-WOSH" method of cooking, the highest level of safety can be guaranteed under any circumstances.

If the flame sensor fails, the system will activate an alarm and trigger auto shut-off. The concentration of hydrogen gas in the air will never be allowed to exceed 4%, regardless of the cause.

Fig. 1: Hydrogen gas for clean cooking

According to our precise evaluation, it has been found that there is little to no heat radiation into the atmosphere when using hydrogen as a fuel for cooking, compared to other fuels. This is because burning hydrogen only releases H2O vapour, so there is no emission of CO_2 into the ambient air. We are currently studying the prevention and minimisation of NOx generation, but even in the worst-case scenario, the amount of NOx released by the system will not exceed the current level of NOx emissions from LPG. Although cooking with hydrogen is a slow process, it is highly efficient and provides healthy cooking with minimal air emissions. The energy consumption required for cooking with our stove is much lower than that of an induction stove.

Design of Stove by Shriram Institute of Industrial Research Team:

- A Piping & Instrumentation Drawing for Clean Hydrogen cooking stove has been prepared as below:

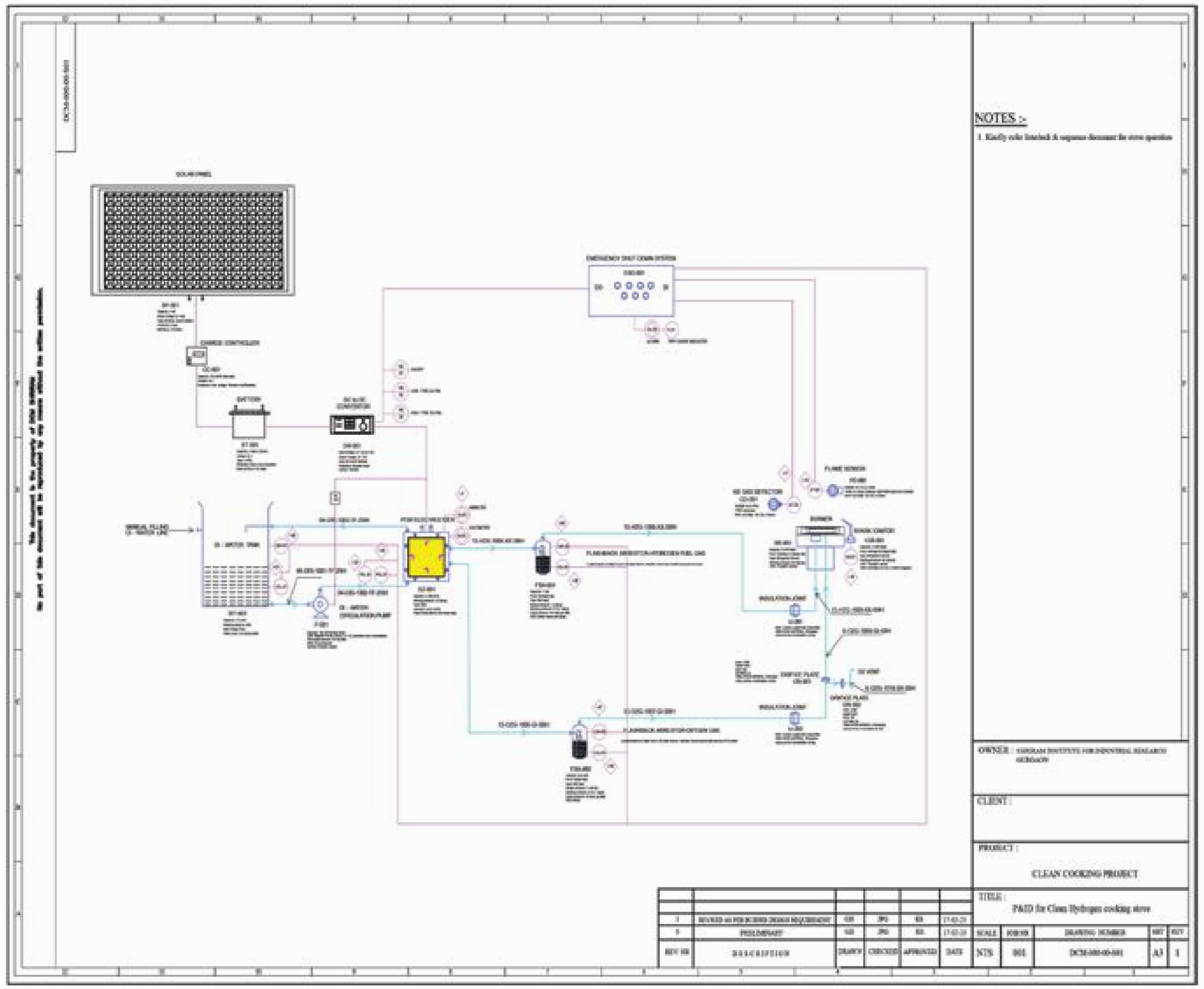
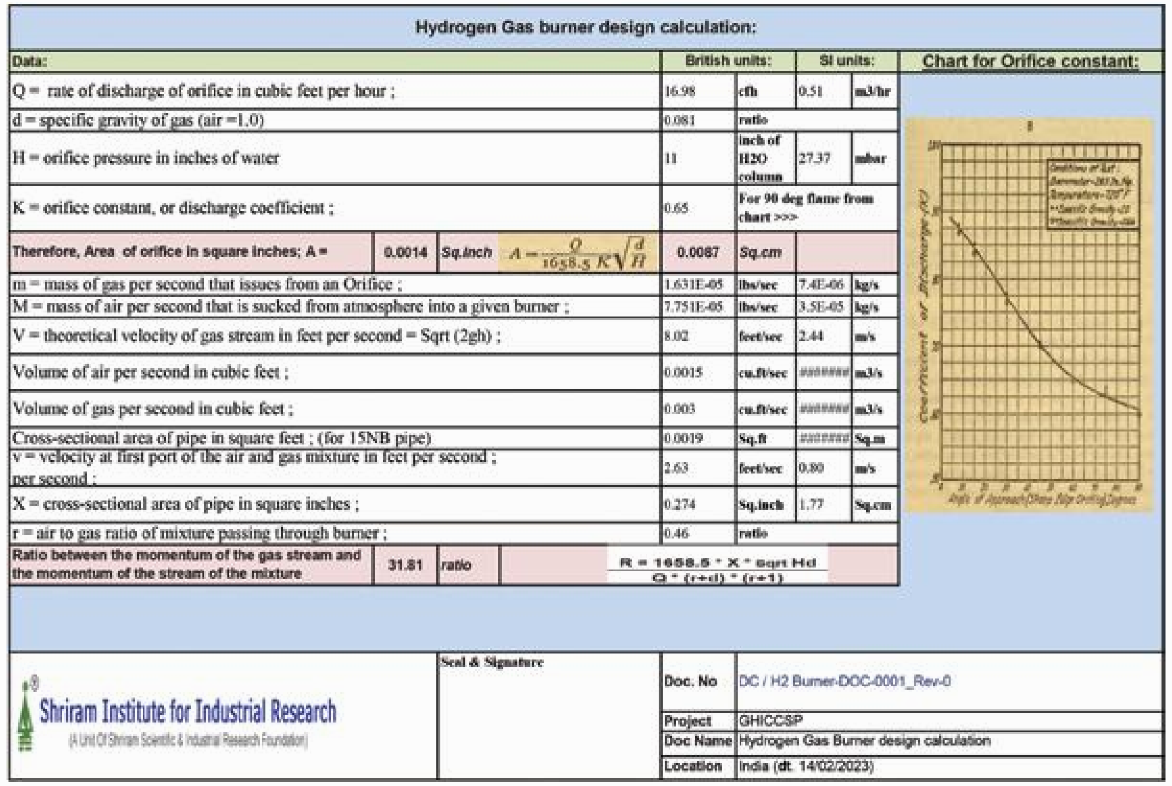


Fig. 2: Hydrogen for clean cooking

- Burner has been prepared precisely as per calculation below:



Hydrogen Gas burner design calculation:

Data:	British units:		SI units:	
Q = rate of discharge of orifice in cubic feet per hour ;	16.98	cfh	0.51	m3/hr
d = specific gravity of gas (air =1.0)	0.081	ratio		
H = orifice pressure in inches of water	11	inch of H2O column	27.37	mbar
K = orifice constant, or discharge coefficient ;	0.65	For 90 deg flame from chart >>>		
Therefore, Area of orifice in square inches; A = 0.0014 Sq.inch $A=\frac{Q}{1658.5\,K\sqrt{\frac{d}{H}}}$	0.0087	Sq.cm		
m = mass of gas per second that issues from an Orifice ;	1.631E-05	lbs/sec	7.4E-06	kg/s
M = mass of air per second that is sucked from atmosphere into a given burner ;	7.751E-05	lbs/sec	3.5E-05	kg/s
V = theoretical velocity of gas stream in feet per second = Sqrt (2gh) ;	8.02	feet/sec	2.44	m/s
Volume of air per second in cubic feet ;	0.0015	cu.ft/sec	#######	m3/s
Volume of gas per second in cubic feet ;	0.003	cu.ft/sec	#######	m3/s
Cross-sectional area of pipe in square feet ; (for 15NB pipe)	0.0019	Sq.ft	#######	Sq.m
v = velocity at first port of the air and gas mixture in feet per second ; per second ;	2.63	feet/sec	0.80	m/s
X = cross-sectional area of pipe in square inches ;	0.274	Sq.inch	1.77	Sq.cm
r = air to gas ratio of mixture passing through burner ;	0.46	ratio		
Ratio between the momentum of the gas stream and the momentum of the stream of the mixture	31.81	ratio	$R = \frac{1658.5 * X * \text{sqrt } Hd}{Q * (r+d) * (r+1)}$	

Chart for Orifice constant:

Shriram Institute for Industrial Research
(A Unit Of Shriram Scientific & Industrial Research Foundation)

Seal & Signature

Doc. No	DC / H2 Burner-DOC-0001_Rev-0
Project	GHICCSP
Doc Name	Hydrogen Gas Burner design calculation
Location	India (dt. 14/02/2023)

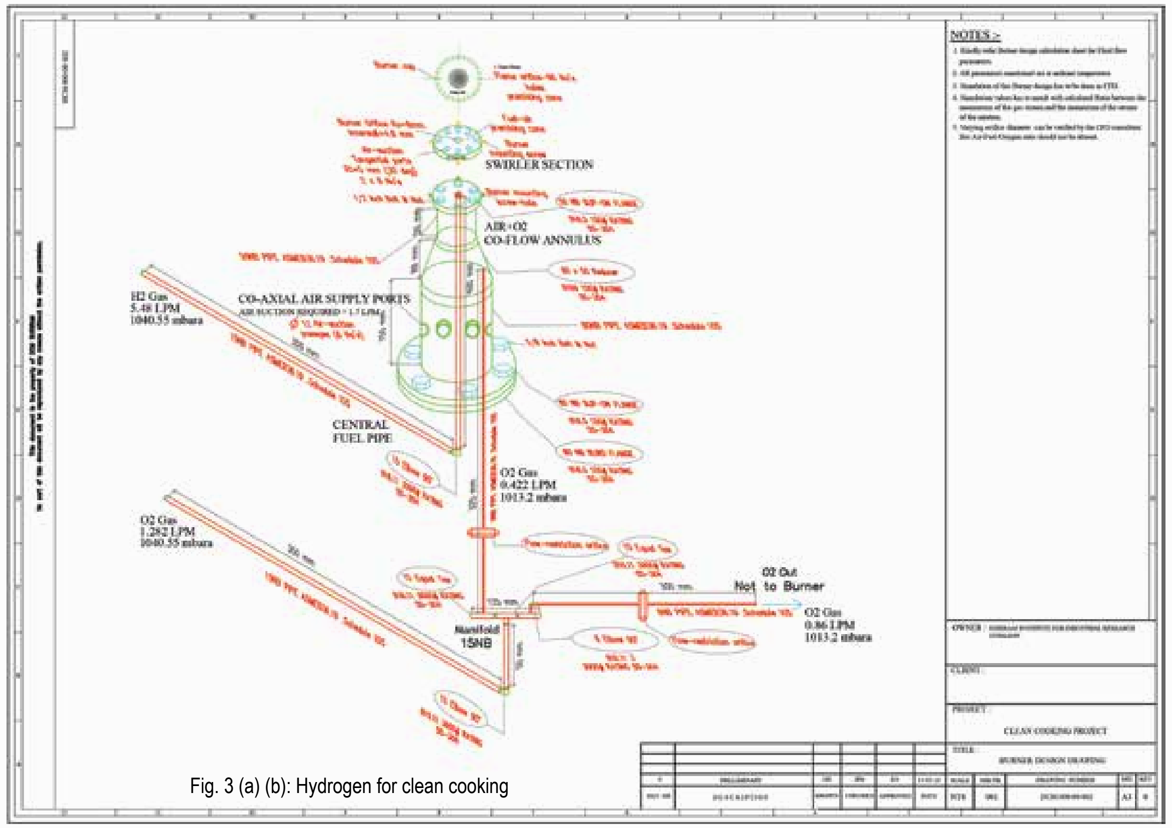


Fig. 3 (a) (b): Hydrogen for clean cooking

Table 1

S. No:	Tag No:	Loop Number:	Instrument Type:	Service:	P&ID Number:	Location:	I/O Type:	I / Output range:		System:	Callibration: Min:	Max:	Set point:	Engg unit:	Interlock number:	Interlock:
1	HS-01	DR-001	Handswitch	Power source	DCM-000-00-S01_R1	Control Panel	DI	0 to 12V		PCS	-	-	1	DI	I-01 to I-11	When hand-switch HS-01 is on power-supply has to be connected with the entire system. All interlocks associated with this switch in the PLC.
2	HS-02	DR-001	Handswitch	Power supply	DCM-000-00-S01_R1	Control Panel	DI	0 to 12V		PCS	-	-	1	DI	-	HS-02 is the Normal or Low Flame selector.
3	HS-03	DR-001	Handswitch	Power supply	DCM-000-00-S01_R1	Control Panel	DI	0 to 12V		PCS	-	-	0	DI	-	HS-03 is the High or full-load Flame selector.
4	LSL-01	WT-001	Level switch - Low (12V operated)	DI-Water	DCM-000-00-S01_R1	Field	DI	0 to 12V		PCS	-	-	30	%	I-01	I-01 When DI-water tank level is High, alarm announcement & Trip cause indication has to be shown till manual filling of water is stopped. The excess water will automatically overflow through the tank drain line hosed to kitchen washbasin.
5	LSH-01	WT-001	Level switch - High (12V operated)	DI-Water	DCM-000-00-S01_R1	Field	DI	0 to 12V		PCS	-	-	70	%	I-02	I-02 When DI-water tank level is Low, system will trip. Trip-release will happen only when Level was topped-up.
6	FSL-01	P-001	Flow switch - Low (5V to 12V operated)	DI-Water	DCM-000-00-S01_R1	Field	DI	5 to 18V		PCS	0	999	600	ml/min	I-03	I-03 When there is no or low-flow from pump outlet w.r.t rated flow, system will get tripped.
7	PSL-01	P-001	Pressure switch - Low (5V to 12V operated)	DI-Water	DCM-000-00-S01_R1	Field	DI	0 to 12V		PCS	0.55	1.5	0.65	bar(g)	I-04	I-03 When there is low pressure from pump outlet, to ensure no flow the system will get tripped.
8	AI-01	EZ-001	Amps Indicator	Power consumption	DCM-000-00-S01_R1	Field	AI	8 to 32V 4-20mA		PCS	0	180	-	Amps	-	I-12 When Voltage goes above 16V or Current raises above 180amps, system will get tripped.
9	VI-01	EZ-001	Voltage Indicator	Power consumption	DCM-000-00-S01_R1	Field	AI	8 to 32V 4-20mA		PCS	0	16	-	Voltage	-	
10	LSL-02	FBA-001	Level switch - Low (12V operated)	DI-Water	DCM-000-00-S01_R1	Field	DI	0 to 12V		PCS	-	-	30	%	I-05	I-06 When there is low head maintained in Hydrogen gas flashback arrestor system will get tripped. Only after manual top-up system will get released.
11	LSH-02	FBA-001	Level switch - High (12V operated)	DI-Water	DCM-000-00-S01_R1	Field	DI	0 to 12V		PCS	-	-	70	%	I-06	I-05 When there is High level maintained in Hydrogen gas flashback arrestor system will get tripped. Only after manual drain-out system will get released.
12	LSL-03	FBA-002	Level switch - Low (12V operated)	DI-Water	DCM-000-00-S01_R1	Field	DI	0 to 12V		PCS	-	-	30	%	I-07	I-08 When there is low head maintained in Oxygen gas flashback arrestor system will get tripped. Only after manual top-up system will get released.
13	LSH-03	FBA-002	Level switch - High (12V operated)	DI-Water	DCM-000-00-S01_R1	Field	DI	0 to 12V		PCS	-	-	70	%	I-08	I-07 When there is High level maintained in Oxygen gas flashback arrestor system will get tripped. Only after manual drain-out system will get released.
14	AV-01	BR-001	Analyzer - Ignitor on (12V operated)	Flame	DCM-000-00-S01_R1	Field	DI	0 to 24V		PCS	-	-	1	DI	I-09	I-09 When HS-01 is on, BR-001 should be in ignited mode. Should stop only when triggered by output from FD-001.
15	AT-02	FD-001	Analyzer - Flame (5V operated)	Flame	DCM-000-00-S01_R1	Field	DI	0 to 3.3V		PCS	-	-	0	DI	I-10	I-10 When HS-01 is on, FD-001 should sense Ignited flame. FD-001 will always be in operation in switch-on mode.
16	AT-03	GD-001	Analyzer - H2 Gas (5V operated)	Hydrogen Gas	DCM-000-00-S01_R1	Field	DI	0 to 5V		PCS	0	200	0.1	ppm	I-11	I-11 When HS-01 is on, GD-001 should sense leakage if available. GD-001 will always be in operation in switch-on mode.
17	AL-01	ESD-001	Alarm (12V operated)	Trip / Overload	DCM-000-00-S01_R1	Control Panel	DO	0 to 12V		PCS	-	-	-	-	I-01 to I-11	Annunciator
18	TI-01	ESD-001	Trip-cause indicator (12V operated)	Emergency Shut-down	DCM-000-00-S01_R1	Control Panel	DO	0 to 12V		PCS	-	-	-	-	I-01 to I-11	Indicators

Observations

- The Indian government can provide solar power for rural areas through a centralised Gram-seva Scheme based on the 'Build Operate Produce Earn' method.
- Private companies can also provide centralised solar power systems using the same method.
- The centralised solar power distribution should only be used for cooking purposes in village homes.
- The solar power distribution should be rated at non-standard DC voltages of 22V, 32V, or 42V to prevent misuse.
- The current market rates for electrolysers are not affordable. However, the Shriram Institute of Industrial Research team is working on manufacturing Indian electrolysers that are highly reliable, safe, efficient, and pocket-friendly.

The work packages prepared for Greenstat-Norway include the following topics

Bottom-up demand evaluation

Bottom-up demand evaluation involves creating a model of household cooking energy demands for a typical year and multiplying it for communities or villages.

A hydrogen demand model can be created based on the cooking energy demand and system efficiencies.

The demand for hydrogen per house for cooking purpose is estimated to be 0.03 kg/hr, and the power required to generate 0.03 kg/hr of hydrogen with market available electrolysers is 1.6 Kw/hr (these market available electrolysers have an efficiency of 66%).

Considering a centralised system capable of supplying 200 homes in a village without disruption, the solar/wind power required will be at the rate of 320 Kw/hr for 200 houses.

The model selected for Hydrogen generation & distribution will be one from the below options

Based on the above information, the estimated market potential for hydrogen cylinders can be calculated as follows:

- Per day cooking requirement for a single home = 0.1 kg/day of hydrogen
- Hydrogen requirement based on cylinder combustion trial = 0.03 kg/hr
- Assuming eight hours of cooking per day, the daily hydrogen requirement per household is 0.24 kg/day (0.03 kg/hr x 8 hours)
- If we assume a village of 200 households, the daily hydrogen requirement for the village would be 48 kg/day (0.24 kg/day x 200 households)
- If we assume a 30-day month, the monthly hydrogen requirement for the village would be 1,440 kg (48 kg/day x 30 days)
- The energy consumption required by the electrolyser to generate 0.03 kg of hydrogen is 1.6 kWh.

Table 2

1	Centralised hydrogen generation at 200 bar(g) pressure along with centralised storage & distribution system with low pressure regulation near domestic boundaries. Individual house operated once-through stove with in-built small electrolyser	Utilising direct solar/wind power during day-time sun hours without battery back-up Utilising solar/wind power with solid battery back-up for 24 hours operation Utilising centralised/offshore generation of solar/wind power with in-built battery for 24 hours operation
2	Cylinder supply for individual homes with specific stove module	Under evaluation whether H2 cylinder can be considered viable for domestic handling

- Therefore, the energy consumption required to generate 1,440 kg/month of hydrogen would be 69,120 kWh/month (1.6 kWh x 0.03 kg/hr x 24 hours x 30 days)
- The weight of 1 kWh of hydrogen is approximately 0.008 kg (based on the lower heating value of hydrogen), so the total weight of hydrogen required per month would be 11,520 kg/month (69,120 kWh/month x 0.008 kg/kWh)
- It is important to note that these are rough estimates, and the actual market potential may vary depending on various factors such as the number of households, cooking habits, and efficiency of the electrolyser.

Recurring and initial costs for LPG per household (main competing technology) are as follows

- The initial cost for procuring an LPG cylinder for household purposes is Rs 1,450 deposit plus a distributor service charge of Rs 24.24 per cylinder. The recurring cost for each cylinder is Rs 1,068.50 for a 14.2 kg cylinder, with a distributor charge of Rs 16.47 for delivery. People residing on elevated floors may choose to tip the delivery personnel additionally as per their wish.
- An LPG regulator is free for every connection. Hose replacement costs a minimum of Rs 180 to be spent every 2-5 years as a safety precaution.
- Apart from LPG, major cities in India now have Piped Natural Gas connections through City Gas pipelines covering 407 districts. The major players are Indraprastha Gas Limited, Mahanagar Gas Ltd., GAIL Gas Limited, Gujarat Gas Ltd., Indian Oil-Adani Gas Pvt. Ltd., and AGP Pratham. Among the total production of 174 mmscmd, 49% (85.26 mmscmd) of city gas is consumed for domestic cooking usage. The remaining contributes to power and fertiliser plant consumption, including manufacturing plant consumption for boilers and other auxiliaries. The current City Gas price averages at Rs 81.17/kg. The initial connection charge for a new City Gas connection is Rs 6,854, out of which Rs 6,500 is refundable upon disconnection.
- Biogas utilisation is nearly 5% of LPG consumption in rural areas. The Union Compressed Biogas Scheme & Gobardhan Scheme developed in India utilising gobar gas and waste-to-biogas for multiple user usage. Industrially, the cost of biogas is expected to be Rs 25/kg. Biogas plant installation charges for an individual home in a rural area will be approximately Rs 30,000.
- Kerosene is also supplied to underprivileged people based on their ration card. Subsidised kerosene in India is available at Rs 13.60/L, while non-subsidised kerosene is available at Rs 72.03/L.
- Electric induction stoves also find usage as an alternative way for everyday cooking in India. The electricity consumption rate averages at Rs 5 per unit.

Geographic zones likely to switch to hydrogen cylinders

- Cylinder storage of Hydrogen at individual house will be an almost uninhabited option.
- But concentrating on centralised storage and solar/wind source availability throughout the year, the following zones can be targeted initially w.r.t rural geographies.
- Already wind generation plants of huge MW capacity are available in areas of:
  - Jaisalmer (Rajasthan),
  - Dhule (Maharashtra),
  - Sangli (Maharashtra),
  - Satara (Maharashtra),
  - Vaspet (Maharashtra),
  - Osmanabad (Maharashtra),
  - Beluguppa (Andhra Pradesh),
  - Mamatkheda (Madhya Pradesh),
  - Nimbagallu (Andhra Pradesh),
  - Kanyakumari (Tamil Nadu).

- Solar generation plants of huge MW capacity already available in areas of:
  - Bhadla (Rajasthan)
  - Pavagada (Karnataka)
  - Kurnool (Andhra Pradesh)
  - NP Kunta (Andhra Pradesh)
  - Rewa (Madhya Pradesh)

- Charanka (Gujarat)
- Kamuthi (Tamil Nadu)
- Ananthapuramu (Andhra Pradesh)
- Galiveedu (Andhra Pradesh)
- Mandsaur (Madhya Pradesh)

- New solar plants with hydrogen generation can be installed in almost all parts of India as per cooking requirements.

Investigation of safety parameters related to hydrogen for cooking

Review of hydrogen regulations in India, limitations on hydrogen storage in homes, necessary safety analysis and/or precautions.

Hydrogen is considered a promising fuel for cooking due to its high energy density and clean burning properties. However, the use of hydrogen for cooking in homes requires careful consideration of safety parameters due to its high flammability and explosiveness.

In India, the use of hydrogen for cooking is not yet regulated or widely adopted. The current regulations related to hydrogen in India primarily focus on its use as an industrial gas or as a fuel for transportation. The Petroleum and Explosives Safety Organization (PESO), which falls under the Ministry of Commerce and Industry, is responsible for enforcing regulations related to the storage, handling, and transportation of hydrogen in India.

The storage of hydrogen in homes for cooking purposes is currently not allowed in India due to safety concerns. Hydrogen gas is highly flammable and requires specialized storage and handling equipment to ensure safety. In addition, the use of hydrogen for cooking requires modifications to existing gas pipelines and appliances, which can add to the cost and complexity of implementation.

Before the use of hydrogen for cooking can be considered, a thorough safety analysis and risk assessment must be conducted to identify and mitigate potential hazards. Precautions such as proper ventilation, leak detection systems, and fire suppression equipment must be put in place to ensure safe operation. Additionally, training and education on the safe handling and use of hydrogen must be provided to users.

In conclusion, while hydrogen has the potential to be a clean and efficient fuel for cooking, its use in homes requires careful consideration of safety parameters and precautions. Currently, the use of hydrogen for cooking is not regulated or widely adopted in India, and further research and development are needed to ensure safe and effective implementation.

List of requirements for the hydrogen transport and storage

In addition to PESO approval, there are several other requirements for the transport and storage of hydrogen, including:

- Safety regulations compliance: The transportation and storage of hydrogen must comply with all relevant safety regulations to ensure the safe handling of the gas.
- Proper container design: The container used for storing and transporting hydrogen must be designed to withstand the high pressure of the gas and must be leak-proof.
- Pressure relief systems: Pressure relief systems must be installed in the container to ensure that the pressure does not exceed safe limits.
- Fire protection systems: Proper fire protection systems must be installed to minimise the risk of fire or explosion.
- Adequate ventilation: Adequate ventilation must be provided to prevent the accumulation of hydrogen in enclosed spaces.
- Emergency response plan: An emergency response plan must be developed and implemented in case of any accident or emergency.
- Training and certification: All personnel involved in the transport and storage of hydrogen must be properly trained and certified to handle the gas safely.
- Environmental considerations: The transportation and storage of hydrogen must take into account the potential environmental impact of any leaks or spills.

Cylinder requirements (design, testing), valve requirements

The following standards to be followed for Hydrogen storage:

- **ISO 16111:2018(en)** standard is applicable for design, construction, storage and testing for hydrogen cylinders.
- **NFPA 2** is hydrogen technologies code.
- **CGA H-5-2014** is installation standard for bulk hydrogen supply systems.
- **GB standard GB/T 34542.1- 2017** provides the safety requirements for storage and transportation systems for gaseous hydrogen.

The following four design types of high-pressure vessels are classified

- **Type I:** Pressure vessel made of metal.
- **Type II:** Pressure vessel made of a thick metallic liner hoop wrapped with a fibre-resin composite.
- **Type III:** Pressure vessel made of a metallic liner fully wrapped with a fibre-resin composite.
- **Type IV:** Pressure vessel made of polymeric liner fully wrapped with a fibre-resin composite. The port is metallic and integrated in the structure (boss).

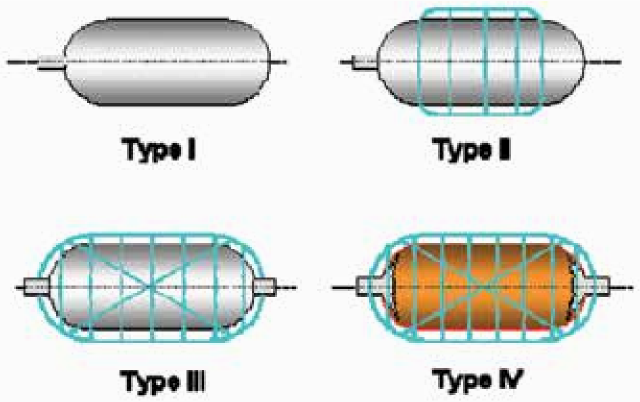


Figure 1. Schematic representation of the 4 pressure vessel types


Type I cylinder | Type II vessel | Type III or IV vessel | Toroid composite vessel

Fig. 4

4.1.4 Licenses and fees

The following licenses have to be applied at PESO, Delhi office, and approval from Chief Controller of Explosives, PESO, Nagpur, to be received in person.

PESO Gas cylinder rules – 2016
1.Form-D- Fees: Rs 10,000
2.Form-E- Fees: Rs 10,000
3.Form-F- Fees: Rs 10,000
4.Form-G- Fees: Rs 10,000
5.Design approval of cylinders- Fees: Rs 10,000
6.Filling permission of cylinders- Fees: Rs 10,000
7.Conversion of cylinders- Fees: Rs 10,000
8.Testing station- Fees: Rs 10,000

PESO static and mobile pressure vessels unfired rules, 2016
1.LS-1A & 1B Form III & V- Fees: Rs 2,000
2.LS-2 Form IV other than cryogenic tankers- Fees: Rs 5,000
3.Approval of fabrication shop- Fees: Rs 5,000
4.Approval of fabrication design- Fees: Rs 2,500
5.Approval for repair vessel- Fees: Rs 2,500
6.Approval of mounting drawing- Fees: Rs 2,000
7.Import of vessels (mostly not required for our project)- Fees: Rs 5,000

4.1.5 Impact Assessment

Reduction in CO_2 Emissions

- It is true that hydrogen combustion results in zero CO_2 emissions when compared to other fossil fuels. However, like all combustion processes, there may be emissions of other pollutants such as SOx, NOx, and trace elements. It is important to demonstrate and monitor these emissions during the implementation of the hydrogen stove to ensure that they are within safe and acceptable limits. This can be achieved through regular emissions testing and monitoring and implementing necessary mitigation measures if required.

Job Creation

- Implementing centralised solar systems in villages not only provides access to clean and sustainable energy but also creates employment opportunities for rural women and other marginalised groups. The requirement for a pre-university certificate is a feasible criterion for eligibility and could potentially attract a wider range of candidates. It's great to hear that there are diverse employment opportunities within the sector, including roles for people with disabilities. Providing internship opportunities for those with vocational diplomas is also an excellent way to provide hands-on experience and skills development. This initiative could have a significant impact on rural communities by increasing access to energy and creating new job opportunities.

Renewable Energy Model

- The estimation of solar energy production and LCOE involves evaluating the solar production over a typical year. According to the Ministry of New and Renewable Energy, the total capacity of solar plants installed in India for power to the grid is 40.1 GW. New solar plant installations can be planned based on the requirement for cooking in almost all regions of India. It is also necessary to determine the amount of energy required per day for a single home to utilise hydrogen for cooking.

For a solar energy system with battery

1.6 kWh x 3 hours per day = 4.8 kW per day
Average sun hours per day = 6 hours
Solar panel output required = (4.8 x 1.5 / 6) * 75% = 1.6 kW
Battery Ah required for a 48 V power back-up system = (1600 W/24 V) * 1.2 * 3 hrs
= 240 Ah
= 5.76 kWh battery of 24 Volt

For a solar energy system without battery:
Cooking requirement is 1.6 kWh

Solar panel output required = (1.6 x 1.5) * 75% = 3.2 kWe

Although the system without battery back-up appears to be more cost-effective in terms of initial investment, the installation charges for the solar panels are double the price. When comparing both options, it is evident that the operation without battery back-up incurs less maintenance cost.

Battery
The solar system calculation showed that a single home requires a battery back-up of 5.76 kWh. If a diversity factor of 70% is applied for a community, then the combined capacity required for a centralised power back-up for 200 homes can be reduced to 806 kWh.

Wind production over a typical year
The total installed wind energy capacity in India is **41.66 GW.**

The Wind Power Sub-Committee had begun to erect 20 wind velocity survey stations across India.

Receiving data for windward direction throughout the year from experimental results will be helpful for the **SIIR** team.

Renewable Wind Energy Model (Based on data from the National Institute for Wind Energy):

The estimated windmill installable potential at 50 m and 80 m level in India is as in Table 3.

Renewable Wind Energy Model (Based on data from National Institute for Wind Energy):
Wind power density map at 80 m level is as below.

Wind Power Density (WPD) is a quantitative measure of wind energy available at any location. It represents the mean annual power available per square metre of the swept area of a turbine and is calculated for different heights above the ground. The calculation of wind power density takes into account the effects of both wind velocity and air density.

Other Renewable Energy Availability (Tidal Energy)
Tidal range (difference between high and low water levels) should be minimum 7 metres to be utilised for energy production.

In India, only the Kutch region has potential right now.

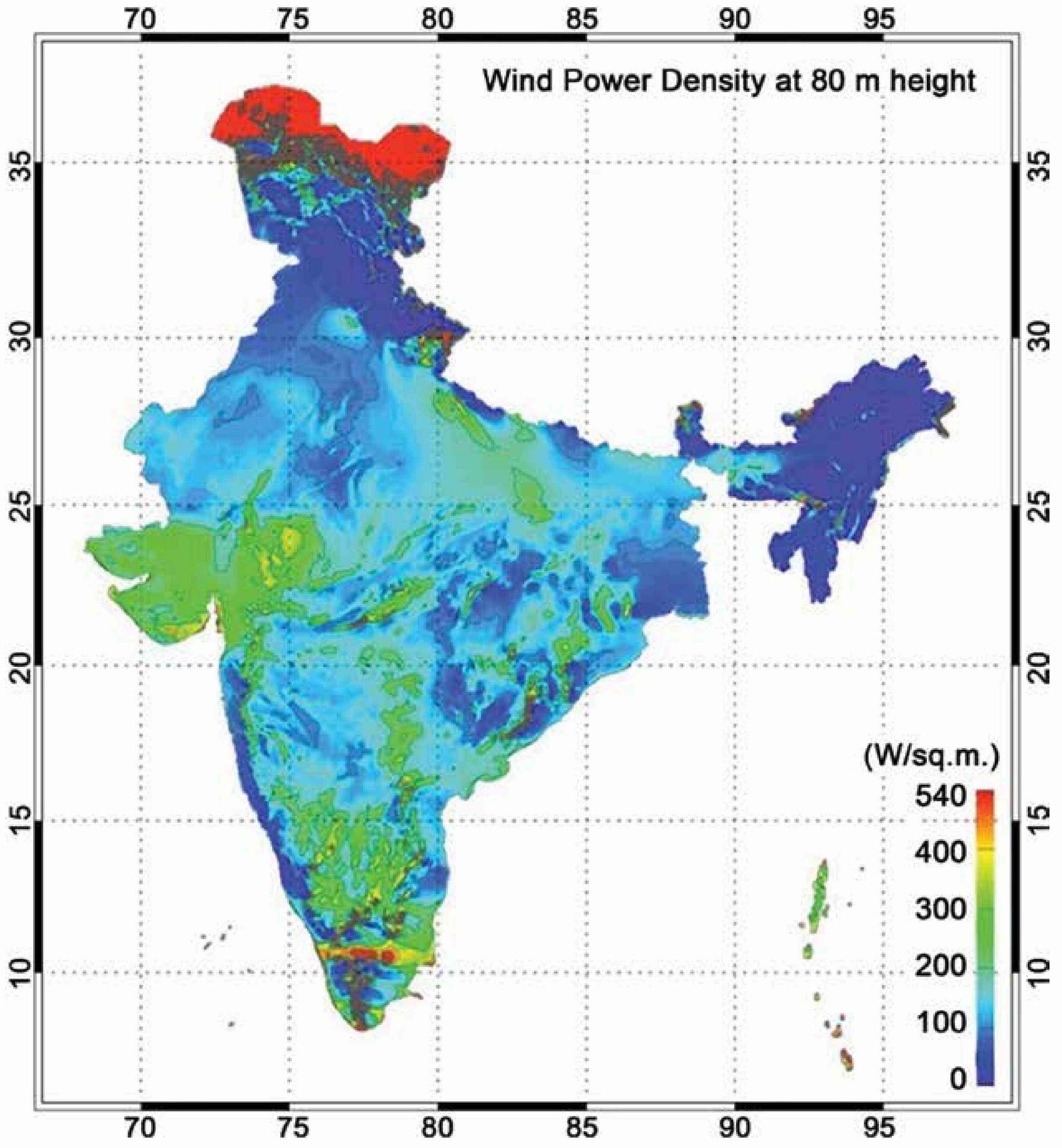
The Shriram Institute team is in discussion with NIOT to evaluate power generation possibilities during low-tidal range with small capacities.

DEENDAYAL PORT (KANDLA)
(GULF OF KACHCHH) - INDIA
LAT. 23° 01' N. LONG. 70° 13' E.
TIME ZONE -0530 TIMES AND HEIGHTS OF HIGH AND LOW WATERS YEAR 2023
JANUARY

	TIME h m	Ht. m		TIME h m	Ht. m
1 SU	0422 0947 1656 2322	2.26 5.93 0.99 6.14	16 M	0238 0817 1521 2154	2.38 5.89 1.11 5.69
2 M	0536 1054 1751	2.33 5.66 0.94	17 TU	0351 0926 1629 2308	2.55 5.63 0.92 5.96
3 TU	0019 0646 1200 1843	6.40 2.26 5.48 0.93	18 W	0515 1043 1739	2.55 5.52 0.68
4 W	0109 0741 1255 1928	6.55 2.14 5.40 0.91	19 TH	0014 0633 1155 1846	6.29 2.38 5.60 0.42
5 TH	0153 0826 1339 2006	6.62 2.05 5.44 0.84	20 F	0112 0743 1302 1948	6.60 2.12 5.83 0.19
6 F	0230 0904 1417 2041	6.65 1.96 5.60 0.72	21 SA	0202 0844 1400 2045	6.86 1.82 6.11 0.01
7 SA	0306 0940 1453 2115	6.69 1.85 5.80 0.60	22 SU	0248 0938 1453 2136	7.05 1.52 6.36 -0.05
8 SU	0338 1014 1526 2148	6.72 1.74 5.96 0.58	23 M	0334 1029 1543 2222	7.18 1.26 6.51 0.05

Table 3

S. No	States / UT's	Estimated potential (MW)M	
		@ 50 m	@ 80 m
1	Andaman & Nicobar	2	365
2	Andhra Pradesh	5394	14497
3	Arunachal Pradesh*	201	236
4	Assam*	53	112
5	Bihar	-	144
6	Chhattisgarh*	23	314
7	Dieu Damn	-	4
8	Gujarat	10609	35071
9	Haryana	-	93
10	Himachal Pradesh *	20	64
11	Jharkhand	-	91
12	Jammu & Kashmir *	5311	5685
13	Karnataka	8591	13593
14	Kerala	790	837
15	Lakshadweep	16	16
16	Madhya Pradesh	920	2931
17	Maharashtra	5439	5961
18	Manipur*	7	56
19	Meghalaya *	44	82
20	Nagaland *	3	16
21	Orissa	910	1384
22	Pondicherry	-	120
23	Rajasthan	5005	5050
24	Sikkim *	98	98
25	Tamil Nadu	5374	14152
26	Uttarakhand *	161	534
27	Uttar Pradesh *	137	1260
28	West Bengal*	22	22
Total		**49130**	**102788**



4.2

Coal Gasification

DR J P GUPTA, MD, Greenstat Hydrogen India Pvt. Ltd.

External nature is only
internal nature writ large.

Swami Vivekananda

4.2.1 Importance of Coal Gasification

Coal plays a significant role in the Indian economy, and coal-based thermal plants generate a considerable amount of electricity (70%) that is consumed and demanded in the energy sector. However, the high ash content in Indian coal poses operational challenges in gasifiers and boilers, resulting in heavy slag formation and corrosion. To overcome this challenge, underground coal gasification (UCG) has enormous potential to recover the high heating value of abundant high-ash coals by in situ conversion to gas.

The Ministry of Coal has approved a policy for recovering gas from lignite resources. Various global groups (China, India, EU, Australia and the U.S.) have contributed to understanding various aspects of UCG through experiments or modelling. Mahajani and his group at IIT Bombay have collaborated with ONGC and conducted experimental and computational studies on UCG. CSIR-CIMFR, NIET, and IIT-Kharagpur have joined hands to investigate the feasibility of UCG in the northeastern region of India based on the coal availability in that region. They have also developed techniques to measure gas concentration within the coal steam and equipment to understand methane concentration in underground mines. CSIR-NCL has contributed to coal combustion using a fluidised bed gasifier and collaborated with GAIL while working on UCG. It is noteworthy that GAIL is one of the major contributors to pursuing UCG on a commercial scale.

Jindal Steel Plant was the first company in India to construct a coal gasification plant, and the world's first to produce DRI steel via this process. State-owned Coal India Ltd. (CIL) is in the planning stages of setting up a coal gasification project at the Dankuni coal complex in West Bengal, which is estimated to require an investment of Rs 5,800 crore. The project aims to convert 1.5 million MT of fuel into other products, reducing emissions in the process. Talcher Fertilisers Limited, a joint venture in Odisha, is working on coal gasification to produce urea, and IOCL and RIL are also pursuing similar projects.

India currently generates 72% of its energy from coal, according to 2020 data. Indian coal is similar to Gondwana coal, with low calorific value (4,500 Kcal/kg) and high ash content, resulting in Indian power plants consuming significantly more coal (0.7 kg/kWh) to generate power compared to U.S. coal with a higher calorific value. The Central Electricity Authority of India predicts that, as a percentage of the country's total power production, coal is expected to decrease from 70% to 50% over the next decade. Syngas produced from coal gasification is piped to industrial users in the Dankuni area near Kolkata.

It is possible to retrofit many coal-based fertiliser plants to produce synthetic natural gas at an economical cost. The estimated production cost for syngas is expected to be below $6 per million British thermal units ($20/MWh). As India's energy demand continues to grow, coal use is expected to increase. Although coal has the potential to be a significant source for the production of hydrogen, concerns about increased carbon emissions due to hydrogen extraction from coal with high moisture content have hindered its encouragement. It is noteworthy that 73 MT of hydrogen is used for refining, producing ammonia, and 42 MT is used for methanol, steel, and other purposes.

Major players in the industry that are expected to venture into coal-to-hydrogen include Air Products, HaldorTopsoe, Thermax, CIL, Mahanadi Coalfields Ltd., Larsen & Toubro, and Dev Energy. Companies with expertise in both gasification and CO_2 capture are likely to make the most progress in this area. Some of the smaller industry players who may venture into this domain include Dev Energy, Praj Industries, and other gasifier industries. BHEL has developed an indigenously prepared high-ash coal gasification technology for methanol production.

In addition, the committee reviewing coal gasification projects in India benefited from recent experiences with projects that convert coal to methanol, including those executed by Thermax and BHEL R&D and EIL R&D's pilot plant. RIL has large gasifiers for petcoke gasification that produce hydrogen, while IOCL R&D has a patented technology and pilot plant for co-gasification of coal, petcoke and biomass. Co-gasification of coal with biomass could be explored as a way to introduce environmental sustainability to hydrogen production from coal.

International Scenario of Coal Gasification

Coal is a significant contributor to the world's electricity supply, accounting for over 37%. Additionally, 70% of the world's steel production relies on coal feedstock. Coal is the most abundant fossil fuel source globally, and although it offers enormous potential, burning it releases over 14 billion MT of CO_2 annually, mainly from power generation. Clean coal technology is being developed to address this issue, allowing coal to be utilised for fuel generation without contributing to global warming.

The coal gasification technology is increasingly significant worldwide due to its sustainability and low hydrogen production cost. In the U.S., hydrogen is primarily produced through steam methane reforming (SMR), where high-temperature steam reacts with a methane source, such as natural gas, accounting for 95% of hydrogen production. Coal gasification accounts for about 4%, and electrolysis accounts for the remaining 1%.

China is currently the largest producer of coal and hydrogen, with 20 million MT of hydrogen produced per year, mostly from coal gasification. Approximately 70% of China's hydrogen comes from nearly 100 coal gasification plants across the country, which results in a lower overall production cost of hydrogen from coal in China compared to natural gas and green hydrogen. However, the emission of CO_2 from coal gasification is high, with an estimated 8 kg of coal producing 1 kg of hydrogen and emitting 20 kg of CO_2 into the environment.

Since the ratification of the Paris Accord in 2016, governments worldwide have made increasingly strong commitments to significantly reduce their GHG emissions. Many countries have set economy-wide net-zero GHG emission targets in their planning, and many have made commitments to rapidly reduce GHG emissions sooner. They have backed up these commitments with ambitious investments in clean energy production and use as part of their decarbonisation strategy. In addition, many large and significant companies have committed themselves to net-zero goals between 2030 and 2050, including leading energy, chemical, shipping and aviation companies. In this context, low-carbon hydrogen has emerged as a significant option to provide net-zero emission energy services.

One way to produce GHG-free hydrogen, known as blue hydrogen, is to combine carbon capture and storage technology with existing gasifiers. Three facilities currently produce hydrogen at scale using this method, with a combined capacity of around 0.6 million MTH_2/year: Great Plains and Coffeyville in the U.S., and Sinopec Qila in China, demonstrating the feasibility of large-scale low-emission hydrogen production. Canada is now home to the world's largest green hydrogen plant, with a 20 MW nameplate capacity. Several countries, including the European Union, Chile, South Korea, Australia, Saudi Arabia, and Portugal, have set ambitious targets for green hydrogen installations.

Japan and Australia have also launched a significant brown coal-to-hydrogen project. Brown coal in Australia will be used to produce liquefied hydrogen, which will be transported to Japan. The project is based in Victoria's Brown Coal Reserves and managed by Kawasaki Heavy Industries. It is particularly important because it will help Japan achieve its goal of net-zero emissions by 2050. As the fifth largest energy consumer in the world, Japan aims to increase annual hydrogen demand tenfold to 20 million MT by 2050, equivalent to around 40% of its current power generation. Australia, a major player in the global LNG trade, hopes that liquefied hydrogen will create a more sustainable market for its coal and gas.

Envirotherm GmbH has constructed 14 gasifiers to produce syngas used in the production of ammonia and urea through coal gasification. These gasifiers have been predominantly built in China and India and use both slagging fixed bed gasifier (BGL type) and circulating fluidised bed technology for gasification and combustion. Gasification is a process that transforms carbonaceous materials, including coal, petroleum coke, and biomass, into carbon monoxide and hydrogen-rich gases, known as syngas. The integrated gasification combined cycle (IGCC), which uses coal gasification as a power-generation technology, is becoming more popular due to the easy accessibility of the raw material (coal) and the positive environmental impact of this technology compared to other combustion technologies. The syngas produced by gasification processes contains a significant amount of hydrogen, which can be further increased by a water gas shift (WGS) process and easily separated into a pure H_2 product meeting industry product quality requirements.

There are three types of gasifiers, namely entrained flow gasifier, fixed bed gasification technology, and fluidised bed gasifier, each having its own strengths and limitations. The entrained flow gasifier is a mature technology but has not been tested for high-ash coal. Fixed bed gasification technology is also well-developed but is restricted to coal with 35% ash content. On the other hand, fluidised bed gasifiers are suitable for high-ash coal, but they are not widely used commercially. Besides coal ash content, other factors such as cold and hot crushing strength, gasification reactivity, surface area, ash fusion temperature (AFT), slag viscosity and behaviour, ash composition, caking nature, rank, and petrographic characteristics are also important in determining the type of gasifier to be used.

Raw syngas produced by the gasifier contains impurities like fine ash, char, slag, and acid gases that need to be eliminated before downstream processing. The report includes various available technologies for this purpose. Depending on the gasifier's configuration and operating conditions, about 3 to 10% of the sulphur present in coal is converted to carbonyl sulphide, which is then converted to H2S through a catalytic hydrolysis process. The H_2S is then removed through an acid gas removal unit. Various commercially available processes are used to remove other impurities such as mercury.

The syngas produced by commercial gasifiers typically contains a high concentration of carbon monoxide (CO) that can be converted to hydrogen using the water gas shift reaction. This reaction involves reacting steam and CO to produce H_2 and CO_2, but the CO_2 produced must be captured and either stored underground or utilised for other purposes. Once the acid gas components have been removed from the shifted syngas, it mainly consists of hydrogen with small amounts of impurities such as CO, CO_2, H_2S, and SO_2. These impurities can be removed using commercially available pressure swing adsorption and membrane technology.

By integrating CCUS technologies, brown hydrogen can be converted into blue hydrogen, which may be more acceptable given the current circumstances, although it may increase the cost somewhat. However, the cost of blue hydrogen is still expected to be lower than that of green hydrogen, considering the current state of technology for producing green hydrogen.

India's current hydrogen demand is 6.7 million MT/year, mainly from refineries and fertiliser plants, with the majority being produced from natural gas as grey hydrogen. However, with plans for decarbonisation and the growth of the green hydrogen sector, the demand is projected to increase to 11.7 million MT by 2030 and 28 million MT by 2050. The committee believes that producing hydrogen from coal, with CCUS technology, could provide a low-cost alternative to imported natural gas. The hydrogen produced from coal can be used in various sectors, such as refineries, fertiliser units, steel plants, and transport. The estimated cost of producing hydrogen from coal without CCUS is targeted to be between $1 and $1.50/kg. However, the cost of CCS technology is estimated to be around $0.50/kg, and its maturity is still uncertain.

The committee recommends establishing coal gasification units near hydrogen demand centres or coal mines to reduce transportation costs. Alternatively, the gasification plants could be located near the natural gas grid so that the hydrogen produced can be injected into the pipeline to some extent, up to 18-20%, without pipeline modifications. This will enable the utilisation of hydrogen produced from coal in industries that currently use imported natural gas.

Coal Availability

Selecting the appropriate type of coal gasifier is crucial and must be based on the specific characteristics of the coal being used. The performance of the gasifier is affected by several key properties of the coal, including its proximate and ultimate analysis, cold and hot crushing strength, gasification reactivity and surface area, ash fusion temperature, slag behaviour, ash composition, caking index, rank, and petrographic characteristics.

- **Cold and hot crushing strength of coal particles**

When using a moving bed gasifier, it is important to have a steady and well-distributed flow of gaseous reactants through the bed, as well as efficient heat and mass transfer between solids and gases. In order to achieve this, the bed must have sufficient permeability, which is determined by the size distribution of the coal particles within it. The coal particle size distribution is controlled by the cold and hot crushing strength of the coal as it moves through the drying, pyrolysis, gasification, and combustion zones of the gasifier. Therefore, the cold and hot strength of coal in a gasification atmosphere is an important factor in determining the suitability of a coal for a moving bed gasifier. In this study, we analysed the cold and hot strength of coal, char after pyrolysis, and partially converted char/aggregates after gasification in the laboratory to determine the suitability of the coal for a moving bed gasifier.

Reactivity and Surface Area

The speed at which the carbon matrix is consumed under specific conditions is referred to as coal reactivity. In a gasification process where the chemical reaction is the rate-controlling step, coal reactivity has a significant impact on process performance, particularly for fluid bed gasifiers. The carbon conversion rate and overall gasification efficiency in fluid bed gasifiers are directly influenced by coal reactivity. The design of gasifier components, selection of operating parameters, and gasifier sizing are all determined by coal reactivity. Reactivity affects the volume of oxidant and gasifying agents needed for the gasifier and the degree of char recycle. Coal reactivity is therefore an essential property for selecting a suitable gasifier for a given coal. Entrained flow gasifiers operate at the highest temperatures among the three main gasifier types, allowing them to handle coal of any reactivity. Reactive coals can be gasified at lower temperatures, resulting in higher cold gas efficiency, while less reactive coals may require higher gasification temperatures to achieve adequate carbon conversion, resulting in lower cold gas efficiency. The operating temperature of a fluidised bed gasifier typically ranges between 800°C and 1050°C, with a low residence time maintained. As a result, the coal must have sufficient reactivity to achieve a high level of carbon conversion in a fluidised bed gasifier.

To operate a moving bed gasifier, a moderate temperature range and longer residence time are required, making it capable of gasifying coal with any level of reactivity. Gasification reactivity is important in determining the effectiveness of the gasification process, and it can be measured using the thermo-gravimetric method. The surface area of coal is also an important factor as it affects the contact between gaseous reactants and the reactive sites in coal during gasification, influencing gasification reactivity. The surface area of coal can be determined through gas adsorption technique.

Ash content

Ash content is an important factor to consider when selecting a gasifier for coal. For coals with low ash content, entrained flow gasifiers are often preferred due to economic and technical reasons. High ash content in coal can lead to decreased efficiency and increased slag production and disposal, even with constant gasifier operating conditions. However, high-ash coal can still be efficiently gasified in moving and fluidised bed gasifiers if other necessary conditions are met. Low-rank Indian coals with high ash content are particularly well-suited for fluidised bed gasifiers.

Ash composition, ash fusion temperature (AFT), slag viscosity/fluid point

The chemical composition of coal ash is an important factor in determining its suitability for a particular gasifier. The ash fusion temperatures (AFT) and slag viscosity/fluid point are both affected by the chemical composition of the ash. Entrained flow gasifiers require an operating temperature above the AFT to keep the slag in the Newtonian flow region. The AFT and temperature of slag fluid point increase with a higher SiO2/Al2O3 ratio but decrease with higher alkali concentrations. Entrained flow gasifiers with refractory linings can be affected by some of the compounds in the slag, such as SiO2, CaO, and iron oxides, which can penetrate the refractory and cause cracks and material loss. To facilitate smooth slag tapping in an entrained flow gasifier, AFT and slag fluid point temperature can be lowered by adding flux (CaO) or blending coal with a low AFT.

To prevent ash agglomeration in a fluidised bed gasifier, it is necessary to use coal with a higher ash fusion temperature than the gasifier's operating temperature. The presence of higher amounts of iron, calcium, and sodium silicates in coal ash can contribute to agglomeration and clinker formation in fluidised bed and moving bed systems. This can lead to issues such as channel burning, pressure drop problems, and unstable gasifier operation in moving bed gasifiers. Careful control of the gasifier operating temperature is required when processing coals with high alkali content. In this study, the coal's ash composition has been analysed using X-ray fluorescence spectroscopy, and the initial deformation temperature (IDT), softening temperature (ST), hemispherical temperature (HT), and flow temperature (FT) of the ash have been determined to assess the coal's suitability for gasification. Additionally, the fluid point temperature of the slag has been assessed to understand the coal's performance towards slag behaviour in the entrained flow gasifier and to identify any potential for agglomeration and clinker formation in fluidised bed and moving bed gasifiers.

Coal Resources in India

India has a significant amount of coal resources, with a total of 352 billion MT, out of which 177 billion MT are proved reserves. This means India holds the fourth-largest coal reserves in the world. In total, the world has 1,074 billion MT of proved coal reserves, and India accounts for approximately 10% of these global reserves. The U.S. has the largest coal reserves, followed by Australia and China.

Category-wise Breakup of Coal Resources

A detailed analysis of the Indian coal reserves by category and depth is given in the tables below.

(Resource in million MT)

Based on Table 1, it can be observed that the majority of India's coal reserves, accounting for 90%, are non-coking coal or thermal coal. This type of coal is primarily utilised for power generation, as well as in industries like cement and brick-kilns. On the other hand, coking coal reserves, which are mainly utilised in the steel production process, comprise only around 10% of India's total coal reserves. India imports about 25% of its coal requirements.

Depth-wise Breakup of Coal Resources

(Resource in million MT)

It is evident from Table 2 that approximately 56% of the total coal resources, or 72% of the total proved reserves, are located at depths of up to 300 metres. The shallower the depth, the easier the mining process. More than 90% of coal production in India is carried out through open-cast mining, typically at depths of up to 300 metres, while the remaining production is done through underground mining.

The tables clearly indicate that India possesses vast coal reserves. Therefore, it would be beneficial

Coal Type	Proved	Indicated	Inferred	Total	% share
Prime Coking	4667.75	645.31	0.00	5313.06	1.51
Medium Coking	14971.60	11245.13	1862.86	28079.59	7.97
Semi Coking	529.68	991.51	186.33	1707.52	0.49
Sub-Total of Coking	**20169.03**	**12881.95**	**2049.19**	**35100.17**	9.97
Non-Coking	156416.10	133945.92	25040.13	315402.15	89.57
Tertiary Coal	593.81	121.17	908.67	1623.65	0.46
Grand Total	**177178.94**	**146949.04**	**27997.99**	**352125.97**	**100.00**
% share	50.32	41.73	7.95	100.00	

Table 1: Source- GSI Coal Inventory, 2021

Depth Range (m)	Proved	Indicated	Inferred	Total	% share
0-300	125560.46	62910.33	8593.29	197064.08	55.96
300-600	32302.84	65561.98	13101.13	110965.95	31.52
0-600 *(for Jharia only)*	14056.10	450.44		14506.54	4.12
600-1200	**5259.54**	**18026.29**	**6303.57**	**29589.40**	8.40
Total	**177178.94**	**146949.04**	**27997.99**	**352125.97**	**100.00**

Table 2: Source- GSI Coal Inventory, 2021

for India to discover sustainable methods of utilising these resources, especially as the world, including India, is gradually moving towards cleaner fuels due to climate change concerns. The use of domestic coal reserves becomes even more crucial, given that India lacks alternative fuel sources – with 82% and 45% of the crude oil and natural gas demand being met by imports, respectively. This reliance on imports exposes India to the risks of price volatility and supply insecurity.

Coal Availability for Gasification Projects

Various measures have been taken to support the establishment of coal gasification plants by both private and public sectors. These measures include providing concessions in the revenue share for the commercial auction of coal blocks. If the successful bidder uses the coal produced in their own plant(s) or in a plant of their subsidiary, affiliate, or associate for the purpose of coal gasification or liquefaction, or sells the coal for gasification or liquefaction, they will be entitled to a 50% rebate on the revenue share quoted by the successful bidder on the total quantity of coal consumed or sold or both for gasification or liquefaction, subject to the following conditions:

- At least 10% of scheduled coal production, as per approved mining plan for that year, shall be consumed or sold for gasification or liquefaction.
- Coal Controller's certification would be required for the quantity of coal consumed or sold or both for gasification or liquefaction.

The Ministry of Coal has suggested granting CIL the liberty to use coal at a rate determined by CIL, for its gasification projects. To address the issue of coal scarcity for coal gasification, the government has directed for a separate auction window to be established for allocating coal linkage to coal gasification projects. The ministry has asked CIL and SCCL to introduce a new subsector for auctioning coal linkages to the Non-Regulated Sector (NRS), which includes production of syngas leading to coal gasification as an end-use sector. CIL and SCCL will decide the applicable floor price as per provisions of the NRS linkage auction policy of 2016, and coal quantity and grade shall be provided as per availability, considering industry demand. The Fuel Supply Agreements (FSA) will be valid for the entire duration of 15 years.

Coal Gasification for Hydrogen

Coal gasification is a process that produces syngas, which can be used to make liquid fuels, chemicals, and hydrogen. Given the current push towards a hydrogen-based energy economy and India's vast coal reserves, hydrogen production from coal gasification is becoming increasingly important. Depending on the feedstock used and the processes involved, the hydrogen produced from coal is designated as black or brown hydrogen, according to the convention of colour coding for hydrogen. Black hydrogen is derived from bituminous coal, while brown hydrogen is derived from lignite coal. When combined with carbon capture, storage, and utilisation, black or brown hydrogen can be converted to blue hydrogen if the overall process does not emit CO_2.

Gasification is the heart of the process for converting coal to syngas. After required cleaning to protect downstream process catalysts from poisoning and to meet emission regulations, the syngas can be converted by water gas shift reactions to a hydrogen-rich gas, which can be further purified to high-purity hydrogen (>99.9%). Gasification is a partial combustion process where carbonaceous feeds are partially combusted in the presence of a controlled amount of oxygen. The oxygen/carbon ratio is adjusted to ensure that most of the feed carbon is converted to CO and most of the hydrogen to molecular hydrogen.

Gasification processes are operated either at near atmospheric pressure or at an elevated pressure in the presence of steam, air/oxygen. The effect of pressure up to 30 kg/cm² on product composition is not significant, but most commercial gasifiers operate at elevated pressures. In gasification, the carbonaceous feed particles pass through three major reactions: combustion (reaction with O_2), Boudouard reaction (reaction with CO_2), and steam gasification (reaction with steam). After entering the gasifier, the feed is volatilised at 1,000–1,500°C , and the resulting hydrocarbons react to give carbon monoxide and hydrogen (syngas) as per the following overall equation.

$$CH_xO_y + (1-y)\, H_2O \rightarrow (x/2 + 1-y)\, H_2 + CO$$

Composition	Range
H2	25 - 30 % (v/v)
CO	30 - 60 % (v/v)
CO2	05 - 15 % (v/v)
H2O	**2-30 % (v/v)**
CH4	**0-5 % (v/v)**
H2S	0.01 - 1 % (v/v)
N2	0.5 – 4 % (v/v)
NH3 + HCN	0-0.3 % (v/v)
Ar	0.2 – 1.0 % (v/v)
COS	0-0.1 % (v/v)
Ni & Fe Carbonyls	1 - 4 ppmv

Table 3: Typical composition of the syngas produced by gasification.

Carbon Capture, Utilisation and Sequestration in Coal-Based Hydrogen Systems

Producing hydrogen through coal gasification results in a significant amount of CO_2 emissions, typically around 10-15 kg per kg of hydrogen. To make coal-based hydrogen production a sustainable alternative, it is crucial to adopt suitable CCUS technology to effectively utilise or sequester CO_2. Globally, the largest uses of CO_2 are for enhanced oil recovery (EOR) and fertiliser production, particularly urea recycling. However, these applications may not be practical in India due to the geographic location of oil fields and coal fields. Adopting such applications would require the construction of large cross-country pipelines. Additionally, utilising CO_2 in fertiliser production would require significant capital expenditure upstream, including ammonia production, which is necessary for converting CO_2 into urea.

According to a 2009 study conducted by TERI, there is a potential for the sequestration of 345 million MT of CO_2 in major coal fields and 2-7 billion MT of CO_2 (GtCO2) in oil and gas reservoirs in India. However, these storage sites are small and scattered, and some coal seams are too shallow to provide a long-term CO_2 storage option. Even if some sites are considered for sequestration, many coal seams would still be in use for many years, making them unsuitable for CO_2 storage. Therefore, before considering carbon sequestration as a possible solution for carbon mitigation, detailed studies are required. Instead, emphasis should be placed on the potential for carbon capture and utilisation.

The development of technology for CCU is in its early stages and different options are being explored by various countries. Some of the technologies being considered include:

- **CO_2 to Methanol:** This requires a large amount of hydrogen. Furthermore, the demand for methanol in the country is very small compared to the volume of CO_2 likely to be generated from coal gasification. Several R&D programmes are being undertaken by companies such as CIMFR, BHEL, IIT-Thermax, EIL, and IOC, but proven technologies have yet to be established.

- **CO_2 to Bioethanol:** Gas fermentation technology has been developed for converting CO-rich gases or CO_2 with hydrogen support into bioethanol through gas fermentation technology. Some plants in Germany and China have been established and are in operation, and one plant is under execution in India as well. As bioethanol production is a priority for the government of India to reduce the import of crude oil, this can be explored as a potential option for CO_2 utilisation.
- **CO_2 to Carbon Black and Graphite Electrode:** A company called Solid Carbon in the U.S. has developed technology up to TRL-6 level for converting CO_2 into carbon black and synthetic graphite for electrodes. However, this process requires large amounts of electricity and can only be considered if renewable power is available. No commercial pilot plant has been established yet.
- **CO_2 to Carbon Flakes:** RMIT Australia is working on a technology that splits CO_2 into carbon flakes and oxygen using a special alloy of gallium and Indium. Although the technology has been tested at the laboratory scale and pilot testing is in progress at the industrial scale, it may take several years to commercialise. Once developed, it can convert CO_2 into carbon flakes.
- **Dry Reforming of CO_2:** Several steel technology suppliers are working on Dry Reforming of CO_2 using methane recovered from coke oven gas or natural gas to create syngas, which consists of CO and hydrogen for use in steelmaking. Currently, one syngas-based steel plant is operational in India. If these technologies are fully developed, they could not only provide an opportunity for bulk recycling of carbon but also minimise the cost of production of various chemicals by using CO_2 as the main feedstock. This technology is also in the pilot stage and has yet to be tried on a commercial scale.
- **CO_2 Electrolysis:** Solid oxide electrolysis cells (SOEC) have been developed and are used commercially to produce carbon monoxide from CO_2, using a technology called eCO. However, this technology is currently used on a smaller scale for producing CO. The carbon monoxide produced is of more than 99.95% purity and can either be used in iron and steel making for reducing iron ore as a substitute for coal, thereby minimising the imports of coking coal, or alternatively can be used for producing bioethanol using gas fermentation technology. A simplified flow sheet of eCO is shown in Fig. 1 below.

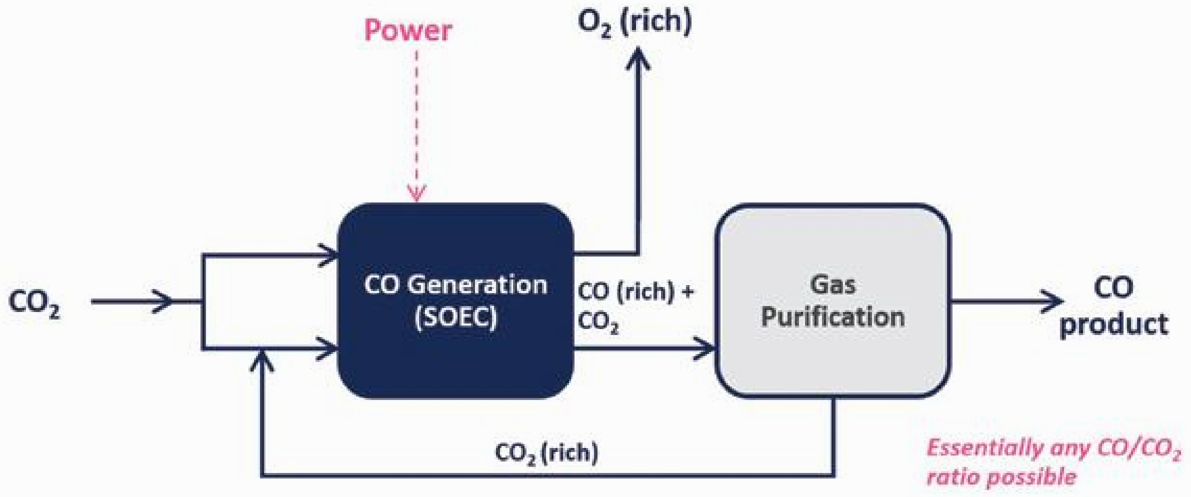


Fig. 1: CO2 conversion into CO

When renewable energy sources are combined with electrolysis, it is possible to transform water and CO_2 into chemical feedstock with little to no carbon footprint. Among the various CCU technologies discussed earlier, the combination of CO electrolysis and bioethanol production using CO and CO_2 may provide a sustainable long-term solution for utilising captured CO_2 and producing hydrogen at a targeted cost of $1-1.50/kg using domestic coal resources. Other technologies may be introduced in the future after conducting techno-economic analysis.

There is potential to recycle the carbon released from burning natural gas to create low-cost and emission-free electricity through a series of heating, cooling, and compression steps. This approach could potentially be extended to the CO_2 produced from coal-to-hydrogen water-gas-shift systems, which could be as clean as or even cleaner than natural gas combustion. This may be an exciting option for India, although a thorough due diligence process would be required.

Quest Carbon Capture and Storage by Shell (Canada)

Shell's Scotford Upgrader power plant in Alberta, Canada, produces crude oil from oilsands' bitumen, which requires hydrogen to lighten the oil. However, this process also results in CO_2 emissions similar to the coal-to-hydrogen initiative proposed in India. To address this, Shell has developed a carbon capture plant called Quest that uses conventional technology to absorb CO_2 using commercially available amine. The absorbed CO_2 is then desorbed and compressed into a liquid, which is transported 65 km away from the plant through various well sites and injected over 2 km underground into porous rock formations. Additionally, Dastur & Co. presented various commercially available technologies for CCUS from their technology partners, including technologies for converting CO_2 to chemicals and aggregates, in addition to geological sequestration and EOR.

Cost Economics: Coal to Hydrogen

According to information from Sinopec China, the cost of producing hydrogen from coal can be around $1/kg with a coal price of Rs 3,500/MT. However, this does not include the costs for carbon capture, hydrogen compression, and ash disposal units. Sinopec uses entrained gasifiers to keep the ash content below 20%. In China, more than 80% of the hydrogen used in the fertiliser, methanol, and petrochemical industries is produced through coal gasification, which costs between $0.90 and $1.50/kg.

Some oil refineries in China also use coal-based hydrogen instead of that produced using steam methane reforming to reduce their dependence on imported oil and natural gas. India could follow the same route and reduce its dependence on imported oil and natural gas by promoting coal-to-hydrogen. Although Indian coal may have higher ash content, the lower input cost of coal could compensate for the higher capital cost. According to estimates from various sources, the cost of hydrogen from coal in India could be in the range of $1.30/kg to $1.50/kg.

An estimate of hydrogen cost based on natural gas and coal as feedstocks, with different feedstock costs based on published information from several sources is given below.

Basis: Plant capacity: 150 MT/day hydrogen generation plant **Feedstock: Natural gas**	
Case 1: Natural gas price - $7/MMBtu	
Cost of hydrogen production:	~ Rs 115/ kg
Contribution of natural gas feedstock:	~73%
Capex:	~9%
Others (Fixed and variable costs):	~18%
Case 2: Natural gas price - $10/MMBtu	
Cost of hydrogen production:	~Rs 151/ Kg
Contribution of natural gas feedstock:	~79%
Capex:	~7%
Others (Fixed and variable costs):	~14%

Table 4 (a)

Basis: Plant capacity: 150 MT/day hydrogen generation plant **Feedstock: Coal**	
Case 1: Coal price – Rs 1,500/MT	
Cost of hydrogen production:	~ Rs 102/kg
Contribution of Coal feedstock:	~16%
Capex:	~44%
Others (Fixed and variable costs):	~40%
Case 2: Coal price – Rs 3,000/MT	
Cost of hydrogen production:	~Rs 118/Kg
Contribution of natural gas feedstock:	~28%
Capex:	~38%
Others (Fixed and variable costs):	~34%

Table 4 (b)

Engineers India Limited (EIL) has also made an estimate of hydrogen production cost with natural gas and typical Indian coal as feedstocks. The findings are as below.

- Natural Gas as Feedstock

The production of hydrogen using SMR technology involves the use of natural gas as the raw material. A typical natural gas-based plant for producing hydrogen comprises a steam reformer, shift reactor, PSA and U&O facilities. EIL has provided data indicating the cost of producing hydrogen in a typical unit as follows:

Case 1	
Parameters	Value
NG price	$7/MMBtu
Cost of H_2 production	Rs 1,01,000/MT
Case 2	
Parameters	Value
NG price	$10/MMBtu
Cost of H_2 production	Rs 1,33,000/MT
Case 3	
Parameters	Value
NG price	$12/MMBtu
Cost of H_2 production	Rs 1,54,000/MT

- Coal as Feedstock:

Gasification technology can be used to produce hydrogen using coal as the feedstock. The plant consists of several key components, including the gasification section, air separation unit, shift & gas cleaning section, PSA & U&O facilities. For this process, typical Indian coal characteristics have been considered. According to data available at EIL, the estimated production cost of hydrogen for a typical coal-based hydrogen unit is as follows:

Case 1	
Parameters	Value
Coal Price	Rs 1,500/MT
Cost of H_2 production	Rs 1,21,000/MT
Case 2	
Parameters	Value
Coal Price	Rs 3,000/MT
Cost of H_2 production	Rs 1,57,000/MT
Case 3	
Parameters	Value
Coal Price	Rs 1,000/MT
Cost of H_2 production	Rs 1,10,000/MT

The estimates for both coal and natural gas are without CCS/CCUS, which is likely to cost around $0.50/kg and has been discussed separately in this report.

Green Hydrogen Production from Renewable Power

Recently, the focus has been on producing green hydrogen which is created through water electrolysis using renewable power sources. According to various reports, the present cost of green hydrogen is approximately $4.50/kg. However, with the latest policies such as the waiver of transmission charges and green power banking, the cost may be reduced to around $3/kg. Nonetheless, the cost of green hydrogen is still higher than that of hydrogen produced from fossil sources. The cost of producing green hydrogen is determined by the green power tariff, the efficiency and utilisation of the electrolyser, and its capital cost.

International Published data on Hydrogen Production Costs

As per an international publication in Science Direct from 2019, the estimated costs of hydrogen production from each method are as follows:

1. Steam Methane Reforming without CCS	$2.08/kg
2. Steam Methane Reforming with CCS	$2.27/kg
3. Coal Gasification without CCS	$1.34/kg
4. Coal Gasification with CCS	$1.63/kg
5. Solar/wind power-based Electrolysis	$5.78-6.03/kg

The current expensive cost of producing green hydrogen and the volatility of natural gas prices, coupled with India's dependence on imported gas, makes a strong case for exploring the coal-to-hydrogen route.

Recommendations and the Way Forward

- **Gasification Technologies**

The committee suggests that the gasification technology chosen should be suitable for high-ash Indian coal, with the ultimate goal of producing hydrogen. After considering the advantages and disadvantages of different techniques available for coal-to-hydrogen production, the committee has concluded that circulating fluidised bed gasification is the most appropriate technique considering the final product requirements and environmental concerns. Therefore, the committee proposes that the technology for coal gasification should be based on a circulating fluidised bed gasification system followed by solid separation and elaborate gas purification.

However, Indian coal's low-grade quality with high ash content (up to 45%) presents challenges for stable operation of circulating fluidised gasification and synthesis gas clean-up. The objective is to select an optimised process for this purpose, involving process intensification concepts and judicious integration of the entire plant. Although several institutions are already working on developing indigenous gasification technology for high-ash coal, commercialisation of the same may take longer.

To achieve the objective of coal gasification mission, i.e., to achieve around 100 million MT coal gasification by 2030 and to promote coal-to-hydrogen to make cheap hydrogen available in the country, external technological support may be necessary. The committee suggests that some policy intervention may be required for an interim period to reserve some of the low-ash coal for coal gasification so that the execution of coal-to-hydrogen project can be expedited.

- **Water-Gas-Shift Reactor and H_2 Purification**

Once the syngas is cleaned up, the water-gas-shift process is necessary to increase hydrogen production, followed by purification of the hydrogen through PSA. While the gasification technologies are well-developed, they still need to be demonstrated on a semi-commercial scale. The water-gas-shift reactor still needs to be tested, although both concepts are well-established. Additionally, other elements need to be explored to comprehensively demonstrate the process. For example, the use of membrane reactors for water gas shift, removal systems for ammonia and H_2S, and thermal management systems to improve overall cold gas efficiency and hot gas efficiency.

- **CCUS for Blue Hydrogen**

To decrease the carbon intensity of hydrogen produced from coal, lignite or petcoke (also known as black/brown hydrogen), it is necessary to use CCUS technology in combination with a conventional gasifier method. This is a major area of focus due to India's climate commitments, and suitable technological options must be selected for the overall scheme of coal-to-hydrogen plant conversion.

The main drivers for CCUS or effective utilisation of CO_2 generated from a coal-to-hydrogen plant are twofold. First, fossil carbon present in the feedstock would be emitted if not captured or utilised. Second, there is a need to maximise hydrogen production by converting CO present in the syngas to additional hydrogen through an energy-intensive water-gas-shift (WGS) reaction.

Many CCS projects are still in the developmental stage, with a few technologies like methanol or bioethanol or electrolysis of CO_2 being used on a commercial scale. However, it is expected that more options will become available in the future. CCS efforts can be broadly categorised into dedicated geological storage and enhanced oil recovery. India has both possibilities, but the net benefit derived by CCS decreases the farther the CO_2 must travel from point of generation to point of use. As the potential for enhanced oil recovery seems to be limited, CCU should be given more focus. Many companies across the globe have various CCU projects at different stages of execution. CCU technologies can be integrated within the complex of coal gasification, gas cleaning, water-gas-shift reactor, CO_2 removal/capture unit, and conversion to chemicals or aggregates. One option that can be considered is the electrolysis of CO_2 to convert it into CO or dry reforming of CO_2 to convert it into syngas and utilise it downstream.

- **Utilisation of Hydrogen**

The main consumers of hydrogen are refineries and fertiliser plants, which currently rely on grey hydrogen produced from natural gas. However, some refineries are planning to become net zero by converting CO_2 to chemicals. If we can produce blue hydrogen from coal with CCUS, we can have a domestically sourced alternative to imported natural gas. With the expected increase in demand for hydrogen (11.7 million MT by 2030 and 28 million MT by 2050), the committee sees significant opportunities for the use of coal-based hydrogen in industries such as refineries, fertiliser units, steel plants, and transportation, making it the most cost-effective source of hydrogen.

- **Way Forward**

The committee believes that India should explore the option of producing hydrogen from domestic coal and take aggressive steps towards incorporating it into our overall hydrogen ecosystem. To achieve this, we can establish a few semi-commercial/demonstration gasification units for converting coal to hydrogen. Additionally, we should integrate CCUS units along with gasification to produce blue hydrogen, which will be more widely accepted. We should select gasification technologies that have the potential for eventual commercial scaling and consider co-gasification of biomass and coal if biomass is available in close proximity to the gasification units.

It is recommended that gasification units be located near hydrogen demand centres or coal mines to reduce transportation costs. Alternatively, we could establish them closer to the natural gas grid, allowing the hydrogen produced from coal to be injected into natural gas pipelines up to 18-20%, which would not require modifications to the pipelines. This would make it easier for industries currently using imported natural gas to transition to domestically produced hydrogen.

The government could consider sending a group of experts, headed by senior officials from the Ministry of Coal and Coal India Ltd., to visit some of the world's top gasification, gas cleaning and conditioning, water-gas-shift reactor, and CCUS technology units for carbon capture, preferably those that convert the captured carbon into chemicals and aggregates.

4.2.2

Indian Coal Gasification Strategy: Current Status and the Way Forward

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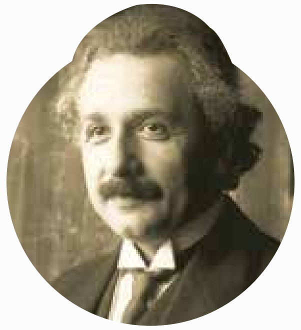


The joy of looking and comprehending is nature's most beautiful gift.

Albert Einstein

The Indian government aims to use 100 million MT/year of coal through gasification by 2030 to reduce the country's dependence on imports of crude oil and petroleum products and to protect against global market volatility. India has large coal reserves and can produce various alternative products like methanol, fertilisers, SNG, chemicals, DRI, hydrogen, thermal applications, etc. through gasification. The NITI Aayog has launched schemes such as the Methanol Economy and Hydrogen Economy programmes to adopt commercially proven gasification technologies for Indian coal, followed by conversion of the resulting syngas into methanol/DME/hydrogen, as well as developing indigenous gasification technology integrated with syngas utilisation.

4.2.2.1 Background

Several Indian organisations attempted coal gasification for coal-to-fertiliser and thermal applications using first-generation entrained flow gasifiers and producer gasifiers about 30 years ago. However, these attempts were short-lived due to the reasons listed below:

- Inconsistent quality of coal supplied for gasification.
- Lack of knowledge/infrastructure about pre-processing of feedstock: blending/washing, crushing-screening strategy, drying, briquetting/ palletisation, etc. to make the feed suitable for the installed gasifier.
- Lack of expertise in physico-chemical characteristics of coal, gasification potential/prospects and operational behaviour vis-à-vis suitable technology, and feed-specific operational philosophy.

- Inconsistent quality of feedstock and prior predictions about the operational behaviour of the feed resulted in frequent operational problems and subsequent failures.
- Environmental issues with the producer-type gasifiers related to the tar/liquid by-products.

These issues led to the gasification projects being economically unfeasible and eventually shutting down or switching to alternative fuels. However, there are some recent successful examples of gasification-based projects. JSPL has developed Asia's largest gasification-based DRI complex using air liquid gasification technology. It produces syngas from a blend of imported and domestic coal with a capacity of 2,25,000 Nm^3/h, although it is currently operating at around 60% of its design capacity.

Talcher Fertiliser Limited has initiated a gasification-based urea plant in Odisha using blends of domestic high-ash non-coking coal and pet coke for syngas production to be used in ammonia and urea production. Larsen & Toubro has commissioned several gasifiers in China and is involved in gasifier fabrication, erection, and commissioning. Reliance Industries Ltd. has developed a gasification complex in Jamnagar using petcoke for syngas production to be used in hydrogen, chemicals, and power production.

Further, several small and medium-scale industries are using producer-type gasifiers for thermal applications in ceramics, tiles, refractory, and steel industries. These attempts indicate that India is trying to exploit the locally available carbonaceous resources to fulfil the requirements in various sectors. However, these industries are still facing problems due to the above-listed shortfalls.

4.2.2.2 Gasification Requirements vis-à-vis Understanding Solid Fuel Characteristics

For venturing into the area of gasification at a commercial level, availability of the suitable gasification technology along with successful operational philosophy is crucial.

Suitable Gasification Technology According to The Feed Properties:
In general, there are three types of gasifiers – entrained flow, fluidised bed, and moving bed gasifier. A more detailed discussion about each type and their respective features, advantages, and disadvantages have been given earlier in this book. However, when it comes to selecting a gasifier or gasification technology, there are several key parameters to consider, which include:

- The gasification technology should be able to handle a wide variety of feedstocks.
- The gasification facility should require minimal feed pre-processing to minimise capital and operational expenses for feed preparation and processing.
- The gasifier should not have any specific feed size limitations that would require alternative routes to use rejected size fractions.
- The gasifier should have minimal or no by-product generation and should be emission-free to avoid additional downstream processing expenses and feedstock losses towards by-products.
- The gasifier should be capable of producing syngas of the desired quality, carbon conversion, yield, and attractive cold gas efficiency to make the process economically viable.

Feed-Specific Operational Philosophy
Establishing a suitable operational procedure for gasifiers is essential to account for variations in feedstock characteristics and prevent operational issues. The operational philosophy should be able to efficiently process the feedstock in the matching gasifier and also in the non-matching gasifier with necessary pre-processing or compromises. In some cases, it is more crucial than selecting the matching gasification technology. The ideal operational philosophy should be capable of gasifying the selected feedstock with minimum operational issues, lower process severity to minimise thermal losses, and successful gasification of available feedstock with desired syngas quality and yield, carbon conversion, and cold gas efficiency. Therefore, selecting a suitable gasifier and establishing feed-specific operational philosophy requires an in-depth understanding of the physico-chemical characteristics of the fuel and ash.

In order to operate gasification operations efficiently and in an environmentally friendly manner using Indian coal and biomass resources in any type of gasifier, it is important to have a deep understanding of the gasification process. In the past, researchers, CFD simulation groups, and operational teams have mainly focused on understanding gas-solid hydrodynamics and gasification reaction kinetics and mechanism. However, this approach may not be sufficient for Indian coal and biomass resources, which have high ash content and alkali-rich mineral matter that can cause operational issues. Therefore, it is crucial to have a thorough understanding of the behaviour of mineral matter in the gasification environment. This understanding is essential for designing/selecting the appropriate gasifier, establishing operational philosophy, and modelling/simulating gasification phenomena. The important aspects that need to be considered for a systematic understanding of the gasification process are listed below.

Gas-Solid Hydrodynamics

- Gasifier hydrodynamics
- Mass & heat transfer
- Diffusion inside solid
- CFD modelling
- Low-density biomass handling, feeding

Gasification Phenomena

- Drying, pyrolysis
- Adsorption/desorption
- Gasification reactions
- Reaction mechanism
- Reaction kinetics
- Variations in particle characteristics w.r.t. time
- Particle-level modelling

Mineral Matter (MM) Behaviour

- Hindrance/obstacle to mass & heat transfer
- Heat consumption/loss
- MM transformation during gasification and complex formation
- Agglomeration/clinker,
- Slag behaviour, fouling

The presence of mineral matter in fuel can directly or indirectly impact gasification and impede mass and heat transfer. The formation of agglomerates, clinkers, and slag can affect the gas-solid hydrodynamics within the gasifier. Therefore, it is important to have a comprehensive understanding of how gas, fuel, and mineral matter interact to effectively utilise Indian coal/biomass through gasification.

Thus, in order to efficiently and environmentally utilise solid fuel resources through gasification, it is necessary to have a thorough understanding of the gasification process, gas-solid hydrodynamics, and mineral matter behaviour. To achieve this, it is important to carefully study the physico-chemical characteristics of the coal/biomass.

Understanding Solid Fuel Characteristics
Traditionally, researchers and industries have used a limited set of physico-chemical properties of fuel and ash to understand and predict gasification phenomena and mineral matter behaviour. However, this approach is insufficient for gaining insights into these areas. Modern practices in similar processes include additional characteristics that depend on the type of gasifier and process conditions. In light of this, CSIR-CIMFR has developed a solid fuel physico-chemical characterization matrix for gasification, which includes relevant characteristics for the specific type of gasifier and their significance in the gasifier's internal processes. The following is a list of physico-chemical characteristics that are necessary for a complete understanding of gasification phenomena and mineral matter behaviour inside the gasifier.

Fuel Characterisation towards Gasification
The following are the key properties that need to be analysed to understand the gasification potential as well as the behaviour of the feedstock.

- **Proximate, Ultimate Analysis and CV:** FC: Solid char for gasification, VM: Tar/liquid, C, H: Syngas yield, Ash: Heat penalty, M: Feeding, Handling, Fluidisation, S: Impurity/ contaminant.
- **Ash Content & Properties:** Operational problems like bed agglomeration, Fouling, Corrosion, Reactivity, Carbon Conversion, and Particle strength.
- **Caking propensity:** Bed agglomeration/ clinkering probability
- **Surface Properties (Surface Area & Porosity):** Gasification reactivity, Blending benefits, Type of gasifier, etc.
- **Gasification Reactivity:** Gasifier capacity/ Residence time, blending propensity, Carbon Conversion, etc.
- **PCD & Shape:** Type of gasifier, Feed preparation and feeding, Fluidisation behaviour, Bed permeability, and Entrainment.
- **Density:** Volumetric loading, handling/ transportation, gasifier capacity, feeder type, fluidization, entrainment, etc.

Physico-chemical Characterisation as an Input for Technology Selection, Utilisation Pattern & Gasification Strategy

These physico-chemical characteristics are not only important for understanding gasification phenomena and mineral matter behaviour, but also for selecting the appropriate gasifier for a specific fuel resource and developing a strategy for its effective use. This will be further discussed below.

- **Technology:** Before embarking on the gasification process, it is crucial to select the appropriate gasifier that matches the characteristics of the available coal/biomass resource. Each type of gasifier has specific requirements for the physico-chemical characteristics of the feedstock, which must fall within a certain range. To facilitate this process, CSIR-CIMFR has established criteria for selecting the suitable gasifier types and technologies available worldwide. These criteria also aid in designing the appropriate gasifiers, including the fuel feeding systems, gasifier hydrodynamics, ash handling and withdrawal systems, as well as downstream syngas cleaning and conditioning modules.
- **Modifying Feedstock:** Maintaining the physico-chemical properties of the feedstock within a narrow range is crucial for consistent syngas quality and smooth operation after selecting the gasifier. However, obtaining consistent quality feedstock throughout the operation is difficult in practice. In case of any deviation from the desired range, pre-processing is required to bring them within an acceptable range, which may include washing or blending with other feedstocks such as coal, lignite, or biomass. To implement this strategy effectively, a thorough understanding of the physico-chemical characteristics of each feedstock and the newly generated feedstock is necessary, as some characteristics are not additive.
- **Pre-processing of feedstock:** Different gasifiers have specific requirements for the size and form of the feedstock, which can be granular, powdered, or in lump form, and within a certain size range. To meet these requirements, a suitable crushing and screening strategy is adopted. In some cases, additional pre-processing steps such as drying, briquetting, or palletisation are necessary to make the feedstock suitable for the gasifier.
- **Operational Philosophy According to the Feedstock:** It is not possible to operate any gasifier using a standard operating procedure because even a slight variation in feedstock characteristics can significantly impact syngas quality and operational behaviour. Therefore, it is crucial to modify the operational procedure based on the feedstock characteristics to ensure consistent operation and desired syngas quality. Hence, it is essential to establish a feedstock-specific operational philosophy to ensure successful gasifier operation with available feedstock. For this purpose, a comprehensive understanding of the physico-chemical characteristics is necessary after preparing the feedstock according to the gasifier requirements.

Therefore, it is important to adapt the gasification technology according to the available coal due to economic, geographical, and political reasons. To achieve this, it is necessary to identify the matching gasification technology and develop an operational philosophy based on an understanding of the physico-chemical characteristics of the coal. To this end, NITI Aayog has tasked CSIR-CIMFR and CMPDIL with executing the Gasification Potential Mapping of Indian Coal programme. This programme has mapped coal mines from three subsidiaries of CIL (MCL, CCL, and ECL) based on available inventory and linkage status. Coal samples from these mines were analysed for physico-chemical characteristics relevant to gasification. CSIR-CIMFR has developed gasifier selection criteria suitable for Indian coal resources and suggested matching gasification technology along with utilisation patterns and gasification strategies for the gainful utilisation of Indian coal resources.

4.2.2.3 Indian Coal Gasification Strategy: NITI Aayog Initiative

The NITI Aayog's Methanol Economy Task Forces have proposed two potential gasification programmes for India to make use of its coal resources.

Option 1: Gasification with Commercially Proven Entrained Flow Gasifier (EFG)

One of the options for utilising low ash-containing coal resources in India is in the ECL area. To demonstrate this, a demo-scale project using low ash coal from the ECL area is proposed to be installed at the Sonepur Bazari/Dankuni Coal Complex (DCC). Due to the high ash content and fusion temperature of Indian coal, ash with a refractory nature, high-temperature Dry Fed Quench Bottom Shell (Air-Products) EFG Technology is proposed for these projects. This technology is environmentally friendly, has easy operation, and is low maintenance. Although Shell claims the suitability of their gasifier for coal having ash content up to 30%, entrained flow technologies have proven applications only for coals with ash content <20%. However, in the case of Indian coal, the operating temperature may need to be maintained on the higher side for EFG to achieve desired slag viscosity, which can be achieved easily in membrane wall-based high-temperature EFG like Shell technology. The ash content from the feed coal is useful for value-added applications. This technology requires high capex but has a high coal throughput. To evaluate the handling capability of Indian high ash coal resources, neighbouring subsidiaries like CCL and MCL can be tested in the EFG at the Dankuni Project for gasification performance and ash content.

Fig. 1: Indian Coal Gasification Strategy: NITI Aayog Initiative

The Talcher Fertiliser Limited (TFL) project is planning to use Shell EFG technology for the production of urea from high ash coal with an ash content of 35-45% from the Talcher area. To make the coal suitable for Shell EFG, it will be blended with petcoke to bring down the ash content. Other proposed projects in CCL and WCL subsidiaries also aim to utilise high-ash coal for different products such as fertilisers and SNG. However, these projects require the indigenisation of entrained flow gasification technologies, as well as an exergy analysis to determine net cold gas efficiency and economic attractiveness. It is also necessary to establish the acceptability of high-ash coal with Quench Bottom EFG and assess the economic feasibility of washing/blending.

Lurgi Fixed Bed Dry Bottom (FBDB) Technology is another option for gasification technologies that is commercially proven. JSPL has installed seven Lurgi FBDB gasifiers in Angul, Odisha for DRI application, using high-ash Indian coal blended with low-ash imported coal. This technology generates ash removal in the form of aggregates and requires frequent maintenance due to high ash content. It also generates tar and liquid products that need to be handled and cleaned downstream. However, there is a possibility of increasing the Lurgi gasifiers' operating capacity through AI techniques and optimising the process by linking coal characteristics and operating conditions. To address issues related to tar and liquid products separation and handling, an Indirectly Heated Advanced Dual Bed Gasifier has been developed to generate tar/liquid-free hydrocarbon gases with the efficiency benefits of the fixed bed gasifier. The Lurgi FBDB technology requires washing or blending with low-ash feedstock to handle high-ash feedstock and alternative uses such as native captive generation due to fines restrictions.

Option 2: Development of the Indigenous Pressurised Fluidised Bed Gasifier (PFBG) Technology

The pressurised fluidised bed gasifier (PFBG) is a promising technology for using high-ash coal without needing to wash or blend it with low-ash feedstocks. It has advantages over other gasification technologies, such as low tar and phenol formation, no moving parts, and low heat loss. However, proven technologies in the fluidised bed category are limited. To address this, a task force under NITI Aayog is developing Indigenous Pilot Scale PFBG Technology as an Option 2. This will provide proof of concept and engineering data to upscale it to a demo PFBG plant. The demo plant will be compared with the commercially proven technologies identified under Option 1, particularly Shell EFG, to evaluate their suitability for Indian coal resources. The best-performing option will be taken forward for commercial installation. Organisations like CSIR-CIMFR, BHEL, EIL, and IIT Delhi-Thermax have installed oxy-blown PFBG Pilot Plant facilities with their technologies. BHEL and Thermax have completed the installation of the syngas-to- methanol module along with syngas micro cleaning and conditioning modules downstream of the gasification island, and CSIR-CIMFR is also in the process of installing downstream modules for methanol generation.

1.5 TPD Oxy-Blown Pressurised Fluidised Bed Gasification (PFBG) Pilot Plant at CSIR-CIMFR

CSIR-CIMFR has successfully established gasification of high-ash Indian coal from MCL and CCL areas with 36% and 40% ash content in a 1.5 TPD PFBG Pilot Plant (TRL-6) using oxy-blown mode (92% O2) without any operational problems. The produced syngas was tar-free with a concentration of 30% H_2 and 25% CO. Based on this and previous experiences, it has been concluded that the indigenously developed oxy-blown PFBG technology can be a potential option for high-ash coal resources. The generated syngas is comparable to commercial gasifiers and can be suitable for various downstream applications after micro-cleaning and conditioning as per process requirements.

Technical Features of the 1.5 TPD Oxy-Blown Pressurised Fluidised Bed Gasification (PFBG) Pilot Plant

- CSIR-CIMFR design, Refractory Lined Gasifier
- Fuel Feed Rate: up to 1.5 TPD
- Gasifying Agents: Air/Oxygen & Steam

Fig. 2: TPD PFBG Pilot Plant at CSIR-CIMFR

- Temperature: up to 1050°C, Pressure: up to 10 kg/cm^2
- Facility dedicated to the nation on 17/11/2020.

Gasification Performance of the 1.5 TPD PFBG Pilot Plant:

- Oxy-blown Gasification of MCL, (Ash 42%) & CCL, (Ash 30%) & Rice Husk with 92% Oxygen & Steam.
- Cumulative operation: >200 hrs.
- Syngas Comp. Coal Vol.%: CO: 25, H_2: 30, CH_4: 3.5, CO_2: 30,
- Syngas Comp Biomass Vol%: CO: 25, H_2: 10, CH_4: 5, CO_2: 40
- Carbon Conversion: Coal >93%, Biomass >95%
- Syngas Yield Coal: 1.43-1.68 Nm^3/kg fuel
- Syngas Yield Biomass: 1.00-1.1 Nm^3/kg fuel
- Indian patent and Copyright

Achievements in the 1.5 TPD PFBG Pilot Plant

- Tar-free syngas generation due to its inherent design and selection of operating parameters.
- Generated syngas is suitable for various downstream applications (methanol, fertiliser, DRI, etc.).
- Achieved ash agglomeration understanding and control which is detrimental in PFBG.
- Developed feed-specific operational philosophy for the plant.
- Basic engineering data from 1.5 TPD oxy-blown PFBG Pilot Plant for upscaling to demo scale plant.
- Mass and Energy Balance for high-ash coal gasification.
- Risk and failure analysis of the 1.5 TPD PFBG.
- Protocols related to start-up, steady operation, shutdown, regular and breakdown maintenance.
- Understanding the feed characteristic and its relevance with gasification performance.
- Next Target: Up-Scaling of the pilot scale PFBG to demo scale.

4.2.2.4 Indigenous Demo Scale Gasification Technology Development Roadmap

As discussed above, pilot-scale developments will provide engineering data to the engineering houses for its upscaling to develop the indigenous demo plant. Considering the pros and cons of the installation options, an indigenously developed demo-scale gasification facility can be installed either as a stand-alone facility or at existing/ planned projects. Moreover, the performance of the indigenously developed gasifier can be compared with commercially proven technologies identified under Option 1, specifically Shell EFG, in terms of gasification efficiency, operational performance, and suitability for Indian coal resources. The following are the installation options along with their pros and cons.

Indigenous Demo Scale Gasification Plant Installation: Indigenous Demo scale Oxy-blown PFBG installation at existing NG-Syngas based Fertiliser/Methanol Plants
With the exception of some instrumentation components, all parts and modules of the PFBG can be designed, developed, and fabricated indigenously. The design, development, and establishment of the heat recovery preheating and super-heating system, gasifying agent distributor, and air-plenum are specific to the scale and can be finalised during the demo phase. When it comes to risk and failure analysis, the indigenous PFBG has fewer risks compared to high-temperature entrained flow gasifier. However, it is essential to have a joint venture between R&D institutions such as CSIR institutions and IITs, engineering houses such as L&T, BHEL R&D, Tata R&D, EIL R&D Gurgaon, and Industries such as coal, fertiliser, steel, tiles/refractory brick, chemical, and liquid/gaseous fuel producers to execute this task.

Up-Scaling of The Pilot Scale PFBG to Demo Scale
As the PFBG performance is not tested for high-ash Indian coal resources on a commercial scale, two alternatives are suggested for the demo scale installation.

Option 1: Dedicated Demo Scale Gasification and Syngas Utilisation Hub.

The option to establish a standalone coal gasification-based methanol demo plant using Indigenously developed oxy-blown fluidised bed gasifier and syngas-to-methanol technologies requires a complete setup that includes feed preparation, gasification, syngas cleaning/conditioning and utilisation, utilities, expert manpower, and supporting infrastructure. This option provides more flexibility but comes with more capex- and opex-related risks. However, it may have certain advantages if the facility is installed at a dedicated technology development hub in the close vicinity of the chemical industrial area to ensure the availability of supporting manpower and infrastructure facilities, as well as supporting vendors in the vicinity. Therefore, establishing a gasification technology development park with centralised support will facilitate retrofitting new developments in the areas of gasification or syngas utilisation modules for their operational performance, evaluation and comparison purposes in the future.

Option 2: Retrofitting PFBG at Existing Syngas Utilisation sites like GNFC/CTM Dankuni/TFL, Odisha.

The option of retrofitting a PFBG at existing syngas utilisation sites like GNFC/CTM Dankuni/TFL, Odisha involves sharing upstream and downstream facilities such as feed preparation, syngas cleaning/conditioning and utilisation, utilities, expert manpower, and supporting infrastructure with minimal capex- and opex-related risks. This option requires only a small investment for coal crushing/screening/handling, gasification and syngas cleaning/conditioning facility, and associated risks. Additionally, the readily available utility and supporting infrastructure at the existing production facility can be shared, and technical support from experienced manpower for operation and maintenance, as well as modifications/upgradations in the gasification facility from time to time can be provided. This option has the flexibility to update/modify the gasification facility without hampering the regular production chain. Depending on feedback, more gasifiers can be added to increase capacity and replace NG-syngas completely with gasification-based syngas.

Establishing Operational Philosophy
Since the SOP cannot be applied to operate the gasifier, it is crucial to establish an operational philosophy that is tailored to the characteristics of the feedstock. To do so, a deep understanding of the physico-chemical properties of the fuel is necessary. The knowledge and experience gained from developing the pilot-scale PFBG can aid in creating this operational philosophy. The established approach can be refined by experimenting with different feedstocks from various mines that exhibit distinct physico-chemical features.

Strategic Location for Installation of the PFBG Demo Plant
To develop a demo-scale PFBG plant, it is important to have the support and involvement of various stakeholders and vendors. Maintenance and frequent upgrades of the plant components may also be necessary, so it is advisable to choose a site for the plant development that is located near chemical industrial areas. This will allow easy access to vendors and service providers for engineering, fabrication, plant components, automation, operation, maintenance, and upgrades or modifications or advancements. GNFC is a suitable site for establishing the demo oxy-blown PFBG, as it already has existing fertiliser and methanol generation plants. Additionally, GNFC has access to lignite resources in the nearby area, which can be used to supplement or replace the natural gas-based syngas and evaluate the performance and feasibility of Indian coal gasification technology.

4.2.2.5. Summary
In view of the installation of the gasification and syngas utilisation facilities suitable for Indian coal resources, the following summarised strategy can be adopted.

- Develop an understanding of the physical and chemical characteristics of solid fuel and its compatibility with gasifiers and operational philosophy. Create a coal properties database for Indian coals to determine their gasification potential.
- Study the behaviour of mineral matter (MM) in gasification, including obstacles to MT and HT, heat energy losses, complex/agglomerate formation, slag behaviour, and operational problems.
- Establish low-density biomass handling and feeding systems.
- Model gasification at the particle level, incorporating physico-chemical properties and interactions between gas, fuel, and MM.
- Understand the dynamic changes in particle characteristics during gasification/pyrolysis.
- Use process intensification techniques such as catalytic gasification, ash removal and handling, and heat recovery systems.
- Install a commercially proven Shell (Air-Products) EFG-based coal-to-syngas plant and integrate it with a syngas-to-methanol/urea/ammonium nitrate/SNG plant.
- Analyse the feasibility of High Temp. Membrane Wall Quench Bottom EFG and washing/blending methods for high-ash coal gasification.
- Optimise the operation of MBG (Lurgi) through the use of AI techniques.
- Develop and establish the operational philosophy of the Indirectly Heated Advanced Dual Bed Gasifier (ADBG).
- Establish a dedicated demo scale PFBG and syngas utilisation hub, retrofitting PFBG with existing syngas utilisation facilities like GNFC, TFL, Dankuni Project, etc. Evaluate the energy efficiency and operational performance of these demo scale gasification technologies with high-ash Indian coals to identify suitable types for commercial exploitation of Indian coal resources.
- Utilise coal ash for cement, composite materials, bricks, etc.
- Utilise biomass ash for soil amendment in farms.
- Evaluate the CO_2 lifecycle and recycle and utilise it in gasification and other value-added applications.

Therefore, it is necessary to implement both dry feed membrane walled entrained flow gasifier technology, which is a proven commercial technology, and develop indigenous demo scale fluidised bed gasification technology simultaneously. To ensure a rapid and successful development of demo units, joint programmes should be conducted between R&D institutions, engineering houses, and industries instead of carrying out independent parallel programmes. Each stakeholder has specific strengths at different levels of technology development and implementation, and a joint venture would benefit from these strengths.

4.3

H2 in SOLID – The 'Missing Piece' in the Net-Zero Logistics Ecosystem

JAMES KHONG, Co-Founder & COO, Galaxy FCT Sdn Bhd.

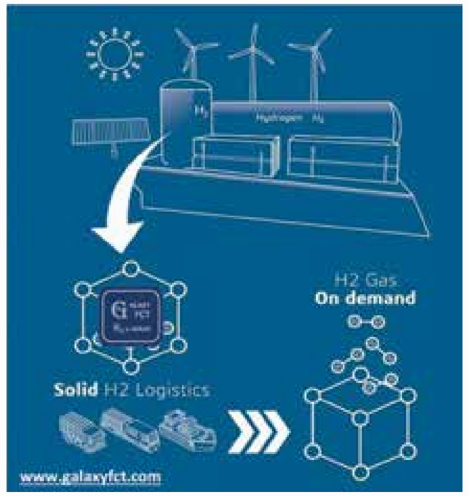
Nature uses human imagination to lift her work of creation to even higher levels.

Luigi Pirandello

Abstract Missing Piece of the Puzzle

The climate crisis is accelerating, and time is of the essence. Decarbonising the global economy is more pressing than ever before. Despite significant progress in clean technology, in particular the ability to make green electrons cheap, mankind still struggles with a couple of persistent pain points. They include the following.

- **Solutions are too Infrastructure Intensive:** It is still very difficult to decarbonise where deployment of logistical infrastructure is not possible nor practicable.
- **Long Duration Storage:** It remains extremely challenging to store lots of clean energy for extended periods without relying on fossil fuels.



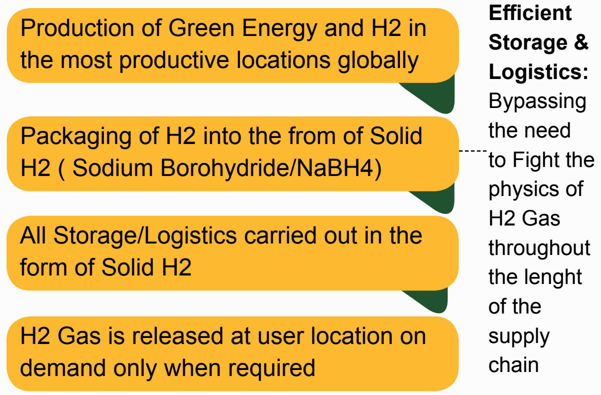
Hydrogen is often considered as the green molecule that mankind needs to complement the green electrons delivered through the grid (augmented by batteries, hereinafter the Green Electron Network), but its challenging physics is proving difficult to overcome. The logistics of Solid H_2 allows hydrogen to overcome the limitations of distance and time, enabling it to be an affordable, portable, and safe green molecule. This results in a supply chain that requires minimal infrastructure.

In this chapter, we will introduce the concept of Solid H_2 and explain why it could well be the missing piece in the clean energy logistics puzzle. We believe that the Solid H_2 logistics ecosystem is on the brink of a major breakthrough that could unlock the full potential of renewable energy worldwide, especially in the fight against climate change. Additionally, the chapter will discuss how India is uniquely positioned to take advantage of this opportunity as a first mover in this emerging field.

4.4.1 Concept and Core Fundamental

Solid H2 Logistics – Introducing the Concept
Solid H2 logistics is based on the idea of using a solid hydrogen dense chemical feedstock to store and transport hydrogen, instead of dealing with the challenging physics of hydrogen gas.

Concept Overview - H2 in SOLID



Production of Green Energy and H2 in the most productive locations globally

Packaging of H2 into the from of Solid H2 (Sodium Borohydride/NaBH4)

All Storage/Logistics carried out in the form of Solid H2

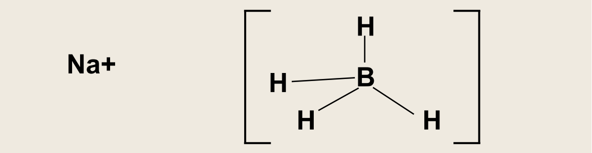
H2 Gas is released at user location on demand only when required

Efficient Storage & Logistics: Bypassing the need to Fight the physics of H2 Gas throughout the lenght of the supply chain

Low Cost Last Mile:
No external energy input required for exothermic rection which releases H2 from NaBH4

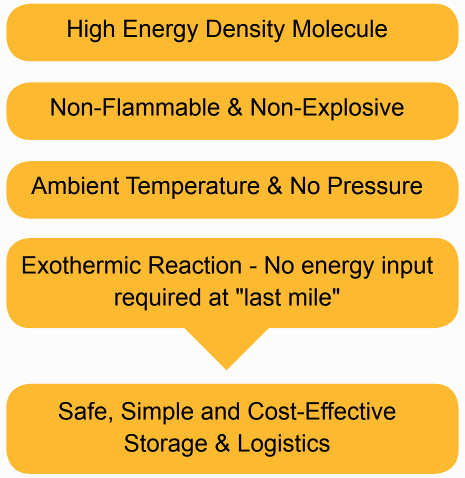
The process involves producing hydrogen using clean energy and immediately packaging it into a solid chemical compound called sodium borohydride ($NaBH_4$). This solid form of hydrogen is then used for all storage and logistics activities, and the H_2 gas is released through a hydrolysis reaction at the user location only when needed. Since the reaction is exothermic, it doesn't require any external energy input at the user location, making it a low-cost option for the last mile.

Sodium Borohydride ($NaBH_4$)
Sodium borohydride is energy dense, non-flammable, non-explosive and can be stored at ambient temperature without pressure. This provides us with the green molecule which is ***safe to store, easy to move and safe to handle*** and hence infrastructure-light across the entire supply chain.



The amount of H_2 gas that can be released with one cubic metre of $NaBH_4$ (600 kg) is around 126 kg. This is significantly higher than the 71 kg of H_2 from one cubic meter of liquid H_2 which needs to be stored at -253°C.

For example, the *Suso Frontier*, the first liquid H_2 tanker, can transport 88.75 MT of H_2 in a vessel with a displacement of 8,000 MT, using just 22 units of 20-feet containers. If each container weighs



High Energy Density Molecule

Non-Flammable & Non-Explosive

Ambient Temperature & No Pressure

Exothermic Reaction - No energy input required at "last mile"

Safe, Simple and Cost-Effective Storage & Logistics

2,000 kg, the entire shipment of 22 fully loaded containers would weigh about 478 MT. Regular container ships can transport these containers, and no specialised vessel or dedicated storage, loading and receiving facilities are necessary at ports, making the shipping process very flexible, simple and cost-effective.

The logistics ecosystem centred around $NaBH_4$ offers a significant advantage in terms of simplicity and efficiency, allowing for rapid execution without the need for extensive logistical or transmission infrastructure. It provides the option to simply ship the product without additional costs and complications.

H2 Volumetric Density Comparison	
Compressed Gas @ 700 Bar	42.0kgH2/m3
Liquid Hydrogen (-253C)	71.0kgH2/m3
Liquid Organic H2 Camers (LOHC)	57.0kgH2/m3
Sodium Borohydride (NaBH4)	126.0 kgH2/m3

Galaxy FCT and Solid H2 Logistics

Galaxy FCT has achieved a technological breakthrough that enables the efficient and rapid release of hydrogen gas from solid $NaBH_4$. In aqueous solutions, $NaBH_4$ typically contains 10% to 20% content. This results in a poor power to weight ratio due to the need to transport a lot of water. However, using the solid form can significantly improve this ratio since water is readily available in many locations and does not need to be transported in most cases. The chemical equation reveals that for every molecule of H_2 released from $NaBH_4$, an additional molecule of H_2 is released from added water, which provides $NaBH_4$ with a relatively high H_2 density.

$$NaBH_4 + 2H_2O \rightarrow NaBO_2 + 4H_2$$

Power to Weight Ratio - Comparison	
Solid H2 (NaBH4)	21.10% wt
Acqueous NaBH4	4.00% wt
Ammonia	17.70% wt
Compressed Gas @700 bar (note)	5.90% wt

NOTE - this is based on a type IV tank on a toyota mirai. If we use steel tank, it would probably be less than 3%. Tank weight not included for others categories.

Aqueous $NaBH_4$ also requires addition of reaction inhibitors to prevent premature H_2 release. This will contaminate the by-product ($NaBO_2$), making recycling of the same much more complex and costly. Galaxy FCT's protocols avoid this completely and the catalysts used can be fully recovered, leaving the by-product uncontaminated and easy to recycle.

A Patented Process

The key components of the H_2 generator (the HyGen) are illustrated in the concept diagram given. The $NaBH_4$ in solid powder form is injected into the main reactor chamber along with water and catalysts. The resulting chemical reaction releases H_2 gas, which is then collected in the buffer tank, enabling delivery of H_2 on demand.

Two key observations:

- The process is exothermic, which means that no external energy input is needed at the user location. This makes the process highly efficient, as energy is often expensive and hard to come by in some locations.
- Because the process is not widely used, the last-mile equipment required for it would be cost-effective once produced on a large scale.

GALAXY FCT PATENTS

PCT Approval Q3 2019, Patents issued in: United States of America, Japan, South Korea, China, India, Saudi Arabia, ARIPO, South Africa, Nigeria and Chile (worldwide pending).

GFCT's recent technology breakthrough is the basis for the evolution of the Solid H_2 logistics ecosystem, and the conditions are favourable for its development. However, the challenge now is to address the scarcity and high cost of $NaBH_4$, which needs to be produced on a large scale and at lower prices to make the ecosystem economically viable.

The U.S. DOE No-Go Decision in 2007

One of the main reasons cited by the U.S. Department of Energy in 2007 for the No-Go recommendation for $NaBH_4$ as on-board vehicular hydrogen storage was its high cost compared to other hydrogen storage options. Additionally, it was noted that the energy density of $NaBH_4$ was lower than that of gasoline or diesel, meaning that a larger volume of storage would be required for the same amount of energy.

However, since then, there have been significant advances in technology, particularly in the field of solid-state hydrogen storage, which have led to the development of new and innovative solutions that were not available at that time. These include GFCT's breakthrough technology in rapid and efficient release of hydrogen gas from solid form $NaBH_4$, as well as other emerging technologies such as metal-organic frameworks and ammonia borane.

Furthermore, the increasing focus on decarbonisation and the transition to a hydrogen economy has led to a renewed interest and investment in hydrogen storage and transportation technologies. This has led to increased research and development efforts in the area of $NaBH_4$ and other solid-state hydrogen storage options, with the potential to address the challenges that were identified in the 2007 report.

Therefore, while the No-Go recommendation for $NaBH_4$ may have been justified at the time, the current landscape of technology and market conditions suggest that there is potential for solid-state hydrogen storage solutions such as $NaBH_4$ to play a significant role in the transition to a decarbonized economy Indeed, with the advancements in technology and the changing economic landscape, the obstacles that once hindered the adoption of $NaBH_4$ for hydrogen storage are being addressed. The shift towards a wider clean energy ecosystem that encompasses not just vehicular applications but other sectors as well, provides a larger market for the technology to thrive. Additionally, the decreasing costs of renewable energy sources make the economics of Solid H_2 logistics more viable. With these factors in mind, the potential for Solid H_2 logistics to take off is greater than ever before.

Solid H_2 Applications

Let's examine the possible uses of the Solid H_2 logistics ecosystem more closely. It's important to understand that the cost structure of Solid H_2 logistics is significantly different from that of conventional clean-tech solutions, which typically require a lot of infrastructure. The production costs of Solid H_2 are the majority of the overall costs, while the costs of storage, handling, logistics, and infrastructure are relatively low. As a result of this cost structure, once the production costs of Solid H_2 are reduced over time, the total cost of energy delivered to the user will decrease. This will rapidly increase the number of applications that fall within the sweet spot, causing global demand for $NaBH_4$

DOE Perspective 2007	A 2023 Perspective
Aqueous $NaBH_4$ had a very poor "power to weight ratio" and cannot meet the minimum threshold DOE required of 6% wt.	Galaxy FCT uses Solid NaBH4 as feedstock and this will make the "power to weight ratio" much higher than the DOE threshold of 6% wt.
The On-Board System proposed by Millennium Cell was considered to too heavy and too big to realistically fit within a passenger car.	We use $NaBH_4$ as clean energy carrier (H_2 gas on demand) for many applications. In vehicles, focus will be on heavy vehicles rather than passenger cars.
Economics: DOE doubted the economics which were predicated on availability of cheap energy ($0.03/kWh) which was unrealistic (in 2007)	In April 2021, PPA price for Desert Solar in Saudi signed for record low of 1.04 cents/ kWh. With greater scale/ technology, we believe future prices can go even lower.

to rise sharply since there is no need to wait for logistical infrastructure to be deployed for this ecosystem to scale. The diagram below shows the different type of applications that will come into the sweet spot as the production cost of $NaBH_4$ falls over time.

Early-Stage Applications
At the beginning stages of the Solid H_2 logistics ecosystem, when the prices of Solid H_2 are high, we anticipate that the focus will be on critical applications that prioritize safety, availability, flexibility, and resilience, as well as those that require long-term storage. Such applications could include emergency back-up power for remote healthcare, vaccine storage, strategic communication, remote military facilities, underground bunkers, and emergency services. These applications are typically critical and require a dependable power source. They are situations where traditional energy sources may not be available, sufficient, or feasible.

Intermediate-Stage Applications
As the production costs of Solid H_2 are reduced through large-scale production, we anticipate that a wider range of mainstream applications will emerge that require greater amounts of energy. Due to its extreme flexibility and resilience, we believe that Solid H_2 applications will complement other hydrogen carriers and serve areas where deploying a large infrastructure network is not feasible, demand is relatively intermittent, and/or there are greater storage requirements at various points in a complex supply chain. These are situations where infrastructure-intensive solutions would be uneconomical and impractical, and Solid H_2 logistics would be better suited.

Maturity-Stage Applications
At this stage, a significant amount of Solid H_2 will be produced at a low cost due to the combination of inexpensive renewable energy, mass production at prime sites, and improved technology. The faster we reach this stage, the more effective Solid H_2 logistics will be in combating climate change. Several significant applications are anticipated at this stage, including:

- **Mining Trucks & Excavators**

Mining activities are responsible for a significant amount of GHGs, ranging from 4% to 7% annually, and it is a challenging sector to transition to electrification. More crucial minerals are required for the energy transition, and if the mining sector remains carbon-intensive, the climate crisis could worsen. Diesel-based mining trucks and excavators contribute considerably to carbon emissions. By using Solid H_2 onboard units to power these vehicles, the carbon footprint of mining activities can be significantly reduced, enabling large-scale mineral production necessary for accelerating the energy transition without pushing the planet beyond the climate tipping points.

- **Green Shipping**

Solid H_2 has the potential to become a desirable energy carrier for sustainable shipping once its price point is favourable. It is a safe, uncomplicated, and cost-effective method for long-term storage with minimal infrastructure requirements, as well as having a high volumetric energy density. Solid storage reduces the risk of leakage, which is a significant problem with LNG, hydrogen gas/liquid, or ammonia fuel shipping. Compared to CO2, hydrogen, methane, and nitrous oxide are much more potent GHGs, with 80 times, 11 times, and 300 times the potency, respectively.

- **Peak Energy & Grid Stability**

As we move towards achieving net zero, the proportion of renewable energy from variable sources in the electricity grid will increase, leading to significant fluctuations in supply due to weather and climate conditions. The effects of climate change will exacerbate this issue, causing more frequent and severe climate events that could further stress transmission infrastructure and lead to energy supply shortages. To address these challenges, large quantities of batteries would be required in any future smart grid system. However, Solid H_2 could be a more cost-effective solution for providing peak energy during these surges, compared to relying solely on batteries. While batteries are best suited for regular energy time-shifting and flexibility, Solid H_2 could more efficiently address the occasional peak demand mismatches that occur.

- **Long Duration Strategic Reserves**

As the world transitions away from fossil fuels, there will be a crucial need for an efficient way to store large amounts of clean energy for extended periods of time, known as strategic reserves. Currently, there are few viable options that depend on specific landforms or require significant fixed infrastructure at specific locations, making them inflexible. Solid H_2, on the other hand, is logistically flexible and efficient, making it an attractive option for long-duration energy storage. As production costs decrease, Solid H_2 could become a practical means of storing strategic energy reserves in a post-hydrocarbon world.

4.4.2 Sodium Borohydride Production Costs

We think that the biggest barrier to the success of the Solid H_2 logistics ecosystem is the cost of producing $NaBH_4$, which is a highly energy-intensive process. This issue was also one of the reasons why the U.S. Department of Energy decided not to pursue it back in 2007. However, we believe that recent global changes and advancements in technology have shifted the situation significantly, and we are close to reaching the tipping point where Solid H_2 becomes much more viable. Moreover, the technical issues related to H_2 gas release from solid have already been solved by Galaxy FCT.

Background – Current Production of $NaBH_4$
Currently, $NaBH_4$ is produced as a specialty chemical at a relatively small global volume, which makes it expensive. The market is controlled by a few large producers, resulting in an oligopolistic market structure. The production process begins with the electrolysis of molten sodium chloride to produce sodium metal, which is highly explosive and needs to be transported submerged in paraffin oil. Downstream plants in the U.S., Europe, and Asia use the Brown Schlesinger process to produce $NaBH_4$. Despite Dow Chemical's introducing the Bayer (One Pot) Process, large-scale production plants still use the Brown Schlesinger process. This involves mixing sodium metal with hydrogen gas at around 300°C to form sodium hydride (NaH), which is then reacted with trimethyl borate ($B(OCH_3)_3$) to produce $NaBH_4$. The production processes also include distillation, separation and drying, and wastewater processing. Global demand for $NaBH_4$ has been growing, and there have been no significant changes in production technology in recent years.

2Na + H2 → 2NaH (200c-350c)
4 NaH + B(OCH3)3 → NaBH4 + 3 NaOCH3
(260c-350c)

The **Key Observation** here is that all the core raw materials are either inexpensive or recyclable, and the biggest component remains energy and process costs.

This means that there is a very significant opportunity for rapid and meaningful cost reduction that can be garnered from leveraging low-cost renewable energy (in the most productive locations), combined with large-scale, continuous production using optimised processes including the recycling of intermediate chemicals and recovery of waste heat.

Roadmap Towards Cost Reduction

The diagram below summarises how we see the roadmap towards continuous cost-reduction in $NaBH_4$ production costs.

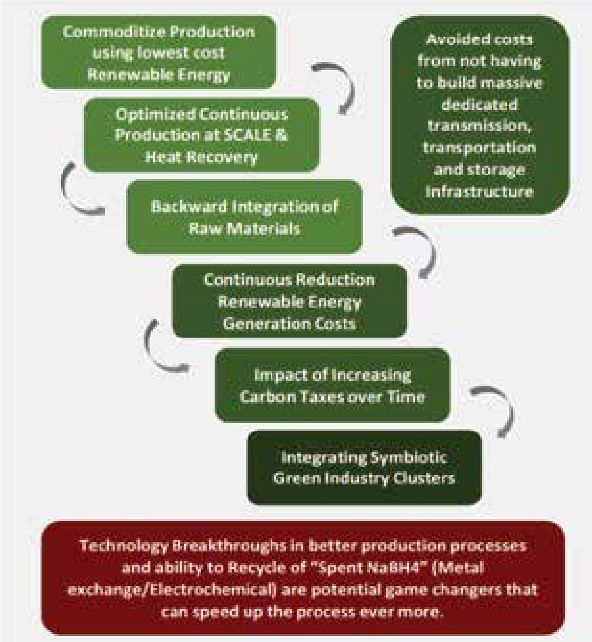
First, we need to commoditise production and move it away from an oligopolistic market. Production should be carried out by way of an optimised and continuous process, which is fully integrated to maximise efficiency.

Assuming the demand for $NaBH_4$ increases significantly and the prices decrease, the amount produced would be much larger than the current capacities, allowing for economies of scale at every level. This would enable end-to-end integration of the production process, optimising heat recovery, recycling, and backward integration of raw materials and consumables, resulting in further reduction of production costs.
It is important to note that the success of reducing

Key Raw Material (estimates) per MT of NaBH4	
NaCl (to produce Na)	6.157 MT
H2O (to produce H2)	0.106 MT
Boric Acid (recyclable)	1.631 MT
Methanol (recyclable)	2.526 MT

Energy Consumption Estimate (per MT NaBH4)	
Down process - Electrolysis of NaCl	26.5 kWh
H2 production - Electrolysis of water	6.1 kWh
Brown Schlesinger process (see Note)	15.0 kWh
Total for 1 MT NaBH4	47.6 kWh
Total for 4.75 kg NaBH4 (1 MT H2 Equiv)	226.2 kWh

Note: These are estimate for the Brown Schlesinger NaBH4 Formation with integrated process at scale (Heating duty of extraction distillation, dryer, recycling of chemicals, etc.)



prices in this scenario does not rely on any technological breakthroughs in the future. Rather, it depends on optimising and integrating existing production processes in previously unprecedented integrated configurations and executing them at a scale that has not been seen before. While future technological breakthroughs would likely accelerate cost reduction and the growth of the ecosystem, they are not essential for success.

Hyperscaling NaBH$_4$ Production at Prime Sites

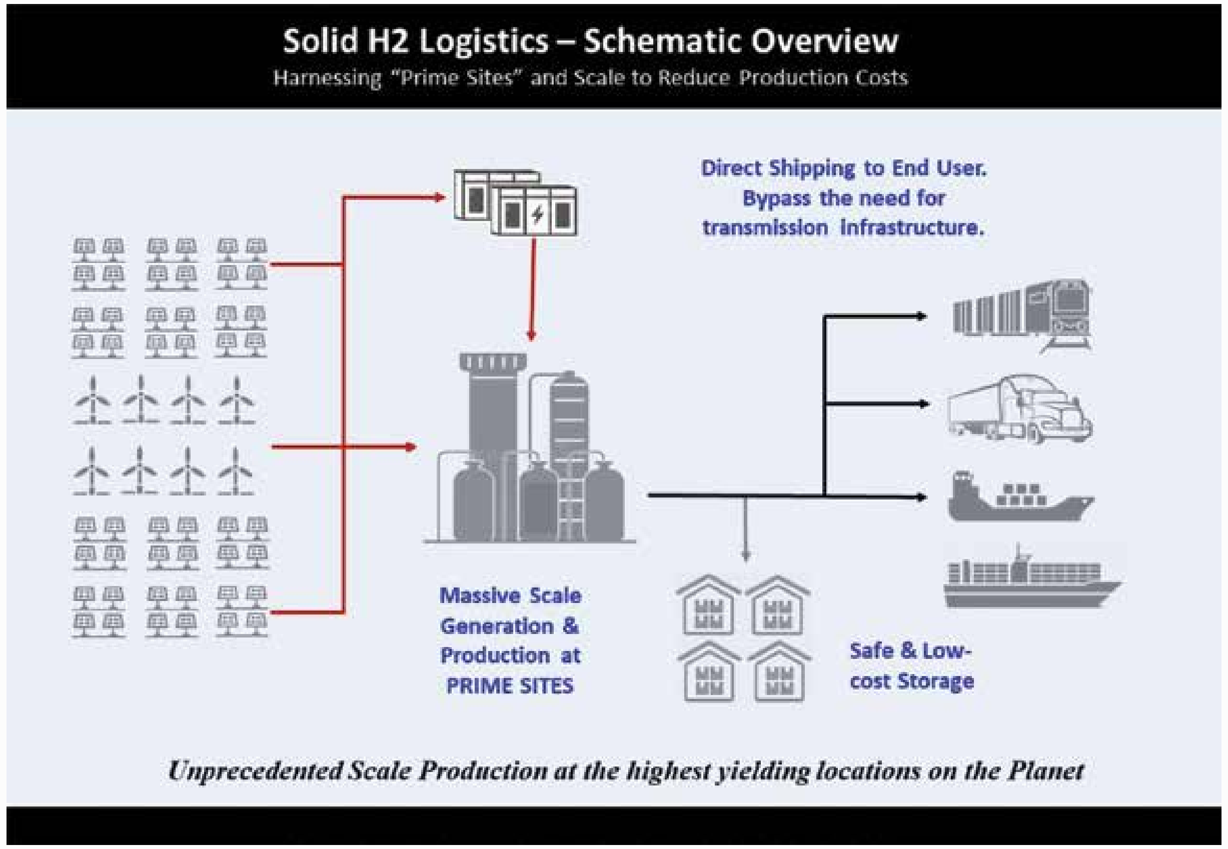
The production of large quantities of green molecules and the rapid reduction of prices can be achieved through the integration of renewable energy production with NaBH$_4$ production at a continuous and large scale. This can be done at prime sites, typically located in harsh windy deserts near the sea. Although these areas may be far from transmission infrastructure or load centres, this is not an issue as all energy generated can be used for NaBH$_4$ production and shipped directly to users worldwide in regular containers. By removing reliance on transmission, previously unused land can be utilised for large-scale production of green molecules, which is essential for responding to climate change. These vast areas of land are low-cost and have little to no competing uses, allowing for unprecedented scale of production and significant economies of scale.

Deploying solar panels or other capital expenditures at the prime sites will yield more energy per unit and cost less. Unlike other projects that require off-take contracts, NaBH$_4$ is an energy commodity that is easy to store and can handle demand and supply fluctuations. This makes it a more viable option for large-scale production, especially compared to infrastructure-intensive projects that produce energy that is challenging or expensive to store.

Continuous Systemic Factors, Lower Production Costs Over Time

The journey towards reducing costs would be aided by several systemic factors that would operate continuously in the background. These factors are:

- The cost per kWh of renewable energy generation will continue to decline year after year. As the world ramps up the use of renewable energy, the cost of producing each kWh of renewable energy will continue to decrease, especially in the most productive locations with minimal land cost.


Solid H2 Logistics – Schematic Overview

Harnessing "Prime Sites" and Scale to Reduce Production Costs

Unprecedented Scale Production at the highest yielding locations on the Planet

- This trend is evident across all renewable energy sources, but solar PV has outperformed the others so far and is expected to continue to do so.

In April 2021, Desert PPA prices hit a record low of 1.04 cents/kWh, but they rose again due to trade wars and de-globalisation. However, we believe that the long-term trend will be for prices to continue to fall, as the learning curve effect (known as Wrights Law of the S-Curves) takes hold. This means that for each doubling of global installed capacity for solar PV, there should be a constant percentage reduction in costs, estimated to be between 30% to 40%.

Despite the repeated success of this S-Curve effect with different products, mankind still underestimates the future savings that can be achieved through it. Historical projections for various products, including semiconductors, computing power, and solar PV, have consistently fallen short of the actual prices achieved. We anticipate that this same trend will occur in the realm of Solid H$_2$ production as volumes increase exponentially over time.

The cost of producing NaBH$_4$ will fall each year as the cost of renewable energy, the largest cost component, continues to decrease. This reduction will happen regardless of any process optimisation or technological advancements. By fully integrating NaBH$_4$ production at hyper-scale and backward integrating all raw materials and consumables at the prime sites, we believe that there will be a learning curve effect that will result in further cost reduction over time.

Systemic Increase in the Price of Carbon:
With each passing year, we are getting closer to depleting our carbon budget needed to limit global warming to 1.5°C and avoid the most severe

effects of the Climate Crisis. Based on IPCC (AR6 2020) data, the carbon budget was approximately 500 Gt CO_2 in 2020, but due to emissions between 2020 and 2022, the remaining budget is estimated to be around 380 Gt CO_2 as of the end of 2022. At the current emission rate, this budget would be exceeded in just nine years.

It is likely that carbon taxes will become necessary as the world tries to reduce carbon emissions. As we approach the carbon budget limit, the true cost of carbon, reflected in some form of carbon tax, will increase significantly. This will make Solid H_2 more economically attractive, as it is a truly green molecule that is logistically efficient, flexible, and resilient. By displacing emissions, it can earn carbon credits and reduce the effective cost per kWh, making it even more cost competitive.

Green Supply Chains getting Increasingly Longer and more Complex

To decarbonise the world, a large amount of green hydrogen production is required, with a significant portion expected to come from low-cost regions that are far from load centres. McKinsey's recent report predicts that green hydrogen will contribute to reducing 80 GT of CO_2 emissions by 2050. The report projects 660 million MT/year of hydrogen demand by 2050, with green hydrogen accounting for over 60% by 2035. It also suggests that the lowest-cost locations for production will be 2.5 times cheaper than high-cost locations, with 400 million MT/year of hydrogen transported over long distances by 2050. To achieve this, infrastructure and transportation investments of $1.5 trillion will be necessary by 2050. Therefore, producing hydrogen at scale in the lowest-cost locations (prime sites) will be crucial for the proliferation of green hydrogen, but it will require significant investment in infrastructure to support long and complex supply chains.

While the power of S-Curves are often underestimated, the viability (executability) of Infrastructure Intensive Solutions tends to be Systematically Overestimated.

When making predictions about the costs of large and complex infrastructure projects, especially those that cross borders and are interdependent, we tend to be overly optimistic. We often overlook potential execution risks, contingent costs, and delays, and allocate insufficient funds to contingencies.

In general, energy generation projects are less prone to execution issues than transmission and pipeline projects. The latter are often plagued by significant problems such as lengthy delays, cost overruns, slower-than-expected adoption rates, and even project abandonment. In some cases, these projects cannot even move beyond the planning stage and into execution without heavy government support.

Optimistic Bias in Costing Infrastructure Intensive Projects
Predictable Risks/Adverse Events too often treated like "Black Swans"

- Limited availability of funds, physical resources and critical minerals
- Poorer countries cannot afford the Infra and lacks the socio-political & economic conditions needed for project to be bankable
- Running out of time to decarbonize, but infrastructure has long lead time
- Dispersed and intermittent demand in many locations (Chicken & Egg conundrum- inability to scale). Likely to have lower than expected utilization rates in many cases
- Land Rights, People Issues NIMBYs and Lawyers resulting in extended delays & massive cost overruns (especially soft costs)
- Increasing geopolitical tension, Multipolarity and Increased Political Instability
- Rising interest rates and global inflation likely to result in cost overruns over time
- Long Term effects of Hydrogen Embrittlement and Last Mile Infra often underestimated.
- More extreme conditions due to climate change increases infra vulnerability

These two biases tend to favour energy storage and delivery solutions that require extensive infrastructure networks, which result in lower energy loss between production and use. However, these biases fail to consider that such solutions are only viable in a limited portion of the world. It is crucial to acknowledge these limitations and use our resources, money, and time on infrastructure that is practical and efficient in the appropriate locations and conditions.

Solid H_2 logistics offers a practical alternative that requires less infrastructure and can complement the existing infrastructure-intensive solutions we have today.

The Strategic Exchange which Underpins Solid H2 Logistics

Solid H_2 logistics is a strategy that prioritises having a green molecule that is easy to store, move, and handle, even if it means accepting lower energy efficiency during production and packaging. It is like a financial investment where you bet on production costs decreasing while the cost of deploying infrastructure increases, essentially going long on production costs and short on infrastructure deployment costs.

The cost of producing renewable energy in the most productive locations in the world, where Solid H_2 production can be integrated at scale with energy production, is expected to decrease rapidly over time. This will be due to the learning curve effect of renewable technologies being accelerated by the surge in demand from HyperScaled production at prime sites. As this happens, the relative energy penalty of $NaBH_4$ production will become smaller and smaller in dollar terms. Solid H_2 logistics will then become even more advantageous as a green energy storage and transportation alternative.

On the other hand, as the supply chain for green H_2 becomes longer and more complex due to the need to produce and transport large quantities from remote areas, traditional logistics become increasingly challenging, intricate, and expensive. The extensive cross-border infrastructure required for this purpose is complex, costly, and subject to various risk factors that are difficult to manage or alleviate.

Green hydrogen logistics present additional challenges compared to conventional logistics due to several reasons: (a) Hydrogen is both hazardous and costly to store, and any discrepancy between the timing of supply and demand can lead to significant costs; (b) the infrastructure required for its transportation is expensive and not adaptable to changing circumstances; (c) specialised vessels, tankers, and equipment for transportation may be unused during return trips; (d) the impact of hydrogen embrittlement in real-world applications may be more problematic and costly than previously assumed.

Solid H_2 logistics has a strategic advantage in that it primarily deals with the costs of production and packaging within a controlled environment, as opposed to managing costs across the increasingly complex and global supply chain. This supply chain presents numerous challenges that are often beyond Solid H_2's control. As the Solid H_2 logistics ecosystem develops further, we believe its strategic advantages will become more apparent.

4.4.3 An India-Centric Perspective

India possesses a variety of advantageous characteristics that make it well-suited to adopt and expedite the Solid H_2 logistics ecosystem, which can provide substantial benefits in return. In the upcoming sections, I will delve into these factors in greater depth, considering not just the technical aspects but also the economic and socio-political considerations. This will help explain why accelerating the development of Solid H_2 logistics represents an appealing blue ocean of opportunity for India.

A recent NREL technology review (Topolski Et. Al, Oct 2022) highlighted the fact that H2 embrittlement impacts not just metal, but also polyethylene as well as polymer pipes, joints, resins, compressors, valves, storage facilities and other non-pipe components as well.

An Executable Pathway Towards Accelerating Net Zero

India has set a goal of reaching 500 GW of non-fossil power generation by 2030, starting from the current base of around 175 GW as of the end of 2022. While this is an admirable and ambitious target, there are various obstacles that need to be addressed. We think that expediting Solid H_2 logistics and establishing HyperScaled Prime Site Solid H_2 production would be a viable and swift approach to achieving these objectives.

- Producing renewable energy on a large scale in remote resource-rich areas (prime sites) without transmission constraints allows for quick deployment at scale with minimal market risk or delay. This approach avoids potential issues related to land rights and NIMBYs, as well as the need for extensive and complex contracts before projects can start.
- By moving green H_2 production to prime sites, productive renewable areas closer to transmission lines are freed up to supply green electrons directly to the grid.
- Solid H2 logistics complements the net zero grid well as it is efficient and feasible in areas or conditions where the net zero grid is weak, such as where infrastructure is insufficient or long-term energy storage is needed.

Accelerating the Renewable Supply Chain

Producing $NaBH_4$ on a large scale at key locations will quickly create a continuous demand for various renewable energy products such as solar panels, batteries, wind turbines, fuel cells, and other related items, collectively referred to as Associated Renewables. This demand will trigger S-Curves that lower the production costs of each product.

This sustained demand for Associated Renewables will steadily increase year after year, providing a favourable environment for the rapid growth of large-scale production of these products within India. The country's abundant technical talent and young population give it a competitive edge in the global market.

Additionally, this domestic demand is more secure and resilient against external economic fluctuations, logistical disruptions, trade wars, sanctions, and unexpected global events like pandemics. With a strong internal base, India can develop an internationally competitive supply chain and achieve its goal of becoming a leading producer of green hydrogen.

The lowering of prices for Associated Renewables due to the power of the S-Curves will result in lower prices for Solid H_2. This, in turn, will increase the number of economically viable applications for Solid H_2, resulting in a significant increase in demand for it. This creates a Virtuous Cycle that drives more HyperScaled prime site production, which leads to greater demand for Associated Renewables, further lowering prices and perpetuating the cycle.

India is uniquely positioned to take advantage of this ecosystem, with its vast deserts, access to the sea, large population and market, geopolitical importance, financial and material resources, and abundant human talent. This presents a blue ocean opportunity that only a select few nations can fully capitalise on.

Integrating Symbiotic Clusters – Desalination & Agrivoltaics

It is frequently emphasised that producing green H_2 requires large amounts of water, and dry desert regions with high levels of sunlight are the most productive for generating renewable energy. Therefore, the most suitable prime sites for large-scale production would be those near the coast, which would allow for easy shipping and enable the production of freshwater through desalination. Given these conditions, it would be mutually beneficial to combine Solid H_2 production with desalination and agrivoltaics.

- Agrivoltaics involves growing crops underneath large solar panel arrays, which can improve land use and food security, while also cooling the panels and increasing their energy generation efficiency. The crops planted beneath the panels will experience reduced water loss and better protection against extreme weather conditions.

- The low energy costs of the desalination plants will be further enhanced by utilising waste heat from production processes to dry the concentrated brine, which is typically an environmental concern. The resulting sodium chloride can be used as raw material in the production of $NaBH_4$.

Combining these clusters will facilitate the optimisation of processes, resulting in improved overall productivity.

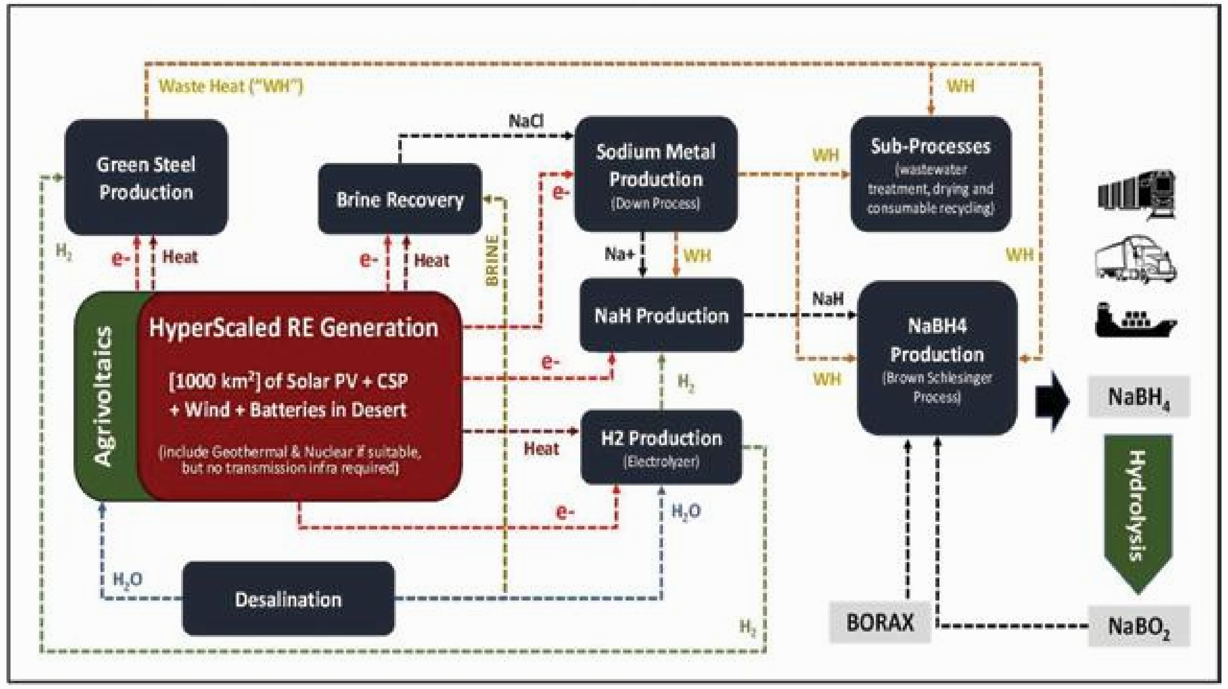
Integrating Symbiotic Clusters: Green Steel and Aluminium Production

India has set ambitious goals for increasing its production of green steel and aluminium, which requires large amounts of clean energy and green hydrogen as feedstock and generates significant waste heat. Integrating these facilities with Solid H_2 production at prime sites would result in further optimisation of processes.

The production plants would have access to low-cost green energy and a reliable supply of green hydrogen. Additionally, waste heat generated by the production plants could be recycled for many of the processes involved in $NaBH_4$ production, including distillation, drying, wastewater processing, and crystallisation of desalination brine.

The following diagram illustrates how the concept of Hyper-Scaling at prime sites can be taken to the next level by integrating these symbiotic clusters.

From an India Perspective **-** the Solid H_2 logistics ecosystem is the missing piece of the puzzle in many ways. It presents a timely opportunity to create a parallel clean energy ecosystem that allows India to bypass the many execution bottlenecks that could potentially hinder its ambitious net-zero goals. This will create a massive local ecosystem that fully leverages the power of S-curves through the rapid creation of a sustained, multi-year demand for all associated renewables along the supply chain. This is particularly significant in critical segments where India needs to develop production scale as they are already dominated by other producers. *[See: Polysilicon Glut & Cheaper Solar Panels?(Clean Technical, Aug 2022)]*



Consider the polysilicon sector as an example. Currently, more than 90% of the global production capacity for polysilicon is in China. There is already intense price competition in the polysilicon market, and research reports indicate that significant overcapacity is expected over the next decade. As a result, it is projected that prices will remain stagnant and hover around the marginal production cost. While polysilicon production is a critical component, there is no room in the market for new entrants to establish themselves and expand.

The acceleration of Solid H_2 logistics can play a significant role in expanding in-country demand within a short time period, creating space and sustained demand for India to develop the strategic sector onshore. This will prevent India from relying on imports for such a critical part of the renewable supply chain, particularly in the polysilicon space where over 90% of global production capacity is in China. The success of this ecosystem depends on existing technologies and processes that have been proven scalable, without relying on unproven future technologies.

India has the necessary conditions to make this ecosystem work and would be extremely symbiotic towards other strategic clusters, such as Associated Renewables, desalination, agrivoltaics, and green steel/aluminium. Additionally, Solid H_2 logistics will enable India to have a parallel clean energy logistics ecosystem that can seamlessly complement the Green Electron Network of the future. Being the first mover in this ecosystem will bring immense benefits, and it is the best time for India to take decisive steps towards making it happen.

4.4.4 Global Climate Collaboration

To rekindle climate collaboration between nations, Solid H_2 logistics can be a practical sub-ecosystem. As the world transitions to a multipolar state, geopolitical tensions have complicated such collaboration and increased the risks and challenges of costly, long-term infrastructure projects. These difficulties are even greater for developing countries and cross-border projects.

All nations understand the crucial significance of climate collaboration in successfully addressing the Climate Crisis, but reaching agreements on the terms has proven to be highly challenging. Despite 27 years of COP (Conference of Parties), little tangible progress has been achieved.

We believe that Solid H_2 logistics presents a promising opportunity to initiate substantial climate collaboration in a practical and mutually beneficial manner. A multilateral treaty could designate several resource-rich locations (prime sites) for joint Hyper Scaled Solid H_2 production, which would allow each country to receive a share of the production that could be shipped back to their own country. This arrangement could yield several benefits:

- Pooling capital resources and achieving greater economies of scale would allow for much larger-scale production. This would expedite the production of green molecules required for decarbonising challenging sectors that electricity grids and batteries are unable to sufficiently serve.
- Investment deployed at prime sites would be more productive, rollout costs per unit would be cheaper, and land costs would be lower. Host countries, typically poorer developing countries, could receive carried interests in return, resulting in a more equitable approach to decarbonisation.
- The cost of capital would be much lower because political risk would be largely mitigated by security arrangements under the multilateral treaty. This would significantly reduce final production costs in a time when global interest rates are trending upwards.
- Solid H_2 could be deployed in all countries worldwide, regardless of their pre-existing infrastructure or ability to afford and deploy clean energy infrastructure in their country. This would complement stand-alone microgrids that could be rapidly implemented in many developing countries that cannot afford massive infrastructure deployment. The process of global decarbonisation would become more inclusive and less burdensome for people living in remote areas.
- Wealthier countries could subsidise poorer ones using the extra value and efficiencies

created through collaboration, rather than funding expensive infrastructure in countries where economic and socio-political factors for infrastructure development are far from satisfactory. This assistance would directly impact decarbonisation efforts in recipient countries.

The significance of Solid H_2 logistics lies in its ability to promote immediate collaboration among nations without the need to resolve the complex issue of funding large-scale infrastructure networks in economically or politically challenging regions. With time running out and limited resources available, infrastructure development must be deployed strategically in the most productive and practical areas. The advancement of Solid H_2 logistics through global collaboration offers a practical alternative to address gaps quickly and generate tangible benefits that can be shared among nations.

Solid H_2 logistics offers a platform for nations to engage in meaningful collaboration within a limited scope that does not negatively impact geopolitical differences. India, as a large and emerging economic power, has the capacity and resources to optimise and refine the technology involved in this ecosystem. Moreover, India's politically neutral stance positions it well to lead the world in fostering collaboration within this ecosystem.

4.4.5 Conclusion

There are several thought-provoking observations that I would like to make in this final segment which underlines the exciting potential that Solid H_2 logistics holds, being the missing piece in the ecosystem.

Closing the Production Gap

Many scientists, as cited in the UNEP Report The Production Gap, published in 2021, have expressed the view that a significant amount of hydrocarbon reserves must remain unused to mitigate the most severe effects of the climate crisis. However, it remains uncertain which countries will make the necessary sacrifices, or if force will be required to achieve the desired outcomes. One solution could be to accelerate the development of Solid H_2 logistics and unlock the full potential of renewable energy globally. This would enable the production of Solid H_2 at a price point that could outcompete fossil fuels and allow market forces to take over.

Amplifying the Power of Feedback Loops

The Carbon Tracker Initiative released a report titled Spiraling Disruption in August 2021, which highlighted the virtuous-vicious spirals that are anticipated in both fossil fuels and renewables due to self-enforcing feedback loops, which are the driving force behind technological revolutions.

When oil production reaches its peak and begins to decline, it will experience a series of negative feedback loops that will accelerate its decline. This is because as production volumes decrease, costs per unit will increase sharply. Conversely, renewable energy sources will experience positive feedback loops that will bring prices down sooner than expected, especially if we pursue renewable energy on a large scale on an accelerated basis.

Solid H_2 logistics will amplify the positive feedback loops in renewable energy by enabling it to rapidly scale infrastructure and bypass real-world obstacles that would otherwise slow down the process. If we can foster global collaboration on a limited and less controversial level to achieve joint production of green molecules, it will further amplify the positive feedback loops.

Mitigating Anticipated Mineral/Resource Bottleneck(s)

The transition to renewable energy has led to a shift in focus towards minerals, as they are now considered the new oil. However, many experts argue that we haven't fully considered the amount of minerals needed for this transition and how we will be able to obtain them in the limited time we have left. There are also concerns that the process of mining and producing these minerals will have a massive carbon footprint, which could potentially do more harm than good.

A detailed study conducted by Simon Michaux in a GTK Finland Report examined the quantity of metals required and found that there is a significant gap between our needs and our ability to produce them. Michaux considered several factors, including the quantity of existing reserves, the deteriorating ore quality in most mines, the long lead time from discovery to mine production, and the fact that only a small percentage of deposits actually become viable mines. He concluded that the current targets are simply not achievable, and we may need to significantly reduce our societal demand for all resources to make the transition possible.

Solid H_2 logistics can help address the issue of mineral shortage by minimising the required amount of critical minerals, construction materials, copper, and aluminium through the use of minimal logistics infrastructure for global scaling. Additionally, the production of Solid H_2 can be configured using primarily solar PV and concentrated solar coupled with stationary batteries, which reduces the need for rare or insufficient minerals required in other storage systems like liquid metal batteries, sodium-ion batteries, sand batteries, liquid air batteries, molten salt or other thermal storage systems. This flexibility in technology choice can mitigate the impact of mineral bottlenecks.

Moreover, Solid H_2 logistics can also alleviate the shortage of electrolysers and the critical minerals required for their production. The hydrolysis reaction to release H_2 gas on demand releases one additional molecule of H_2 from added water for each H_2 molecule released from $NaBH_4$, effectively doubling the capacity of each electrolyser. Additionally, configuring electrolysers within a HyperScaled production environment can result in a higher plant load factor compared to using electrolysers conventionally near user load centres where green energy is likely to be supply-constrained.

Energy Conservation – Structural Considerations

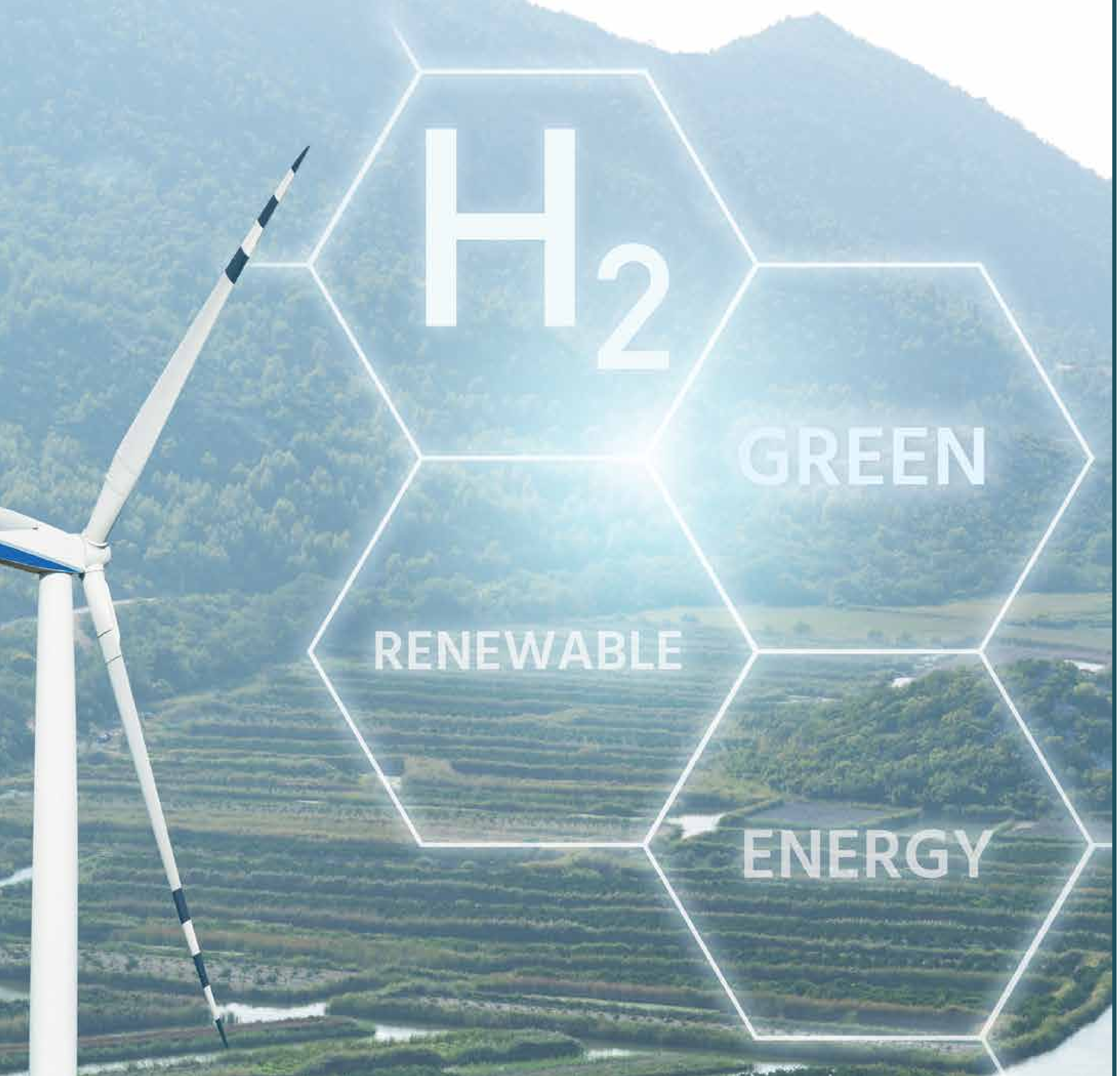
There are three main categories of decarbonisation measures: reducing consumption, electrification, and decarbonising what cannot be electrified. While reducing consumption is the most direct and effective way to decarbonise, it is also the least popular and politically difficult solution. However, recognising that the climate crisis is rooted in overconsumption and resource exploitation, we must eventually address the issue.

Solid H_2 logistics is flexible and resilient, making it well-suited for high-value applications while minimising wasteful ones. An infrastructure-intensive ecosystem requires continuous high energy consumption within a small area to be efficient and incentivises consumption regardless of its value. However, energy and food are subject to diminishing returns, and deploying infrastructure in certain areas may encourage low-value applications while neglecting underserved areas. In India, where infrastructure is lacking in many areas, developing Solid H_2 logistics can distribute clean energy efficiently and prevent distortions in pricing, enabling high-value applications while discouraging wasteful ones. Any unused energy can be stored and used at a later time at minimal cost.

Solid H_2 logistics offers a flexible logistics system that allows for the selective prioritisation of energy consumption for high-value critical applications. This system not only encourages energy conservation but also minimises the pain associated with the need for energy conservation.

Final Thoughts

In summary, the available evidence suggests that the benefits of the Solid H_2 logistics ecosystem are significant and recent developments have brought us close to a turning point. This sub-ecosystem could be the missing piece in the greater clean energy ecosystem, with the potential to solve some of the biggest climate issues we face and generate positive feedback loops for renewables. We believe that the case for Solid H_2 logistics goes beyond the Pareto principle, where a small amount of effort could produce a large number of results. Given the urgency of the climate crisis, we must make every effort to accelerate this ecosystem and explore all possible avenues.



SECTION -5

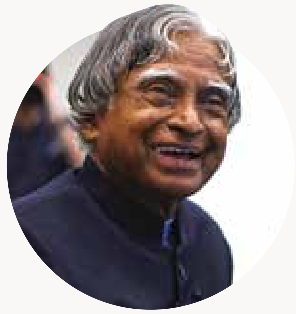
IMPORTANCE OF PROCESS SAFETY IN HYDROGEN ECONOMY

Current Global Progress in Hydrogen Codes and Standards | Global Hydrogen Safety Research – Present & Future | Safety for a Green Hydrogen Economy

5.1

Current Global Progress in Hydrogen Codes and Standards

Dr J P GUPTA, MD, Greenstat & RAJENDRA NARKHEDE, Senior Vice President, Consulting, Gexcon



All birds find shelter during a rain, but eagle avoids rain by flying above the clouds.

Dr A P J Abdul Kalam

Despite agreements made at the 26th session of the Conference of the Parties (COP26), we are still falling short of our goal to limit the rise in global temperatures to 1.5°C. To achieve this goal, the Intergovernmental Panel on Climate Change (IPCC) has stated that we need to reduce GHG emissions by 43% by 2030 compared to 2019 levels.

However, the latest report from the Paris Agreement shows that the pledges of the 193 parties involved will only reduce emissions by 0.3% by 2030 compared to 2019 levels. As a result, we are projected to experience a temperature rise of 2.4°C with 2030 targets, and even higher at 2.7°C with current policies, which would have catastrophic effects on the planet.

One potential solution to this problem is green hydrogen, a more environmentally friendly alternative to fossil fuels. Green hydrogen is produced by splitting water through electrolysis, powered entirely by renewable energy, which means it generates no polluting emissions. This makes it the cleanest and most sustainable hydrogen option. Hydrogen storage is critical for advancing hydrogen and fuel cell technologies in applications such as stationary power, portable power, and transportation. Hydrogen can be stored physically as either a gas or a liquid, but both require specific conditions to maintain its properties.

According to market studies, by 2050, hydrogen will account for 18% of total worldwide energy consumption, potentially reducing the amount of CO_2 released into the atmosphere by 6 gigatons per year and creating 30 million jobs within a $2.5 trillion industry. Given the central role that hydrogen can play in decarbonising our societies, there is an urgent need to produce, store, and distribute hydrogen in large quantities and in new locations.

The transport sector has been identified as an early adopter of hydrogen technology, and the development of refuelling infrastructure is crucial to unlocking its potential.

5.1.1 Typical Station Activities and Equipment

Although all hydrogen refuelling stations use similar equipment, they may have different designs depending on the specific processes involved in producing, delivering, storing, and dispensing hydrogen. Below is a summary of refuelling stations for both gaseous and liquid hydrogen.

Gaseous Hydrogen Refuelling Station

Gaseous hydrogen refuelling stations are currently operational and being constructed for various types of vehicles, including light-duty and heavy-duty vehicles, as well as material handling equipment. These stations provide hydrogen in the form of compressed gas, at different pressures depending on the type of vehicle being serviced. Light-duty vehicles typically require hydrogen at a pressure of 70 MPag, while other vehicles require hydrogen at a pressure of 35 MPag.

Liquid hydrogen refuelling station

In refuelling stations that use liquid hydrogen storage, a tanker truck delivers the hydrogen and pumps it into an above-ground tank, where it is kept at a very low, cryogenic temperature. The liquid hydrogen is then converted into gas, compressed, and stored in above-ground cylinders that can be used for dispensing. As customers refuel their vehicles, the cylinders are filled with gaseous hydrogen. However, the storage of liquid hydrogen typically requires more space compared to storing hydrogen in its gaseous form.

5.1.2 Relevant Standards and Codes

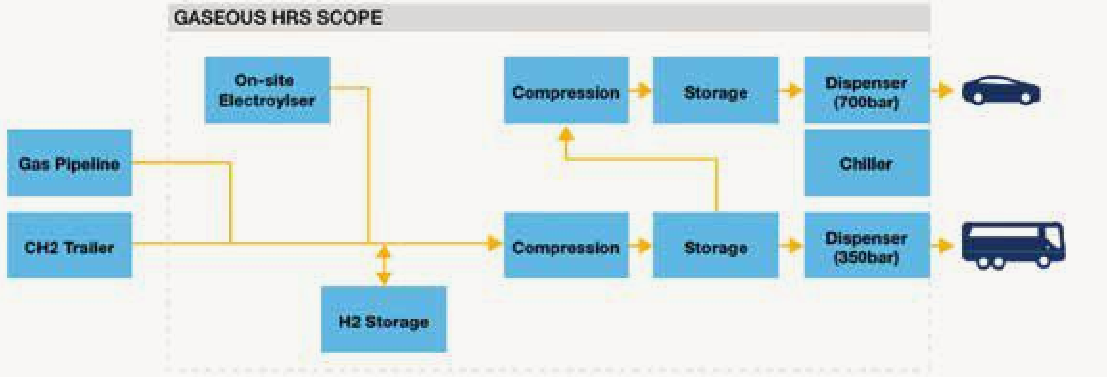


Fig. 1: A typical gaseous hydrogen refuelling station and key hydrogen systems.

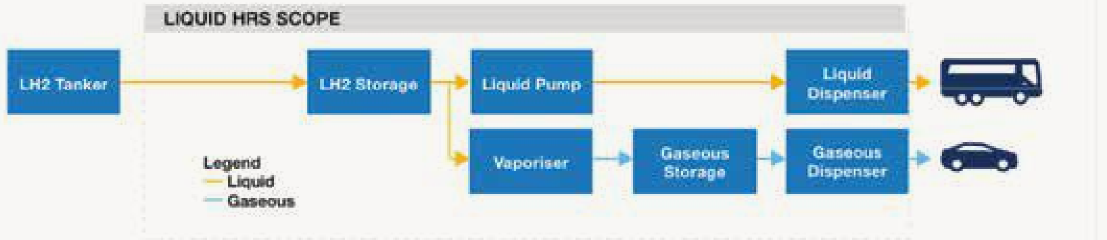


Fig. 2: A typical liquid hydrogen refuelling station and key hydrogen systems.

AS 22734:2020
Hydrogen generators using water electrolysis – Industrial, commercial, and residential applications (ISO 22734:2019, MOD)
The Australian Standard has incorporated ISO 22734:2019 but with changes that are relevant to Australia. The standard outlines the necessary specifications for the construction, safety, and performance of hydrogen generators that use electrochemical reactions to produce hydrogen by electrolysing water. These generators are commonly factory-matched or modular appliances.

AS 16110.1:2020
Hydrogen generators using fuel processing technologies, Part 1: Safety (ISO 16110-1:2007, MOD)
The Australian Standard has modified ISO 16110-1:2007 to suit local requirements. The standard outlines the necessary specifications for hydrogen generators, which are self-contained or factory-matched systems that can produce a hydrogen-rich stream suitable for various devices, such as fuel cell power systems or hydrogen compression and delivery systems. These generators have a capacity of less than 400 m^3/h at 0°C and 101,325 kPa and convert input fuel into hydrogen.

AS ISO 16110.2:2020
Hydrogen generators using fuel processing technologies, Part 2: Test methods for performance
This document has adopted ISO 16110-2:2010, which outlines the procedures for testing the performance of hydrogen generators with a capacity of less than 400 m^3/h at 0°C and 101,325 kPa. These generators are self-contained or factory-matched systems that produce a hydrogen-rich stream suitable for various devices such as fuel cell power systems or hydrogen compression and delivery systems. They convert fuel into hydrogen, and ISO 16110-2:2010 specifies the test procedures for measuring their performance.

AS TS 19883:2020
Safety of pressure swing adsorption systems for hydrogen separation and purification (ISO/TS 19883:2017, MOD)
The Australian Standard has incorporated ISO/TS 19883:2017 with changes that are relevant to Australia. The standard identifies the necessary safety measures and design features that are used in the commissioning, operation, and design of pressure swing adsorption systems that separate and purify hydrogen. This standard applies to all kinds of impure hydrogen streams and includes both stationary and skid-mounted pressure swing adsorption systems that are used for hydrogen separation and purification in commercial or industrial settings. The standard also applies to small-scale PSA hydrogen systems installed within containers, where permitted by local regulations.

AS ISO 16111:2020
Transportable gas storage devices – Hydrogen absorbed in reversible metal hydride
The Australian Standard has adopted ISO 16111:2018, which outlines the necessary requirements for material, design, construction, and testing of transportable hydrogen gas storage systems known as "metal hydride assemblies" (MH assemblies). These MH assemblies use shells that do not exceed an internal volume of 150 L and have a maximum developed pressure (MDP) not exceeding 25 MPa. The standard applies to refillable storage MH assemblies where hydrogen is the only transferred media. However, it does not apply to storage MH assemblies intended for fixed fuel-storage onboard hydrogen fuelled vehicles.

AS ISO 19881:2020
Gaseous hydrogen – Land vehicle fuel containers
The Australian Standard has adopted ISO 19881:2018, which outlines the necessary requirements for material, design, manufacture, marking, and testing of refillable containers designed for the storage of compressed hydrogen gas for land vehicle operation. These containers are permanently attached to the vehicle, have a capacity of up to 1,000 L water capacity, and a nominal working pressure that does not exceed 70 MPa. The standard is applicable to fuel containers that contain fuel cell grade hydrogen for fuel cell land vehicles and Grade A or better hydrogen in accordance with ISO 14687 for internal combustion engine land vehicles. The standard also includes requirements for hydrogen fuel containers that are suitable for use on-board light-duty vehicles, heavy-duty vehicles, and industrial powered trucks like forklifts and other material handling vehicles.

AS 19880.3:2020
Gaseous hydrogen – Fuelling stations, Part 3: Valves (ISO 19880-3:2018, MOD)
The Australian document has adopted ISO 19880-3:2018, with some changes, which outlines the requirements and test methods for the safe performance of high-pressure gas valves used in gaseous hydrogen stations up to the H70 designation. The standard covers several types of gas valves, including check valves, excess flow valves, flow control valves, hose breakaway devices, manual valves, pressure safety valves, and shut-off valves.

AS 26142:2020
Hydrogen detection apparatus – Stationary applications (ISO 26142:2010 (ED 1.0) MOD)
The Australian Standard has adopted ISO 26142:2010 with some changes, which outlines the performance requirements and test methods for hydrogen detection devices designed to measure and monitor hydrogen concentrations in stationary applications.

AS ISO 14687:2020
Hydrogen fuel quality – Product specification
This document has adopted ISO 14687:2019, which outlines the essential quality characteristics of hydrogen fuel when distributed for use in stationary and vehicular applications.

AS TR 15916:2021
Basic considerations for the safety of hydrogen systems (ISO TR 15916:2015, MOD)
The Australian Standard has adopted ISO/TR 15916:2015 with some modifications, which presents guidelines for the safe use of hydrogen in its gaseous and liquid states, as well as its storage in different forms, such as hydrides. The document outlines the essential safety concerns, hazards, and risks related to hydrogen use and describes the relevant properties of hydrogen. Further, separate and applicable standards cover detailed safety requirements associated with hydrogen and its particular applications.

5.1.3 International Standards and Codes

ISO, IEC, and ITU develop standards that can be adopted by countries for national use. Standards Australia supports and welcomes the development and implementation of international standards. Various international standards exist for hydrogen refuelling stations, but not all of them have been adopted in Australia. It is important to exercise caution while applying them to ensure that they meet the desired safety requirements. Some examples of other significant international standards that are relevant to hydrogen refuelling stations are also available.

ISO 19880 series
The International Standards Organisation (ISO) Technical Committee (TC) 197 is responsible for creating the ISO 19880 series, which sets out the basic safety and performance requirements for gaseous hydrogen stations.

SAE J2601 series
The SAE J2601, along with J2799, offers recommendations on how to refuel hydrogen storage systems to reach a high state of charge (SOC) while staying within the safe operating limits of the internal tank pressure and temperature.

SAE J2799 series
SAE J2799 aims to facilitate the consistent and coordinated development and deployment of hydrogen refuelling interfaces for Fuel Cell Electric Vehicles (FCEVs).

NFPA 2
NFPA 2 establishes basic measures for ensuring safety in the production, installation, storage, transportation, and handling of hydrogen in the form of compressed gas (GH2) or cryogenic liquid (LH2).

5.2

Global Hydrogen Safety Research – Present & Future

Prof JAN ROAR BAKKE, Executive Vice President, Gexcon Norway

Man shapes himself
through decisions that
shapes his environment.

Rene Dubos

Abstract

Ensuring the safety of hydrogen and fuel cell technologies is crucial for their acceptance and success. Any major accidents or failures could result in significant loss of investment and public trust in these technologies. This chapter discusses the importance of safety planning, monitoring, and reporting in hydrogen and fuel cell projects, both current and future. While progress has been made, there is still much to be done, including scaling up projects, increasing ambition, and providing more funding to developing countries to help them transition to green economies and adapt to the effects of climate change. This chapter provides an overview of the latest trends in hydrogen safety technology around the world, as well as a focused review of recent and upcoming research.

Why Hydrogen is being Considered as the Fuel of the Future

Currently, the majority of the world's energy is derived from non-renewable fossil fuels, which are finite and unsustainable in the long run. The global population is increasing, and as natural resources are depleted, concerns over meeting future energy needs are growing. Moreover, the waste generated by fossil fuels causes environmental damage by releasing pollutants, particulates, and increasing CO_2 emissions, which contribute to global warming. Over the past two decades, the quest for clean, sustainable energy sources has gained momentum in response to concerns about sustainability and environmental impact. Solar, wind, and other renewable energy sources are being developed and utilised, but none of them are capable of delivering a reliable and affordable energy supply on their own. [1]

As a flexible and scalable energy source, hydrogen is emerging as a promising alternative to fossil fuels. In addition to being a fuel and energy carrier, hydrogen has the potential to store energy from various primary sources, making it a more versatile renewable energy option than other alternatives.

Evolving Research and Technological Development for Hydrogen Safety

As countries work to reduce GHG emissions, hydrogen fuel is receiving significant attention from researchers and innovators. One of the main challenges to the wider adoption of hydrogen as a fuel is developing effective storage and transportation solutions. This chapter discusses the current trends in hydrogen fuel innovation and identifies potential research areas that may offer commercial opportunities.

Fuel cell technology, which generates electricity through the chemical reaction of hydrogen and oxygen, was first developed in the 1970s. Because the reaction only produces water, heat, and power, using hydrogen has little impact on GHG emissions.

In 1997, as many as 192 countries signed the Kyoto Protocol, an international agreement aimed at reducing GHG emissions [4]. Since then, efforts to explore and develop hydrogen as an alternative fuel have progressed. The number of patents related to hydrogen fuel has steadily increased since 1997, according to the American Chemical Society (CAS) database, indicating the growing global interest in commercialising this technology.

Overview of International Research and Development on Hydrogen Safety

Although there are challenges both economic and technical, hydrogen is gaining momentum due to its versatility and potential as a clean, limitless, and carbon-neutral energy source. Consequently, intense research and development efforts are being conducted in many countries by both public and private sectors. The production of eco-friendly hydrogen in alternative and less expensive ways has become a top priority. Governments are also enacting hydrogen policies, and by early 2021, more than 30 countries had produced hydrogen roadmaps, with over $0.07 trillion in public funding committed to hydrogen development [5]. Major industry players are recognising hydrogen's potential, and some companies involved in the hydrogen industry have seen a rise in their share values.

Norway's Yara, a fertiliser company, and Statkraft, a Norwegian utility company, are collaborating to produce emissions-free ammonia for use as fuel in ships, as fertiliser, and for industrial applications using hydropower for a large-scale commercial ammonia plant in Porsgrunn. Repurposing an existing ammonia plant has significantly reduced the capital investment, and this project could pave the way for commercially competitive green ammonia. The plant could provide Norway's maritime industry with an early competitive advantage, besides producing an essential export product. [8], [9].

Promote Research and Development

There are some positive developments in the hydrogen industry, with several governments implementing projects to fund research and development throughout the hydrogen lifecycle. However, these initiatives are still relatively new, and compared to previous commitments made in the early 2000s, current public R&D spending on hydrogen is lower. It will require a coordinated effort to address potential bottlenecks in the value chain. The table below shows some bilateral agreements between governments that are currently active on hydrogen development, from 2019 to 2021. [10]

Selected active bilateral agreements between governments on hydrogen development, 2019-2021. [10]

Current Research and Development on Hydrogen (Generation, Storage & Safety)

In order to achieve the target of net-zero GHG emissions in the near future, renewable energy and hydrogen are the most versatile and clean

Countries	Objective
Norway - India	Development of Centre of Excellence (CoE) at IIT Delhi and UPL Institute of Sustainable Technology, Ankleshwar.
Germany- Australia	Formulate new initiatives to accelerate development of a hydrogen industry, including a hydrogen supply chain between the two countries. Focus on technology research and identification of barriers.
Germany - Canada	Form a partnership to integrate renewable energy sources, technological innovation and co-operation, with a focus on hydrogen.
Germany - Chile	Strengthen co-operation in renewable hydrogen and identify viable projects.
Germany - Morocco	Develop clean hydrogen production, research projects and investments across the entire supply chain (two projects have already been announced by the Moroccan agencies MASEN and IRESEN).
Germany-Saudi Arabia	Co-operate on the production, processing and transport of hydrogen from renewable energy sources.
Morocco - Portugal	Examine opportunities and actions needed to develop hydrogen from renewable energy sources.
Netherlands - Chile	Establish a structured dialogue on the development of import-export corridors for green hydrogen, aligning investment agendas and facilitating collaboration among private parties.
Netherlands- Portugal	Co-operate to advance the strategic value chain for producing and transporting renewables-based hydrogen, connecting the hydrogen plans of the two countries.
Japan – United Arab Emirates	Co-operate on technology development, regulatory frameworks and standards to create an international hydrogen supply chain.
Japan - Argentina	Strengthen collaboration on the use of clean fuels and promote investments to deploy large-scale hydrogen production from renewable energy sources.
Japan - Australia	Issue a joint statement highlighting the commitment already in place between the two countries and recognising the importance of co-operation on an international hydrogen supply chain.
Singapore-New Zealand	Boost collaboration on establishing supply chains for low-carbon hydrogen and its derivatives, and strengthen joint R&D, networks and partnerships.
Singapore - Chile	Foster co-operation on projects and initiatives to advance hydrogen deployment through information exchange and the establishment of supply chains and partnerships.
Australia - Korea	Develop joint hydrogen co-operation projects with specific action plans.

fuel options for power, transportation, and storage applications. Research in these areas is a top priority to ensure safe adoption. However, the lack of technical data to define adequate safety margins poses a significant barrier to the widespread use of hydrogen infrastructure. It is essential to assess and minimise the risks to personnel and bystanders to convince regulatory authorities, regional fire marshals, fuel suppliers, and the general public that hydrogen refuelling is safe for consumer use.

The development of secure, affordable, high-performance, high-pressure hydrogen systems for consumer environments requires confidence in the safety performance of high-pressure hydrogen systems, including material performance in hydrogen service environments. Therefore, meaningful materials characterisation and qualification methodologies need to be developed, along with an understanding of material performance, through extensive R&D efforts.

The subprogramme called Safety, Codes and Standards is focused on conducting research and development that helps to understand the relevant physics, critical data, and safety information used to create and update codes and standards that are technically sound and valid. These codes and standards provide the technical foundation for the safe deployment and commercialisation of fuel cell and hydrogen technologies in various applications.

The HySEA project is being funded by the European Union's HORIZON 2020 programme, specifically the Fuel Cells and Hydrogen 2 undertaking. The consortium partners in the HySEA project include Gexcon (the coordinator), the University of Warwick, Universita di Pisa, Impetus, Fike Europe, and Hefei University of Technology (HFUT).

The HySEA project's primary goal is to carry out research on vented deflagrations in enclosures and containers that are used in hydrogen energy applications. The ultimate objective is to develop standardised vent sizing requirements that promote the safe and successful deployment of hydrogen energy systems. The partners involved in the project have extensive knowledge and expertise gained from both experimental and numerical investigations of hydrogen explosions. The experimental programme includes conducting full-scale vented deflagration experiments in standard ISO containers, taking into account the impact of obstacles that resemble the levels of congestion typical in industrial systems.

Additionally, the project involves creating a range of predictive models, such as empirical engineering models and advanced computational fluid dynamics (CFD) and finite element (FE) tools. HySEA has a specific set of goals, including generating high-quality experimental data, characterising different strategies for explosion venting, developing predictive models for reliable predictions of pressure loads, exploring explosion hazards and mitigation measures, and formulating recommendations for improving standards related to vented explosions.

The specific objectives of HySEA are:

- Conduct experiments in real-life enclosures and containers with congestion levels similar to those in industrial settings to produce high-quality data on vented deflagrations.
- Investigate different strategies for explosion venting, including hinged doors, natural vent openings, and commercial vent panels.
- Request blind predictions from the scientific and industrial safety community for reduced explosion pressure in selected explosion scenarios.
- Create and validate engineering models and computational fluid dynamics (CFD) tools to predict pressure loads in vented explosions.
- Develop and validate predictive tools for overpressure and impulse and generate P-I diagrams for typical structures relevant to hydrogen energy applications.
- Use validated CFD codes to assess explosion hazards and identify mitigating measures for larger enclosures like warehouses.
- Propose recommendations for enhancing relevant standards for vented explosions in Europe (EN-14994), America (NFPA 68), and other applicable regions.

We have provided a list of ongoing research studies related to green hydrogen in Annexure I, which includes research on topics such as hydrogen storage, hydrogen production, and electrolysis.

Future Research Areas

There are several research areas that the CoE on Process Safety and Hydrogen could investigate in the future. For example:

- The CoE on Process Safety and Hydrogen could explore several research questions, such as the impact of congestion on the risk of detonation in hydrogen plants, and how to design plants accordingly.
- Another area of investigation could be the conditions that trigger spontaneous ignition of high-pressure and high-temperature hydrogen releases, as in steelmaking.
- The CoE could also study the ignition potential resulting from the negative Joule-Thomson effect, which is a topic that often

generates informal inquiries.

- Additionally, the CoE could investigate the effectiveness of different types of detection systems for liquid hydrogen, and how they contribute to safeguarding hydrogen plants. For instance, are hydrogen detectors placed close enough to potential release sources to enable prompt action?

Table 2: Current Ongoing Hydrogen Production/Generation Research Projects

Sr. no.	Research Title	R&D Focus Areas	Project summary description	Lead Organisation
			Hydrogen Production/Generation	
1.	Renewable hydrogen production by Reverse Electrodialysis	Electrolysis, electricity, techno-economic evaluation	The purpose of this project is to evaluate the obstacles and financial advantages associated with utilising reverse electrodialysis for the purpose of harnessing the osmotic energy that is released when freshwater mixes with seawater. The energy produced can be captured in the form of a blend of renewable hydrogen and electricity. The primary benefit of the project is to gain a deeper insight into the capability of this technology to produce hydrogen at a comparable or lower cost than solar electricity production, particularly in regions where freshwater and saltwater sources converge.	University of Melbourne
2.	Solar photocatalytic hydrogen production	Photochemi-cal and photocataly-tic processes, techno-economic evaluation	The objective of this project is to create a small-scale photocatalysis hydrogen production technology that can use water and sunlight to generate hydrogen. The process, which is similar to nanoscale electrolysis, offers a cost-effective alternative to other renewable hydrogen production methods due to its simplicity.	University of Adelaide
3.	Sustainable Hydrogen Production from Used Water	Electrolysis, water use and treatment	The project aims to address the challenge of water scarcity in hydrogen production by developing an innovative approach using used water as the feed for water electrolysis. The project will investigate the effects of impurities in the wastewater on the performance and longevity of water electrolysis systems, and establish recommendations for developing durable electrolysis systems and optimising the operation and maintenance of current waste-water treatment plants. Ultimately, this project will advance the implementation of water electrolysis as a practical and sustainable approach to large-scale hydrogen production.	The University of Queensland
4.	Waste Biomass to Renewable Hydrogen	Biomass and waste conversion, electrolysis, computa-tional modelling	The project intends to create a useful method of transforming waste organic matter into hydrogen or hydrogen-carriers that can be utilised or sold. This will be achieved by developing a biomass reforming system that can extract hydrogen or hydrogen-carriers such as bio-alcohols and bio-acids from biomass. The system will consist of a biomass pre-conditioning reactor and a flow electrolyser cell that work together to generate renewable hydrogen, without any CO2 emissions.	University of New South Wales (Sydney)
5.	Enabling cost-effective and large-scale H2 and NH3 production technologies	Green Hydrogen	The goal of the project is to create affordable and efficient technologies that can facilitate the production of large quantities of H2 and NH3. Taking a technology-neutral approach to this will allow for the necessary increase in production capacity required for both domestic and export purposes.	SINTEF Industry
6.	Developing H_2 and NH_3 techno-logy solutions for use in otherwise hard-to-abate maritime and industrial sectors	Technology development	This project aims to develop technology solutions for hydrogen (H2) and ammonia (NH3) that can be utilised to reduce carbon emissions in the maritime and industrial sectors, which are typically challenging to decarbonise.	SINTEF Ocean, SINTEF Industry, IFE
7.	Production of hydrogen from natural gas and renewable energy sources	Renewable energy	The project will concentrate on developing processes for hydrogen production from natural gas, which is among the raw materials that Norway plans to refine more in the future. Additionally, the project will examine hydrogen production from renewable energy sources and photobiological hydrogen production, which is the metabolic production of hydrogen in microorganisms using sunlight.	Faculty of Information Technology, Engineering and Economics at Østfold University College
8.	Standard-sized heavy-duty hydrogen	**Applied research chemistry, electro-chemistry**	**The aim of this project is to create an open standard for heavy-duty fuel-cell modules that will determine their size, interfaces, control, and test protocols. The goal is to promote the use of fuel cells and hydrogen in the heavy-duty mobility sector, where electrification with batteries is not feasible. The standardised modules may be combined in a system, much like AA batteries, and can be used for multiple sizes, thus increasing their versatility.**	**SINTEF**
9.	Pressurised large-scale hydrogen production by alkaline water electrolysis	Electrolysis	The project aims to develop an advanced alkaline electrolyser that operates under pressure for the purpose of producing large quantities of hydrogen. The main objective is to create state-of-the-art pressurized alkaline electrolysis technology that can be scaled up for industrial use.	NEL HYDROGEN ELECTRO-LYSER AS

Continued...

5.3

Safety for a Green Hydrogen Economy

Dr Chitra Rajagopal, Director CoE Process Safety & Risk Management for Hydrogen Economy, IITD

The law of nature is the strictest expression of necessity.

Jacob Moleschott

Abstract

Hydrogen is seen as a promising solution to address the challenges of climate change, global warming, and energy security. It offers a way to store excess renewable energy and generate heat and electricity without increasing GHG emissions. The use of hydrogen can provide a practical pathway for the replacement of fossil fuels and the transition towards a net-zero economy.

In India, hydrogen is at the forefront of the country's renewable energy roadmap to meet its commitments made in COP26. India has set ambitious targets for 2030, aiming to become a global hub for the production and export of safer green hydrogen/chemicals. Achieving these targets requires the development of an adequate ecosystem and addressing technological challenges related to all aspects of the hydrogen economy, including production, storage, transportation, and utilisation. Safety issues must also be addressed to ensure the successful adoption and deployment of hydrogen technologies.

The key players, including government organisations, industry partners, and research institutes, must understand and address safety issues across the entire value chain to achieve India's net-zero emission targets in the future hydrogen plan. This involves developing infrastructures, national strategies, policies, regulations, codes, and standards (RCS), setting up testing, inspection and certification facilities, and capacity building through education based on developed standards and regulations to ensure safe operation.

Additionally, skill development programmes at different levels for the workforce, regulators, and emergency responders, as well as public sensitisation to facilitate acceptance and adoption of best practices for industry, must be adopted. A systems approach must be implemented, and human factors in hydrogen systems design must be incorporated to create user-friendly hydrogen facilities. Evolution of risk acceptance criteria for hydrogen systems, use of the latest tools such as data analytics, and techniques such as CFD and VR for risk assessment, training, and communication, e-laboratory for accidents analysis, and setting up a hydrogen safety resource and database management must be considered.

Hydrogen: The Need for Safety

- **Unique Properties of Hydrogen**: To make hydrogen and hydrogen-based systems a practical option for users as an alternative to conventional energy systems, safety is crucial. The unique properties of hydrogen, including its high flammability, increase the risk of fire and explosion if not handled properly. Therefore, ensuring safety in the design, operation, and maintenance of these systems is essential to promote their adoption as a safe and clean energy source.
- **Focus on Safety**: In order for hydrogen and hydrogen-based solutions to be considered as viable alternatives, safety is a critical factor that needs to be taken into account during the design, operation, and maintenance of energy systems. The safety of employees, assets, and surrounding people should be ensured to guarantee smooth operation. A significant accident involving a hydrogen project could have a negative impact on the public's perception of hydrogen systems. However, there is insufficient knowledge about critical safety aspects related to the widespread deployment of hydrogen technology, which poses a bottleneck for industry, authorities, end-users, and the general public. Therefore, safety must be given top priority as the hydrogen energy industry matures and moves toward commercialisation.
- **Hydrogen- key characteristics:** The measurement procedure plays a crucial role in accurately interpreting the key characteristics of hydrogen such as flammability, ignition properties, and materials compatibility, which are not scientifically well-defined properties of the gas itself.
- **Unique Hydrogen Flammability Limits**:

% Volume of H_2 in air	Property
8	not robust enough to propagate a flame throughout an entire mixture
9	downward propagating flames have a lean limit
7.5-8	horizontal propagating flames have a lean limit
4	upward propagating flames have a lean limit

Table 1A: Flammability limits of hydrogen

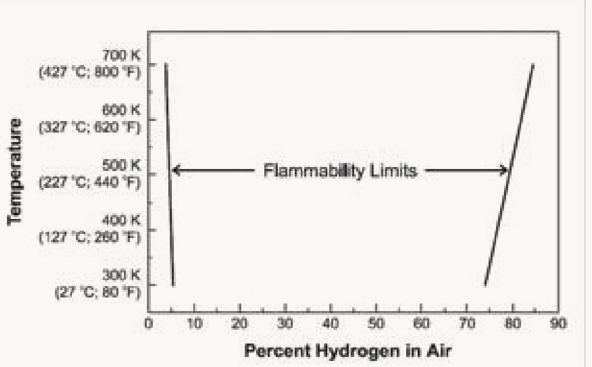


Fig. 1: Graphical representation of hydrogen flammability
https://www.researchgate.net/figure/Variation-of-hydrogen-flammability-limits-with-temperature_fig1_314305254

- **Ignition Energy**: The frequently cited value for hydrogen minimum ignition energy is 0.017 mJ, which is for air mixtures that contain between 22% and 26% hydrogen by volume. However, leaks of hydrogen are usually less than 10% by volume, at which concentration the ignition energy for both hydrogen and methane are approximately 0.052 mJ.

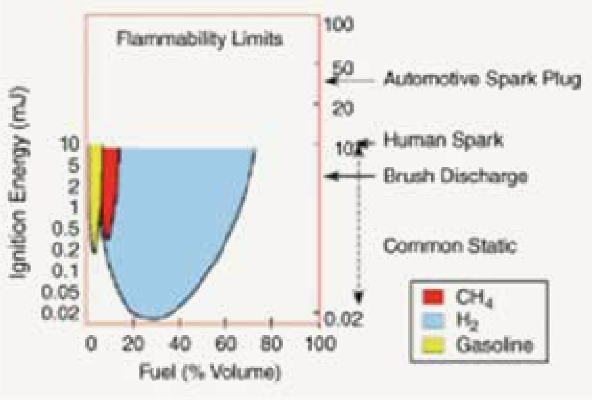


Fig. 2: Ignition energy of H2, CH4, and gasoline in air

Hazard	Fatality criteria	Need for adjustment for hydrogen scenarios
Blast pressures	-0.2-0.5 bar	Duration of blast load will be much shorter (2-20ms) than for hydrocarbon scenarios (20-250ms), duration should be considered assessing vulnerability to people and structures.
Flashfire	LFL	People trapped in hydrocarbon flashfire (-1300°C at LFL) are assumed fatally injured. At hydrogen LFL (4%) flames will only burn upwards, 8% concentration is required to burn sideways and downwards. Flame temperatures for these concentrations are low (370-700°C). The fatality limit for hydrogen flashfires should rather be 8% than 4% (LFL).
Jetfire	-12.5 kW/m²	The expected duration and size of a release should be taken into account selecting radiation threshold, most relevant hydrogen jet fires will be of limited extent and duration and higher thresholds may be acceptable.

Table 1B: Vulnerability / fatality thresholds to be considered for adjustment for hydrogen systems

Hydrogen risk contributors	
Handling related issues	Material properties related issues
Leakage and release	Embrittlement
Jet fire	Permeation
Explosion	Carbon fibres damage
Thermal radiation	Blistering
Thermal variation	Fire resistance
Vapour cloud	Low temperature - changes of material properties

Table 2: Classification of hydrogen risk contributors

5.3.1 Learnings from Past Accidents

It is important to maintain a database of previous hydrogen-related accidents and study them to reduce the likelihood of future accidents and minimise their impact. If left unaddressed, accidents can be detrimental to the entire process. A report (H2Tools) surveyed hydrogen accidents and found 230 incidents mainly in Europe and the U.S. that resulted in damage to property, injuries, and loss of life.

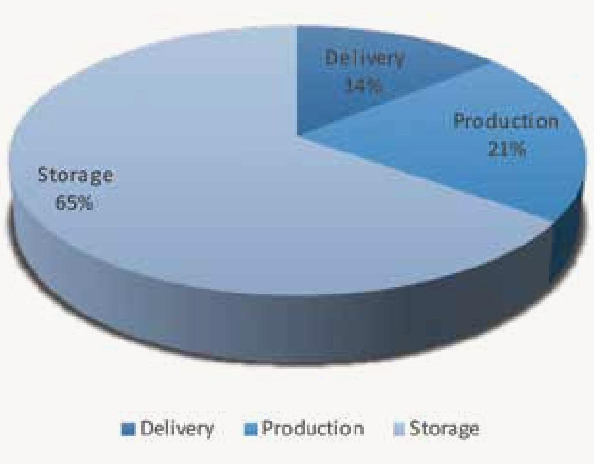


Fig. 3: Accidents in value Chain

Sector	Number of events by sector	
Chemical/ Petrochemical industry	259	62.11%
Hydrogen transport and distribution	43	10.31%
Nuclear power plant	23	5.52%
Laboratory / R&D	15	3.60%
Power generation	13	3.12%
Hydrogen production	10	2.40%
Aerospace	5	1.20%
Entertainment	3	0.72%
Hydrogen-powered vehicle	2	0.48%
Stationary fuel cell	0	0.00%
Other/Unknown	44	10.55%
Total	**417**	**100.00%**

Table 3: Sector-wise distribution of Hydrogen Accidents
https://www.clean-hydrogen.europa.eu/system/files/2021-09/Lessons%2520learnt%2520from%2520HIAD%25202.0-Final.pdf

Hydrogen Incident and Accident database (HIAD) has recorded approximately 600 accidents and incidents relevant to hydrogen, with a rate of 60% for hydrogen fire and explosion.

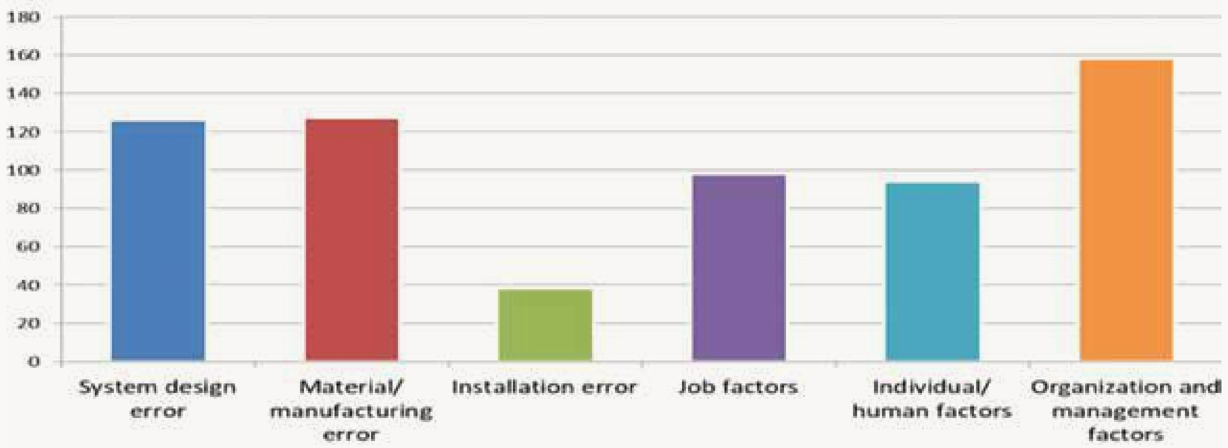


Fig. 4: Numbers related to causes of the events (multiple causes per event considered)
https://www.clean-hydrogen.europa.eu/system/files/2021-09/Lessons%2520learnt%2520from%2520HIAD%25202.0-Final.pdf

Table 4: Hydrogen Accidents - Industrial

Category	Number of Incidents	Percentage Total Accidents
Undetected Leaks	32	22
Hydrogen-Oxygen Off-gassing Explosions	25	17
Piping and Pressure Vessel Ruptures	21	14
Inadequate Inert Gas Purging	12	8
Vent and Exhaust System Incidents	10	7
Hydrogen-Chlorine Incidents	10	7
Others	35	25
Total	**145**	**100**

Source: Zalosh, R. G., and T. P. Short. Comparative Analysis of Hydrogen Fires and Explosion Incidents. C00-4442-2, Factory Mutual Research Corp., Norwood, MA (1978)

Table 5: Categories and subcategories used in lessons learnt analysis

Categories	**System design**	**System manufacturing, installation and modification**	**Operator errors**			**First responders**
			Job factors	Individual/ human factors	Organization & management factors	
Sub- categories	Design related	Material compatibility	Maintenance and inspection	Bypassing key interventions	Out of date inspection plan	Insight of H2 safety and accident scenarios
	Corrosion related	Venting system	Safety device during maintenance	Inadequate training of H2 truck drivers	Inspection of safety equipment	Delay in limit inventories
	Fatigue	Weak points	Safety practice and procedures	Monitoring pressure of the filter	Procedures for plant modification	Training
	Pressure relief valve	System installation	Lack of clear instructions	Irregular purging of the system	Safety supervision during repairing work	Emergency response inhibited by poor drainage
	Equipment factor		Chemical compounds prone to H2 generation	Verification of design and operation conditions	Procedures for fast isolation of the release sources	Lack of sufficient evidence gathering
	H2 generation due to malfunction		Insufficient check after repair	Emergency procedure not followed	Guidance about lifetime of critical components	Extinguishing fire before H2 release stopping
	Venting		Insufficient purging Before re-using	Guidance to prevent unwanted H2 generation	Explosivity control before maintenance	Efficient safety crew
	H2 accumulation			Handover between shift and day staff	Distinction between emergency and operating alarms	
	2nd order redundancy on critical systems			Ignorance about volatile pressure of hydrocarbons in tanks		
				workplace safety violation		

(https://www.clean-hydrogen.europa.eu/system/files/2021-09/Lessons%2520learnt%2520from%2520HIAD%25202.0-Final.pdf)

Recommendation:
It is recommended that India establish a comprehensive database containing records of past accidents, incidents, near misses, and component failure rates. This database would enable better identification of safety gaps and hazards in various industries, leading to more effective safety planning and management.

e- Laboratory
To introduce new technologies such as hydrogen fuels, reducing uncertainty is essential. Investigating incidents of unusual behaviour and near-misses that represent unidentified failure scenarios can help narrow down uncertainties and identify potential risks. Therefore, such investigations are critical for effective safety planning and the successful implementation of new technologies.

To enhance the flexibility and interactivity of accident prevention efforts, it is recommended that India develop an e-Lab capable of virtually calculating risks associated with various categories in complex systems. Such a tool would enable the evaluation and comparison of different risk scenarios and the identification of potential hazards and risk mitigation strategies.

Figure. 5: Example of e-lab

(https://elab.hysafer.ulster.ac.uk/)

5.3.2 Current National and International Hydrogen Frameworks

For more than a century, the chemical and petrochemical industries, as well as the industrial gas sector, have safely utilised hydrogen. There are established global frameworks for partnerships among countries, as well as national-level platforms that bring together various stakeholders.

Recommendation: It is recommended that a focused working group on hydrogen safety be established in India in alignment with existing global and national hydrogen safety frameworks. This working group should collaborate with these frameworks to ensure that India's efforts are consistent with global best practices and can benefit from shared knowledge and experiences. By doing so, India can effectively address the emergent need for hydrogen safety and contribute to a safer global hydrogen economy.

Table 6: Hydrogen Frameworks and organisation

Organisation	Location	Objectives
Hydrogen Council [27]	Global	It is a global partnership of leading companies for hydrogen to foster the clean energy transition.
Hydrogen Technology Collaboration Program (TCP) [28]	Global	It creates a global hydrogen resource to accelerate international hydrogen implementation and utilisation.
International Association for Hydrogen Energy (IAHE) [29]	Global	It manages a scientific journal, International Journal of Hydrogen Energy, and organises Hydrogen Energy Conferences.
International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) [30]	Global	It aims to enable and accelerate the transition to clean energy and mobility systems using hydrogen and fuel cell technologies across.
Hydrogen Europe [31]	Europe	It brings together various industry partners to support the delivery of hydrogen and fuel cell technologies. It is a partner in the European Joint Undertaking on Hydrogen supporting activities in fuel cell and hydrogen technologies in Europe.
Fuel Cells and Hydrogen Joint Undertaking (FCH JU) [32]	Europe	It supports research and technology advancement and demonstration activities in fuel cell and hydrogen energy technologies in Europe.
The Fuel Cell and Hydrogen Energy Association (FCHEA) [33]	USA	It represents various leading industry partners and organisations to provide a consistent voice to regulators and policymakers.
National Renewable Energy Laboratory (NREL) Hydrogen and Fuel Cell [34]	USA	It focuses on the development, integration, and demonstration of hydrogen production, delivery, storage, and fuel cell technologies for different applications.
Department of Energy Hydrogen Program [35]	USA	It manages research and development in the hydrogen sector including production, delivery, infrastructure, storage, fuel cells, and multiple end- uses across different applications. It also supports efforts on technology validation, development and integration as well as safety and standards.
Sandia National Laboratory (SNL) Hydrogen program [36]	USA	It contributes to the science of advanced hydrogen safety and fuel cell technologies.
Australian Association of Hydrogen Energy [37]	Australia	It provides a platform to share the knowledge and understanding of the production, storage, transport, safety, distribution and end-use of hydrogen energy.
Australian Hydrogen Council (AHC) [38]	Australia	It is the platform for the hydrogen industry that represents members across the entire hydrogen value chain.
Commonwealth Scientific and Industrial Research Organisation (CSIRO) - HyResrouce [39]	Australia	It aims to deliver science and technology that reduces barriers across hydrogen value chains.

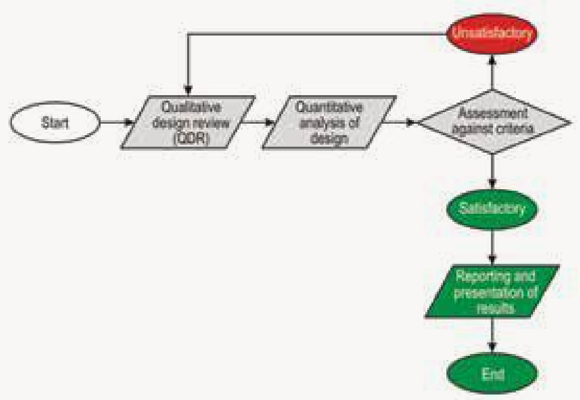


Fig. 6: Safety Algorithm
(https://hyresponder.eu/wp-content/uploads/2021/04/Lecture-1-slides.pdf)

5.3.3 Hydrogen Safety Engineering

To safeguard against accidents involving hydrogen, the principles of science and engineering are applied through Hydrogen Safety Engineering [2] (HSE). This approach utilises a design framework and technical subsystems to protect human life, property, and the environment from any harmful effects of accidents involving hydrogen.

- To ensure the success and acceptance of hydrogen and fuel cell systems, it is crucial to have a strong safety engineering design, proper education, and workforce training. This can only be achieved by the development and advancement of the hydrogen safety engineering (HSE) profession.
- The safety design for hydrogen should be viewed as an engineering responsibility, and designers should have a deeper comprehension of hydrogen safety rather than relying solely on regulatory control.

A Systems Approach to Hydrogen Safety

India's national hydrogen energy roadmap has emphasised the importance of a total systems approach to developing hydrogen technologies through public-private partnerships. Equally essential is the adoption of a systems safety approach for hydrogen that covers the entire value chain, as outlined in the MIL STD 882 standard. This approach can help identify potential safety hazards and risks associated with the production, transportation, storage, and use of hydrogen, and enable effective risk mitigation strategies to be put in place.

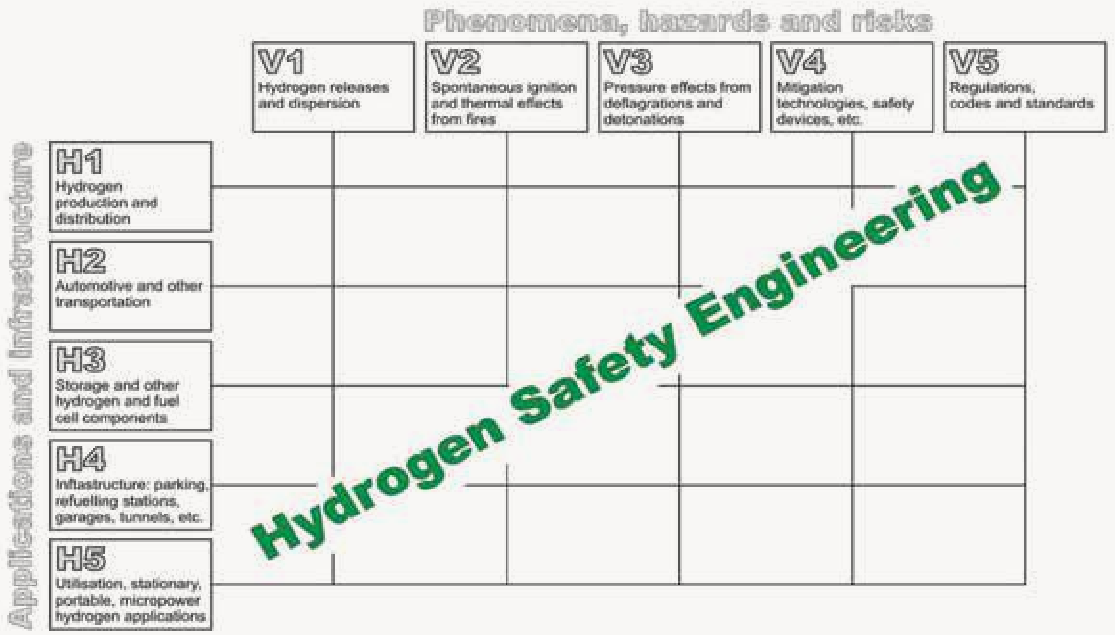


Fig. 7: Safety Application framework
(https://hyresponder.eu/wp-content/uploads/2021/04/Lecture-1-slides.pdf)

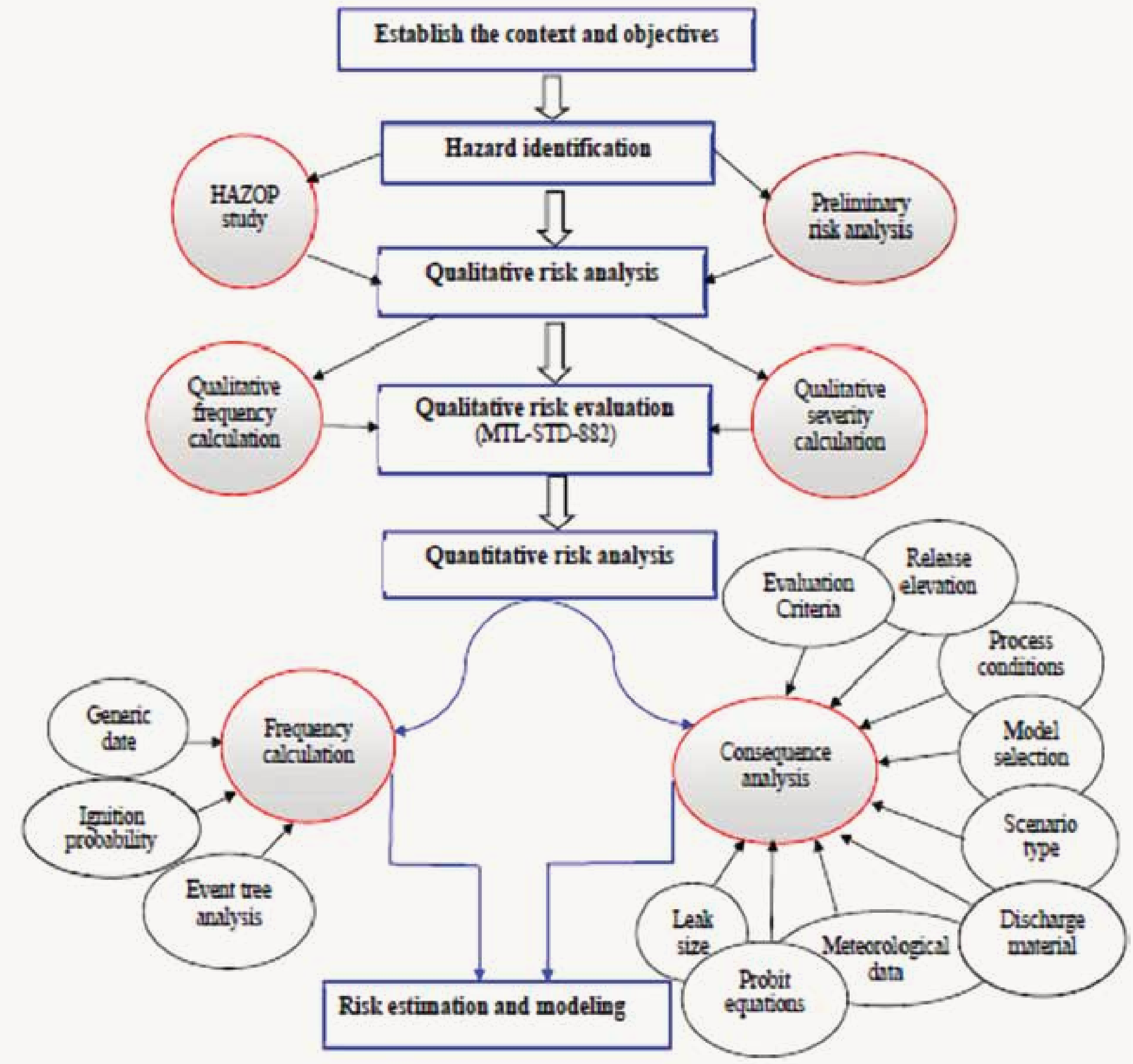


Fig. 8: QRA and consequence analysis
(https://www.sciencedirect.com/science/article/pii/S0360319915019205)

Quantitative Risk Assessment for Performance-based Permitting

The Hydrogen Technologies Code, NFPA 2, permits the use of risk-informed approaches for permitting hydrogen fuelling installations, including the use of performance-based evaluations of specific hydrogen hazards. This allows for a more flexible and targeted approach to safety evaluation and risk management, considering the unique characteristics and hazards associated with hydrogen fuelling installations. By using risk-informed approaches, stakeholders can better identify and assess risks associated with hydrogen technologies, and develop appropriate safety measures to ensure safe and sustainable deployment of hydrogen as an energy carrier.

Table 7: NFPA 2 Required Performance Criteria

Criteria type	Performance criteria requirement with NFPA 2 Ref. ^{2}	Specific performance criterial
Fire conditions	No occupant who is not intimate with ignition shall be exposed to instantaneous or cumulative untenable conditions [2:5.2.2.1].	Untenable conditions resulting from fire are calculated based on the Tsao and Perry thermal dose probit model which combines both a heat flux intensity and an exposure time [5].
Explosion conditions	The facility design shall provide an acceptable level of safety for occupants and for individuals immediately adjacent to the property from the effects of unintentional detonation or deflagration [2:5.2.2.2].	The hydrogen system is not located within a building structure that is occupied. The acceptable overpressure exposure is characterized by the Eisenberg probit model for lung hemorrhage [5].
Hazardous materials exposure	The facility design shall provide an acceptable level of safety for occupants and for individuals immediately adjacent to the property from the effects of an unauthorized release of hazardous materials or the unintentional reaction of hazardous materials to cryogenic hydrogen or pre-cooled hydrogen at the dispenser is established for this analysis [2:5.2.2.3].	The acceptable level of safety for a hydrogen release is considered to be the displacement of oxygen levels (hypoxia) no lower than 12% for more than 6 min [6]. Also, a localized temperature criteria of no lower than -46 °C (-50 °F) for exposure [7]. This criterion is based on frostbite temperatures for <5 min exposure time.
Property protection	The facility design shall limit the effects of all required design scenarios from causing an unacceptable level of property damage [2:5.2.2.4].	The stakeholder for this project should agree on a property protection value for an acceptable value.
Vent and Exhaust System Incidents	Means shall be provided to evacuate, relocate, or defend in place occupants not intimate with ignition for sufficient time so that they are not exposed to instantaneous or cumulative untenable conditions from smoke, heat, or flames [2:5.2.2.6].	There are no additional performance criteria for untenable conditions above those already defined for fire, explosions, and hydrogen exposure since smoke exposure is not a relevant hazard due to the facility being outdoors.
Emergency responder protection	Buildings shall be designed and constructed to reasonably prevent structural failure under fire conditions for sufficient time to enable fire fighters and emergency responders to conduct search and rescue operations [2:5.2.2.7].	The hydrogen system is not located within a building structure that is occupied. The acceptable overpressure exposure is characterized by the Eisenberg probit model for structure failure to determine if explosion affects the occupied retail store building [5].
Structural failure	Buildings shall be designed and constructed to reasonably prevent structural failure under fire conditions for sufficient time to protect the occupants [2:5.2.2.8].	The hydrogen system is not located within a building structure that is occupied. The acceptable overpressure exposure is characterized by the Eisenberg probit model for structure failure to determine if explosion affects the occupied retail store building [5].

Performance-based designs as a code-compliant alternative to meeting prescriptive requirements

To meet the safety requirements of unique applications that cannot comply with prescriptive code requirements, the emerging field of performance-based design is being utilised. Compliance is demonstrated by comparing a compliant prescriptive-based design with a performance-based design using Quantitative Risk Assessment (QRA) methods and hydrogen risk tools. The use of this template helps to streamline the expansion of performance-based design for hydrogen refuelling applications.

A methodology for implementing performance-based design of hydrogen facilities is required in India, particularly for situations where compliance with prescriptive separation distances, such as in refuelling stations, cannot be met.

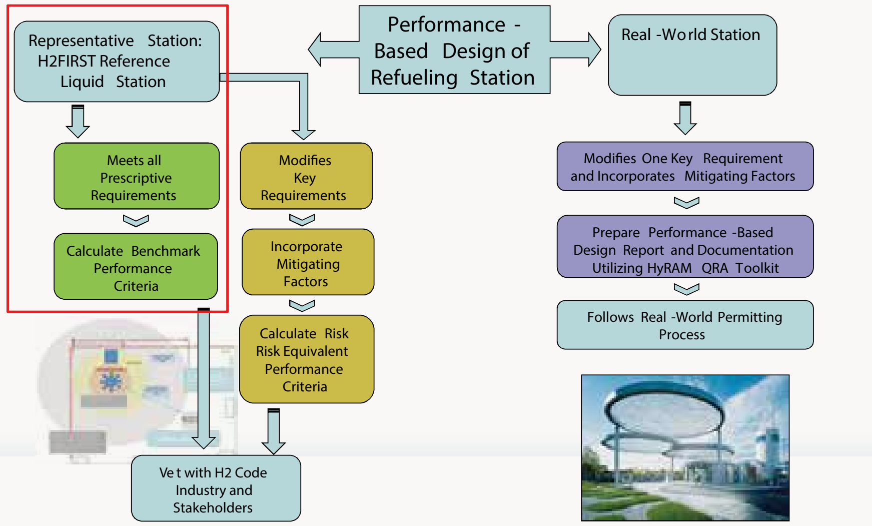
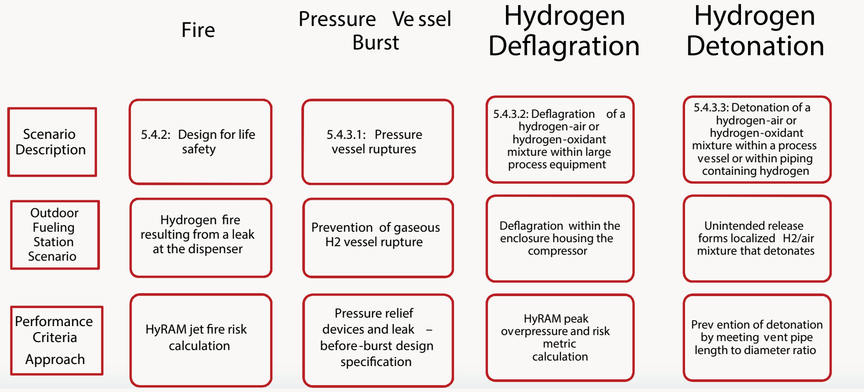
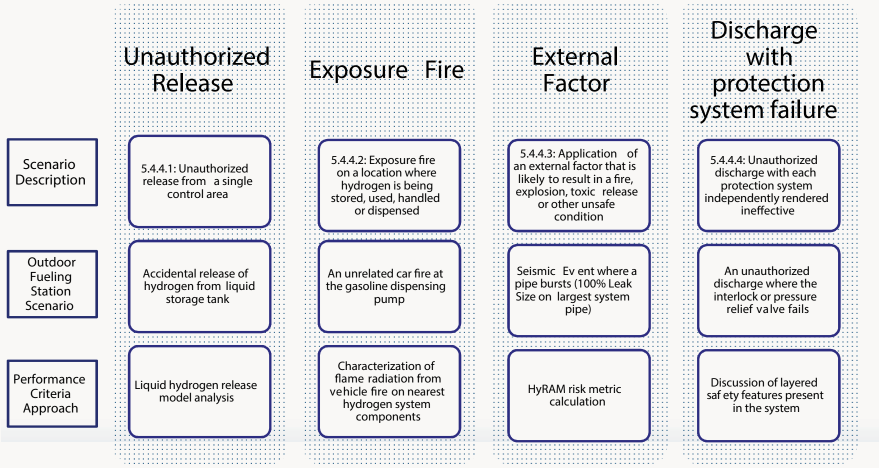


Fig. 9: Application of QRA to Benchmark PBD criteria
(https://www.osti.gov/servlets/purl/1334069)



	Fire	Pressure Vessel Burst	Hydrogen Deflagration	Hydrogen Detonation
Scenario Description	5.4.2: Design for life safety	5.4.3.1: Pressure vessel ruptures	5.4.3.2: Deflagration of a hydrogen-air or hydrogen-oxidant mixture within large process equipment	5.4.3.3: Detonation of a hydrogen-air or hydrogen-oxidant mixture within a process vessel or within piping containing hydrogen
Outdoor Fueling Station Scenario	Hydrogen fire resulting from a leak at the dispenser	Prevention of gaseous H2 vessel rupture	Deflagration within the enclosure housing the compressor	Unintended release forms localized H2/air mixture that detonates
Performance Criteria Approach	HyRAM jet fire risk calculation	Pressure relief devices and leak – before-burst design specification	HyRAM peak overpressure and risk metric calculation	Prevention of detonation by meeting vent pipe length to diameter ratio

Fig. 10: NFPA 2 Performance-Based Design: Fire & Explosion Scenarios
(https://www.osti.gov/servlets/purl/1334069)



	Unauthorized Release	Exposure Fire	External Factor	Discharge with protection system failure
Scenario Description	5.4.4.1: Unauthorized release from a single control area	5.4.4.2: Exposure fire on a location where hydrogen is being stored, used, handled or dispensed	5.4.4.3: Application of an external factor that is likely to result in a fire, explosion, toxic release or other unsafe condition	5.4.4.4: Unauthorized discharge with each protection system independently rendered ineffective
Outdoor Fueling Station Scenario	Accidental release of hydrogen from liquid storage tank	An unrelated car fire at the gasoline dispensing pump	Seismic Event where a pipe bursts (100% Leak Size on largest system pipe)	An unauthorized discharge where the interlock or pressure relief valve fails
Performance Criteria Approach	Liquid hydrogen release model analysis	Characterization of flame radiation from vehicle fire on nearest hydrogen system components	HyRAM risk metric calculation	Discussion of layered safety features present in the system

Fig. 11: NFPA 2 Performance-Based Design: Hazardous Materials Scenarios
https://www.osti.gov/servlets/purl/1334069

3D Risk Management for Hydrogen Installations

In order to manage the risks associated with hydrogen facilities, an integrated solution is required that includes a site-specific 3D geometry model, a computational fluid dynamics (CFD) tool, and a methodology for frequency analysis and quantitative risk assessment (QRA). Additionally, state-of-the-art visualisation techniques can be used to communicate risk and support decision-making. The focus is on potential dispersion, fire, and explosion scenarios resulting from loss of containment of gaseous hydrogen.

The 3D risk management approach combines consequence assessments and event frequencies to create 3D risk contours for explosion pressure and radiation loads. The use of a virtual 3D model provides a user-friendly interface for a safety-related information database, including relevant case histories, to facilitate organisational learning from previous accidents. It also allows for simulation of realistic accident scenarios that take into account detection and mitigation systems and the escalation of accidents. India should adopt 3D risk management for all upcoming hydrogen projects.

5.3.4 Evolution of National Risk Acceptance Criteria for Hydrogen

It is necessary to establish national criteria for acceptable risk by considering both societal and individual risks, and to build a consensus among all stakeholders. This will enable risk levels calculated from QRA studies for hydrogen installations, plants, procedures, etc., to be compared against the desired safety level. To reduce risk to acceptable levels, both probabilistic and deterministic measures to reduce risk should be identified and implemented.

Basis for Selection of Individual Risk Guidelines:

Established safety goals and quantified criteria form the basis for acceptance of risks. These goals include ensuring that the risk to individuals from hydrogen accidents does not significantly increase their overall risk of unintentional injuries outside their control. Additionally, the risk of hydrogen refuelling stations should be comparable or lower than that of gasoline or CNG stations. Data on fire frequency at public gasoline stations in the U.S. can provide some reference. It may also be useful to look at other countries' regulations for facilities with hazardous gases and their risk criteria.

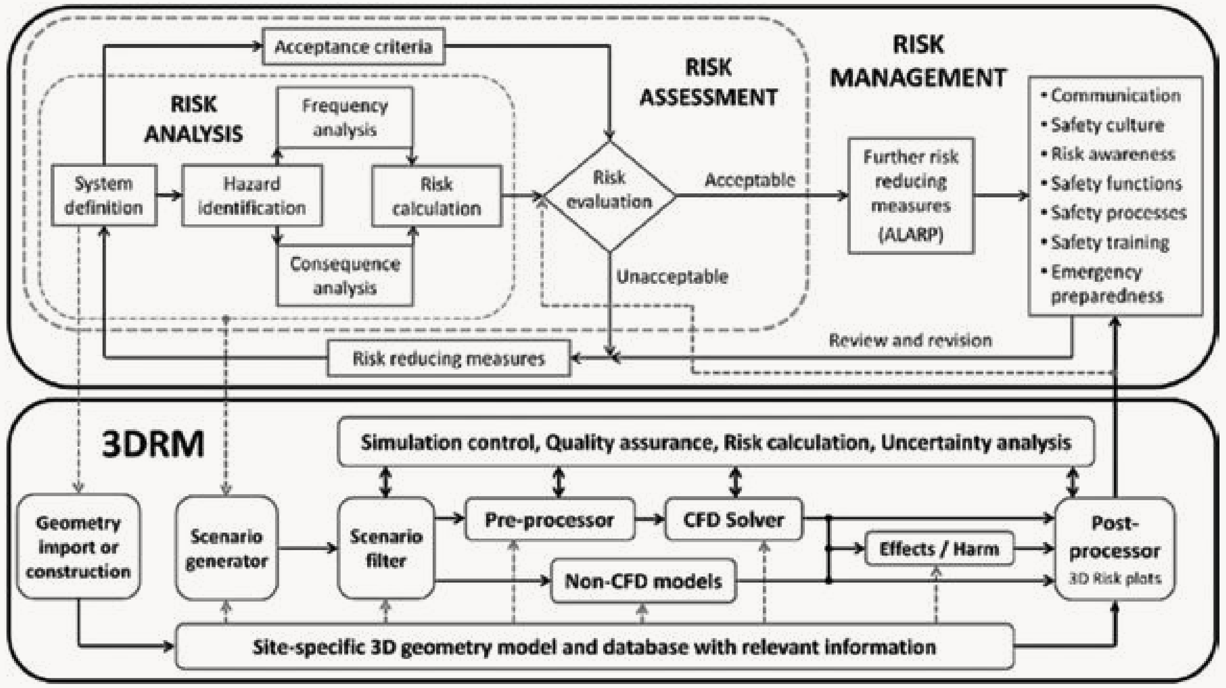


Fig. 12: 3D risk analysis and management

- To establish risk acceptance criteria for hydrogen facilities, it is necessary to have clear safety goals and measures. For example, the risk from hydrogen accidents should not significantly increase the overall risk of unintentional injuries for individuals. Moreover, the risk associated with hydrogen refuelling stations should be no greater than that of gasoline or CNG stations, which can be informed by data on fire frequency in public gasoline stations in the U.S. It may also be useful to survey countries that have established risk criteria for facilities with hazardous gases.
- The acceptance of risks for hydrogen facilities requires the establishment of safety goals and their quantification. These goals include limiting the risk to individuals from hydrogen accidents such that it does not substantially increase their existing risk of unintentional injuries over which they have no control.
- Furthermore, the risk associated with hydrogen refuelling stations should be equal to or lower than that of gasoline or CNG stations, which can be informed by data on fire frequency at public gasoline stations in the US. Other countries' regulations for hazardous gas facilities can also provide useful references for establishing risk criteria.

Benefits of a Risk-informed Approach:

- Provides a justifiable and sound technical approach to determine the required separation distances for hydrogen facilities.
- Shows that the separation distances for hydrogen facilities can be significantly impacted by factors such as the design of the facility, the operating pressure, the frequency of component leakage, and the chosen risk assessment criteria and consequence measures.

Example: Acceptable Risk for Hydrogen Refuelling Station

Risk acceptance criteria are established for all groups of individuals who may be exposed to accidents resulting from a refuelling station, and different types of criteria are employed for these groups. These groups are described below.

Table 8: Different groups for Criteria

Group	Affected People	Risk Management
Third Party	People living and working in the vicinity of the refuelling station or visiting/travelling	Both societal and individual (geographical) risk measures should be considered
Second Party	Refuelling station customers	These individuals will be exposed to the risks at the refuelling station for a limited period of time, while visiting the facilities. Therefore, the risk contribution to each individual is expected to be relatively low. However, it would be inappropriate to use this as a reason to disregard the potential risks altogether. Even low-risk scenarios should be considered and evaluated in order to identify and mitigate potential hazards, and ensure the safety of all stakeholders involved in the deployment and use of hydrogen fuelling stations.
First Party	Hydrogen refuelling station personnel	A higher risk level will be considered acceptable for this group than for Third party.

It is important to enhance safety measures and improve the ability to bounce back from incidents, but people often struggle to balance the likelihood of small risks with the potential for severe consequences. A precautionary approach that prioritises resilience, with the involvement of stakeholders in later stages, may be the best approach. Establishing a culture of trust and transparency while emphasising the need for action and demonstrating a willingness to compromise could be the way forward. Comparing risks with existing ones can facilitate communication. Although larger storage and distribution facilities will always require individual assessment, standard procedures can be used for smaller facilities once a few successful projects have been completed to simplify and reduce costs.

5.3.5 Human Factor Design for User-friendly Hydrogen Installations

The majority of accidents in process industries are caused by human factors, accounting for nearly 80% of them. As humans are an indispensable component of these industries, it is critical to prioritise their safety and consider their needs when designing new systems or improving existing ones.

Research has shown that integrating human factors into safety management systems and ergonomics design can effectively prevent accidents. Process hazard analysis, safety management systems, risk assessment, and classification systems should all incorporate human factors throughout the design, implementation, and operation phases.

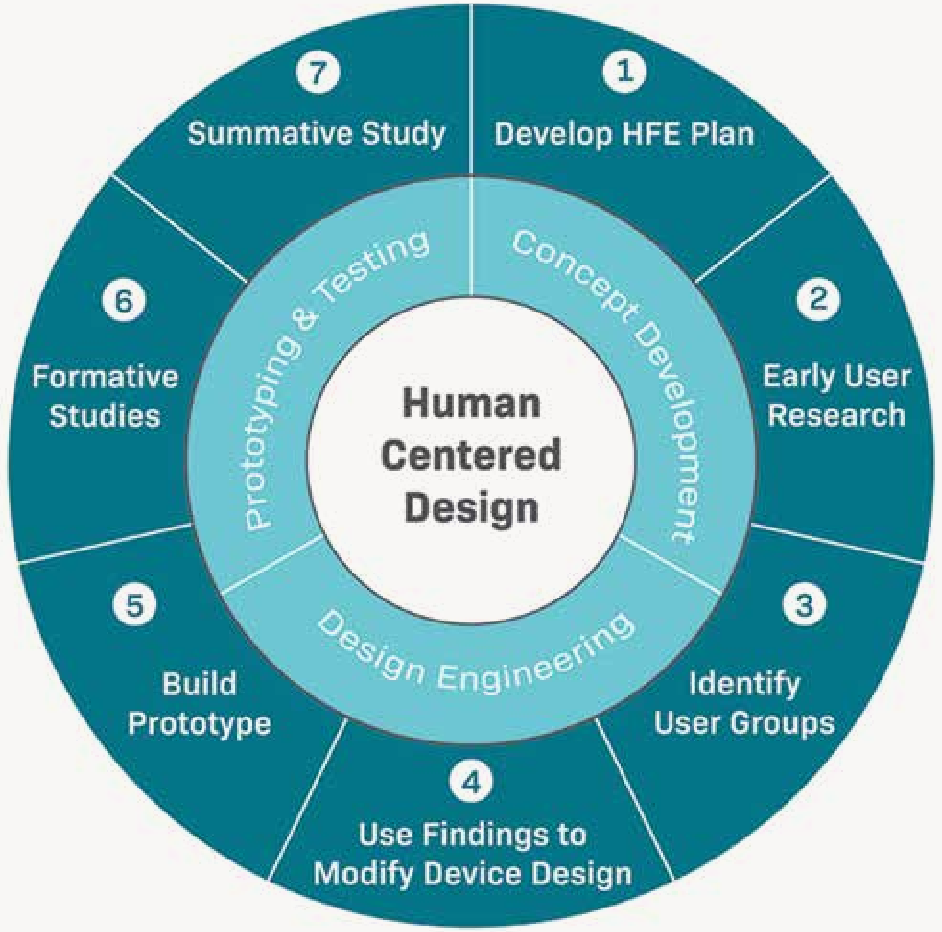


Fig. 13: Human centred design

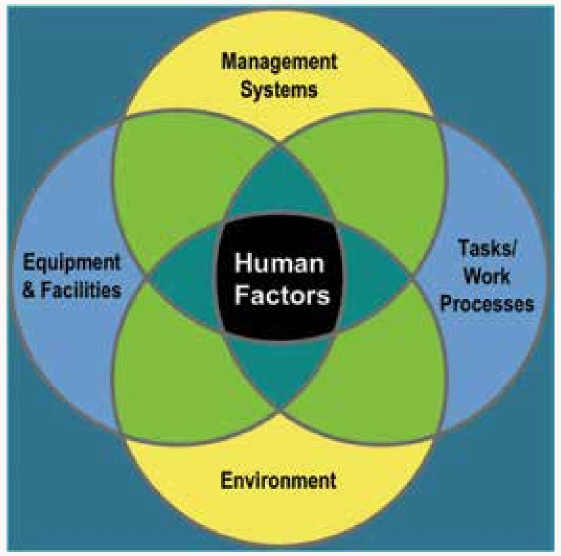


Fig. 14: Human Factor Integration
(https://www.opuskinetic.com/2018/06/how-to-successfully-integrate-human-factors-engineering/)

Necessity of Human Factor Engineering

ISO 13407, which is the standard for designing human-centred interactive systems, emphasises that incorporating human factors and ergonomics into the design process can improve efficiency, effectiveness, and safety of the system. Human factors need to be considered during both analysis and mitigation stages for existing facilities, as well as at the engineering stage for new systems. The goal is to reduce or eliminate system features that rely heavily on human sensory, physical, or cognitive input, which can cause errors and require extensive training. This can be achieved by minimising the need for substantial human input and by designing systems that are easy and safe to use. [source: https://doi.org/10.1016/j.ress.2007.01.002].
To ensure the safety of every system, it is important to identify the critical events that could be caused by humans. Facility and organisational systems should be designed to minimise human fatigue. Comprehensive documentation of the entire system and previous incidents, along with proper training, should be a top priority. Accessibility of the workplace and ergonomic design should also be considered when designing a new system. Various studies have been conducted abroad to address human errors for all aspects of the hydrogen value chain, and regulations are in place to manage these risks [COMAH 2015].

Recommendation:

As hydrogen systems are still emerging in India, it is important to consider the unique risks associated with hydrogen compared to conventional fuels. To ensure safe and effective deployment of these systems, it is recommended to design them with a focus on human factors. This includes understanding human tendencies, behaviours, and decision-making processes, and incorporating these factors into the design of hydrogen systems. By doing so, we can ensure that hydrogen systems in India are optimised for safe and user-friendly operation, and minimise the potential for accidents or incidents.

5.3.6 Reliability, Availability, Maintainability and Safety (Rams)

Improving the reliability of hydrogen infrastructure is crucial for reducing the cost of hydrogen. Presently, the cost of dispensing hydrogen is approximately four times higher than that of gasoline. Enhancing the reliability of the system involves increasing the reliability of individual components through reliability engineering programmes. This approach can lead to lower maintenance costs, increased availability of the system, faster development of components, and a decrease in the rate of failures.

Fig. 15: Reliability Engineering Venn Diagram
(https://www.vervetronics.com/services/reliability-engineering/)

5.3.7 Big Data, Data Analysis and Tools for Hydrogen Safety Analysis

The emerging hydrogen technologies should focus on Industry 4.0 and digitalisation to improve their efficiency and cost-effectiveness. By using deep data analysis, these technologies can benefit from increased efficiency and cost savings. Several studies have already demonstrated the potential of integrating hydrogen with Industry 4.0.

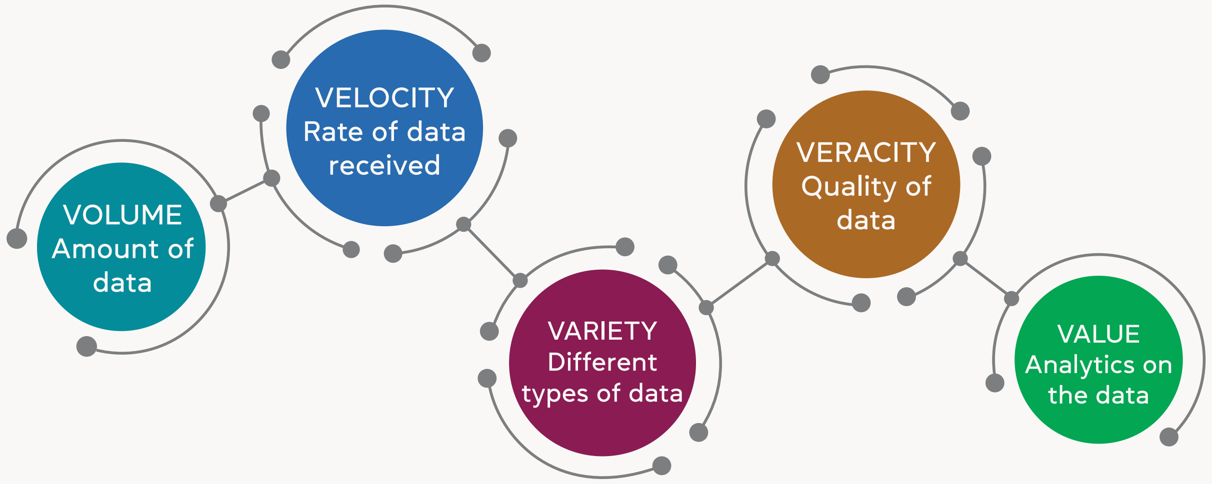


Fig. 16: The 5V's of Big Data (Quorum, 2016)
(https://doi.org/10.1111/opec.12118)

Applications of Data Analytics

The process of creating a digital replica of a physical object or system, known as digital twins, can benefit from data analytics. This emerging technology incorporates the internet of things, software simulation, and data analytics to create a replica that can significantly transform condition monitoring and maintenance operations.

Illustrative examples:

A. Jaribion et al. created a digital twin prototype for a hydrogen high pressure vessel, which helped to analyse the scalability and adaptability of a new design.

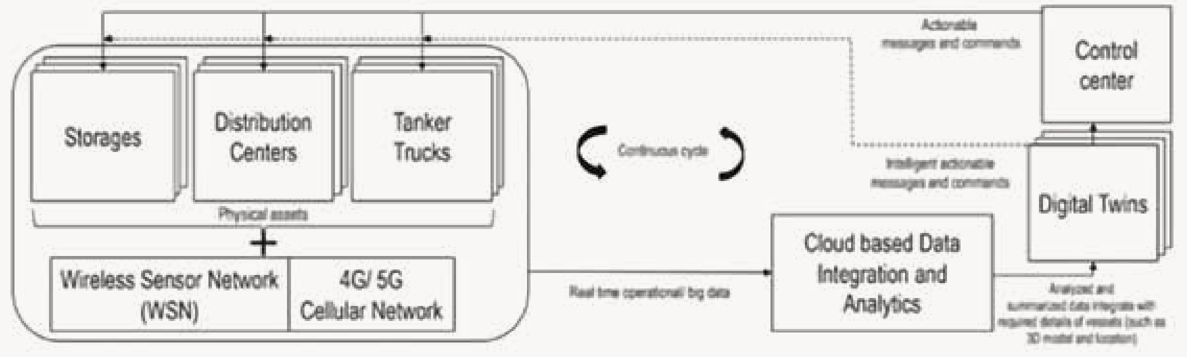


Fig. 17: Deployment of digital twins in hydrogen storage and transportation

Fig. 18: The digital twin of the hydrogen vessel in action

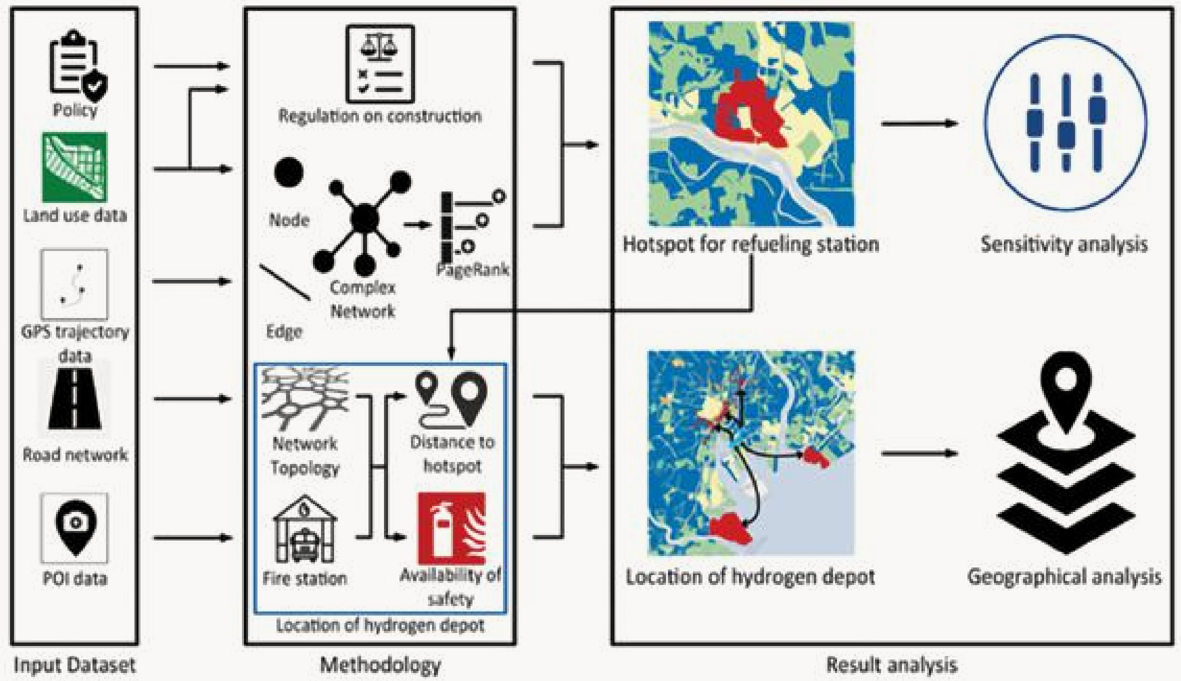


Fig. 19: Locating priority of hydrogen facilities based on multiple big data fusion.

In Japan, a multiple dataset fusion method was employed to effectively utilise data analytics and identify priority locations for constructing hydrogen facilities in Tokyo.

Data Uncertainty Analyses
The process of performing QRA involves some uncertainties that need to be considered, such as:

- Choosing a suitable model to describe leak frequencies based on leak diameters.
- Choosing appropriate leak rates for data analysis
- Grouping generic and hydrogen data into leak size categories
- Selecting the prior distributions for the Bayesian process
- Considering the typical facility configuration when determining system leak frequency.

Fuzzy Approach is Proposed to Deal with Uncertainty in Data
Illustrative Case Studies:
The aim of the study is to determine the best Hydrogen Energy Storage (HES) method for Turkey by evaluating the alternatives of tank, metal hydride, and chemical storage. Expert opinions and literature review are utilised to determine the alternatives. To address the complex decision process that may involve subjective data or vague information, a combined approach of Buckley extension based fuzzy Analytical Hierarchical Process (Fuzzy-AHP) and linear normalisation based fuzzy Grey Relational Analysis (Fuzzy-GRA) is applied. This combined Multi Criteria Decision Making (MCDM) methodology is utilised with different defuzzification methods to solve the HES selection problem.

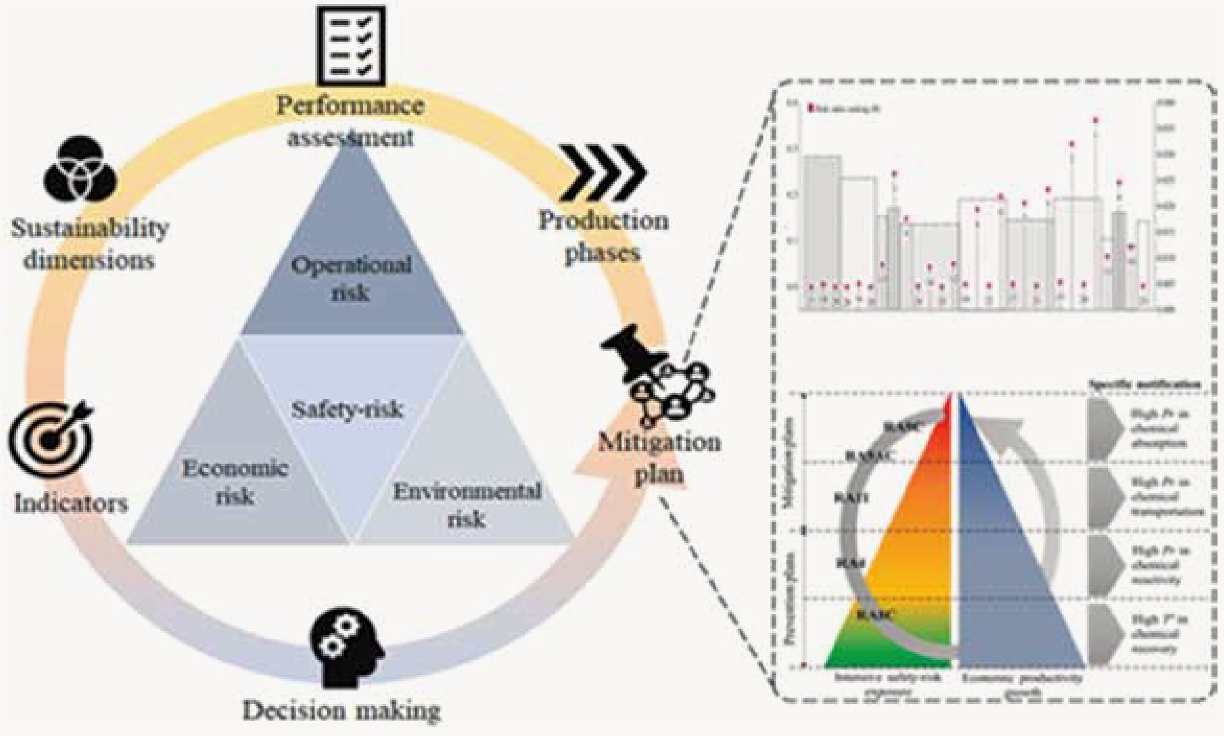


Fig. 20: Fuzzy approach to data
(https://doi.org/10.1016/j.jclepro.2022.130780)

To evaluate the risk associated with Wind-Photovoltaic-Hydrogen (WPH) storage projects, an enhanced fuzzy synthetic evaluation technique based on cloud model is employed. Firstly, a set of expert questionnaires is used to identify and classify 14 key risk factors into four groups, which include economic, technical, environmental, and safety risks. Secondly, Analytic Hierarchy Process is used to assign weights to these risk factors based on their level of importance. Lastly, an improved fuzzy synthetic evaluation approach based on cloud model is proposed to assess the overall risk level of WPH storage projects.

Bayesian Networks for Decision Support Under Uncertainty
Bayesian networks are graphical models that represent the conditional dependencies between variables and can be used to model complex systems with many interacting components. There are several examples of how Bayesian networks have been used in decision making, including risk assessment, reliability analysis, and environmental impact assessment.

Benefits of using Bayesian Networks

The advantages of using Bayesian Networks are as follows:

- Developing a reliable probability distribution for challenging problems such as HRA, aging, and software
- Dividing complex problems into measurable or elicitable components
- Enhancing transparency and traceability through additional levels of detail
- Addressing dependencies within the system
- Utilising available data to solve problems in

the absence of relevant data, as is the case with HRA.

- Leveraging the expertise of relevant professionals in a suitable manner with respect to probability elicitation
- Providing causal understanding beyond statistical analysis.

A Bayesian Networks Approach for Safety Barriers Analysis: A Case Study on Cryogenic Hydrogen Leakage

The article discusses the use of Bayesian networks to analyse safety barriers in a case study involving cryogenic hydrogen leakage from a storage tank on a fuel-cell-powered maritime vessel. The study evaluates the failure probability of safety barriers and their potential consequences. The results demonstrate the effectiveness of using Bayesian networks for quantitative risk analysis and safety assessment in critical accident scenarios, thus providing greater confidence in the safety of using hydrogen as an energy carrier for maritime applications.

Hydrogen systems pose a challenge due to the limited availability of data, and stakeholders may be hesitant to share data due to legal consequences in the event of an accident. However, data on failures in hydrocarbon installations, especially offshore data, has been collected over the years and can serve as a prior distribution in Bayesian approaches. LaChance et al. (25) utilised this data in conjunction with limited hydrogen data to create a posterior distribution that could be applied to hydrogen installations. The Bayesian method is an effective way to integrate all available data and provide valuable insights for decision-making.

5.3.8 Use of CFD for Risk and Hazard Modelling

The use of computational fluid dynamics (CFD) can enable the simulation of various problems and risks that are associated with the hydrogen value chain. CFD involves the use of advanced simulation software that runs on high-performance computers.

Benefits of Using CFD

One of the key benefits of CFD is that it allows for the consideration of mutually dependent phenomena such as geometry, thermal properties, electrochemistry, and fluid dynamics. CFD models are particularly useful for predicting large-scale accidents, which are often difficult to replicate experimentally due to infrastructure and cost constraints. Additionally, CFD makes it possible to simulate intricate geometries and real-world conditions without the high costs associated with experimental set-ups. Although CFD has some limitations, it is considered a valuable tool for hydrogen safety and risk assessment.

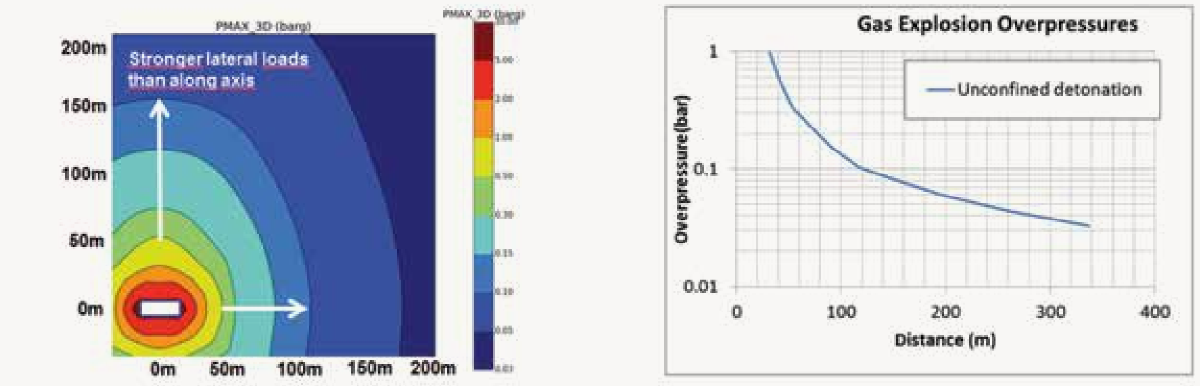
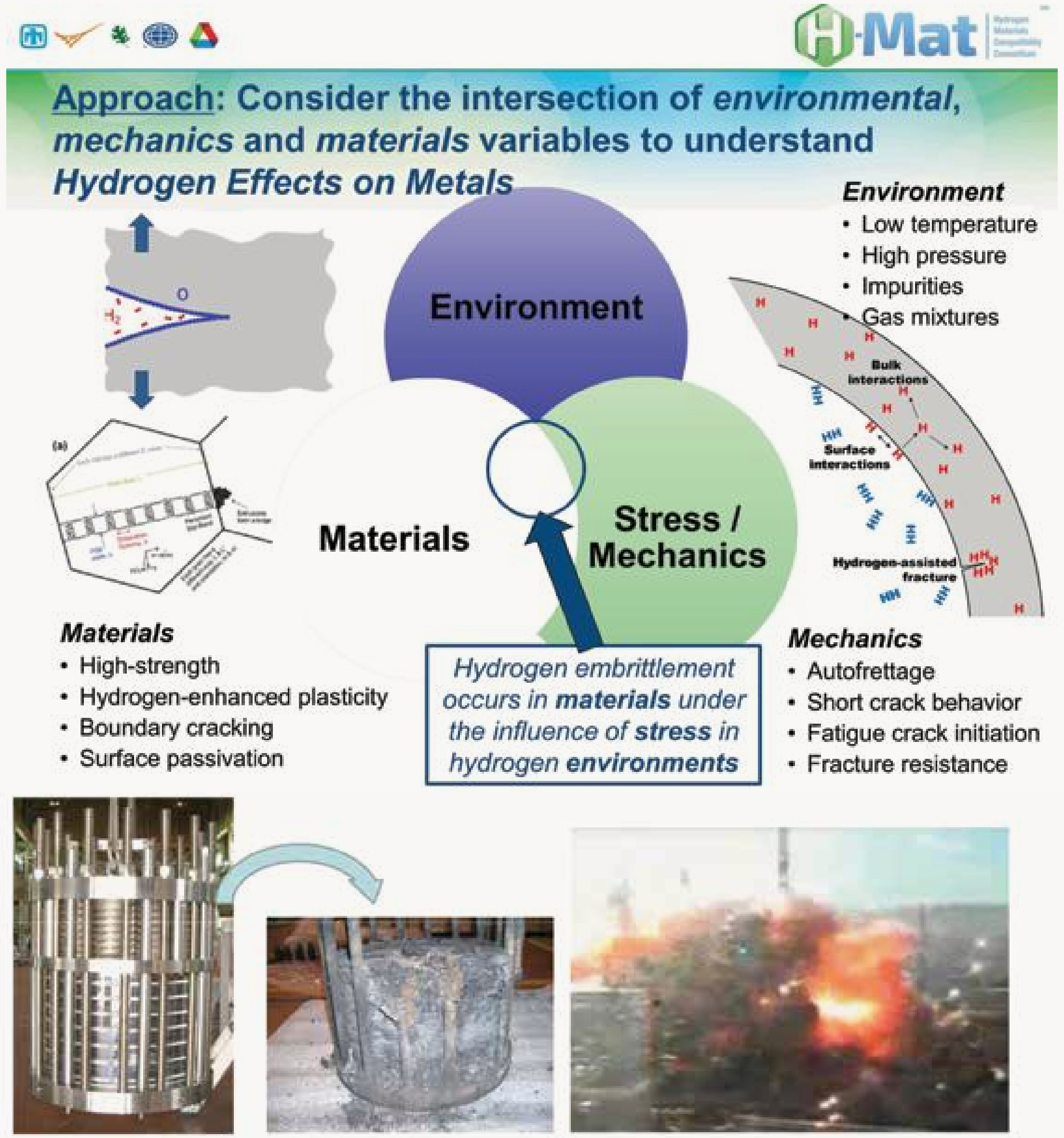


Fig. 21: TNO Multi- Energy method (LR tool-right) for getting good blast estimates quickly; CFD calculation (FLACS– left) for better precision, taking into account source, buildings, and target characteristics.

There are several software options available for numerical simulations and CFD benchmarking for hydrogen safety applications. These include commercial software packages like ANSYS Fluent, ANSYS CFX, and FLACS, as well as open-source options such as OpenFOAM and ADREA-HF.

5.3.9 Materials Compatibility for Safety in Hydrogen Service

Ensuring materials compatibility is an important aspect to ensure the safety of hydrogen systems. The failure of hydrogen equipment and associated damages can occur due to several factors such as embrittlement, blistering, and metal hydride formation, which can result in serious consequences like fire or explosion. Therefore, a thorough assessment of the materials, including both metals and non-metals, is necessary to ensure their suitability for hydrogen service in various operating and emergency conditions, including compatibility with the operating pressure and hydrogen quality/purity.


H-Mat

Approach: Consider the intersection of *environmental*, *mechanics* and *materials* variables to understand *Hydrogen Effects on Metals*

Environment
- Low temperature
- High pressure
- Impurities
- Gas mixtures

Materials
- High-strength
- Hydrogen-enhanced plasticity
- Boundary cracking
- Surface passivation

*Hydrogen embrittlement occurs in **materials** under the influence of **stress** in hydrogen **environments***

Mechanics
- Autofrettage
- Short crack behavior
- Fatigue crack initiation
- Fracture resistance

Fig. 22(a): Titanium electrolyser before and after the accident (https://hyresponder.eu/wp-content/uploads/2021/04/Lecture-1-slides.pdf)

Fig. 22(b): Fracture face of Hot dip galvanised (HDG) high strength steel anchor rods
https://link.springer.com/article/10.1007/s11668-017-0250-2

Table 9: Non-metals Suitability for Hydrogen Service
ISO/PDTR 15916:2014.

Component	Description	Exemplary material grades
Compressed hydrogen pressure vessels	Type IV	**Polymer liner:** High-density polyethylene (HDPE), Polyamide (PA); **composite vessel:** glass or carbon fiber, epoxy resin
Pipelines	High-pressure distribution (>10 MPa)	**Polymer liner:** HDPE, PA
Piping, tubing	Low-pressure distribution (<10 MPa)	HDPE, Polypropylene (PP), Poly(vinyl chloride) (PVC), Chlorinated poly(vinyl chloride) (CPVC)
Mechanical compressors	Seals and coatings	Polytetrafluoroethylene (PTFE), Polyetheretherketone (PEEK)
Dispensing hoses		Nitrile rubber, Fluoroelastomer (FKM), Polycarbonate (PC)
Flange connectors (low-pressure <10 MPa)	O-rings, gaskets	Nitrile rubber, FKM, PTFE
Threaded connectors (high-pressure >10 MPa)	O-rings	Nitrile rubber, FKM
Valves	Pistons	PEEK
	O-rings, fittings, etc.	Nitrile rubber, FKM, PTFE
	Seals and gaskets	PTFE, FKM, nitrile rubber, PEEK, PA, Ethylene propylene copolymer (EPM), fluorosilicone, silicone, Neoprene (CR)
	Valve seats	PA, PTFE, Polychlorotrifluoroethylene (PCTFE), Polyimide (PI)

5.3.10 Hydrogen Safety Resources and Database Management

The establishment of a hydrogen safety database can support the growth and longevity of the hydrogen value-chain. The use of digital platforms and data-driven tools is vital in establishing uniform safety procedures across various sectors. Proper database management is crucial in enabling the safe and widespread deployment of hydrogen infrastructure and the value-chain.

Fig. 23: Safety Resources

Table 10: Active Hydrogen Safety working Groups in the world.

Organisation	Location	Objectives
Centre for Hydrogen Safety (CHS) [71]	Global	It is a global group to promote hydrogen safety and best practices worldwide.
DOE Hydrogen Program - safety activities [72]	USA	It aims to identify the factors that must be considered to minimise the safety hazards related to hydrogen applications as a fuel.
The European Hydrogen Safety Panel (EHSP) [73]	Europe	It assists the FCH 2 JU in assuring that hydrogen safety is adequately addressed and managed.
MultHyFuel - Safety and Permitting for Hydrogen at Multifuel Retail [74]	Europe	The goal of MultHyFuel is to provide safety and permitting strategies for hydrogen at multifuel retail.
The European Committee for Standardisation Working Group on Hydrogen (CEN/CENELEC WG Hydrogen) [75]	Europe	It focuses on the analysis of new technologies and standardisation in the field of hydrogen safety.
Health, Safety, and Executive (HSE) - Hydrogen Safety [68]	UK	It aims to enable the future of hydrogen-powered applications such as domestic combined heat and power by providing safety guidelines.
Hy4Heat [76]	UK	It aims to provide safety and feasibility assessment to replace natural gas (methane) with hydrogen in residential and commercial buildings and gas appliances.

The U.S. Department of Energy maintains the H2Tools website, which provides information and resources related to hydrogen safety. One of the resources available on the website is the Hydrogen Safety Bibliographic Database, which includes references to books, journal articles, conference papers, and other documents related to hydrogen safety. This database can be useful for researchers, engineers, and others working on hydrogen-related projects who need to stay up to date on the latest research and best practices in hydrogen safety.

Hydrogen Safety Tools

The methodology for the review and analysis of hydrogen safety data collection tools involves the following steps:

- Identify the purpose and scope of the data collection tool: This involves understanding the objectives and goals of the tool, as well as its intended audience.
- Evaluate the design of the tool: This includes reviewing the format, structure, and usability of the tool. Is it easy to use? Are the questions clear and concise? Is the format user-friendly?
- Assess the quality of the data collected: This involves analysing the accuracy, completeness, and reliability of the data collected by the tool. Are the data points valid and reliable? Are there any missing or incomplete data points?
- Analyse the effectiveness of the tool: This involves evaluating the tool's ability to achieve its intended goals and objectives. Does it provide useful insights and recommendations? Is it effective in identifying potential safety hazards and risks?
- Identify areas for improvement: Based on the evaluation and analysis, identify areas where the tool can be improved to enhance its effectiveness and usability.

- Provide recommendations: Based on the findings, provide recommendations for enhancing the design and effectiveness of the tool, and for improving data collection and analysis processes.

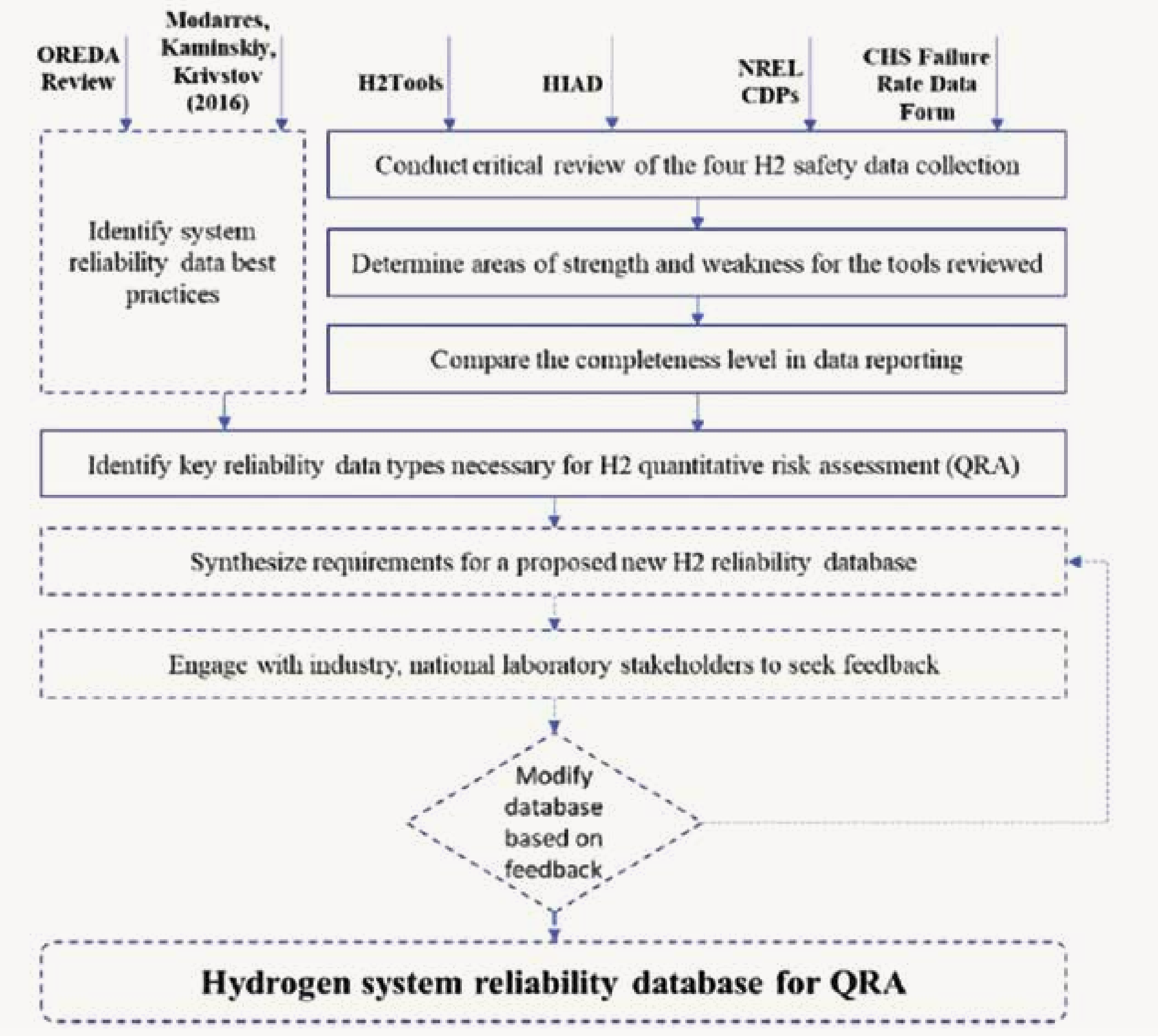


Fig. 24: Resources Algorithm

Table 11: Databases of incidents and accidents

Database	Contents	Designed/ maintained by
Hydrogen Analysis Resource Centre (HyARC)	Provides reliable data for calculations and modelling in evaluating	Datasets are maintained by H2Tool, and they can be accessed through the Energy Information Administration (EIA), DOE programmes in the U.S.
Hydrogen Risk Assess-ment Models (HyRAM) toolkit	To evaluate hydrogen safety, a combination of deterministic and probabilistic models are used to assess accident scenarios, analyse physical effects, and assess hazards to people and structures. This involves using validated models for hydrogen release and flame dynamics, as well as incorporating probabilities of equipment failures to create probabilistic models for the impact of heat-flux on humans and assets.	Designed by Sandia National Laboratory in the U.S.
Hydrogen Incident and Accident Database (HIAD)	The platform is anonymous and similar to H2Tools, and serves as a data source for risk assessment and a platform for sharing lessons learned and risk communication. The platform contains 598 incidents dating back to 1937, which have been gathered from a variety of sources such as historical databases, journal articles, media, and self-reporting. The platform features a comprehensive and well-documented data entry form. The aim of the project is to keep track of accidents and incidents related to hydrogen across various stages of its value chain including production, transport and usage. This will facilitate monitoring of different hazard issues related to hydrogen. Additionally, the project provides a communication platform to share lessons learned from accidents and incidents to improve risk assessment and risk communication. The project aims to enhance the understanding of unintended hydrogen events, identify strategies to avoid incidents and reduce the consequences of accidents.	European Commission Joint Research Commission (JRC). designed by EHSP in Europe
Hydrogen/Fuel Cell Codes & Standards dataset	The platform monitors the progress of hydrogen and fuel cell standards globally, with a specific focus on four areas: stationary fuel cells, hydrogen and fuel cell vehicles, portable and micro fuel cells, and hydrogen infrastructure.	Supported by the Fuel Cell & Hydrogen Energy Association in the U.S.
H2Tools Lessons Learned	• The anonymous accident database collects reports on hydrogen-related events. • The database is maintained by the Pacific Northwest National Laboratory. • It is used to share lessons learned from hydrogen safety incidents globally. • The information is presented in open-ended narrative fields or qualitative data.	
Centre for Hydrogen Safety (CHS) data tool	• A tool is being developed to submit data on failure rates of hydrogen equipment and components. • The objective is to improve quantitative risk assessment for hydrogen fuelling stations. • The data submission tool includes a combination of open-ended quantitative fields and predetermined lists. • This represents a step forward in collecting quantitative data for hydrogen safety.	
Compo-site Data Products (CDPs)	• NREL (National Renewable Energy Laboratory) gathers data related to the operation and maintenance of 44 hydrogen fuelling stations in the U.S., as of 2020. • Data is collected for various aspects such as site summary, fuel logs, fill performance, dispensing, compression, delivery, hydrogen cost, and hydrogen quality, along with failure and maintenance data. • The data includes information on deployment, safety, maintenance and reliability, performance, cost, utilisation, hydrogen quality, and component energy (for example, compressor and dispenser energy in kWh/kg). • The information obtained can be used as a reference point or a benchmark for standard hydrogen fuelling station data.	NREL

Recommendation

Building a comprehensive and reliable database for hydrogen safety systems is crucial for promoting safe and efficient use of hydrogen in India. Collaborating with national and international laboratories, research institutions, and industries can help gather valuable insights and identify best practices for hydrogen safety data collection, which can be used to inform policies and regulations related to hydrogen use in the country.

5.3.11 Adoption of Best Practices for Hydrogen Systems

Elements of Best practices

The elements of best practices for hydrogen systems are:

- Risk Assessment: A comprehensive risk assessment should be carried out for the entire hydrogen system to identify potential hazards and assess their severity and likelihood.
- Design: The design of the hydrogen system should incorporate safety features to minimize the risk of accidents. This includes selecting appropriate materials, ensuring proper ventilation, and implementing emergency shutdown procedures.
- Operations and Maintenance: Standard operating procedures (SOPs) should be developed and implemented for the safe operation and maintenance of the hydrogen system. Regular inspections and maintenance should be conducted to ensure proper functioning of equipment and systems.
- Training and Education: All personnel involved in the hydrogen system should be properly trained on the safe handling and operation of the system. This includes operators, maintenance personnel, and emergency responders.
- Emergency Response: Emergency response procedures should be established, and personnel trained to respond to potential hydrogen-related incidents. This includes identifying potential hazards and developing appropriate response plans.
- Regulatory Compliance: All applicable regulations and standards should be complied with to ensure safe operation of the hydrogen system. This includes compliance with codes and standards related to hydrogen systems, storage, and transportation.

The safety cycle is an illustration of the continuous process of hazard identification, risk assessment, risk management, and evaluation of the effectiveness of risk control measures. This process should be repeated throughout the lifecycle of the hydrogen system to ensure ongoing safety.

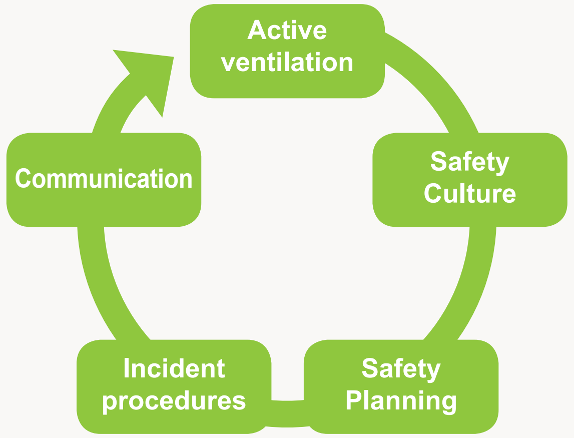


Fig 25 Safety cycle

Principles for Development and Design

The principles for development and design of best practices for hydrogen systems include:

- \- Making the knowledge base easily accessible to all individuals working with hydrogen and related systems, including those who are new to the field.
- \- Utilising the expertise and knowledge gained from the Hydrogen Safety Panel and other established best practices.
- \- Ensuring that the tool is usable and useful at each stage of updating or adding technical content.
- \- Collaborating with other national laboratories such as LANL, SNL, and NREL, other government agencies such as NASA, and the International Energy Agency (IEA) to share knowledge and best practices.

Safety Practices

- Safety culture: Refers to the values, attitudes, and behaviours within an organisation or among individuals that prioritise safety as a top concern.
- Safety planning: Involves identifying potential hazards, assessing risks based on their likelihood and consequences, and implementing measures to mitigate those risks.
- Incident procedures: Outlines steps to take in the event of an incident to ensure the safety of personnel and the public, as well as to protect equipment and facilities.
- Communications: Includes documentation, bulletins, labelling, warning placards, workplace safety measures, and emergency response protocols to effectively communicate information related to hydrogen safety.

Safety Plan for Each Hydrogen Facility

A comprehensive safety plan for each hydrogen facility should include the following elements, such as:

- Nature of the work being performed.
- Organisational policies and procedures related to safety.
- Identification of Safety and Vulnerabilities (ISV)
- Risk reduction plan to mitigate identified hazards and vulnerabilities.
- Operating procedures to be followed during normal and abnormal conditions.
- Equipment and mechanical integrity plan to ensure safe operation.
- Management of procedures for implementing and updating safety protocols
- Project safety documentation, including design, installation, and operational documents.
- Personnel training to ensure they have the knowledge and skills to safely perform their jobs.
- Safety reviews and assessments to evaluate the effectiveness of the safety plan.
- Safety events and lessons learned to incorporate new knowledge and experience into the safety plan.
- Emergency response plan to respond to any incidents or accidents.
- Self-audits to ensure ongoing compliance with safety regulations and standards.

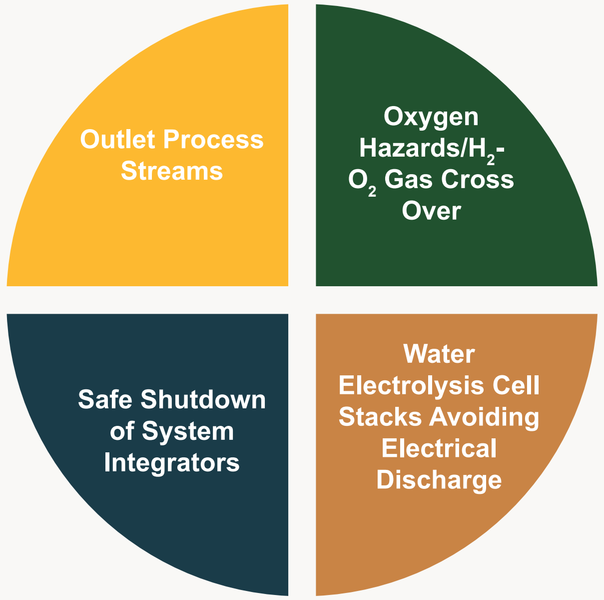


Fig. 26: Example – Electrolyser Safety

5.3.12 Regulations, Codes and Standards (RCS)

To promote a clean hydrogen economy, regulations play a crucial role. However, the shortage of knowledgeable people in regulatory and government coordination and the need for case-by-case approval make the process time-consuming and resource-intensive for both the applicants and regulatory authorities.

To address this, regulatory and legal frameworks should be reformed to provide a clear and predictable environment that supports industry investment and innovation while ensuring safety and creating job and economic opportunities.

Therefore, the next steps for India include implementing a regulatory reform programme and completing the national hydrogen infrastructure assessment.

Table 12: RCS development and Provider

S No	Approach to RCS Development	Provider
1.	Providing technical input based on evidence to standard development organisations such as ISO, to ensure that the standard requirements are based on sound technical principles	International Association for Hydrogen Safety (HySafe) and IEA HIA (International Energy Agency Hydrogen Implementing Agreement) Task on hydrogen safety
2.	A risk-based strategy for the development of hydrogen standards and codes has been adopted at the global level (ISO/TC197) and national levels (such as NFPA 2 and NFPA 55).	
3.	A toolkit is being developed for hydrogen applications to assess hazards. This toolkit will translate scientific research findings into practical formulas and will include risk metrics that are relevant for making decisions about safety and codes and standards.	

RCS for Hydrogen Fuelling Infrastructure

Although hydrogen has been used for many years, hydrogen-powered vehicles and stationary power generation using hydrogen are relatively recent developments. The establishment of international regulations, codes, and standards for hydrogen fuelling infrastructure is considered a crucial factor in the commercialisation of hydrogen fuel cell electric vehicles worldwide.

Development of Standards

To achieve the cost-effectiveness of hydrogen systems, it is necessary to have clear regulations, codes, and standards at both national and international levels.

A successful hydrogen economy requires the adoption and adaptation of international codes and standards, as well as the development of consistent national standards that are harmonized with international ones. Additionally, clear procedures and regulations are necessary to ensure the safe implementation, reliable scale-up, and adaptation of hydrogen systems.

Benefits of National Hydrogen Safety Standards and Harmonisation with International Standards:

- Enables reduction of risks to people and assets to an acceptable level by implementing consensual rules.
- Protect the environment from unacceptable damage due to failures in hydrogen operation, process and services.
- Provide consistency between international jurisdictions that enables efficient use of hydrogen-related equipment built in other countries.
- Assist industries to enhance their skills by learning from countries that are pioneers in hydrogen sector development.
- Facilitate regulatory authorities and licencing agencies in facilitating and normalising their permitting procedures.

Codes are typically embraced by regional authorities to govern the built environment, such as buildings and facilities. In contrast, standards provide instructions and criteria for goods and related operations to obtain a regulatory-like position.

Global Efforts

Collaboration between industry, governments, and safety experts is essential for the development of hydrogen codes and standards. Together, they have created, evaluated, and distributed codes and standards for hydrogen and fuel cell technologies and systems, resulting in updated regulations for vehicles, fuel delivery and storage, parking facilities, refuelling interfaces, stationary and portable fuel cells, and hydrogen generators.

Additionally, digital platforms and data-based tools have been established to promote consistent procedures for hydrogen safety in different sectors. Although this is an ongoing process, leading standard bodies such as ISO, IEC, NFPA, ASME, CGA, and IMDG have made strides towards developing standards and codes for hydrogen pressure vessels, pipelines, fuel cell vehicles, and the use of hydrogen in maritime applications.

Furthermore, many countries are also actively involved in developing their own national standards and regulations for hydrogen safety, often drawing on the international standards and best practices. For example, Japan has established its own safety standards for hydrogen stations, and Germany has developed a comprehensive set of safety guidelines for hydrogen applications in the transport sector. This global effort to develop and harmonise safety standards for hydrogen is crucial to support the safe and widespread deployment of hydrogen technologies.

- ISO
- the International Electro-technical Commission (IEC)
- the National Fire Protection Association (NFPA)
- the American Society of Mechanical Engineers (ASME)
- the Compressed Gas Association (CGA)
- European Industrial Gases Association (EIGA)
- International Maritime Dangerous Goods (IMDG)

There are equivalent and mirror organisations in different countries such as;

- British Standards – U.K.
- Japanese Standards Association - Japan
- American Society for Testing and Materials -U.S.
- CSA Standards - Canada and the U.S.
- National Institute of Standards and Technology – U.S.

Table 13: Standards update for hydrogen

ISO	✤ ISO/TC 197 Hydrogen Technologies ✤ ISO/TC 8/SC 2 Ships and Marine Technology - Marine environment protection to facilitate participation in the development of a new liquid hydrogen loading arm ISO standard. ✤ ISO/TC 22/SC 41 Fuel system components and refuelling connector for vehicles propelled by blends of natural gas and hydrogen ✤ ISO/TC 22 Road vehicles ✤ ISO/TC 58 Gas cylinders ✤ ISO/TC 67 Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries ✤ ISO/TC 161 Controls and protective devices for gas and/or oil (relevant to distributions networks)
IEC	✤ IEC TC 105 Fuel Cell Technology ✤ IEC TC 31 Equipment for Explosive Atmospheres ✤ IEC/TC 69 Electric road vehicles and electric industrial trucks
NFPA	✤ ASME B31.12 Hydrogen piping and pipelines ✤ ASME B31.1 Power piping ✤ ASME B31.3 Process piping
CGA	✤ CGA G-5, Hydrogen Pipeline Systems ✤ CGA H-2, Hydrogen Storage Systems ✤ CGA H-3, Standard for Cryogenic Hydrogen Storage ✤ CGA H-5, Standard for Bulk Hydrogen Supply Systems ✤ CGA H-13, Hydrogen Pressure Swing Adsorber ✤ CGA P-28, OSHA Process Safety Management and EPA Risk Management for Bulk Liquid Hydrogen Systems ✤ CGA PS-33, CGA Position Statement on Use of LPG or Propane Tank as Compressed Hydrogen Storage Buffers ✤ CGA PS-46, CGA Position Statement on Roofs Over Hydrogen Storage Systems

Illustrative Examples

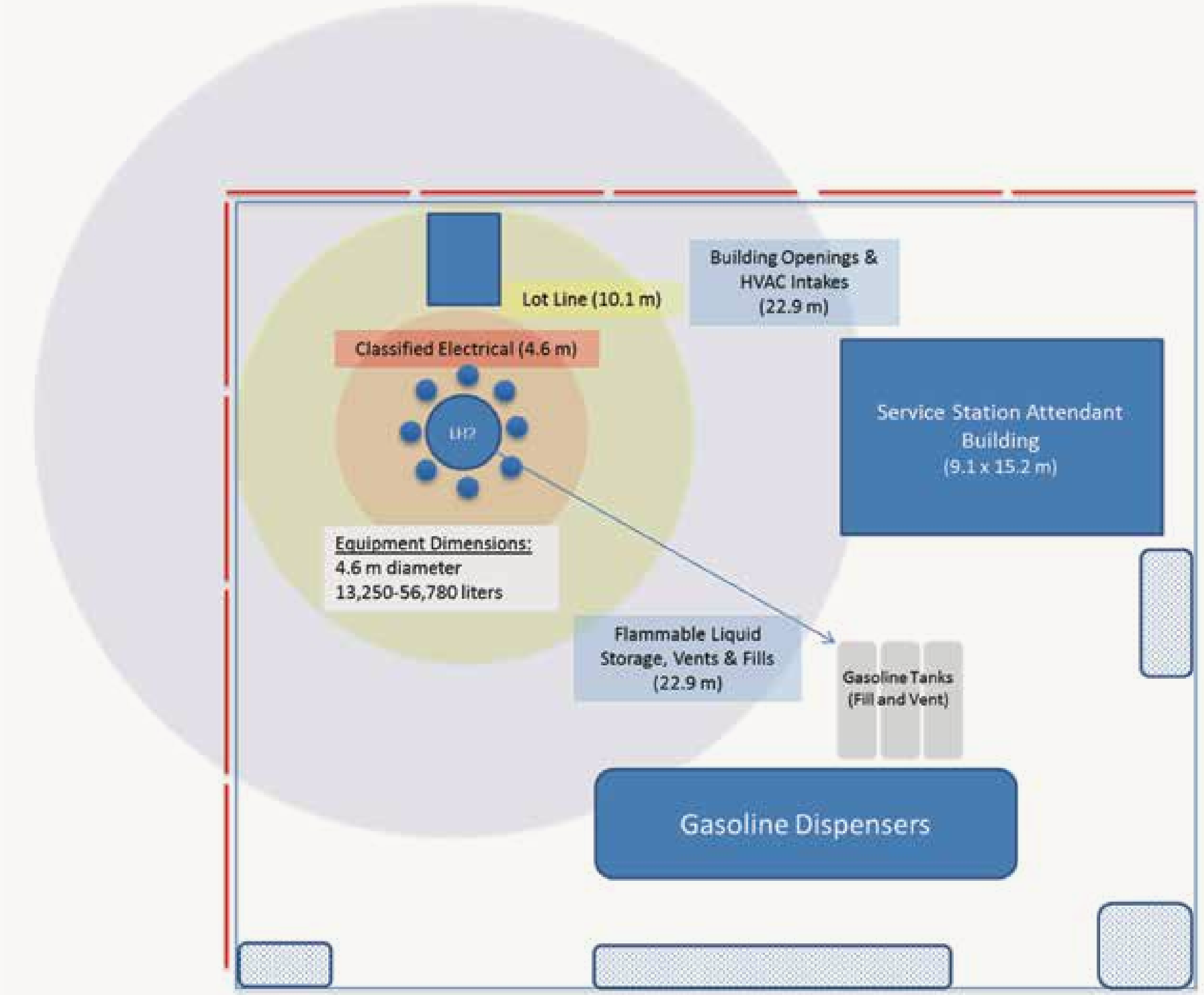


Fig. 27: Separation distances in NFPA 2 for liquid hydrogen stations
https://www.osti.gov/servlets/purl/1334069

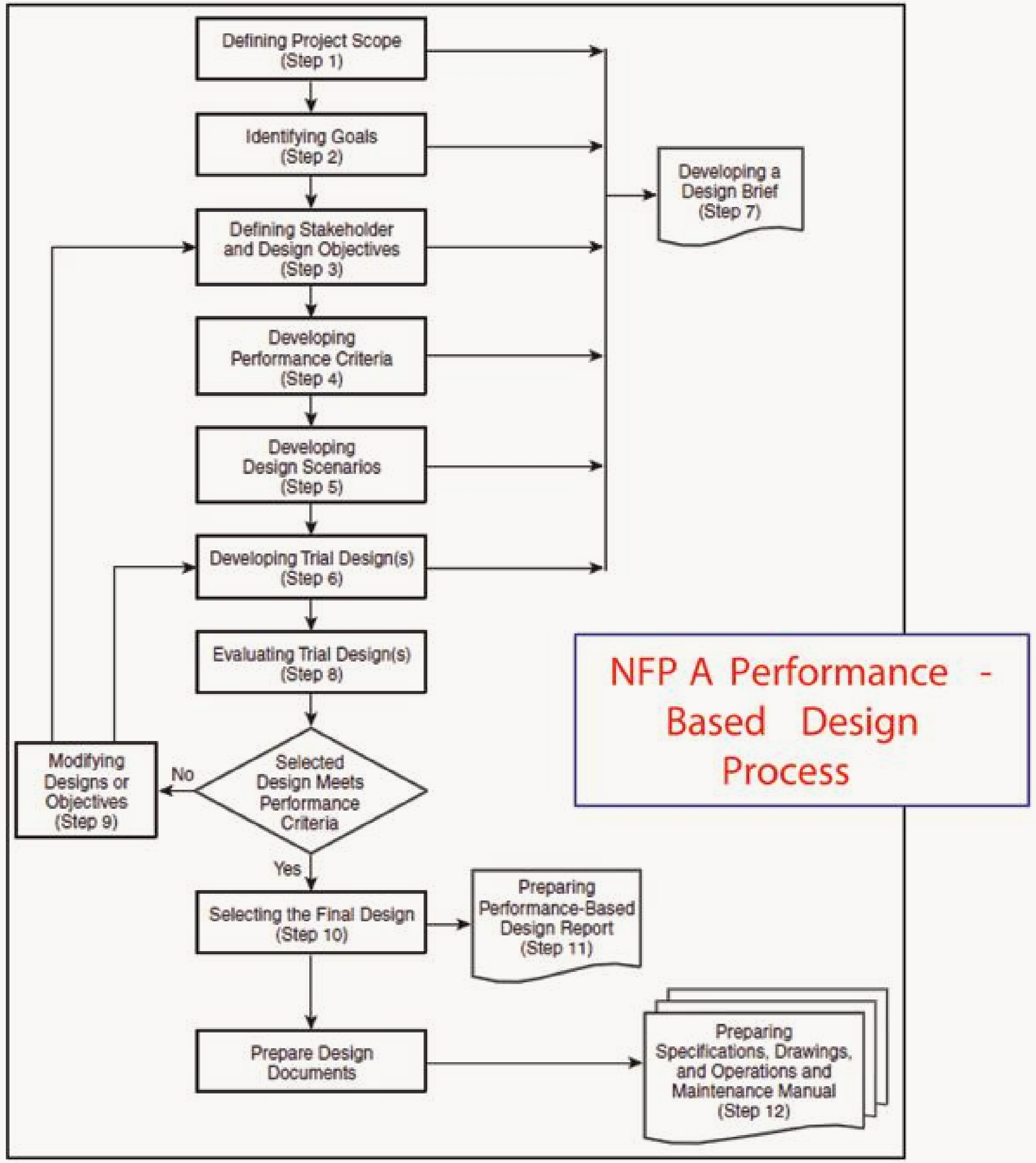


Fig. 28: NFPA Performance-Based Design Process
https://www.osti.gov/servlets/purl/1334069

Indian Status

To effectively implement hydrogen as an alternative fuel, it is crucial to create Indian standards and regulations that are consistent and harmonised with international standards, based on practical, theoretical, and experimental data. It is important to ensure that hydrogen energy infrastructure and installations meet all relevant codes and standards to ensure safety, reliability, and compatibility with the built environment. The Bureau of Indian Standards (BIS) represents ISO and the International Electrotechnical Commission (IEC) in India, which helps to develop internationally aligned standards in the country.

In recent years, India has been setting up frameworks and working groups to establish partnerships with various organisations related to hydrogen. Some of the notable partners include the Hydrogen Council, International Association for Hydrogen Energy (IAHE), and International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). These organisations work closely with hydrogen safety associations like the Centre for Hydrogen Safety (CHS), the European Hydrogen Safety Panel (EHSP), the European Committee for Standardisation, and Health, Safety, and Executive (HSE) group in the U.K.

Research Area

To ensure consistent safety procedures for hydrogen, additional research is necessary, with a focus on hydrogen fuel properties and its effect on other gases when blended with natural gas, the physical behaviour of hydrogen in the event of an accidental release, the compatibility of materials with hydrogen, and risk assessment methods that apply to hydrogen operations.

Moreover, India's National Gas Laws must be amended to permit gas blending in distribution networks. This necessitates additional research into the safety evaluation of hydrogen injection into gas pipelines to determine the degree of each component of the natural gas infrastructure's suitability for hydrogen concentration. To facilitate the export of large quantities of hydrogen, it is necessary to locate suitable storage facilities that can handle the complex infrastructure requirements. These potential storage sites need to undergo dynamic risk analysis to ensure their safety and reliability.

Stakeholder Involvement

To achieve maximum effectiveness in the development and coordination of codes and standards, it is important to involve a wide range of key stakeholders. These stakeholders may include industry partners, standards development organisations, research organisations, authorities having jurisdiction, local government in locations where projects will be deployed, and trade organisations involved in technology development and deployment. Outreach activities should also involve these stakeholders to ensure that everyone is aware of the latest developments and best practices.

5.3.13 Capacity Building

To establish a thriving hydrogen economy, it is crucial to have a well-trained workforce. This includes providing training to not only the workforce but also to emergency responders and regulators to remove any obstacles in the development process. Dissemination of guidelines can aid in updating industry practices and developing competency and qualifications as the hydrogen infrastructure grows.

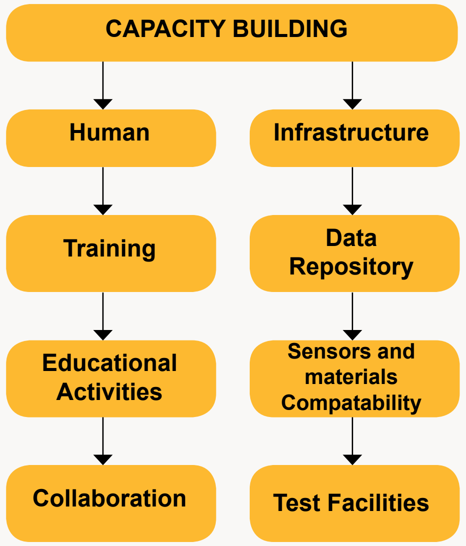


Fig. 29: Capacity Building
Introduction of a course on hydrogen safety for first responders
(https://hyresponder.eu/wp-content/uploads/2021/04/Lecture-1-slides.pdf)

VR and CFD Development for Training and Risk Communication

Hydrogen is different from other fuels due to its unique properties and storage methods at high pressure or low temperature. Thus, the potential hazards and associated scenarios will differ from other fuels. To model the consequences of leaks, fires, and explosions, computational fluid dynamics (CFD) and other related tools can be employed. Virtual reality (VR) and augmented reality (AR) can also be used to facilitate effective risk communication.

Virtual Reality for Safety and Emergency Training and Risk Communication

- VR can be utilised to present CFD data in real-time in a visual format.
- Interaction with the simulation system, such as changing ignition points or adding/removing objects, can be incorporated into VR development.
- VR can be employed for hydrogen safety training and risk communication purposes.

Safety Training

Virtual Reality (VR) can be utilised to provide workers and emergency responders with training and prepare them for scenarios that they may encounter in the hydrogen chain, which they may not have experienced before. It can create realistic scenarios where the workers can learn how hydrogen may release or get ignited and understand the importance of proper and quick evacuation.

Risk Communication

The utilisation of VR technology can aid in effectively conveying the risks associated with hydrogen to employees, enabling them to comprehend why certain safety measures, operating protocols, and layouts are necessary for their safety and well-being.

Understanding the Accident

The utilisation of VR can aid in comprehending the fundamental physical processes involved and evaluating the factors that either reduce or escalate the risk. By combining CFD with VR, it becomes possible to visualise an accident as it occurs and comprehend the sequence of events in real-time.

Emergency Control Centres

If there is an accident or incident at a hydrogen facility, CFD simulations can be used to provide decision support to centralised emergency control centres, which can monitor the situation and take appropriate action such as initiating alarms, providing evacuation guidance, starting emergency ventilation, and implementing water mitigation. This involves combining observation systems (e.g., gas or smoke detectors), knowledge of ventilation systems or meteorological observations, and fast CFD scenarios to simulate the incident. The simulations can predict the future development of the scenario, evaluate different mitigation options (e.g., ventilation), and decide where to evacuate people and what actions to take.

The company GexCon has developed a prototype tool called VRSafety which allows for the visualisation and interactivity of results from CFD simulation tools such as FLACS and KFX.

Recommendation: VR tools need to be developed indigenously for in house training which can also be used interactively with CFD tools in real time.

Developing VR tools indigenously for in-house training can have several benefits such as cost-effectiveness, customisation to specific training needs, and easier accessibility for employees. Additionally, integrating these VR tools with CFD simulations in real-time can enhance the training experience and provide a better understanding of complex scenarios.

However, developing VR tools requires a significant investment in terms of time, expertise, and resources. It may be more feasible for organisations to collaborate with existing VR development companies or seek out open-source VR solutions that can be customised to their needs.

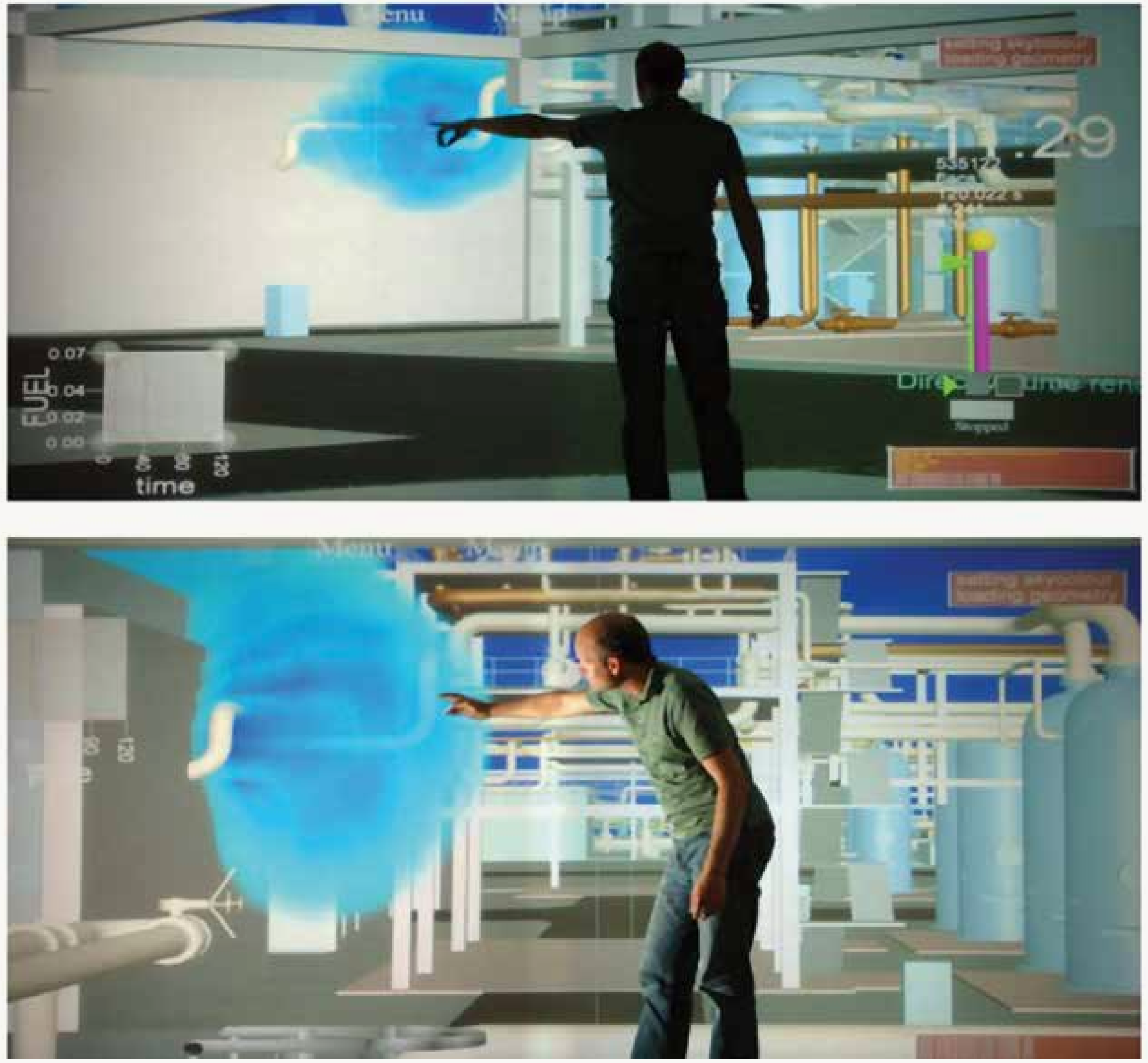


Fig. 30: FD And VR For Risk Communication and Safety Training

5.3.14 Centre of Excellence: An Ecosystem to Nurture Hydrogen Safety in India

To address the safety concerns associated with hydrogen technologies, it is necessary for India to establish a centralised organisation that focuses on hydrogen safety and its future challenges. One potential solution is to establish a Hydrogen Centre of Excellence (CoE) that brings together industry, academia, research institutes, and knowledge partners to collaborate on all aspects of R&D related to hydrogen. These CoEs would establish an ecosystem covering the entire value chain, including R&D on safety for hydrogen production (grey, blue, and green), transportation, and storage, and provide inputs for the development of safety standards. They would also support the government in formulating policies and assist the National Green Hydrogen Mission in formulating policies based on the best international practices followed globally to make hydrogen energy available by 2030 and beyond[15].

Currently, Nayara Energy has established a Centre of Excellence in Process Safety and Risk Management at IIT Delhi, in collaboration with Gexcon, a leading global consultant for fire and explosion safety. By establishing a CoE, India can position itself as a global leader in hydrogen technology and leverage the growing investment in R&D, capacity building, and compatible legislation, while also creating demand among its large population. Such initiatives have the potential to make India the preferred choice as both a knowledge provider and exporter of safe and reliable hydrogen technology worldwide.

Fig. 31: Centre of Excellence Activities

CoE Focal Areas

Focal areas for the CoE include research on hydrogen and process safety, risk assessment for M. Tech and Ph.D. students, and training in hydrogen process safety using Virtual Reality and Augmented Virtual Reality. The CoE will also offer capsule courses on hydrogen and process safety for decision-makers and Board of Directors, as well as support for industry-sponsored projects and consultancies in hydrogen risk assessment.

Other focus areas will include safety audits and certifications, forensic investigations and audits for higher learning, and support for regulatory authorities to keep up with evolving international developments. The CoE will also provide advanced laboratory and test facilities for hydrogen safety research, advanced research in the development of hydrogen models based on field data and forensic audit post-accident, and forensic hydrogen audits pre- and post-accidents.

Additionally, the CoE will develop codes and standards for hydrogen production, storage, transportation, and dispensing, and support the National Disaster Management Authority (NDMA) in developing a national strategy based on global best practices and VR training. Finally, the CoE will document and investigate all hydrogen-related accidents.

Hydrogen Safety Training
3D Consequence Analysis and Quantitative Risk Assessment

- Implementation of safety training using 3D computational fluid dynamics (CFD) and computer-aided (CA) technology combined with virtual reality (VR)
- Analysis and communication of risks associated with societal and environmental factors
- Understanding of accidents and their consequences
- Conducting process risk analysis and safety reviews to comply with regulations
- Support for installation design, such as optimising safety distances and ventilation layout
- Optimisation of gas detection studies
- Conducting simulations for dispersion, explosions, and fires
- Sizing, verifying, and optimising structures and equipment for safety purposes.

Virtual Reality (VR) Training Tools

- VR- In Safety Training
- VR – In Risk communication
- VR – In Understanding the accident.

Research Areas:

- For gaseous hydrogen (GH_2)
    - Investigation of gas accumulation in rooms with ventilation
    - Examination of properties of GH2 jet fires
    - Analysis of spontaneous ignition and flame propagation in congested environments, including deflagration-to-detonation transition
    - Development of methods for explosion mitigation
- **For liquefied hydrogen (LH_2)**
    - Currently, there is insufficient knowledge about the potential blast that could occur if a large vapour cloud produced by the release of hydrogen in liquid form ignites after a significant delay, which is a concern for the large-scale deployment of hydrogen. Further research in this area would help to reduce the uncertainty regarding the possible outcome.
    - Other areas that require further study include BLEVEs (Boiling Liquid Expanding Vapor Explosions) of storage vessels, releases of LH2 on and under water, combustion and dispersion of clouds generated by LH2 pools, ignition by electrostatic charging during LH2 releases, and the effect of temperature on the combustion properties of H2 and LH2 jet fires.
- **Modelling Studies** can help estimate leak and ignition frequencies, which in turn can be used to evaluate risks and compare them to acceptance criteria. These evaluations are crucial for using hydrogen as an energy carrier in various settings, such as nuclear plants, chemical factories, synthesis gas processes, and microprocessor factories.
- **Assessment of the Safety Integrity Level of hydrogen systems** to determine the requirements for instrumented risk reduction measures. Safety Integrity Level (SIL) of hydrogen systems in order to determine what measures need to be taken to reduce risk. SIL is a measure of the reliability and performance of safety instrumented systems (SIS) that are intended to prevent or mitigate hazardous events. The determination of SIL involves identifying potential hazards, assessing the likelihood and consequences of those hazards, and selecting appropriate risk reduction measures based on the level of risk. This process is crucial in ensuring the safe design and operation of hydrogen systems.

5.3.15 Conclusions and the Way Forward

To meet its goal of becoming a leading producer and exporter of safe green hydrogen by 2030, India must take a multifaceted approach that emphasizes the safety of the hydrogen ecosystem. This will require a combination of existing technologies that are suitable for Indian conditions, innovations, and adherence to safety codes and standards. The transition to a hydrogen economy will need to be accelerated and undertaken with focused effort.

The major obstacles to realising an economical, environmentally friendly, and safe hydrogen economy are the expenses linked with manufacturing, storing, operating, and maintaining hydrogen systems, as well as concerns regarding the safety, dependability, and regulatory approvals of such systems.

Safety considerations should be integrated into a project from its inception. The effective implementation of hydrogen as an energy carrier will depend on having the appropriate technology, risk-based standards and codes, risk assessment, and risk communication. This includes considering the acceptability of consequences in relation to the expected frequency of occurrence of an event for different groups of the population, as well as the vulnerability of structures based on the zone type and environment.

It is important for risk communication to carefully balance the potential risks and benefits in terms of both economic and ecological factors. Transparency is also crucial, taking into account public perceptions and concerns. The International Risk Governance Council has issued white papers on this topic.

To improve risk assessments, there is a need to enhance methods and data to minimise uncertainties and maintain sufficient resilience in the system, allowing for rational decision-making techniques to be applied.

To achieve this, an ecosystem can be established through the creation of “Centres of Excellence” in each state.

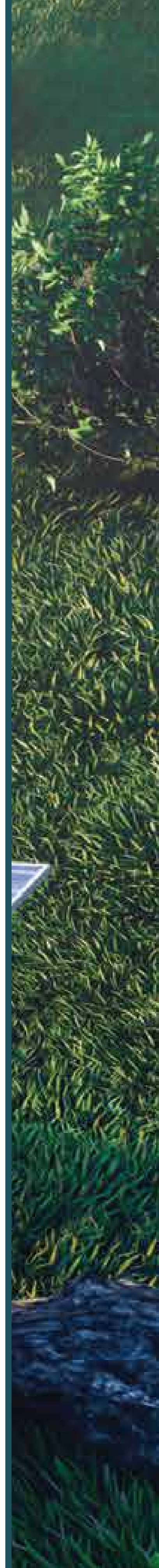
Acknowledgements
I gratefully acknowledge the work done by the interns at the CoE, Mr Karan, Ms Vasundhara and Mr Athul Rag for their contributions to this chapter.

Image Credit: afeguardsafety.net/course/hydrogen-sulphide-safety-training

SECTION -6

CARBON DIOXIDE AND HYDROGEN: A NEW PATHWAY

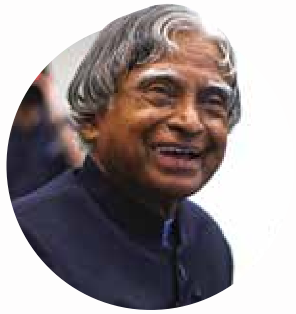
Carbon Dioxide as the New Oil Reservoir
of the Future | CO2 + H2: A New Pathway



6.1

Carbon Dioxide as the New Oil Reservoir of the Future

Prof G D YADAV, National Science Chair, Government of India



Once your mind stretches
to a new level it never
goes back to its original
dimension.

Dr A P J Abdul Kalam

Abstract

The leading economies of the world should focus on producing green hydrogen as part of their efforts to achieve net-zero emissions. Green hydrogen is particularly useful in converting various sources of biomass and CO_2 into fuels and chemicals through different catalytic processes. The hydrogenation of biomass produces numerous valuable products using durable, multi-metal catalysts. Refineries in the future will transform CO_2 into hydrocarbons, methanol, dimethyl ether, formic acid, alcohols, syngas, electricity, hydrogen vehicles, fuel cells, ammonia, and fertilisers, among other things, using green hydrogen. This will result in a carbon-negative economy that will lower the earth's temperature below 1.5°C . The "111" challenge (1 kg H_2 for $1 in 1 decade) is a significant challenge being pursued around the world. Our team has developed patented processes for producing green hydrogen for less than a dollar per kilogram (ICT-OEC Technology) and converting CO_2 into methanol, dimethyl ether, hydrocarbons, and 14 other bio-based chemicals. Some of this research is currently being scaled up.

Introduction

The excessive use of fossil fuels like crude oil, coal, and natural gas in recent decades is mainly responsible for the unprecedented levels of CO_2 emissions causing climate change, global warming, floods, and famines. Fossil fuels will eventually run out, necessitating significant efforts to find alternate, sustainable, and cost-effective sources of energy and materials. In 2021, global GHG emissions from fossil fuels and changes in land use resulted in 40 GtCO2-equivalent. Since the Industrial Revolution, billions of tons of CO_2 have been released into the atmosphere, and the concentration currently stands at 421 ppm, with the U.S. as the largest emitter and China in second place [1].

However, India is not far behind, and as the world population grows, energy and material demands will increase, leading to a change in ranking. The Paris Agreement of 2015 aimed to limit the global temperature rise to less than 2°C and preferably below 1.5°C by adopting new technologies, energy efficiency, and alternative sources, with the goal of achieving net-zero emissions by 2050 [2].

In November 2021, India pledged to achieve net-zero emissions by 2070 at the COP26 held in Glasgow [3]. However, to reach the net-zero goal more quickly, promoting carbon-negative energy supplies is urgently needed.

The world's economies currently rely heavily on carbon, but it's predicted that by the middle of the 21st century, there may not be any economically viable crude oil reservoirs left to exploit. Hence, alternate sources must be found for chemicals, materials, and energy. It's projected that by 2050, as much as 73% of the world's energy will come from renewable sources such as solar, wind, geothermal, hydro, nuclear, and hydrogen. Among these sources, hydrogen will play a crucial role in providing chemicals and materials from waste or renewable carbon, making it a saviour of the environment [6].

Both blue and green hydrogen will be part of the energy mix, with green hydrogen and green ammonia policies already declared by the power ministry of the government of India in February 2022, envisioning that 50% of India's energy needs will be met by renewable sources.

Waste plastic is also an important source of energy, chemicals, and materials that can be utilised through green technologies, reducing the burden on the environment and augmenting energy and material supply [7]. It's important to note that whether it's a fossil fuel or a renewable carbon source, the fate of the carbon is ultimately CO_2, which must be dealt with to reduce global warming. (Fig. 1).

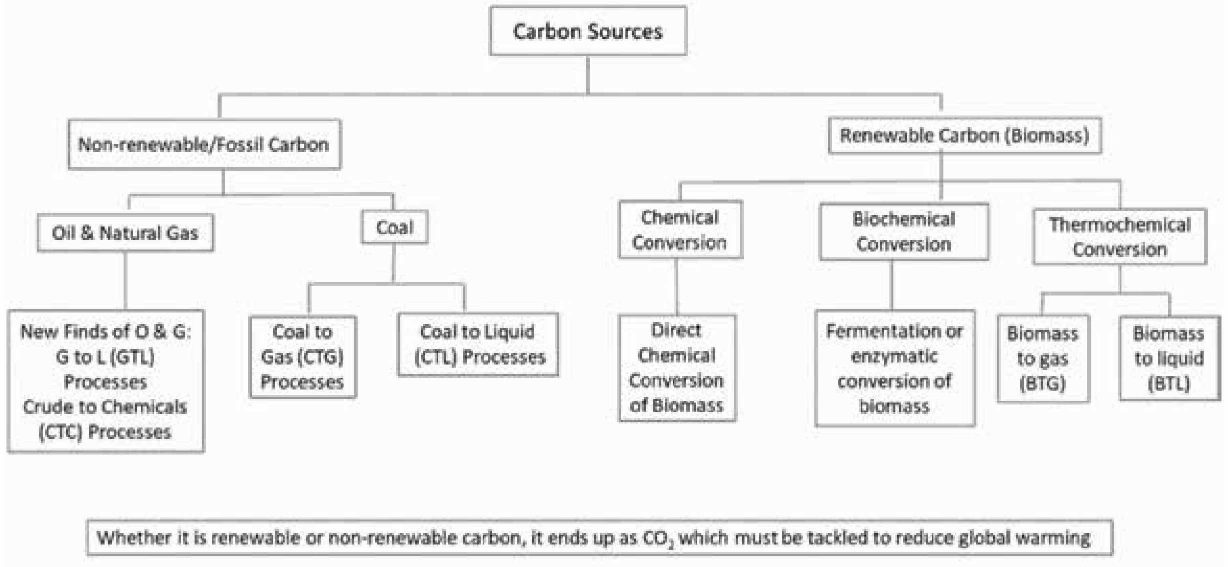


Fig. 1: Carbon conversion processes to manufacture useful products. Carbon has been solely responsible for advancement in lifestyle, comfort, luxury, transport, instant communication and longevity [5].

6.1.1 Hydrogen Production Technologies

Hydrogen can be used as a fuel in various applications, including fuel cell power generation and fuel cell vehicles. When burned, it produces only water, making it a clean source of energy. However, the use of coal and oil to manufacture fuels, chemicals, and materials is not sustainable and has caused significant harm to the environment.

Although the renewable energy share is expected to rise to around 73% by 2050, with a total of 49,000 TWh [6], coal will still play a role, which means that CO_2 will need to be hydrogenated. Therefore, the share of hydrogen in the global energy mix could increase from 2% in 2018 to 13-24% by 2050, with a CAGR of approximately 8% at the midpoint.

The Hydrogen Council [8] and the European Union [9] predict that an investment of $150 billion by 2030 will be necessary. In a net-zero carbon economy, green hydrogen can convert CO_2 into fuels and chemicals, as well as transform (waste) biomass and waste plastics into fuels and chemicals. Thus, CO_2 and hydrogen are linked in multiple ways to protect the environment and provide future stocks of chemicals and energy.

Hydrogen can be produced by water splitting or from any carbon source, fossil or renewable using steam reforming or pyrolysis. Steam reforming is accompanied by CO_2 emissions (Figure 2).

The production of hydrogen can be classified into different types, including grey, blue, and green hydrogen. Other categories, such as turquoise and brown hydrogen, are also sometimes mentioned. The primary difference among these types is the energy source used to produce hydrogen, with grey hydrogen being produced from fossil fuels, blue hydrogen utilising non-renewable feedstock with carbon capture utilisation and storage, and green hydrogen being produced from renewable energy sources such as wind, solar, hydro, or nuclear energy.

Green hydrogen is produced using electrolysis or thermochemical inorganic water splitting cycles, while blue hydrogen is produced through steam reforming of biomass or natural gas, which involves capturing and storing the resulting CO_2.

The grey hydrogen production method is the most common, but it produces significant CO_2 emissions. The turquoise method involves methane pyrolysis, while brown hydrogen is produced from coal without carbon capture. Biomass-derived blue hydrogen is a net-zero source and has been extensively researched, including by the author's group, which has patented and published several research articles on the subject. [7-15].

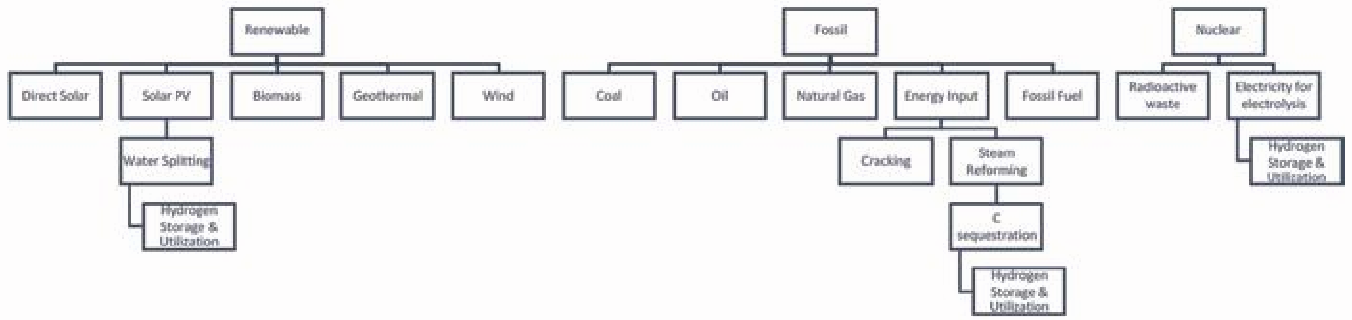


Fig. 2: Hydrogen production methods from different sources

Table 1: Merits and demerits of different hydrogen production processes

Type of Hydrogen	Brown	Grey	Torquise	Blue	Green	Green (ICT-OEC Process)
Source	Coal	Natural gas	Natural gas	Natural gas	Renewable electricity	Themo-chemical
Process	Steam reformin g	Steam reforming	Pyrolysis	Steam reforming	Electrolyzer Water splitting	Cu-Cl water splitting closed loop
Products	No carbon capture &storage	No carbon capture &storage	Hydroge n and carbon as coprodu cts	Most carbon capture & storage	No GHG O_2 as coproduct	No GHG O_2 as coproduct
Ton of CO_2 emitted per ton H_2	19	11	0 (solid Cas product)	0.2	0	0
Cost per kg H_2 US$	1.2-2.1	1-2.1	1	1.5-2.9	3-7.5	0.95 (credit of 0.9 for 02 not considered)

The green hydrogen produced using electrolysis of water is currently not economical but actively pursued by governments and major players in the field. Based on the information provided by the Hydrogen Council [16-17], the IEA [18], and Bloomberg New Energy Fund (BNEF) [19], the following statistics offer insights into the hydrogen economy.

- Electrolyser costs: $1,100/kW (2020) to $550/kW (2030), $220/kW (2040).
- The Institute of Chemical Technology (ICT)-ONGC Energy Centre (OEC) Cu-Cl thermochemical process is predicted to produce hydrogen at less than $1/kg for 100 TPD capacity (author's own work on pilot scale).
- Costs of CCS increases the costs of steam reforming of natural gas from $990/kWh to $1,850/kWh.
- Low-carbon fossil-based hydrogen: Cost in 2030 from $2.50-3 in the EU.
- Green hydrogen: $1.30-2.90/kg (Fig. 3).
- Target for solar electricity to be cost competitive with the current fossil-fuelled system.
- If the cost of installed PV power can be reduced from the present cost of about $5/W installed to about $1/W installed, the cost of solar electricity is predicted to reach $0.10/kWh.

The ICT-OEC thermochemical Cu-Cl developed in this author's lab is a closed loop process with energy supply from solar energy stored in molten salts [5, 7]. In contrast, the production of grey hydrogen through steam reforming of fossil carbon is a prevalent and affordable method used by various industries, but it also releases carbon dioxide. This practice is gradually losing favour due to the negative environmental impact. Refineries currently use grey hydrogen in eight of their conversion processes, leading to large amounts of CO_2 emissions. In contrast, hydrogen and ammonia are seen as green fuels of the future, as they can produce green hydrogen and nitrogen through catalytic splitting. Achieving a hydrogen economy is feasible only if the cost of green hydrogen becomes comparable to that of grey hydrogen. (Fig. 3).

The '111' Challenge

At present, the cost of producing clean hydrogen ranges from approximately $2.50 to $6.80/kg. The primary obstacle to large-scale green hydrogen production is its high cost. The Hydrogen and Fuel Cell Technologies Office (HFCO) of the U.S.

Department of Energy is working on developing technologies that can produce green hydrogen at a cost of \$2/kg by 2025 and \$1/kg by 2030, using net-zero-carbon processes. This effort is aligned with the Hydrogen Energy Earthshot initiative's goal of reducing the cost of green hydrogen by 80% to \$1/kg within a decade (known as "111") [20]. Fig. 3 illustrates the various applications of green hydrogen.

6.1.2Green Ammonia

Although hydrogen has a high energy density on a mass basis, the need for large storage volumes and the lack of existing infrastructure hinder the growth of the hydrogen economy. To address this, ammonia has emerged as a promising solution for the transportation and storage of fuel, which can be converted back into hydrogen at the user end. The Haber-Bosch process is commonly used for industrial ammonia production, where atmospheric nitrogen and grey hydrogen are catalytically reacted under high temperatures and pressures. The manufacture of ammonia results in approximately 420 million MT/year of CO_2 emissions worldwide, with an additional 830 million MT/year of CO_2 emissions from grey hydrogen production, accounting for about 2% of annual GHG emissions. Green ammonia, produced sustainably, can help reduce GHG emissions in agriculture by serving as a source of fertiliser. It can also be used as a clean fuel for transportation, especially for powering ships. Due to its higher energy content and density, green ammonia can be used in all applications of green hydrogen (Fig. 4).

Hydrogen has a higher mass energy density at 120 MJ/kg compared to ammonia's 18.6 MJ/kg, which has made it a popular alternative fuel. However, the advantages of green ammonia might outweigh those of hydrogen due to its higher density and the fact that it only needs to be compressed to 10 atm or cooled to -33°C to be stored, while hydrogen needs to be compressed to 350-700 atm or cryogenically cooled to -253°C. Ammonia is an ideal energy carrier because it can be stored at lower temperatures, and it is also suitable for storing and transporting energy from renewable sources. Another advantage of green ammonia is that it can utilise the existing distribution network used for fertilisers, where it is stored in large, refrigerated tanks and transported through pipelines or waterways. This existing infrastructure could also be utilised for other purposes if extended beyond the fertiliser sector (Fig. 4).

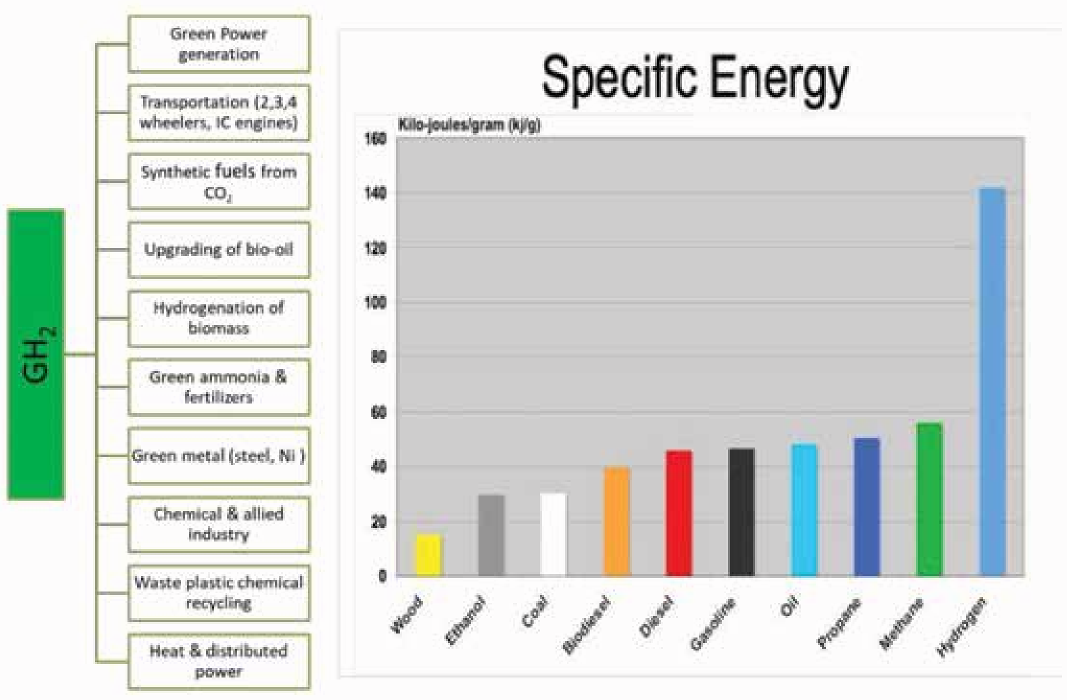


Fig. 3: Applications of green hydrogen in energy sector, CO2 and biomass conversion

6.1.3 Fossil Carbon and Climate Change

Carbon dioxide and methane are the two primary GHGs responsible for the majority of the man-made GHG effect and resulting climate change. Any future processes or concepts aimed at reducing CO_2 emissions must consider the entire lifecycle to ensure that additional CO_2 is not released beyond what is already being removed from or released into the atmosphere. CCS is widely recognised as an important option for reducing the increasing concentration of CO_2 in the atmosphere. CCUS technologies are seen as a practical solution that involves the recycling of CO_2 into various essential industrial compounds, fuels, and feedstocks. This approach brings together the synergies and innovations of catalytic chemistry, chemical engineering, material science, and biological sciences to address climate change. However, some criticise CCUS technologies for allowing continued use of fossil fuels.

The steel industry is a major contributor to climate change, releasing over 3 billion MT of CO_2 annually, with each ton of steel emitting 2.3 MT of CO_2. China and India are the top steel producers globally. In order to limit global warming, the steel industry needs to completely reduce its carbon footprint and switch to using green hydrogen to produce green steel. Other metal industries must also follow suit. While CO_2 has received a lot of attention, methane is another powerful GHG that must not be ignored. Economically, it is disadvantageous for developing countries without their own fossil fuel resources to spend billions of dollars on importing them from foreign countries. For example, in 2020, the rapidly growing Indian economy spent \$130 billion on importing 228.6 trillion MT of crude oil. To address this, the Indian government is investing in the development of new technologies, such as renewable resources such as solar, wind, and hydro, as well as coal-to-fuels and chemicals, 2G ethanol, biodiesel, and other alternatives to reduce the country's reliance on imports. According to BP Energy, India is projected to account for more than a quarter of the net global primary energy demand between 2017 and 2040, [6] with 42% of this new energy demand being met through coal, which will result in a doubling of CO_2 emissions by 2040.

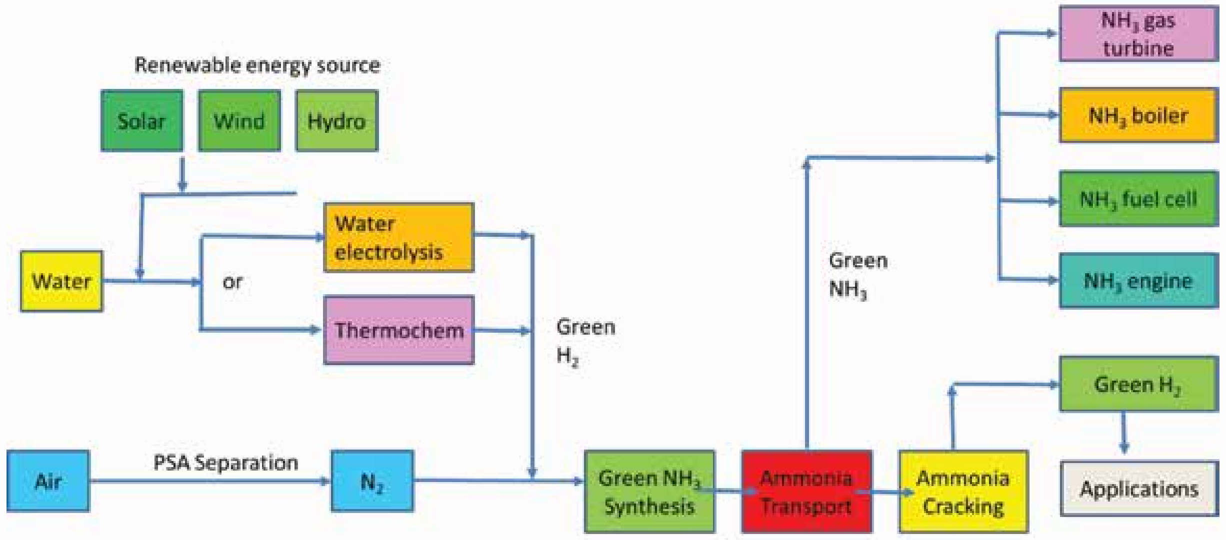


Fig. 4: Synthesis and applications of green ammonia. Both water and air will be the feed stocks for green hydrogen and green ammonia.

The Paris Agreement of 2015 aims to minimise the risk and consequences of global warming by setting two long-term temperature goals: keeping the global average temperature rise below 2°C above pre-industrial levels and taking more aggressive measures to limit the temperature increase to 1.5°C above pre-industrial levels. To achieve these goals, a 20/20/20 strategy was established, which involves reducing CO_2 emissions by 20%, increasing the market share of renewable energy by 20%, and improving the efficiency of current technology by 20%. This will require significant research and innovation efforts [23,24].

6.1.4 Carbon Dioxide as the Future 'New Oil Reservoir'

CO_2 is non-toxic, non-flammable and highly stable. Since it is released during various industrial processes, including power generation, refining, and fermentation, it contributes to GHG emissions. Rather than treating it as a liability, it can be utilised as a renewable carbon source for the production of chemicals, fuels, and materials through innovative and cost-effective catalytic processes. However, due to its stability, CO_2 requires highly active catalysts to activate it. By using CO_2 as a feedstock, the net zero goal can be achieved, and it can be considered as the 'new oil'. In the future, refiners will rely on CO_2 as a raw material for manufacturing fuels, chemicals, and polymers/materials, with green hydrogen serving as the primary reactant.

As an economical, safe, and renewable carbon source, CO_2 turns out to be an attractive C1 chemical building block for making organic chemicals, materials, and carbohydrates (e.g., foods). Utilising CO_2 as a feedstock for chemical production not only helps reduce the amount of CO_2 emissions in the atmosphere but also presents a significant challenge for innovation and industrial development. Reducing atmospheric CO_2 levels while also meeting the world's growing energy demands is a challenging task that requires long-term planning and CO_2 mitigation strategies such as shifting from fossil fuels to renewable energy sources, CO_2 capture and storage and CO_2 capture and utilisation (CCU). CCUS is a key area that can achieve CO_2 emission targets while simultaneously producing energy, fuels, and chemicals to meet increasing demand. The CCU process involves capturing and separating CO_2 from emission gases and converting it into valuable products such as urea, salicylic acid, cyclic carbonates, and polycarbonates. [25-28].

Currently, there are many techniques available for capturing CO_2, such as physisorption, chemisorption, carbamation, amine physical absorption, amine dry scrubbing, membrane separation, and mineral carbonation. These capture technologies offer the potential for CO_2 to become the 'new oil' of the future by converting it into synthetic fuels using specialised multiphase reactors. This approach also allows for high-level energy storage and network regulation from renewable energy production. However, this requires the development of novel catalytic processes and facilities for the future industry. The main source of concentrated CO_2 is flue gases from power plants that use fossil fuels. Separating CO_2 requires a large amount of energy, up to 100 MW of a typical 500-MW coal-fired power plant would be needed for today's CCUS based on the alkanolamines absorption technologies[29-30]. Therefore, it would be advantageous to convert flue gas mixtures from power plants into vehicle fuel without separating the CO_2 beforehand. Utilising CO_2 in industrial chemical production is a part of CO_2 management, but the amount of CO_2 that can be used for this purpose is relatively small compared to the total amount in flue gas.

Bulk chemicals routinely manufactured from CO_2 include urea to make nitrogen fertilisers, salicylic acid as a pharmaceutical ingredient, and polycarbonate-based plastics (Fig. 5).

The author's laboratory has demonstrated that catalytic conversion of CO_2 into methane and higher hydrocarbons, methanol, dimethyl ether (DME), formic acid, and other formates is possible when using hydrogen as a reactant (as shown in Fig. 6). This process can be considered a part of the hydrogen economy.

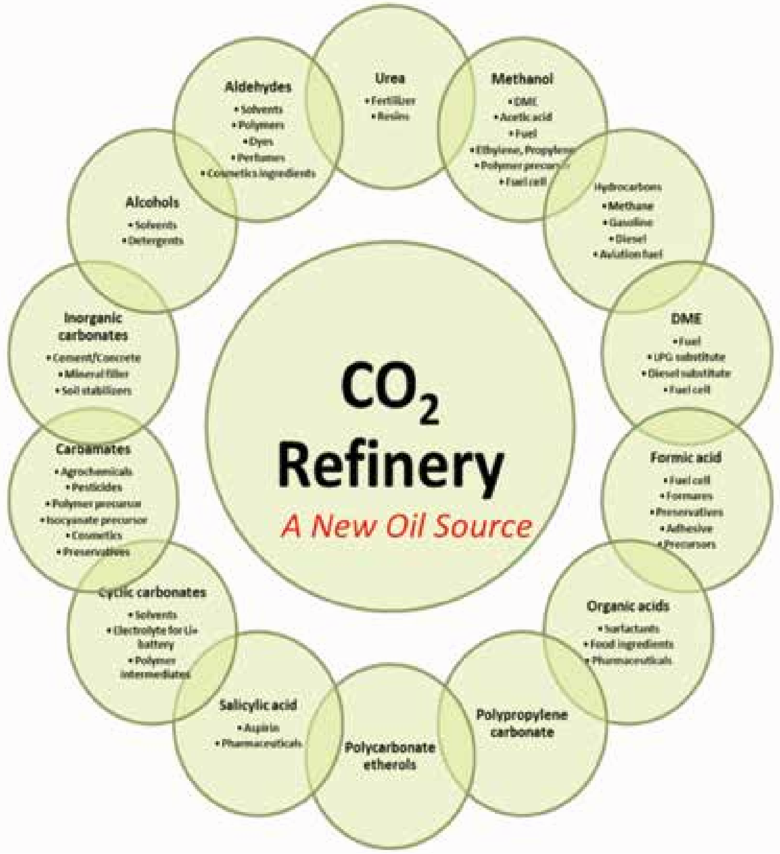


Fig. 5: CO2 refinery: A new oil reservoir for making chemicals and materials.

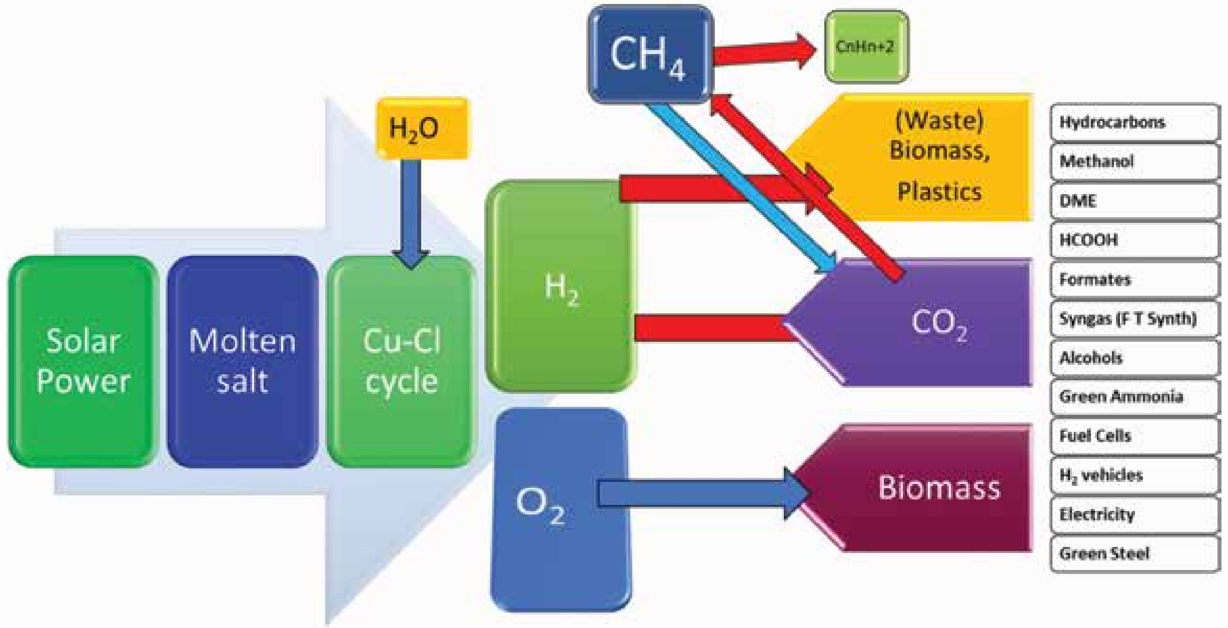


Fig. 6: Carbon dioxide conversion to valuable commodity fuels and chemicals using green hydrogen developed in author's lab by ICT-OEC technology [5-7].

The utilisation of CO_2 as a solvent is a viable option with the use of supercritical CO_2 providing benefits such as control over stereochemistry, improved product purification, and environmental benefits for the production of fine chemicals, pharmaceuticals, and enhanced agricultural production. Additionally, it can be used in tertiary oil and gas recovery through CO_2 flooding and in ponds of genetically modified algae that can convert power-plant CO_2 into biodiesel[31-33]. However, extracting CO_2 on a large scale, including from the atmosphere, is a challenging task, but it could be accomplished with the aid of innovative catalytic technologies, process intensification, and multi-phase reactor design.

Flue Gas as Source of CO2

From economic and environmental perspectives, there is a significant advantage in utilising flue gases directly, rather than pre-separating and purifying CO_2. A typical composition of flue gases from natural gas-fired power plants may contain approximately 8-10% CO_2, 18-20% water, 2-3% oxygen, and 67-72% nitrogen by volume, while a flue gas from coal-fired plants may contain around 12-14% CO_2, 8-10% water, 3-5% oxygen, and 72-77% nitrogen by volume. The temperature of flue gases at furnace outlet is usually around 1,200°C, which will gradually decrease along the heat transfer path, while the temperature of flue gases exiting to the stack is approximately 150°C. Although pollution control technologies can effectively remove SOx, NOx, and particulate matter, CO_2, water, and oxygen still remain largely unaffected[34-37]. Some important chemistries using CO_2 are given in Fig. 6.

Converting CO_2 into gaseous or liquid hydrocarbon requires high temperatures (523-723K) and pressures (20-40 atm), but the process has low conversion rates due to issues with CO_2 activation. As a result, current technologies are not economically viable for industrial use. However, efficient heterogeneous catalysts can help reduce the energy required for reactions by lowering the activation energy. There is a great deal of research on using pure CO_2 in various ways, including plasma, photocatalytic systems, electrochemical reduction, and heterogeneous catalysis[34-37]. Efforts have been made to create continuous processes that can convert CO_2 from flue gas into cost-effective and valuable products that can meet future energy and material needs. However, the process of CO_2 valorisation and carbon sequestration relies heavily on hydrogen.

The reduction of CO_2 emissions from around 40 gigatons in 2021 to approximately 10 gigatons can limit the global temperature increase to 1.5 °C by 2050[6]. In order for hydrogen to have a significant impact in addressing climate change and achieving climate neutrality, it needs to be produced on a much larger scale using green technologies that exclusively rely on water splitting. To achieve this, the hydrogen economy must overcome a number of challenges, such as developing a large-scale infrastructure for refilling stations, reducing the cost of production, transportation, and storage of hydrogen. These challenges can be addressed through collaborations among companies, nations, and research institutions, as well as by implementing supportive government policies at the local level[8]. In order for the hydrogen economy to become a reality and contribute to mitigating climate change, green hydrogen must be produced at a cost of below $1.50-2/kg. Interestingly, the cost of producing hydrogen using the Institute of Chemical Technology-ONGC Energy Centre (ICT-OEC) hydrogen production technology, which was developed by the author and involves water splitting in conjunction with solar energy, is less than $1/kg[7].

The use of carbon-based technology, whether renewable or fossil, poses the problem of emitting CO_2, which can be addressed by utilising hydrogen to convert CO_2 into various chemical products such as methane and higher hydrocarbons, methanol, dimethyl ether (DME), formic acid, formates, carbonates, ammonia, and urea. Among these products, DME stands out as it is the cleanest, non-toxic, non-corrosive, non-carcinogenic, and environmentally friendly substitute for CFC. It can also be effectively used in diesel engines, produces no soot or black smoke, and serves as an alternative to LPG for cooking fuel. The existing LPG infrastructure can be utilised for DME, making it an excellent substitute for LPG[38-41].

Hydrogen has the potential to store renewable energy alongside batteries and can act as a backup for seasonal changes. The steelmaking process is responsible for emitting over 3 billion MT of CO_2 annually, making it the most impactful industry in terms of climate change. To address this issue, the steel industry needs to reduce its carbon footprint considerably. In this regard, hydrogen can replace fossil fuels in some carbon-intensive industrial processes like steel and chemical industries. It can also provide solutions to parts of the transport system that are difficult to decarbonise, complementing electrification and other low-carbon fuels.

6.1.5 Biogas a Source of CO_2

Biogas is a renewable source of carbon produced through anaerobic fermentation of various types of biomasses, such as wet biomass, animal waste, harvest surplus, and municipal solid waste. It usually contains 50-75% methane and 25-50% CO_2. Although it can be directly used for heat and electricity generation, the high CO_2 concentration in the feed gas leads to low heat value. Biogas reforming into syngas with a H_2/CO ratio near one is a more efficient option to fully utilise both CH_4 and CO_2 for various industrial applications. Depending on the H_2:CO ratio in the reformed bio-syngas, it can be used as a feedstock for producing methanol, dimethyl ether, long hydrocarbon chains via the Fischer-Tropsch process, or ammonia synthesis using the Haber route.

Using gaseous biofuels for transportation has the added advantage of diversifying feedstock sources. One such fuel is biomethane, which is also known as renewable natural gas (RNG) or sustainable natural gas (SNG). Biomethane is produced by upgrading biogas to have a methane concentration of 90% or greater, which allows it to be distributed through the existing natural gas grid and used in existing appliances. Additionally, the use of biogas containing CO_2 as a co-reactant for methane conversion in the dry reforming process is a promising approach[42], as CO_2 can provide additional carbon atoms for the reaction and serve as a better oxidant than oxygen or air.

Adding CO_2 to the feed gas in the dry reforming process will increase the conversion of methane and the yield of the desired product. However, this will also result in a complex product mixture that includes syngas, gaseous hydrocarbons, liquid hydrocarbons, and oxygenates. The liquid hydrocarbons have a high-octane number and the oxygenates consist mainly of alcohols and acids. It may be more economically desirable to develop a new catalytic system for directly converting methane and CO_2 into higher hydrocarbons and oxygenates[43]. It's important to note that carbon should not be used as a fuel source, but rather for the production of chemicals and materials. All non-carbon sources of energy, such as solar, wind, geothermal, tidal, nuclear, and especially hydrogen derived from water splitting, can meet the requirements of the Paris Agreement[5].

(Waste) Biomass as Precursor for Chemicals and Materials

Biomass is a form of renewable energy that has an energy value per unit mass that is lower than fossil fuels. However, it can be converted into biofuels (in solid, liquid, and gas forms such as methane and hydrogen) for sustainable development. Green hydrogen, produced through water splitting, will play a crucial role in this conversion process.

There is a growing global interest in using lignocellulosic biomass to produce sustainable biofuels and bio-derived chemicals. The key components of the biomass – cellulose, hemicellulose, and lignin – have the potential to produce several building block intermediates for modern bio-refineries. Cellulose and hemicellulose consist mainly of C6- and C5-sugars respectively, while lignin is mainly composed of phenolic units. This diverse range of chemical functionalities presents a promising alternative to petroleum resources.

Lignocellulosic biomass, whether it is waste or intentionally grown, can be used to produce various chemicals through different catalytic processes. The composition of cellulose, hemicellulose, and lignin can be depolymerised to create fuels and chemicals (Fig. 7). The significance of green hydrogen is apparent, as it is required for hydrogenation/hydrogenolysis, dehydrogenation, and oxidation processes that create highly valuable bio-based chemicals[5]. Additionally, several other essential chemicals can be produced through methods such as condensation, hydrolysis, hydration, isomerisation, dehydration, esterification, alkylation, dealkylation, oligomerisation, and demethoxylation[44-45]. Table 2 lists the top 14 platform chemicals that can be derived from biomass.

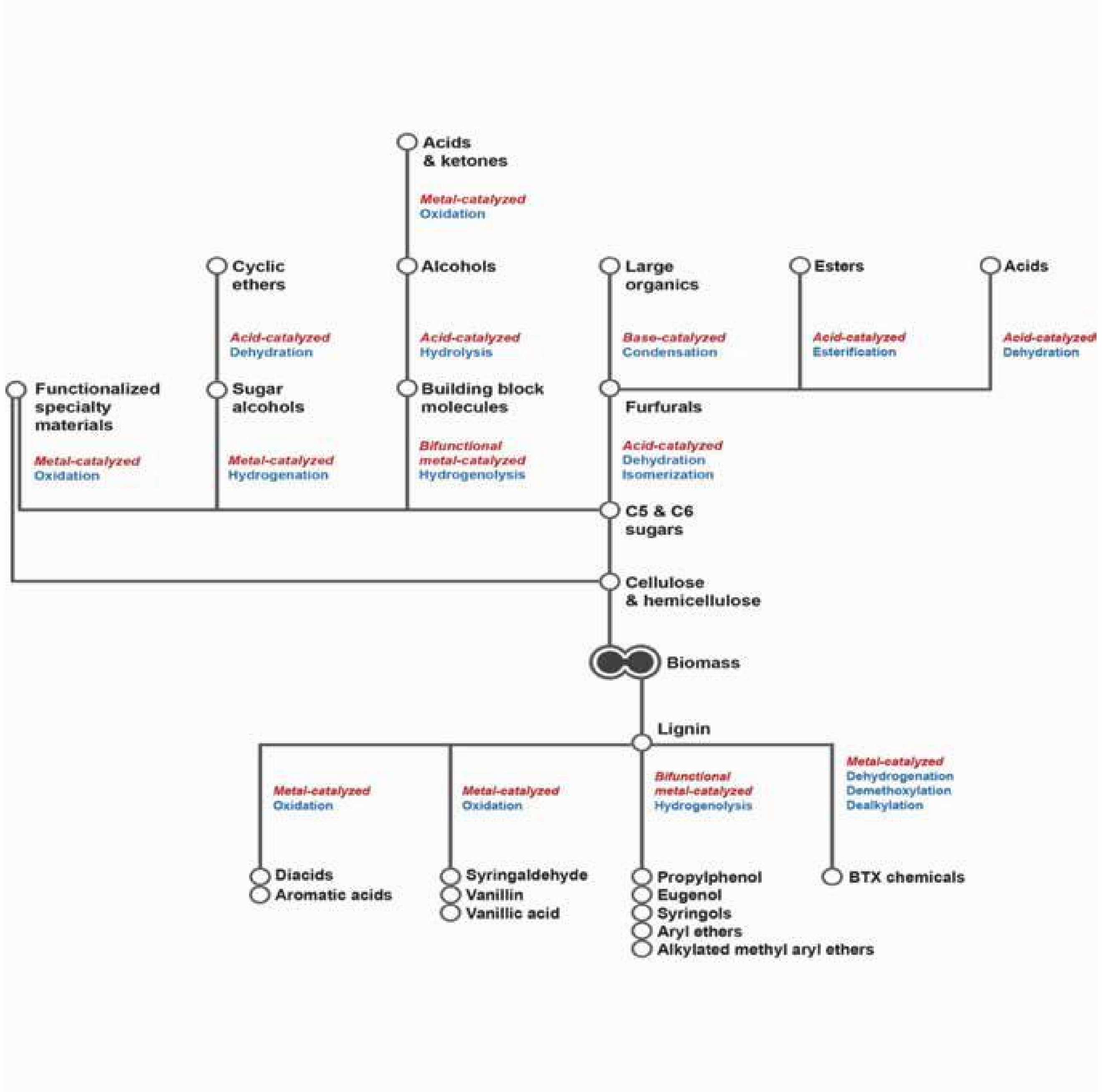


Fig. 7: (Waste) Biomass-based valuable products: Importance of hydrogenation and oxidation (green hydrogen)

Agricultural waste is generated in large quantities across the world, and can be transformed into biofuels through a range of techniques including thermochemical conversion such as combustion, gasification, pyrolysis, hydrothermal liquefaction, biochemical conversion such as anaerobic digestion, microbial fermentation, enzymatic hydrolysis, and chemical treatment like biodiesel production and transesterification.

Biochar, liquid bio-oils, and hydrocarbon gases are produced through biomass pyrolysis. Biochar is useful in agriculture for retaining water and nutrients, as well as binding urea to make fertiliser. Blue hydrogen can be produced through steam reforming of bioethanol or other biomass-derived chemicals such as methanol, butanol, ethylene glycol, and glycerol. This process of hydrogen production from biomass, known as blue hydrogen, has the potential to produce low-carbon hydrogen and capture CO_2 to offset hard-to-abate emissions.

Using sustainable biomass feedstocks, such as agricultural waste and residue, can minimise negative impacts on food security and biodiversity. By utilising waste biomass and bio-derived alcohols, blue hydrogen can be produced to provide CO_2 removal and low-carbon hydrogen in the short term. This hydrogen can help decarbonise hard-to-electrify areas, store energy from irregular renewable power, and serve as a chemical feedstock. In contrast, grey hydrogen is produced from fossil natural gas and is responsible for approximately 2% of global GHG emissions. The hydrogen produced from biomass generates a high-purity stream of CO_2, making it ideal for CCUS. The production of bio-hydrogen coupled with CCUS is the only hydrogen production method that can result in net-negative CO_2 emissions.

Biomass feedstocks used for bioenergy are typically grown in large monoculture plantations in countries such as Brazil and India, leading to various social and environmental issues including compromising food security, harming biodiversity, and increasing competition for natural and agricultural land, among others. However, with the increasing demand for food production and concerns about biodiversity loss, it is essential that biomass feedstocks for blue hydrogen production have minimal impact on these factors. As a result, purpose-grown bio-energy crops are becoming less attractive, and instead, crop residue, household food waste, and livestock manure are seen as most suitable for biogas production through anaerobic fermentation. These feedstocks do not require purpose-grown bio-energy crops and do not compete with productive agricultural

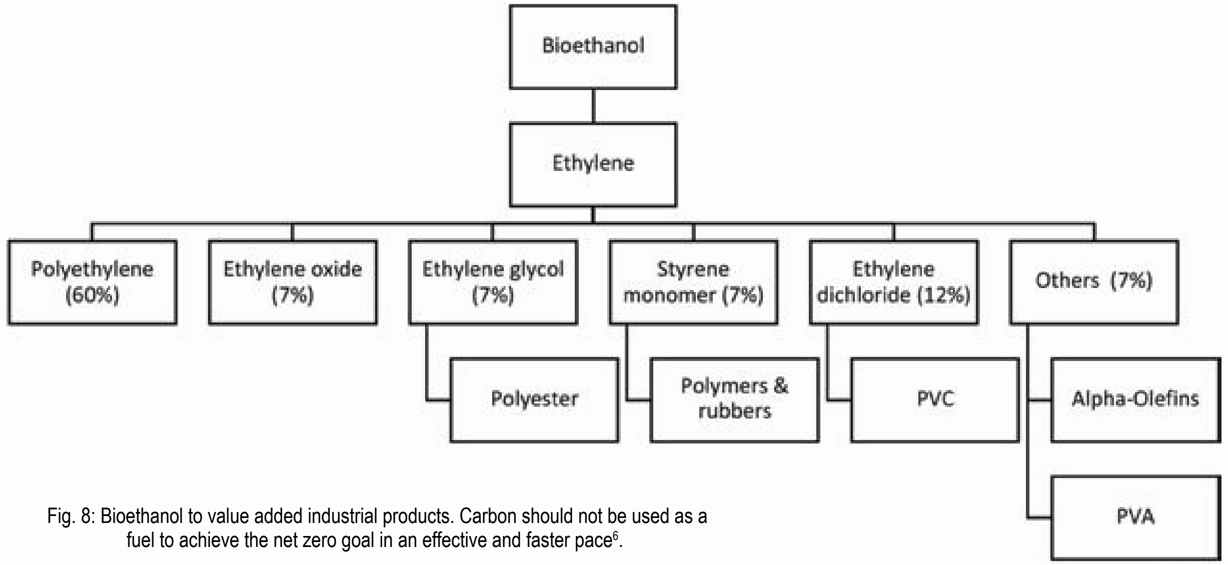


Fig. 8: Bioethanol to value added industrial products. Carbon should not be used as a fuel to achieve the net zero goal in an effective and faster pace[6].

land, thus avoiding harm to biodiversity through agricultural expansion.

In a landmark research paper[5], we demonstrated that utilising bioethanol as a raw material for producing chemicals is more cost-effective and environmentally sound than using it as a biofuel. One kilogram of crude oil provides 32 MJ of energy and 0.2 kg of chemicals, whereas 1 kg of biomass generates either 6 MJ of energy or 0.8 kg of chemicals. Therefore, converting biomass into chemicals is more profitable than refining it into biofuels. It is recommended that biomass should not be used as a fuel source but instead should be transformed into valuable chemicals and materials, such as bioethanol (as shown in Figure 8).

Both green and blue hydrogen can be applied to industries that are difficult to electrify, such as cement, steel, refining, ammonia, and glass. To utilise biomass as a source, it needs to be separated into its cellulose, hemicellulose, and lignin components. The cellulose and hemicellulose can be used to create various platform chemicals like levulinic acid, 5-hydroxymethylfurfural (HMF), and furfural. Lignin can be transformed into hydrocarbon compounds such as olefins or aromatic derivatives, jet fuel, and ethylene. The catalytic hydrogenation of (hemi)cellulose, hexose, furans, organic acid, lignin, and other bio-derivatives can create valuable products and add to the income of farmers. Cellulose can be converted into combustible gases, such as methane, by hydrogenation.

Sugars, including hexoses and pentoses, can be dehydrogenated into furfural and HMF. These chemicals are important intermediates for producing tetrahydrofurfuryl alcohol, levulinic acid and its esters, furfuryl alcohol, HMF, γ-valerolactone, and others. Lignin can be transformed into benzene, toluene, and xylene, which are major petrochemicals used in the chemical industry and account for 60% of all aromatic compounds, through hydrogenation or hydrogenolysis. Depolymerisation of lignin is necessary to produce platform chemicals and to upgrade bio-oils by hydrogenation and biochar.

Polyols are suitable substrates for the production of H_2 or syngas, which can be further used as building blocks for manufacturing methanol and other chemicals, including liquid hydrocarbons via the Fischer Tropsch synthesis.

After cellulose and hemicellulose are broken by acid or reductive catalysed hydrolysis, glucose and xylose can be hydrogenated into the corresponding C6 and C5 polyols, sorbitol and xylitol, respectively. C6–C2 polyols, including 1,4-butanediol (1,4-BDO), 1,2- and 1,3-propylene glycol (1,2-PDO and 1,3-PDO) and ethylene glycol (EG), are extensively used as ingredient or additives in food, pharmaceutical and cosmetic industry as well as cheap monomers for the manufacturing of polymers, coatings, adhesives, etc. Xylitol is the most widely used sweetener characterised by a lower calorie-content and reduced glycemic index (GI) with respect to sucrose. Sorbitol has been successfully used for over the years for making polyurethanes. Ethylene glycol is an antifreeze agent which is a main component in the production of bio-PET while other bio-based diols, besides their direct uses, are now used as co-monomers in bio-elastomeric polymers. New catalytic technologies require a cost-effective reduction of the oxygen content in bio-polyols permitting the production of H_2, fuels and other valuable chemicals. Glycerol is the co-product of biodiesel, typically 10% by weight, can be used to make more than two dozen chemicals. Unless glycerol is valorised, biodiesel production cannot compete with petro-diesel. Thus, farmers should recognise that there are marvellous opportunities to valorise agricultural waste using green and blue hydrogen to increase their income. Only the growth of grain or fruit production will not enhance their income but making sensible use of all parts of plants and waste thrown or burnt as waste will be part of a circular economy.

Waste Plastic Refining: Chemical Recycling

The process of refining plastics is known for its high GHG emissions. Ethylene production alone is expected to have a 34% increase in CO_2 emissions between 2015 and 2030. Despite its popularity in construction and consumer goods, PVC is known to have higher energy consumption and CO_2 emissions compared to other plastics such as polypropylene (PP) and polyethylene (PE). Although PVC has good insulation properties, it is inferior to PP and PE in terms of thermal resistance. Other commonly used polymers like PET, nylon, and PU also contribute to carbon footprint and global warming. However, recycling PVC has shown to have a positive impact in mitigating climate change[84].

Globally, packaging accounts for around 40% of plastic use, and single-use plastics (SUPs) are a significant contributor to plastic waste due to their disposable nature. SUPs are used in various industries such as tire manufacturing, fabric production, and coatings. To reduce plastic waste, consumers should have access to alternatives such as refundable deposit schemes, regular waste collection, and avoiding mixing plastic waste with other types of waste. The three primary methods for dealing with packaging waste are landfill, incineration, and recycling. Incineration has the most significant impact on climate, while adding to a landfill has less impact but still has environmental concerns. Recycling is the best option, but it is often not economically viable due to the low commercial value of recycled plastics compared to virgin plastics. Chemical recycling methods such as depolymerisation and hydrogenation are promising alternatives to traditional recycling methods. According to the World Energy Council (WEC), if the current trend in plastics production and incineration continues, GHG emissions are expected to rise to 49 million MT/year by 2030 and 91 million MT/year by 2050.

SUP Ban Is Not the Solution but Incentive for Collection of SUPs

A potential solution to encourage the collection of single-use plastics (SUPs) from consumers is to implement a refundable deposit scheme. The deposit should be higher than the cost of the product and clearly labelled to prevent additional pollution. This would incentivise consumers to return used goods to any convenient location. For example, if a plastic straw, PET bottle, or milk pouch is given to the customer for a refundable deposit of Re 1 per piece, regardless of size or thickness, they are more likely to return it to collect their deposit. To reduce the burden, all articles should be accepted for deposit return. The government has introduced a Swachh Bharat cess to deal with plastic waste, but authorities should ensure that plastic waste is collected at a fair price to encourage rag pickers to collect all plastic items, not just PET bottles.

Currently, 80% of PET waste is recycled in India, but it is unclear how much rag pickers earn from this. Processing PP lids is done elsewhere, and the blue pigment used makes this a challenging task. It would be better to avoid using pigments in PP lids. Another solution is to use PET bottles for milk packaging since they are non-breakable, lightweight, easy to open and close, and offer cost savings in production and transport. Implementing a deposit scheme on milk pouches with a design that allows for easy recycling could also be effective. Cutting the bag and discarding a small part of it should be avoided. Generally, milk pouches are washed with water to extract the last drop of milk by most housewives.

Refundable deposits on SUPs can be collected by various groups such as school children, office workers, and housewives, similar to newspaper delivery. The collected SUPs can then be easily sorted and recycled to avoid the cost of sorting and segregation during the recycling process. The collector can charge a small percentage of the deposit and use digital technology to refund it.

The Ellen MacArthur Foundation survey shows that only around 2% of plastics are recycled through chemical conversion into similar products, while 8% are downcycled into lower quality chemicals, and the rest are either sent to landfills, incinerated, or end up in the environment in some form or the other. To reduce emissions associated with plastics, waste reduction, material retention, and recycling are needed. Chemical recycling can be done through depolymerisation and repolymerisation, or by converting the polymer into chemical building blocks that can be used to produce new polymers. Polymer upcycling, such as converting

SUPs into new products, is also becoming popular. Achieving government-established recycling targets requires collaboration between consumers, municipalities, and petrochemical production, supported by improved technology along the recycled plastics supply chain. Public opinion and media images of environmental degradation can also drive change. By working together, a solution to this global problem can be found.

The circular economy approach to plastics requires innovative solutions, as plastics continue to be an essential component of transportation and there are no viable substitutes available at a global scale. Designing plastic products with circularity in mind involves principles of reuse, recycling, and remanufacturing, with single-use plastics being an exception rather than the norm.

Recycling plastic poses additional challenges because various additives are used to improve the performance, functionality, and aging properties of the base polymer. These additives include functional additives such as plasticisers, lubricants, stabilisers, and flame retardants, as well as colourants, fillers, and reinforcements. Identifying, separating, and disposing of these additives presents a significant obstacle to recycling plastics into virgin resin[48].

Although mixed plastics can be incinerated for energy recovery, this process often creates carcinogenic pollutants, and only a small fraction of waste is incinerated in the U.S. Therefore, incineration underestimates the potential value that these polymers hold.

Gasification and pyrolysis are thermal processes that are commonly used to depolymerise plastics into fuel oil. Hydrothermal processing (HTP) is another depolymerisation process that uses water as a solvent, catalyst, or reactant. HTP takes place in an autoclave at moderate temperatures and pressures, using supercritical water to liquefy polyolefins into oil or gas products[45-46] (Figure 9).

Solvolysis is a depolymerisation process that uses solvents such as xylene, toluene, hexane, and methanol to recover common polymers like HDPE, LDPE, and PS in high yields. On the other hand, methylene chloride (MDC) and benzyl alcohol are effective solvents for dissolving PVC and PET. Chemolysis is another depolymerisation process that uses chemicals to depolymerise polymers, particularly condensation polymers like PET and PU. However, chemolysis cannot depolymerise additive polymers like polyethylene (PE) and PP. Chemolysis reactions include aminolysis, glycolysis, and methanolysis. Selective solvent extraction (SSE) and chemolysis are suitable for sorted plastics and condensation polymers, respectively, but they cannot be used to treat mixed plastic[44].

HTP has been shown to be effective in depolymerising a wide range of plastics, including non-polyolefin plastics like PVC and PET, as well as polyolefins like PP. The resulting products from HTP include fuels, naphtha, and wax, among others. However, it's important to note that while HTP shows promise as a plastic recycling method, it is still in the early stages of development and commercialisation[44-45,46].

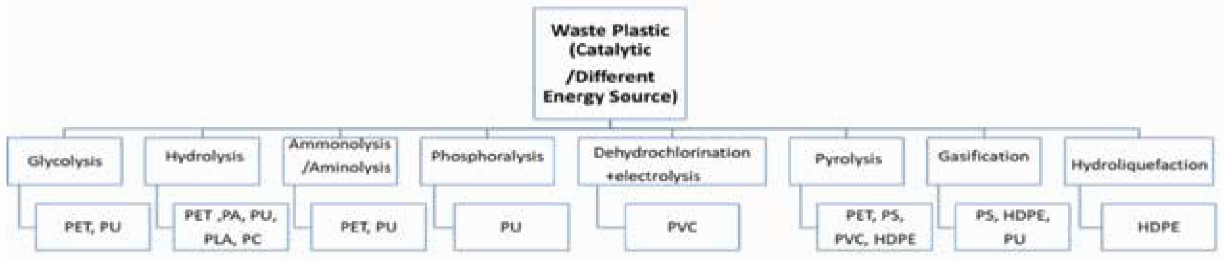


Fig. 9: Waste plastic valorisation

6.1.6 Hydrogenation of Plastic Waste to Valuable Fuels, Monomers, Chemicals

Hydrocracking of plastic waste using metal catalysts is a promising technology as it can convert plastic waste into valuable products while addressing the issues of troublesome atoms such as Cl, N, O, and S. Hydrogenation can also remove dioxins from the waste stream and prevent the formation of super toxic products. In addition, metal impurities can be removed through hydrodemetallation during the process. The use of solid acid supports in hydrocracking can further enhance the efficiency of the process. The technology for absorbing HCl, NH_3, H_2O, and H2S during the process is already well established (Fig. 10). Overall, hydrocracking with metal catalysts is a viable solution for plastic waste management.

A catalytic cascade process was used, where hydropyrolysis was coupled with downstream vapour-phase hydrotreatment to upcycle mixed plastic waste into fuels. This tandem vapour-phase hydrotreatment technology is feedstock-agnostic and therefore capable of upcycling different kinds of personal protective equipment (PPE) waste[47]. Thus, hydrotreating can be used as a favourable chemical upcycling technology for accomplishing a sustainable plastic circular economy.

6.1.7 Future Direction

The production of green hydrogen and the achievement of the '111' objective, as well as the economical use or reuse of CO2, pose several challenges. One major challenge is determining the most effective way to access energy sources, as converting CO_2 into fuels and chemicals requires a significant energy input. Another challenge is the development of new reaction pathways, including innovative heterogeneous chemical and enzyme catalysts, and the design and operation of multiphase reactors that achieve process intensification at a reasonable cost.

Although various methods have been reported in the literature for utilising pure CO_2, such as plasma, photocatalytic systems, electrochemical reduction, heterogeneous catalysis, and others, most of these approaches have only been tested on a laboratory scale. Few attempts have been made to develop continuous processes that economically convert CO_2 from flue gas into value-added products on a commercial scale to meet future energy and material needs. In the next two decades, capturing CO_2 from different industries, such as fossil-fuel-based power plants, natural gas processing plants, bioethanol plants, and cement plants, could become an essential approach for mitigating climate change. Most of the captured CO_2 is likely to be stored deep in depleted wells through CCS.

The idea of utilising CO_2 for subsequent use is being considered as a way to reduce the cost of CCS. CO_2 is now seen as a valuable resource rather than just a pollutant, as it can be used to produce fuels, chemicals, and materials. While the chemical industry currently uses a significant amount of CO_2 to produce urea, its conversion into useful chemicals is not expected to have a major impact on global GHG emissions, given the large amount of CO_2 emissions. However, researchers are making progress in developing efficient methods for CO_2 conversion, and its potential use could be significant.

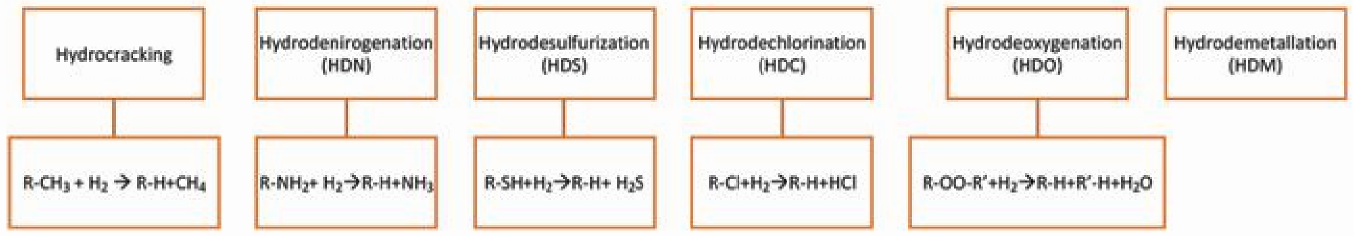


Fig. 10: Hydrogenation of waste plastic to hydrocarbons

The transportation industry urgently needs decarbonisation, as most power plants still use coal and petroleum, which emit large amounts of COX, SOX, and NOX into the environment. Electric cars and hydrogen vehicles are becoming increasingly popular, but the current refineries could use green hydrogen in their catalytic hydrogenation processes, reducing CO_2 emissions from natural gas steam reforming. It is predicted that extracting oil from the earth using current technologies may not be feasible by the mid-2050s. These issues, along with commitments to the Paris Agreement, net zero carbon by 2050, and containing global temperature rise, have spurred the development of a new clean energy alternative that must be renewable and compatible with existing infrastructure. Building new infrastructure quickly and cost-effectively is a daunting task, and there are only a few options available that can meet the essential characteristics of the energy supply chain: energy generation, storage, distribution, and utilisation.

6.1.8 Conclusion

The net zero plan aims to limit global temperature rise to below 1.5°C , requiring a reduction of CO_2 emissions from about 40 Gt to less than 10 Gt by using renewable energy sources instead of carbon-based ones. Green hydrogen will have a significant role in converting CO_2 into valuable materials and chemicals, and in 2050, renewable resources such as solar, wind, hydrogen, hydro, and nuclear energy will contribute about 73% of the required 49,000 TWh energy. Hydrogen production, including blue and green hydrogen, will account for about 24% of the total renewable energy and will be cheaper than grey hydrogen.

However, current CO_2 conversion technologies require high temperatures and pressures, and the activation of CO_2 is difficult, making them not economically viable. The development of efficient heterogeneous catalysts is essential to reduce the energy required for reactions, activate CO_2, and control selectivity toward desired products. In all these chemical processes, hydrogen is an essential energy carrier that must be produced using energy from other sources.

The sustainable methanol economy involves using renewable energy to produce methanol from captured CO_2 and cheap hydrogen. This method is seen as a potential solution to the world's energy crisis and to mitigate climate change. Catalytic hydrogenation of CO_2 for methanol synthesis has seen advancements in technology and has the potential to provide a carbon-neutral energy source by utilising CO_2 released from various industries. Hydrogen is typically produced from hydrocarbon processing, but renewable energy sources such as geothermal, wind, hydropower, and solar energy offer cheaper options for hydrogen production. The best approach is to produce hydrogen using renewable energy and use it for CO_2 hydrogenation to create methanol, DME, and ammonia. Thermochemical water splitting cycles, such as Cu-Cl, could be used for cheap green hydrogen production if coupled with solar energy, as demonstrated in the ICT-OEC hydrogen production technology.

DME is considered a second-generation fuel that has the potential to significantly reduce carbon emissions in the transportation sector and beyond. It can be produced in an ultra-low carbon or carbon-negative manner and has various applications including serving as a means to transition towards renewable hydrogen, blending with propane, and replacing diesel. Additionally, DME can be produced from captured CO_2 from flue gases or power plants.

The idea of carbon dioxide$_2$ refineries, which view CO_2 as a new oil reservoir, is not far-fetched. Hydrogen can replace fossil fuels in carbon-intensive industrial processes, such as steel and chemical industries. It can also help solve challenges in transportation that may not be easily addressed through electrification or other low-carbon fuels. Net zero emissions should be achieved much earlier than 2050, within the lifetime of many readers. Biomass, including waste and plastic waste, can serve as major sources for chemicals and materials through hydrogenation/hydrogenolysis and oxidation, contributing to environmental protection and providing fuel, materials, and energy.

Using bioethanol and other biomass derived chemicals to produce blue hydrogen is not a sustainable solution for achieving the net zero goal by 2050. Instead, carbon should be utilised as a source of chemicals and materials. Bioethanol is more valuable as a feedstock for biorefineries than as a fuel. Chemical recycling of waste plastics can also have significant benefits, as large quantities of plastic waste can be converted into fuels and chemicals using hydrogenation. It is important to implement a circular economy in all sectors and prioritise material recycling through physical, chemical, and biological means, while using green energy to reduce greenhouse gas emissions and combat climate change. Hydrogen will play a key role in achieving these objectives.

6.2

CO2 + H2: A New Pathway

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When an idea exclusively occupies the mind, it is transformed into an actual physical and mental state.

Swami Vivekananda

The global economy heavily relies on fossil fuels for energy, leading to an increase in GHG emissions[1]. According to the IEA, fossil fuels make up 80% of the world's total energy supply and contribute to 98% of global GHG emissions[2]. India's numbers are similar, with 73% of its energy supply coming from fossil fuels and 98% of its GHG emissions being attributed to them. Carbon-intensive industries such as iron and steel, cement, chemical and petrochemical, pulp and paper, and aluminium continue to contribute significantly to carbon emissions[3-4]. Decarbonisation programmes are necessary, and renewable energy systems that produce green hydrogen through electrolysis using solar or wind power offer a sustainable solution. The development of process pathways that convert redundant carbon into intermediates or chemicals for clean and sustainable use is necessary. Renewable energy integration and decarbonisation of current energy systems should go hand in hand[5].

Acar and Dincer[5-6] proposed a 3S (Source, System, Service) approach for hydrogen energy systems that use hydrogen as an enabler for the carbon recycling industry to combat climate change and the energy crisis. They found that the solar route is environmentally advantageous and provides a sustainable route for green hydrogen production.

This chapter discusses various ways in which green hydrogen (H_2) can be coupled with CO_2 capture and utilisation. The discussion includes realistic scenarios involving fossil fuels, biomass, and ammonia (NH_3). The first section examines the use of low-quality fossil fuels such as coal, and how they can be used with a green hydrogen production system. In the second section, the focus is on converting biomass into activated carbon or green hydrogen. The third section explores the coupling of green hydrogen and green ammonia. Finally, the chapter addresses the challenges associated with implementing green hydrogen infrastructure and achieving net-zero emissions.

6.2.1 Coupling Green Hydrogen with CO2 Abatement and Utilisation

Coal to Chemicals

Around 43-55% of India's total energy needs are fulfilled by coal[2-7], which is heavily carbon intensive. Despite this, it serves as a major raw material for petrochemicals and essential chemical industries. Methanol, a significant petrochemical product, is produced using a Cu-based catalyst in a catalytic reactor employing a mixture of CO and H_2, known as synthesis gas. This synthesis gas can be further used to produce olefins, gasoline, aromatics, ethers, ethanol, formaldehyde, or utilised in a fuel cell[8]. The generation of synthesis gas is the primary factor in the economy of the methanol synthesis process. The traditional approach to producing synthesis gas involves steam reforming of natural gas, followed by the water-gas-shift reaction to increase the hydrogen yield.

However, heavier feedstocks like coal or heavy hydrocarbons necessitate gasification. Downstream gases from a coal gasifier can be processed in a WGS reaction unit to produce CO_2 and H_2. The crude synthesis gas, containing sulphides and CO_2, is routed to an acid gas removal system to separate H_2S and CO_2 by absorption with methanol. The cleaned synthesis gas is then routed to a conventional methanol synthesis catalytic reactor to produce methanol and water vapour. The crude methanol product stream can then be concentrated using a distillation system[9-10]. The typical process flow sheet for such a process is shown in Fig. 1. The retrofitted CO_2 capture and sequestration (CCS) system can be ignored in the traditional route.

Clearly, the abovementioned chemical process is characterised by high CO_2 emissions. Coal gasification, for instance, is characterised by the following reactions:

$$C+H_2O \rightarrow CO+H_2 \qquad \Delta H = 131.4\ kJ/mol (8.1)$$

$$CO+H_2O \rightarrow CO_2+H_2 \qquad \Delta H = -42\ kJ/mol (8.2)$$

$$C+O_2 \rightarrow 2CO \qquad \Delta H = 172.6\ kJ/mol (8.3)$$

$$C+2H_2 \rightarrow CH_4 \qquad \Delta H = -75\ kJ/mol (8.4)$$

$$CH_4+2O_2 \rightarrow CO_2+2H_2O \qquad \Delta H = -890.3\ kJ/mol\ (8.5)$$

Therefore, to address the carbon emissions issue, the process needs to be updated with a CO_2 capture and utilisation system. There are two options available for this purpose: first is the permanent storage of CO_2 in geological formations such as the Tomakomai CCS demonstration project or the Drax Power limited bioenergy with carbon capture and storage (BECCS) project[12-13]. However, this approach may not be feasible in many areas where there are no such formations. Therefore, an alternative approach is to directly catalytically hydrogenate CO_2 to create carbon-based chemical products

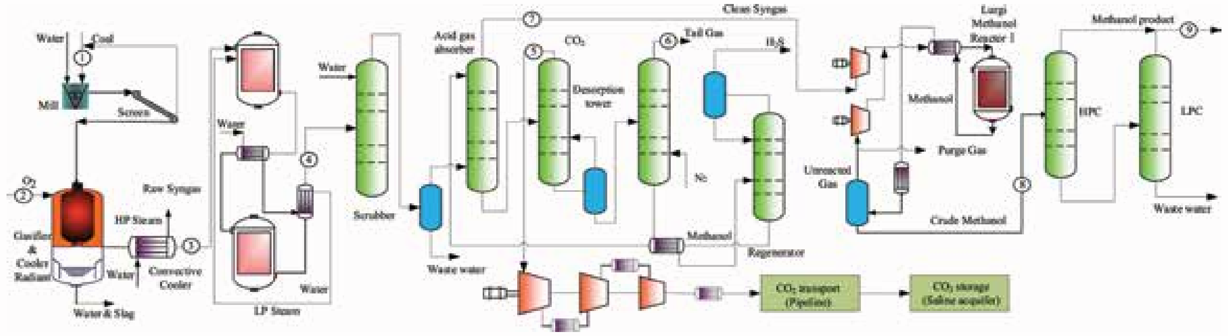


Fig. 1: Process flowsheet of a coal to methanol process retrofitted with CCS system [10].

such as methanol, dimethyl ether, or formic acid[14]. This method shows promise but requires high-purity hydrogen, which can be generated through water electrolysis powered by renewable energy such as solar or wind power. Water can be split into oxygen and hydrogen by passing electricity through two electrodes in the water, and this can be done using either alkaline electrolysers (AE) or proton exchange membrane (PEM) electrolysers. Large-scale systems require either unipolar or bipolar AE electrolysers connected in parallel or series, respectively. In contrast, solid polymer electrolyte (SPE) or PEM electrolysers utilise a solid proton conducting membrane, and they produce high-purity hydrogen streams[15-17]. The reactions involved in these systems are shown in Table 1, and the process flow sheet retrofitted with a green hydrogen production system is shown in Fig. 2, which is the same as the one in Fig. 1. Hongwei et al have discussed the suitability of the two schemes depicted in Fig. 1 and Fig. 2, which show the integration of green hydrogen production and CCUS during coal-to-methanol conversion. According to their findings, the use of green hydrogen in the coal-to-methanol process results in an energy efficiency greater than 50% with only indirect CO_2 emissions, which are less than 0.5 MT CO_2/MT CH_3OH. The estimated production cost is around \$200/MT CH_3OH, and the payback period is approximately six years with an internal rate of return of 11%. These values are lower than those of processes without CCS or green hydrogen production integration.

Biomass Valorisation

Unlike coal, which was discussed in the previous section, biomass is a renewable energy source that is low-cost and highly available. It has the potential to replace fossil fuels during the transition to solar, wind or hydropower. The importance of biomass energy consumption for nations to achieve their sustainable development goals (SDGs) has been previously reported by Güney and Kantar[18].

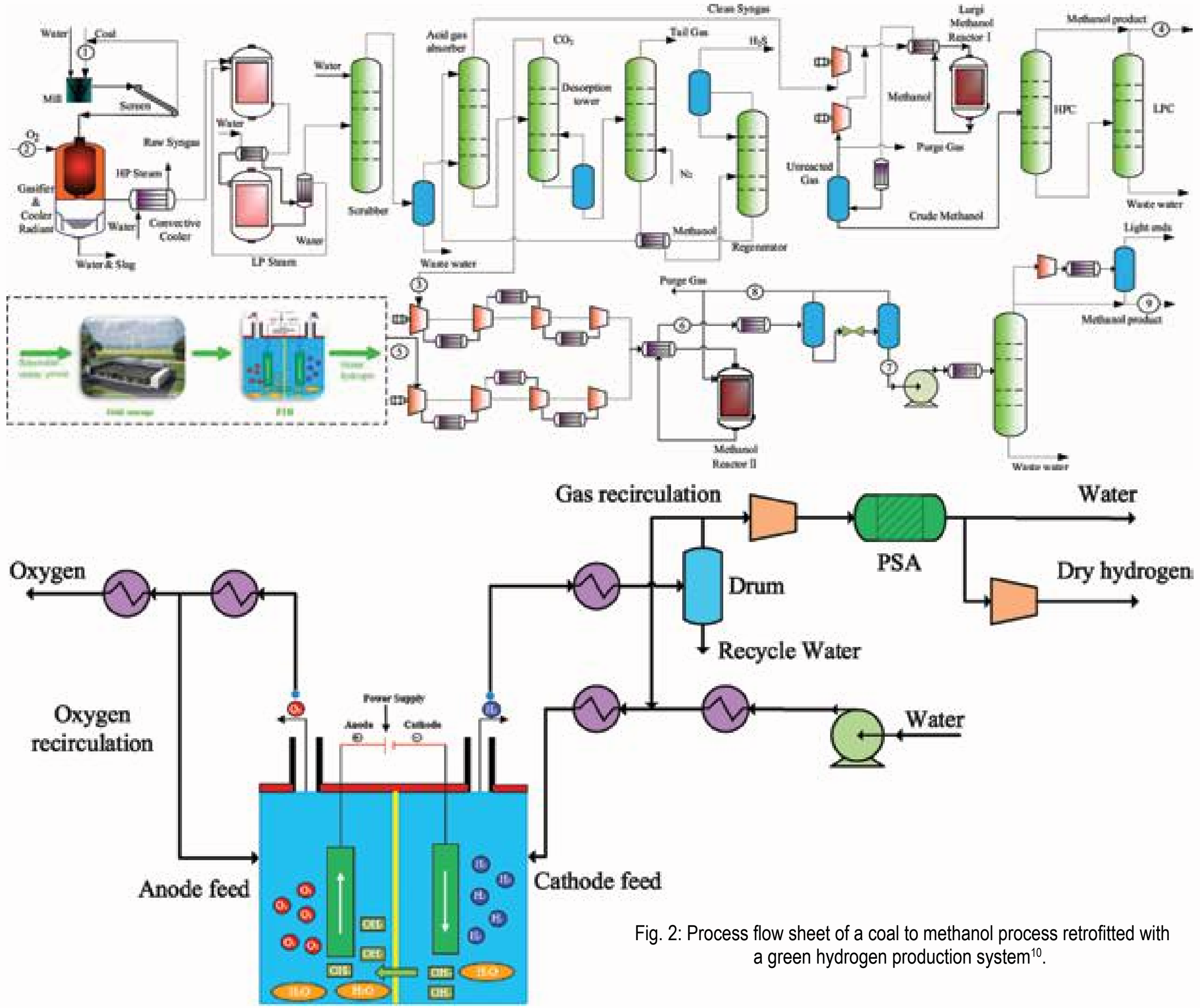


Fig. 2: Process flow sheet of a coal to methanol process retrofitted with a green hydrogen production system[10].

The concept of biorefinery is strategically important for nations in this regard, as it has the potential to produce chemicals and biopolymers. However, it is critical to achieve sustainability in the process[19-20]. Biomass gasification can be used to produce synthesis gas consisting of CO, CO_2, H_2, and CH_4. It has been documented earlier as a competitive and cost-effective solution for rural electrification in comparison to photovoltaic systems or even grid extension[21-22]. Biomass pyrolysis and fermentation also offer alternative approaches for energy generation.

Biomass processing through gasification or pyrolysis, as discussed in section 8.2.1, also produces carbon dioxide. However, unlike coal, biomass is a renewable resource and the amount of CO_2 generated is not considered excessive as it can be reabsorbed by plantations. The CO_2 produced can be separated using solid adsorption, liquid amine absorption, or chemical looping processes[23]. Other technologies for CO_2 capture and utilisation, such as rotating packed beds, membrane reactors, microreactors, biological processes, electrochemical processes, and plasma technology-based processes, are available for pilot and demonstration level deployment[24].

The resulting CO_2 stream can be hydrogenated to produce methanol or other high-value chemicals, while the biomass can be converted into value-added products like activated carbon. Achieving sustainability in these processes is critical, and the biorefinery concept holds strategic importance for nations to achieve their sustainable development goals.

The process flow scheme in Fig. 3 illustrates an example of a typical process for converting biomass to hydrogen while capturing CO_2. This process involves several stages including biomass drying, pyrolysis, bio-char activation/combustion, flue gas reforming, and chemical looping. The first stage is drying the biomass to remove moisture and generate steam. Pyrolysis follows to break down the large biomolecules in the dried biomass into small molecules, which generates flue gas and solid bio-char. Flue gas, and steam are then mixed in a reforming reactor to produce hydrogen, which also contains CO_2.

The carbon dioxide is then separated in a chemical looping unit, where it is treated with quicklime (CaO) to form $CaCO_3$, effectively separating it from the hydrogen gas mixture. The $CaCO_3$ is then transported to a second reactor where the calcination process takes place, generating CaO and pure CO_2. By circulating CaO and $CaCO_3$ in two heat-integrated reactors, much of the CO_2 can be absorbed in-situ and an enriched hydrogen gas mixture is produced in the output stream. The remaining CO_2 in the gas mixture can be used during the conversion of bio-char to activated carbon in the activation unit or directed to other industries[25]. The hydrogen produced can also be directed to a fuel cell.

The process depicted in Fig. 3 can also be modified to produce hydrogen instead of activated carbon. In this case, a combustor is added after the pyrolysis step to burn the biochar and generate flue gas, which is then directed to a reforming unit for hydrogen production. The CO_2 generated in this process can be captured using a chemical looping unit with CaO as the carrier.

This approach has been preferred over liquid amine absorption or adsorptive separation due to its inherent advantages such as internal circulation and on-site utilisation of CO_2, and no external supply of CO_2 is required for activated carbon production[26-27]. However, this process consumes more steam for hydrogen production, and CO is generated as a by-product. The reactions involved in each section of the process are given in Table 2. Additionally, it has been reported that the process schemes in Fig. 3 are CO_2 negative.[25]

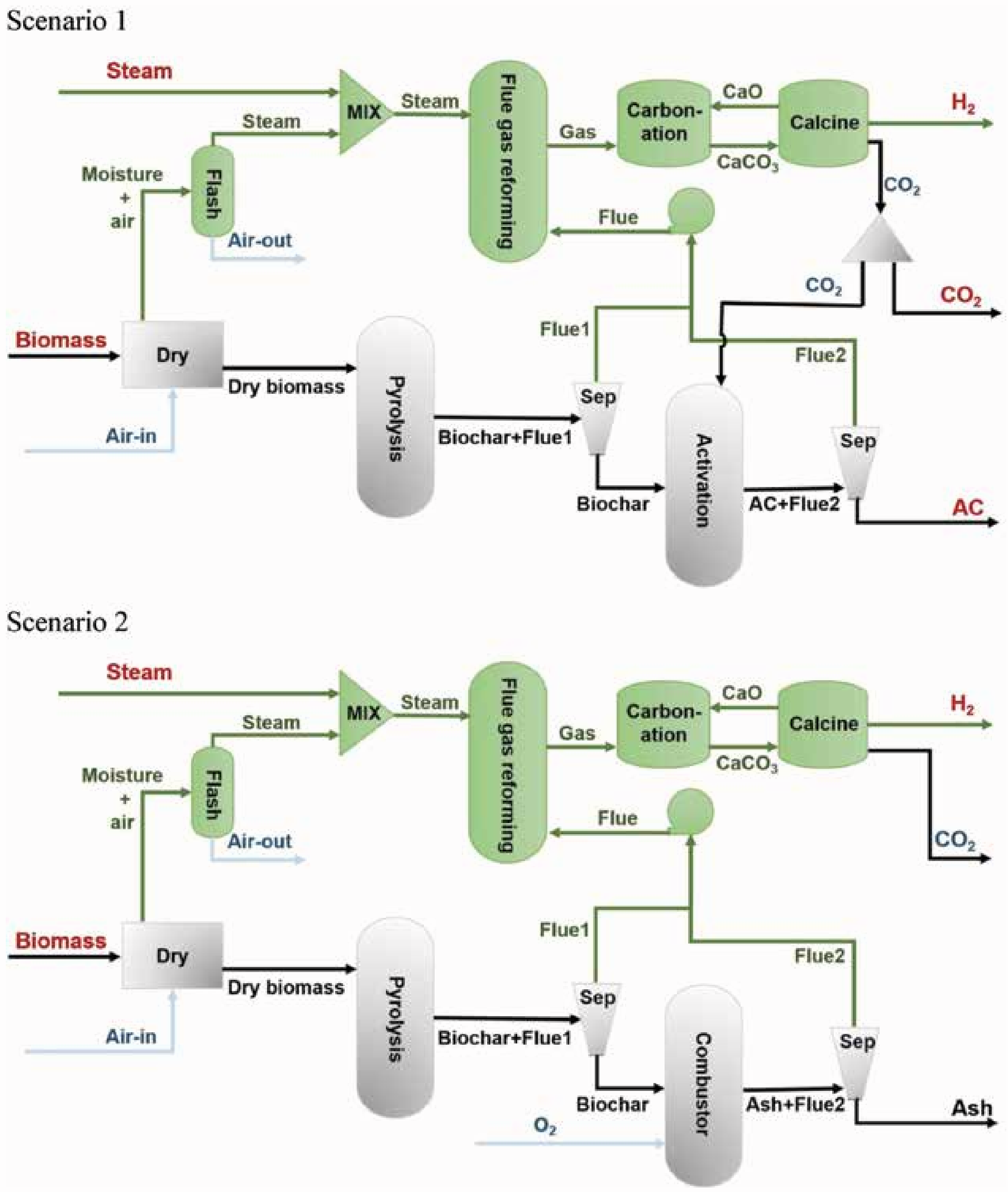


Fig. 3: Process flow sheet for the biomass to activated carbon and biomass to hydrogen process [25].

Table 2: Reactions involved in the different sections of the biomass conversion process given in Fig. 3[25].

Pyrolysis	Complex process
Activation	$C+CO_2 \rightarrow 2CO$
Flue gas reforming	$CO+H_2O \rightarrow CO_2+H_2$ $CH_4+H_2O \rightarrow CO+3H_2$
Chemical looping	$CaO(s)+CO_2(g) \rightarrow CaCO_3$ $CO+H_2O \rightarrow CO_2+H_2$ $CH_4+H_2O \rightarrow CO+3H_2$

6.2.2 Coupling Green Hydrogen and Green Ammonia

Earlier, we discussed the conversion of coal and biomass into various products such as synthesis gas, methanol, activated carbon, and hydrogen. However, a major challenge is the need for a relatively pure CO_2 stream to be obtained from these processes for its utilisation in valuable chemical production such as methanol. On the other hand, green hydrogen and green ammonia are considered the ultimate clean energy solutions as they do not contain carbon[28-29]. Green hydrogen can be produced through water electrolysis powered by renewable energy sources. Ammonia, which can replace hydrogen in some applications, can also be produced in three major categories: brown, blue, and green ammonia. The traditional method for ammonia production is the Haber-Bosch process that uses iron-based catalysts with Al, Zr or Si and K oxides as promoters. The raw materials needed for this process are air, water, hydrocarbons (natural gas or naphtha), and power.

The reaction for ammonia synthesis is given below:

$$N_2+3H_2 \leftrightarrow 2NH_3$$

Increasing the pressure favours the equilibrium yield of ammonia in the exothermic reaction. However, a rise in temperature has a negative impact on the equilibrium, although it increases the reaction rate. Therefore, it is important to maintain optimal operating conditions for profitability. The ammonia production process consists of six stages: (1) production of reactant gases, (2) purification, (3) compression, (4) catalytic reaction, (5) recovery of ammonia, and (6) recirculation. However, brown ammonia manufacturing units are known for emitting excessive amounts of CO_2. When a carbon capture system is added to a brown ammonia unit, the resulting ammonia is referred to as blue ammonia.

Green ammonia is produced by using green hydrogen, which is generated through solar water splitting or other renewable sources, and nitrogen obtained through an air separation unit[28]. The Haber-Bosch reaction is then carried out using the nitrogen and hydrogen to produce ammonia. The process does not require a steam reforming unit, shift converters, or methanators. In addition to the major sections, there is a deoxygenation and hydrogen compression unit.

The ammonia synthesis loop is similar to the traditional design. Various demonstration projects are already commissioned worldwide to explore the potential of green ammonia to reduce CO_2 emissions. These include Yara and Linde's 24 MW green hydrogen demonstration plant in Norway[30], CF industries' 20 MW green hydrogen installation to produce 20,000 TPY plant of green ammonia using technology provided by Thyssenkrupp[31-32], and Stamicarbon's 70 MW power to fertiliser plant in Kenya[33]. In India, NTPC REL and NFL have signed an MoU to explore opportunities for the supply of a 90 MW RE-round the clock system to produce 50 TPD of green ammonia by NFL[34]. The process is depicted in Fig 4b. Research has already produced novel Li-, Ru-based catalysts and non-noble metals to enable N2 reduction to ammonia at lower temperatures and pressures, with improved kinetics.[28]

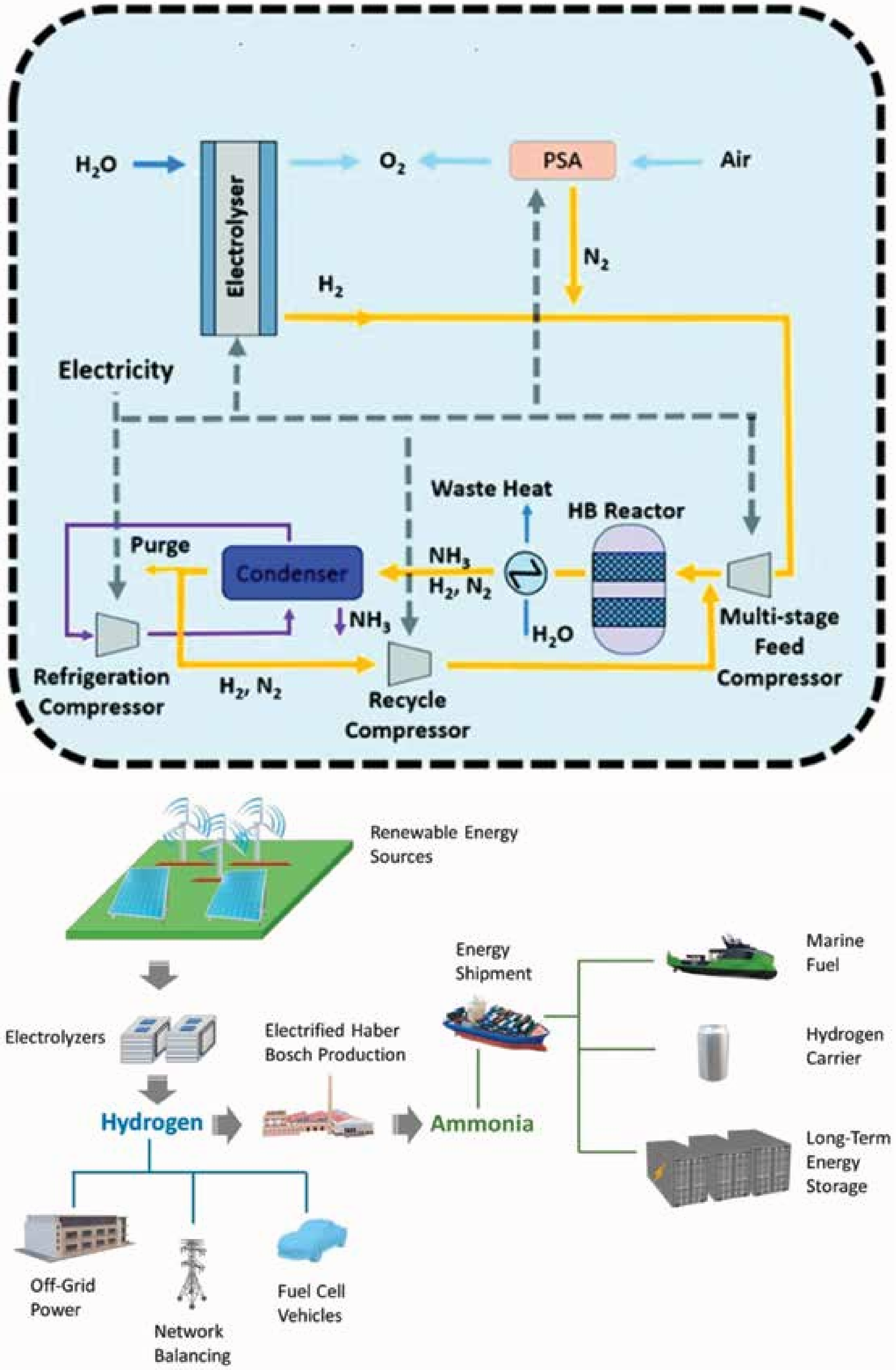


Fig. 4(b): Green hydrogen-driven e-Haber Bosch process and a proposed green hydrogen and green ammonia production unit[28].

Challenges

The transition to a carbon-free economy by deploying green hydrogen systems is a challenging task, despite many feasibility and demonstration studies presenting positive results.

Acar and Dincer[5] have outlined four steps for the transition towards a fully developed and sustainable hydrogen economy, including research, innovation, technology development, and commercialisation; initial market penetration and infrastructure development for small, large, stationary, and portable needs; ensuring availability of hydrogen to all end-users by making the system commercially viable; and the creation of a fully developed hydrogen infrastructure and market available in all regions for all types of demands. Recently, a popular newspaper opinion piece emphasised that governments must create policies to increase domestic demand, such as blending mandates and procurement of green hydrogen-derived products, like green steel, green methanol, and green ammonia. Public funds should be allocated to support R&D for novel electrocatalysts and scale up their production in the form of electrolyser stacks. National and global green chemical supply chains must be developed, and partnerships must be capitalised to establish rules and standards for the hydrogen economy and market[35].

In terms of safety, the use and supply of hydrogen pose additional challenges. The public should be educated about hydrogen's properties, such as its lightness, low minimum ignition energy, and flammability limit in air. Hydrogen also heats up upon expansion, and loss of containment must be considered during the development of green hydrogen infrastructure. Embrittlement can cause explosive mixtures, and safety measures must be taken to prevent accidents. To ensure safety, a dedicated pipeline supply network would be required for hydrogen refuelling stations, but this may not be cost-effective in the short term.

Liquid hydrogen can be transported by tankers from green hydrogen generation facilities to refuelling stations. Hazard identification analysis must be conducted to identify release scenarios and their potential consequences. These scenarios could be caused by design and construction failures, equipment failure, incorrect operation, road traffic accidents, or contamination. Consequences could include fire, explosion, BLEVE, dispersion, and no release. However, there is a lack of available models and experimental data for such incidents[36-37].

The water electrolysis unit is a crucial part of the process pathways discussed in sections 8.2 and 8.3 for producing green hydrogen. There are various types of electrolysers available, and choosing the right technology is critical, considering factors such as efficiency, durability, operating conditions, capital and operating expenditure, and rate of return.

Table 3 outlines these parameters for AE and PEM, which are presently the standards for commercial green hydrogen production. However, the lifetime of the stack is highly dependent on several factors such as the nature of the electrolyte, applied current density, voltage range, electrode materials and their thickness, membrane type, catalyst loading, operating hours, and load variation, despite the original equipment manufacturers (OEMs) claiming the stack lifetimes.

The efficiency of the stack is directly related to the efficiency of electrochemical reactions. Resistance due to electrical and ionic factors, as well as the electrode and electrolyte used, should be considered. Higher current density leads to higher hydrogen production rates, but it reduces efficiency due to ohmic, activation, and mass transport losses, which ultimately results in higher power requirements. Electrode efficiency can be improved by increasing the electrochemical active surface area using novel mixed oxide electrocatalysts such as Co-, Ni-, and Fe-based oxides, which possess low internal resistance. Operating conditions must be such that they do not reach corrosive limits, and superhydrophilic or superaerophobic electrodes can optimise current density and increase hydrogen production rates[17,28,38,40].

The stability of diaphragm membranes can be affected by various factors, such as an alkaline environment, gas permeation, impurities, local hot spots, and high temperatures. To prevent gas crossover and ensure electrolyte resistance, it is necessary to develop novel diaphragm membranes[17,39]. Additionally, improper water circulation and a demand for ultra-pure, demineralized water can pose challenges to the deployment of electrolysis units.

A decrease in water quality can also reduce the cell or stack lifetime. At present, OEMs require ultra-pure water, which may be a hidden cost, particularly in areas with severe water stress. Reverse osmosis units are commonly used to desalinate water, but high recoveries are essential to minimize water wastage. Research is needed to assess the suitability of non-distilled water or wastewater in electrolysis plants. Beswick et al. [41] suggest that water supply will not be a limitation for green hydrogen electrolysis units because the energy cost of RO desalination units is only $0.53-1.50 per m3 of clean water produced, which hardly affects the cost of hydrogen production. They argue that improving electrolyser technology and integrating it into current energy systems are critical for the deployment of green hydrogen.

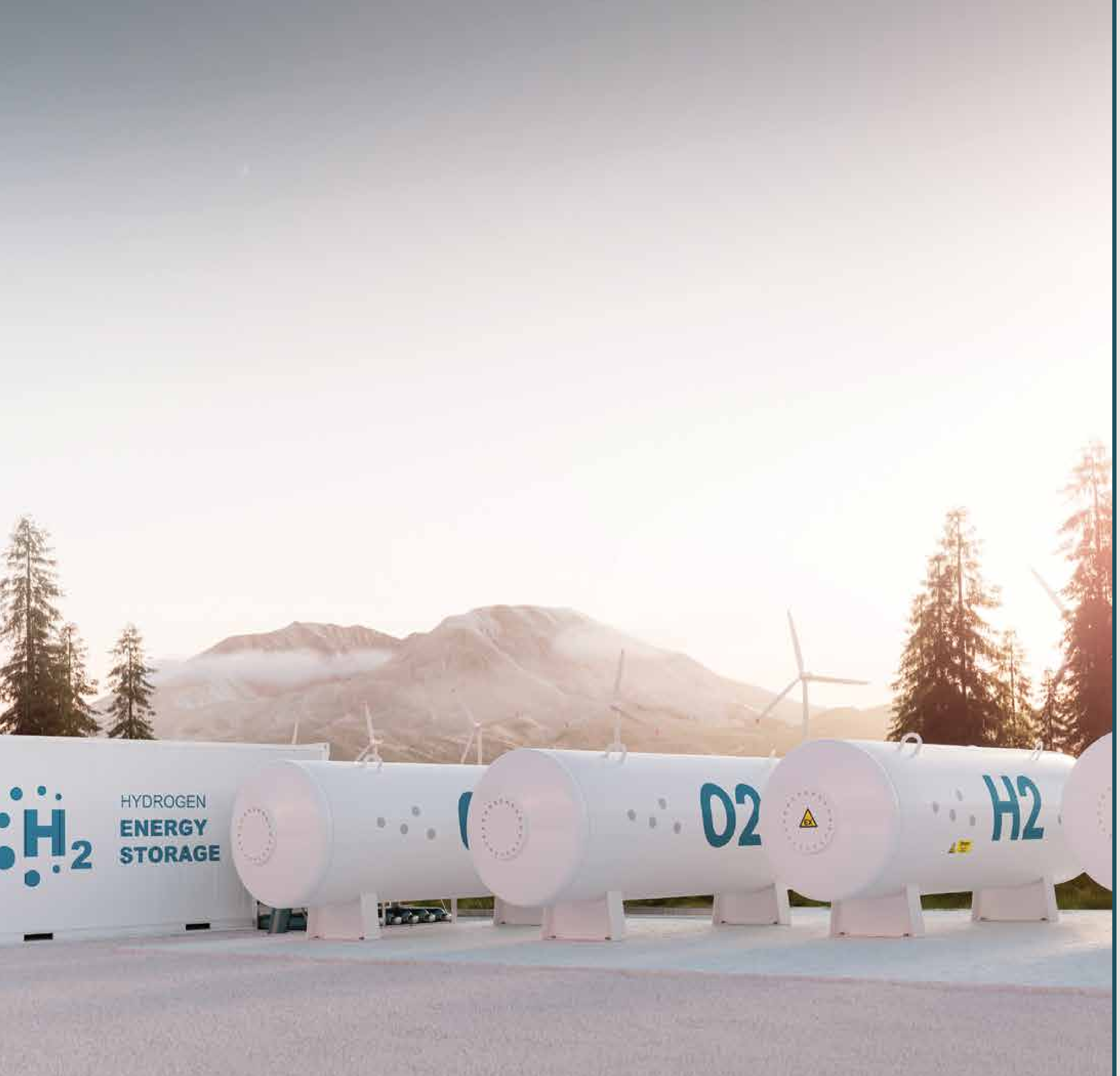
Converting green hydrogen to green ammonia can help avoid safety concerns associated with hydrogen use. While several catalytic methods for conversion have been reported, further research is necessary to understand the reaction mechanisms involved and how green hydrogen and green ammonia synthesis systems can be integrated.

Table 3: Electrolysis technology selection factors[17,39].

	Stack life (h)	Stack efficiency	Capex (system)	Opex	Nominal current density (A/cm^2)	Voltage range, V	Temperature range (°C)	Pressure range (bar)	Electrolyte	Carrier	Capacity (Nm^3/h)
AE	100,000	78%	700-900 $/kW for 20 MW capacity	3% of Capex	0.4-0.8	1.4-3	Ambient - 120	1-200	25-30 wt% $(KOH)_{aq}$/ $(NaOH)_{aq}$	OH^-	1-500
PEM	10,000-50,000	66%	900-1200 $/kW for 20 MW capacity	2% of Capex	0-3	1.4-2.5	50-80	1-350 (700)	perfluoro-sulphonic acid (PFSA)	H^+	1-250

Although ammonia is toxic and energy-intensive to decompose[28], it can serve as an energy carrier for storing hydrogen for longer durations. However, ammonia combustion can lead to NOx emissions, which can be more harmful than CO_2 emissions. Hence, technologies to convert ammonia back to hydrogen are being explored.

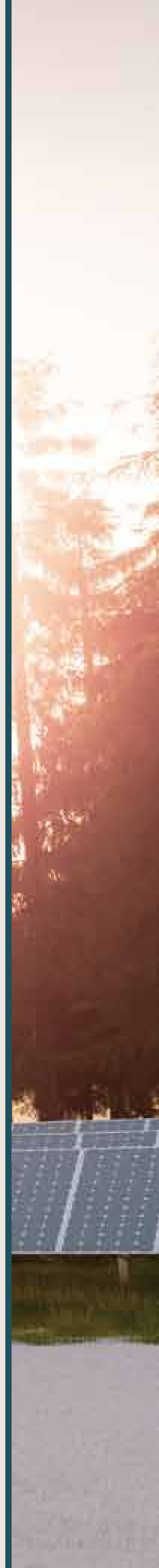
Developing a robust mix of clean energy systems is important for a carbon-free future, and green hydrogen energy solutions can play a significant role. Nonetheless, there are technical and policy challenges that need to be addressed, and the relationship between key chemicals such as methanol, ammonia, and green hydrogen requires further exploration.



SECTION -7

CLIMATE CHANGE MITIGATION THROUGH FUSION OF ANCIENT WISDOM WITH GREEN ENERGY

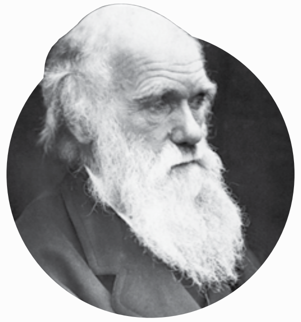
Learning from Nature – the Regenerative Perspective on Business and Leadership | Lifestyle for Environment Circular Economy | Spiritual & Cultural Transformation the Only Way to Mitigate Climate Change | Inner and Outer Peace Under Speaking Tree | Messages from Hon'ble Prime Minister of India, Shri Narendra Modi



7.1

Learning from Nature – the Regenerative Perspective on Business and Leadership

DR KAREN LANDMARK, Chair of the Board, Greenstat ASA, Norway



> It is not the strongest species that survive, nor the most intelligent, but the one most able to adopt to change.
>
> **Charles Darwin**

Centuries of social, economic, and technological change have influenced our relationship with nature. While humans have traditionally relied on the natural world for sustenance, spiritual practices, and general well-being, recent decades have seen an unprecedented strain on this relationship. We are deeply connected with the stress we place on our ecosystems, and this is reflected in the growing global mental health crisis. Climate change, deforestation, ocean acidification, and loss of biodiversity are pushing the planet's limits and have potentially catastrophic consequences. These crises are linked to social, economic, and political factors, making a holistic approach to addressing them necessary. Our relationship with nature is fundamental to survival and well-being for all life on earth, rather than a matter of aesthetics or morality. Therefore, it is essential to recognise and address the root causes of these crises and work towards creating a more sustainable, just, and harmonious relationship with the natural world.

How and why have humans ended up in a negative spiral? For most of human history, we have lived in harmony with nature, respecting its rhythms and cycles. However, in recent centuries, our way of life has dramatically changed, and human activity has fundamentally altered the planet, resulting in the new era called Anthropocene. Over 50% of the world's land shows signs of human activity. For example, the fertiliser industry binds more atmospheric nitrogen than all ecosystems combined, the fishing industry depletes marine organisms, and the global animal population has decreased by around 60% since 1970. Our actions cause emissions that are the root cause of climate change, and our demand for materials and food leads to land degradation. Despite these negative effects, our cities have grown, and we have made incredible advancements. While modern life can be fulfilling for many, it is important to understand the reasons for our negative impact and work towards a more sustainable relationship with nature.

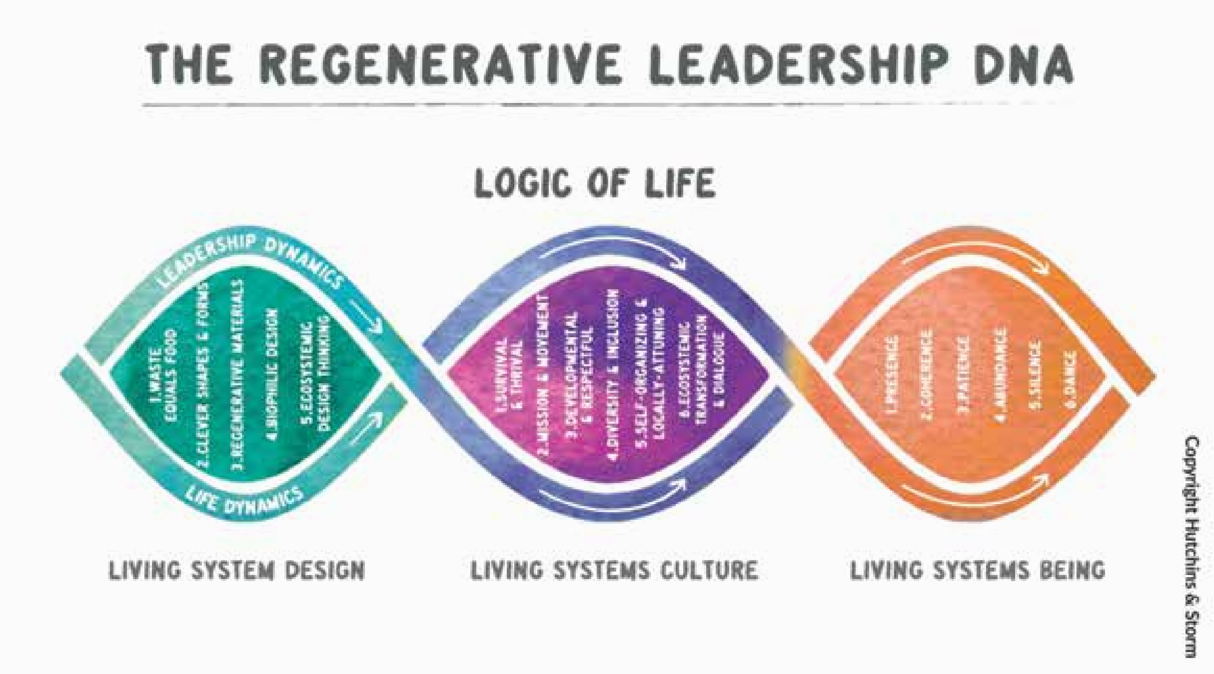
To put it differently, the reason behind the downward spiral that humans are currently in, and the logic that led to it, is a crucial topic for discussion. For most of human history, we lived in harmony with nature and its rhythms, but over the last few centuries, our way of life has caused irreparable harm to the planet, and this era is now known as the Anthropocene. Our activities have caused significant damage to ecosystems, leading to issues such as polluted air and water, income inequality, and a general sense of unease. Our civilisation's principles have strayed from the 'logic of life', which relied on living with nature and not merely exploiting its resources. We must find ways to restore our relationship with nature, and leaders need to have a deep understanding of the complex challenges we face to address them effectively.

What is Regenerative Leadership and Why is it Important

The concept of regenerative leadership, which is rooted in ancient ideas, is a new idea that focuses on the lessons that nature can teach us about leadership and the type of leadership that is necessary to deal with the growing complexity of the global landscape. This type of leadership philosophy emphasises the need to have a positive impact on both people and the planet, taking a holistic approach to balancing economic, social, and environmental sustainability to promote thriving and regenerative communities. Regenerative leadership is distinct from the idea of sustainability in a business and leadership context, which focuses on making less harm and leaving nature in the same state it was presented to us. The regenerative perspective acknowledges that we have already shifted the baseline and that nature is currently out of balance. Therefore, our actions should contribute to the regenerative power of nature and assist in restoration. This approach applies the 'logic of life' and reconnects the inner and outer ecosystems, values diversity, relations, and interconnectedness, and aligns humanity with the cyclic nature of our ecosystems. Unlike traditional leadership styles that prioritise short-term gains, regenerative leadership prioritises long-term success through collaboration, inclusiveness, and value-driven decision-making.

Laura Storm and Giles Hutchins argue in their book Regenerative Leadership: The DNA of Life-affirming 21st Century Organizations that there is a missing link between our inner and outer living systems when it comes to leading and operating organisations and communities. They suggest that we can apply the wisdom of nature to business by viewing an organisation as a living system that is constantly evolving, rather than as a machine that needs fixing. Additionally, they suggest that we can understand an organisation's place and role within its surrounding environment and ecosystem. By applying living-system logic to product design, organisational culture, and our own being, we can gain new perspectives and innovations that support life.

Storm and Hutchins propose five principles that leaders can follow to apply the 'logic of life' in their leadership style. Firstly, they should adopt life-affirming circular principles, such as creating a safe and evolving environment for people to grow and fail, as well as incorporating regenerative materials. Secondly, leaders must acknowledge the constant change in everything and thus build self-organising systems that do not conform to hierarchical structures. Thirdly, they should recognise the interconnectedness of all life and seek to form win-win-win partnerships with others and nature. Fourthly, leaders should embrace diversity and actively seek individuals from different cultures and educational backgrounds to bring new ideas and growth. Finally, leaders must acknowledge the cyclical nature of life and



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create organisations that are in tune with seasonal changes, allowing time for rest and reflection, actively listening and encouraging contemplation, meditation and reflection.

(Re)aligning with nature.

Do not harm the environment; do not harm the water and the flora; earth is my mother, I am her son; may the waters remain fresh, do not harm the waters. Tranquillity be to the atmosphere, to the earth, to the waters, to the crops and vegetation.

– A Vedic prayer.

The Vedic tradition places a strong emphasis on ecological balance and protection of the environment. The Vedas acknowledge the importance of maintaining a cyclic pattern in nature, balancing elements, and other natural phenomena. According to an article published in the Times of India by K.N. Sharma in 2009, the seers of the Vedas believed that the well-being of Mother Earth was dependent on the preservation and sustenance of the environment. They prayed for forgiveness for any inadvertent actions that might lead to excessive exploitation of the earth. The seers spoke on behalf of the earth, advocating for its principle of replenishment: 'You give me, and I give you.' They emphasised the need to protect the earth and its vital organs from harm and damage, recognizing that the earth is our mother and we are her sons. The Vedic tradition encourages a deep respect for nature and its interconnectedness with all living beings, and advocates living in harmony with the natural world.

Currently, there is a growing awareness of the level of human impact on nature. This awareness is not only evident visually, but it is also felt physically, mentally, and spiritually. As a result, a new paradigm is emerging that seeks to realign humanity with nature by working in harmony with the finely tuned and cyclical natural world instead of working against it. Unlike our current linear economic system that relies on unsustainable and wasteful principles, nothing in nature goes to waste. Therefore, this is a defining moment in human history where we can adopt the knowledge inherent in all systems and discard that which is detrimental to life. Regenerative leadership across all our organisations can be a valuable tool in reconnecting our inner and outer ecosystem, with the potential to rebuild a life-affirming economy that is in balance with our natural resources.

7.2

Lifestyle for Environment

DR J P GUPTA, MD, Greenstat Hydrogen India Pvt. Ltd.

We are the Environment.

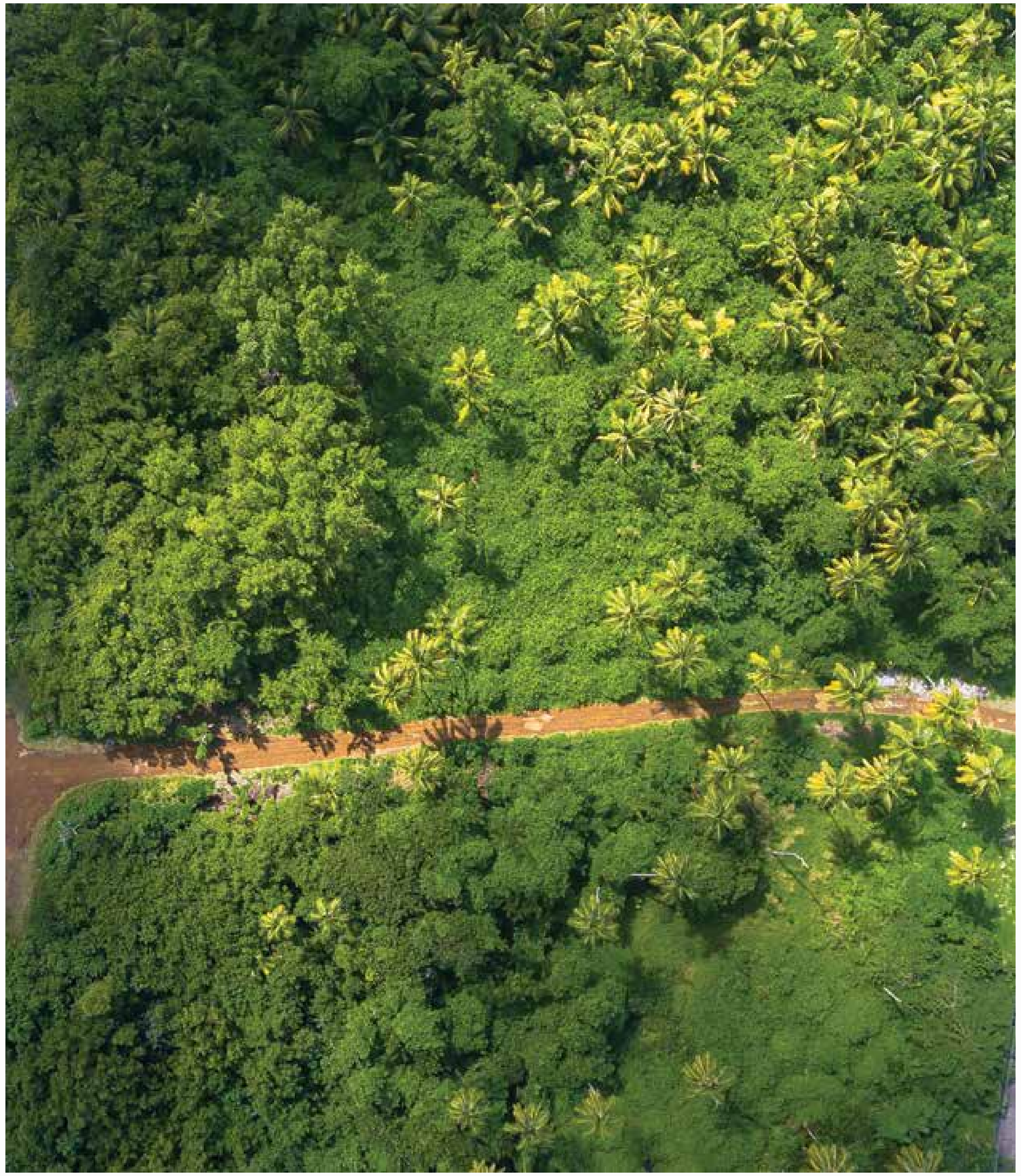
Charles Panati

United Nations, Climate Change | UN Climate Change Conference U.K. 2021

The degradation of the environment and the impact of climate change are worldwide issues that have effects on ecosystems and people all around the planet. It's been projected that if corrective actions are not taken, around 3 billion people could experience long-term water scarcity, and the global economy could suffer a reduction in GDP of up to 18% by 2050. In the past 20 years, many significant measures have been implemented globally to address these problems, including policy changes, economic incentives, and regulations. However, not enough attention has been given to individual, community, and institutional actions, which can also have a substantial impact. The United Nations Environment Programme (UNEP) has indicated that if one billion individuals out of the world's population of eight billion adopt environmentally friendly behaviour, carbon emissions could be reduced by about 20%.

In this context, the term 'Lifestyle for the Environment (LiFE)' was introduced by Prime Minister Narendra Modi during the COP26 in Glasgow on 1st November 2021. It aims to encourage individuals and institutions to adopt a mindful and sustainable way of living to protect and preserve the environment. LiFE places an individual and collective responsibility on everyone to lead a lifestyle that does not harm the earth, and those who practice such a lifestyle are recognized as Pro Planet People (PPP).

However, changing one's lifestyle can be challenging as habits are deeply ingrained in our daily lives and are continually reinforced by our environment. To overcome this challenge, the LiFE 21-Day Challenge has been launched in India, which encourages people to take one simple environment-friendly action daily for 21 days to develop sustainable habits. The challenge aims to help people change their lifestyle one step at a time and become Pro Planet People. Research suggests that it takes at least 21 days of practising an action to turn it into a habit.



7.3

Circular Economy

DR J P GUPTA, MD, Greenstat Hydrogen India Pvt. Ltd.

All the differences in the world are of degree, and not of kind, because oneness is the secret of everything.

Swami Vivekananda

India has set an ambitious goal of becoming a five-trillion-dollar economy by 2025, which could result in increased resource and energy consumption and waste generation. However, to achieve this target while adhering to sustainable development principles, it is crucial to minimise our carbon footprint and prioritise circular economy principles. The circular economy emphasises reusing, repairing, refurbishing, remanufacturing, and recycling, which can help reduce waste that ends up in landfills or incinerators, lower carbon emissions, and promote the use of clean energy.

Unlike linear systems that focus on creating, using, and disposing of products, circular systems are closed-loop systems that extend the use of products and make use of old equipment for refurbishment or new product creation. This approach reduces the need for raw materials, resources, energy, and polluting processes.

In addition, circular economy principles can be applied to all sectors, and the regenerative approach can counter the capitalist society's throwaway attitude of make, use, and dispose. The developing world has been implementing circular strategies for a long time due to a lack of resources, which has resulted in reusing, recycling, and remaking objects with the same or different purposes, leading to significant material and cost savings.

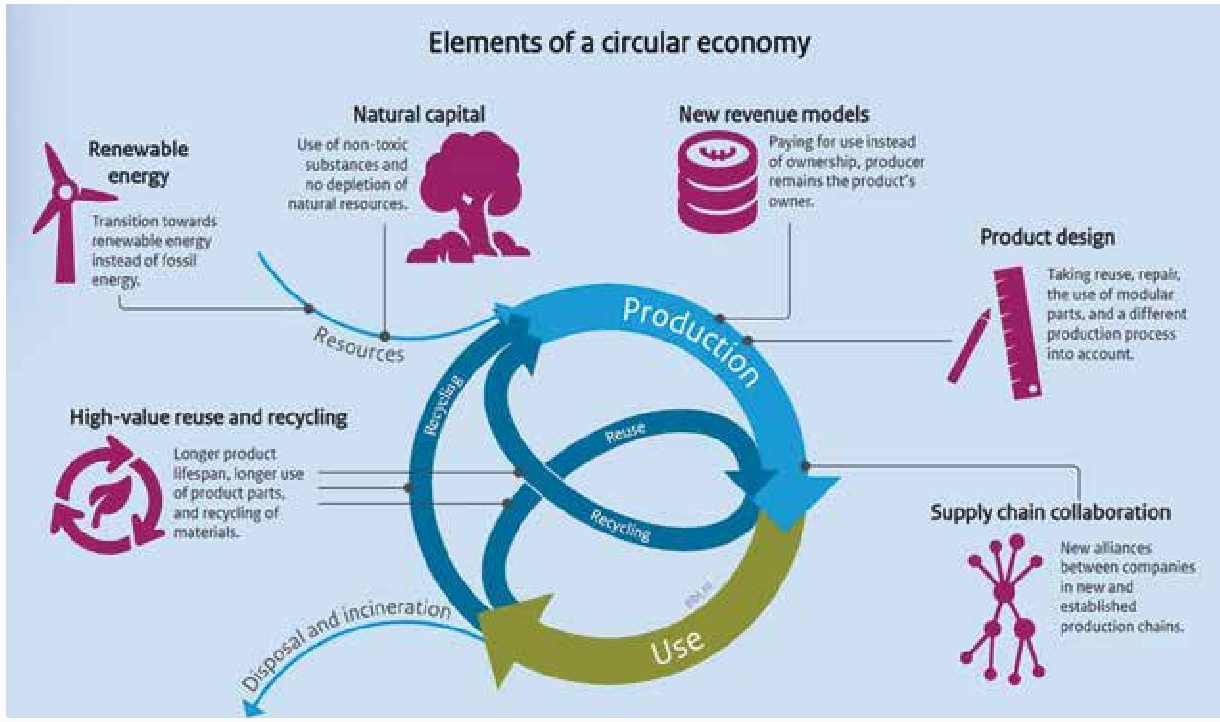


Fig. 1: Some of the elements of a circular economy mentioned above and others in relation to each other (Source: PBL, 2019)

The three R's of the circular economy, reduce, reuse, and recycle, are critical to its success. By reducing the use of raw materials, reusing products and components as much as possible, and recycling materials in high-quality ways, we can move towards a more sustainable and regenerative economy. In addition to these strategies, circular systems also promote the sharing of resources, such as through product-service systems and collaborative consumption models, which can further reduce waste and promote sustainability. It's essential to adopt circular economy principles in all sectors, including manufacturing, agriculture, energy, and transportation, to achieve sustainable economic growth while protecting the environment.

Stringent environmental laws will force many non-compliant vehicles off the roads, creating opportunities for circular strategies to reuse old parts in remade vehicles. The plastic industry is another sector with great potential for circular economy. Of the 8.3 billion MT of plastic produced globally between 1950 and 2015, as much as 6.3 billion MT became waste, with 4.9 billion MT ending up in dumpsites. With plastic manufacturing expected to increase, circular strategies that encourage reuse, recycling, remanufacturing, and safe disposal can help reduce the amount of plastic waste. Waste plastic can be used for thermal insulation of houses. Last year, major Indian plastic industries formed an alliance against plastic waste, and more than 700 electronics producers have come together to reduce e-waste. The textile industry also has significant potential for reusing, repairing, refurbishing, remaking, and recycling clothing, which would reduce the loss of natural resources worth over $500 billion annually. Economic analysis suggests that the circular economy could bring annual benefits of Rs 40 lakh crores in three key areas: cities and construction, food and agriculture, and mobility and vehicle manufacturing by 2050. However, India's material consumption is expected to rise from 7.5 billion MT in 2015 to 15 billion MT in 2030.

India currently extracts resources, including mining of virgin resources, at a rate almost three times higher than the global average. To reduce consumption and waste, the government is aiming to improve resource efficiency and waste management, with a target of achieving a 50% recycle rate for key materials within five years. This will require the establishment of a National Resource Efficiency Authority to develop strategies for key sectors, such as automobiles, plastic packaging, building and construction, electrical and electronic equipment, solar photovoltaic, and steel and aluminium. The British Standards Institution has already launched the standard 'BS 8001:2017' to promote circular economy principles in organisations. India is also considering implementing its own regulatory framework, including a National Material Recycling Policy, National Policy on Resource Efficiency, and a Bureau of Resource Efficiency. The integration of resource circularity in Industrial Revolution (IR) 4.0 strategies is also important. By 2030, circular economy may provide opportunities worth $218 billion per year in India. With an increasing human population, resource efficiency and circularity are necessary for sustainable development. Resource efficiency and waste management must become the key drivers of a green strategy to create growth, new enterprises, and a clean environment.

7.4

Spiritual & Cultural Transformation the Only Way to Mitigate Climate Change

DR J P GUPTA, MD, Greenstat Hydrogen India Pvt. Ltd.

You have to grow from the inside out. None can teach you, none can make you spiritual. There is no other teacher but your own soul.

Swami Vivekananda

Human activities are causing climate change and global warming, and the burning of fossil fuels is contributing to this acceleration. The global average temperature has risen 1.4°C since 1880, with nine of the 10 hottest years on record occurring since 2000. CO_2 levels have reached 400.84 parts per million, the highest levels in the last 650,000 years. In certain parts of northern India, temperatures have surpassed 47°C for the first time ever since March 2022.

Evidence from various sources like ocean sediment, ice cores, tree rings, sedimentary rocks, and coral reefs indicates that the current warming is occurring 10 times faster than it did in the past. Human reliance on fossil fuels, consumption-oriented economies, the drive for ever-increasing profits and continuous growth have all contributed to the modern world's development dreams. For decades, we have assumed that the destruction of nature is inevitable in the face of progress. But, the decreasing forest cover, high levels of pollution, and extreme weather changes have disproved this notion. The way we have and continue to act is endangering life on earth, including the lives of all plants and animals.

The reality that we cannot continue to harm nature for development or remain indifferent to environmental damage is finally being acknowledged worldwide. The focus is now on finding a new paradigm for economic growth, called Sustainable Growth or Sustainability, that will not compromise the environment. This search is intensifying as people look for a new philosophical foundation that puts nature ahead of human self-interest, recognising the fundamental interconnectedness of all things. Natural science is not merely a description of nature, but rather an aspect of the interplay between nature and humanity. When the universe is perceived as a single large family, which includes all living beings, ecological harmony is possible. This worldview was recognised by the Vedic civilisation, which proclaimed *vasudhaiva kutumbakam.*

It was later reinforced by the Upanishadic Age's philosophical framework of cosmological unity and sustainability. Such a holistic worldview can provide a new development paradigm, a novel socio-economic system free of exploitation, and a redefined relationship between humans and nature, thereby achieving the ecological balance that is essential today.

The concept of sustainability is often seen as futuristic, but we tend to overlook the valuable lessons that can be learned from ancient wisdom. While the push for sustainability is relatively new, we can still draw inspiration from traditional farming and water management methods. By combining innovation and technology with these ancient techniques, we can create solutions that meet our current needs.

When we think of innovation and technology, we typically think of modern advancements, futurism, and industrial progress. However, ancient natural technologies may hold the key to adapting to climate change that we so desperately need in modern times.

It's important to understand that some ancient innovations and processes could still be beneficial to us today. By looking both forwards and backwards, we can equip ourselves with a diverse range of tools to tackle climate change. Many countries around the world are turning to ancient wisdom for guidance and have achieved a level of innovation that effectively balances what was previously considered unattainable.

Humanity can learn from ancient wisdom to create sustainable infrastructure that works in harmony with nature. As we face the challenges of climate change, we have the opportunity to blend modern knowledge and ancient wisdom to create a more earth-friendly way of living.

There are ongoing studies to explore how we can utilise this type of wisdom on a global scale. The impact of extreme weather has caused problems for farmers around the world. Some have turned to modern technologies, while others have looked to old processes that have proven successful in the past. Keith Elverson, an expert at UNEP, suggests that we need to consider both forward and backward thinking to develop a wide range of tools to adapt.

Examples of successful adaptations utilising ancient wisdom can be seen across the globe. For instance, the floating rice of Vietnam's Mekong Delta is a traditional farming technique that has been rediscovered by researcher Nguyen V K. Farmers learned to work unconventionally against intense floods and swamps to grow high-yield varieties, including ancient grains. Floating rice has become well adapted to floods, as its foliage grows much above the level of floods.

Harvesting rainwater: In Bhuj, on India's west coast, the ancient practice of rainwater harvesting has been mastered. The people of Bhuj have been diverting rainwater from two ephemeral channels and storing it in large reservoirs built on the site. The Arid Communities and Technologies (ACT) group has been working to understand the traditional water harvesting and management system in Bhuj and to revive it with the help of local communities. A small, old well that was recently cleaned up by volunteers is now supplying water to about 50 families.

The BHERI waste-water aquaculture system management in Kolkata, India, is an innovative organic technology that has made its way to a number of countries for organic aquaculture and to use wastewater in a sustainable way. The system consists of around 300 fishponds that carry out chemical-free water purification by relying on a combination of bacteria, algae, sewage, and sun instead of coal-based power. It serves as a source of food, an agricultural field, and a way of cleaning wastewater before it enters the Bay of Bengal.

The utilisation of ancient techniques can be seen in various ways such as implementing ducks instead of pesticides to manage insects. A farmer named Fang Yongjiang from Heilongjiang, China, used an approach that was chemical-free and required no technology.

He introduced ducks into rice paddies to feed on the weeds and insects, eliminating the need for pesticides. The ducks' droppings also served as natural fertiliser. Starting with just a handful of ducks over 25 acres, Fang expanded the method, and in a few years, other rice growers also implemented this ancient wisdom, resulting in 500 acres of pesticide- and fertiliser-free rice paddies monitored by ducks.

Another example is in Bolivia, where Oscar Saavedra's non-profit, Sustainable Amazonia, taught 500 families a 400 BC agricultural method. The method involves building 7-feet high elevated fields that stood higher than floodwater levels and were surrounded by canals. During flood season, the canals would hold the water to prevent the fields from flooding, and during droughts, the nutrient-rich canal water would be used to irrigate the fields.

In the context of climate change, we can learn from ancient water wisdom by returning to the open well culture, using only the dynamic water table, recharging aquifers, and reserving the deeper aquifers for droughts and other emergencies.

Numerous ancient innovations are in harmony with nature and utilise available resources intelligently to create a mutually beneficial relationship. These methods can be simple or complex but are often documented in our history books if we examine them closely. As the saying goes, history repeats itself, and our ancestors faced many of the same modern problems we face today.

The Borana tribe in Kenya, which herds cattle in arid Isiolo County, has successfully survived droughts by reintroducing an abandoned traditional grazing management method called 'Dedha' (meaning 'council' in the local dialect). The system involves placing decision-making authority in the hands of elders who ensure that all herders have sufficient pasture and water for their animals. According to Victor Orindi of the Adaptation Consortium, a group that works to mitigate the effects of climate change in Kenya, since Dedha was reinstated in 2011, the Borana have lost fewer animals to drought. Additionally, conflicts over natural resources have decreased, and the country is currently passing legislation to officially recognise the authority of Dedha councils.

In order to create a more sustainable future for areas in need of development, projects like AlUla's Cultural Oasis in Saudi Arabia are utilising ancient techniques and updating them with new technology and innovative thinking. These practices aim to address sustainability issues such as desertification. Meanwhile, in West Africa's Azawak region, the impact of climate change has resulted in water scarcity and desertification, severely affecting both the environment and the traditional nomadic communities who rely on it for farming. Amman Imman, an NGO, is using water harvesting methods to restore ecosystems and improve the livelihoods of those who have been forced to migrate.

The lands of indigenous people hold a large part of the world's remaining ecosystems. These people have lived in harmony with nature for millennia without sacrificing progress, demonstrating that there is hope for environmentally friendly solutions to modern problems through ancient wisdom. However, it's important to recognise that ecology depends on interdependence of multiple processes and schools of thought, making it impossible to rely on one single approach to address all environmental problems. Rather, the smart way to adapt to climate change is to listen to those who have shown resilience in the face of it for years and strike a balance that benefits everyone.

No matter where we reside, our reliance on the interconnected web of life remains the same. Examining past solutions that proved successful can guide us towards a timely correction of our course. Integrating ancient wisdom with sustainability necessitates not only an alignment of the economy with nature and society but also a connection of the past with the present, the present with the future, and technology with culture. This will bring about a spiritual and cultural transformation from greed-based to need-based development.

Humanity and the environment we inhabit have an interdependent relationship. The environment fulfils all the fundamental necessities required for the survival of human beings and animals. Prior to the industrial revolution, humans lived in harmony with nature. However, the relationship between humans and nature shifted with the advent of industrialisation. The consequences of industrialisation began to surface in the early 1960s. Problems arose when human greed increased, and people began demanding more than what was required. Machines replaced humans, and mass production of goods increased. Furthermore, automation and mechanisation in agriculture reduced employment opportunities in rural areas, leading to a migration of people from rural to urban areas. Improved facilities and modern healthcare also contributed to a significant increase in the global population.

The Industrial Revolution was initially intended to improve the standard of living for human beings and fulfil their basic needs. However, the focus has shifted from meeting necessities to obtaining greater comfort, which is causing damage to the environment and increasing the likelihood of human disease. For instance, the installation of air conditioning has become increasingly common around the world, with projections estimating a substantial increase in usage by 2050. The overuse of air conditioners contributes to rising temperatures and global warming, which poses a threat to human survival. Additionally, mental illness is on the rise, obesity rates are high, and societal disharmony is becoming more prevalent.

As GHG emissions continue to increase, there have been more frequent and severe weather events, including droughts and floods. Climate patterns have become unpredictable, leading to natural disasters worldwide. Sea levels are rising slowly but steadily, and oceans are becoming increasingly acidic due to the absorption of carbon dioxide. Plastic waste is accumulating in the ocean, which is having a significant impact on marine life. Furthermore, deforestation has accelerated to meet the growing demand for agriculture and human settlement, resulting in a significant reduction in forest cover.

Overall, the Industrial Revolution's original goal of improving living standards has given way to an emphasis on comfort and convenience, causing harm to the environment and humanity's health. The consequences of these actions have been widespread, including environmental damage, unpredictable weather patterns, and natural disasters. It is critical to reconsider our approach to development and prioritise sustainability to ensure a healthy and prosperous future for both humans and the planet.

The lack of connection with nature has resulted in a plethora of issues. Our ancestors lived in peace with nature and their environment, which facilitated a contented and prosperous life. They followed rituals and practices that encouraged a harmonious existence with nature. Each ancient custom and ceremony had a concealed benefit that aided humans in living in tandem with nature. However, as society began to disregard the roots of ancient wisdom, the relationship between humans and nature started to suffer. The relentless pursuit of comfort and money has brought the world to the brink of extinction. Although economic growth has been substantial, it has taken a severe toll on the environment. There has been a significant decline in agriculture and the availability of fresh water.

In today's fast-paced world, humans are recklessly exploiting natural resources through various activities such as deforestation, mining, fossil fuel usage, industrialisation, carbonisation, and emission of harmful chemicals into air, water and land. The neglect of their consequences has led people to revert to traditional and sustainable ways, as used by our ancestors. Although the current development cannot be stopped, it can be harmonised through several ancient practices for the sustainable and mutual growth of nature and everything that exists. Some of these techniques or practices include organic farming to reduce land pollution and air pollution caused by the emission of harmful pesticides and chemicals used in their production. Rainwater harvesting, a major practice in ancient civilisations and still used today in some parts of Rajasthan, ensures the availability of potable water.

In the modern-day lifestyle, there is an excessive use of vehicles, with some families owning more cars than family members. There are more clothes and houses than what is actually needed. This lifestyle is based on greed rather than need. If we look at ancient India or even today in Indian villages, people use motor vehicles only when they need to travel exceedingly long distances.

For shorter distances, walking is preferred, which not only saves the environment but also keeps the human body fit and healthy. Materialistic possessions were kept to a bare minimum, with only what was needed. Used items were reused and recycled. The entire lifestyle was based on the circular economy.

Yoga practice is a powerful tool for changing behaviour to safeguard the community and the environment. Yoga helps to bring about change on both an individual and community level. Yoga involves working with nature's forces, which are not just physical energies but also spiritual forces, both internally and externally, to harmonize with nature. We must balance our own energies, such as the body, mind, breath, and spirit, internally. We must also reconcile ourselves with the natural world and the Cosmic Spirit that underpins it from the outside. Each of us is a manifestation of the entire universe, and we can only truly understand our purpose in life when we discover the universe within ourselves.

Spiritual and Cultural Transformation

The practice of yoga promotes certain principles such as non-violence, discipline, and honesty, which are essential to developing individuals who are committed to their socio-political and physical environment. The focus on simplicity and environmentally sustainable decisions leads to more conscientious and thoughtful behaviour. Practicing yoga brings together the body and mind to achieve inner peace and understanding, leading to spiritual transformation. It helps individuals relieve stress and trauma and achieve relaxation, leading to a state of inner tranquillity. Yoga allows negative energy to be released from the body while positive energy is spread throughout the environment.

The practice of yoga offers physical benefits that should not be ignored. It can lead to improved fitness and function of bodily systems. Regular yoga practice also instils a sense of respect and dedication to the earth, inspiring individuals to act in environmentally friendly ways both at home and in the workplace. By working cooperatively and living on a smaller budget while volunteering locally, individuals can reduce their carbon footprint and contribute to a better future for the planet.

Yoga and meditation promote harmony and peace in society and can prevent the exploitation of natural resources. In ancient India, people were more dependent on fresh foods, but modern demand for processed foods has led to a significant increase in pollution levels. By prioritising personal and societal betterment over the accumulation of material possessions, individuals can become more aware of their environment and surroundings.

Overall, yoga offers physical and mental benefits while also encouraging individuals to act in ways that promote a better future for the planet.

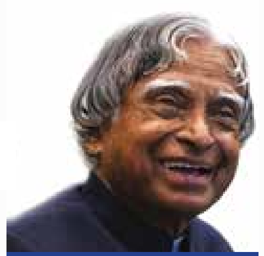
The modern society has always been in a race for happiness and pleasure which has led to humans being filled with greed and jealousy. In order to fulfil their unwanted needs, people have started exploiting nature in their own ways. Ancient wisdom, on the other hand, focused on having only what is required and never gave much importance to material things like money or physical facilities. The human-caused climate change is the result of human greed rather than human necessities. Ancient wisdom has rituals and components that have the ability to inspire the global community beyond that. Stress and depression have become silent killers in today's society, and yoga in a circular economy is a practical way to relieve stress and find peace.

To make a significant shift, all corporate houses should go for small cars, small and simple offices, and small houses, and showing off wealth should be seen as a sin. Similarly, all politicians and leaders should lead a very simple life, as they interact with the public. This will send a message which India can convey to the international community. The use of khadi woven clothes should be promoted, as this will reduce the consumption of polythene and Rayon fibre.

7.5 Inner and Outer Peace | Under Speaking Tree

THERE IS NO WAY TO PEACE, PEACE IS THE WAY

By Rajyogi B K Brijmohan



> Dreams are not which you see while sleeping, but dreams are those that don't allow you to sleep before fulfilling them.
>
> **Dr A P J Abdul Kalam**

Gandhiji's words, 'There is no way to peace, peace is the way', are very apt. If peace is the goal, how can war be the way? To him, only peaceful and non-violent methods needed to be employed as the right means to achieve the objective of peace. For him, the means should justify the end, and not vice versa.

It is not 'peace' but 'peacelessness' which often results in inertia, indolence, complacency and compromise with core values. Peace is never a weakness, but a great harmonising and stabilising strength of the soul. It's a positive and powerful state of mind. Peace and balance of mind are interconnected and indispensable virtues for victory and success in any sphere.

Verily, peace of mind never implies inaction or abnegation of actions. Rather, it energises and empowers the inner being not to get disturbed or perturbed but to remain alert, agile, active and accurate. It enables us not to react but to respond positively, proactively and decisively from a position of strength and stability.

Efforts at restoration of peace are undertaken, not out of fear of the fray, but for avoiding unnecessary loss of life and property on both sides. Negotiating for peace does not mean running away from war but to find, face, fight and finish the very genesis and every possibility of conflict.

Normally, when we think or talk of peace, we wrongly see or take it as our desired destination, without realising that it's always inherent within us as our close companion and conscience keeper. This is why we usually struggle for peace, instead of working or living in peace. Apparently, we forget that peace is our *swadharma*, soul's dharma, our original intrinsic nature.

While *swa* alludes to the inner self, *dharma* connotes our core values, *sat gun* or the seven divine dispositions like wisdom, purity, peace, love, happiness, bliss and positive powers which are innate in every person. The Bhagwad Gita eulogises *swadharma* as more powerful and preferable to *parodharma*, *prakriti dharma*, which is negative in nature and energy.

Swadharma, divine virtue, as real religion of humankind, has also been extolled in several scriptures. The Mahabharat mentions: '*Yatodharmo, statojaya*', where there is virtuosity, there is victory, and '*dharma rakhyatirakhitah*', the one who protects virtue is protected by it. One such virtue and core quality of the human soul is peace which is key to courage, confidence, concentration, creativity and contentment.

The Buddha has beautifully expounded the efficacy of peace in the following words: 'The ego mind says let everything around fall in place, it will be peaceful, while the soul's inner voice whispers, let me be peaceful first, everything around will fall in place.'

In Kaliyuga today, people have ceased to listen and stick to their inner voice and *swadharma* of peace. For that, the world now is suffused with negative energy-vibrations emanating from widespread violence, sorrow, suffering, pain and peacelessness.

The need of the hour is to eliminate these negative circles of human concerns and conflicts, by expanding the positive circles of peace, harmony and happiness in human minds, across the globe. To achieve this, there is an urgent need for collective practice and cooperative promotion of India's rich culture and heritage of spiritual wisdom, rajyog meditation, universal values, simple, positive and healthy lifestyle.

Speaking Tree, Times of India, September 21, 2023| International Day Of Peace

THE WORLD NEEDS EMPATHY MORE THAN SYMPATHY

By Sumit Paul

Urdu poet Ahmad Nadeem Qasmi writes:

'Ye jazbahumdardi se badhkarhotahai
Kisi kedard ko samajhne se behtarhotahai
Saarejahan ka dard jab apnalagnelagtahai
Aur khud ka gham sab se kamtarlagtahai'

This emotion is greater than sympathy
It's more profound than understanding someone's pain
When the sorrows of the whole world seem your very own
Your own grief pales in comparison.

He is referring to empathy in the above quatrain. It's not for nothing that empathy is known as *Sartaaj-e-jazbaat*, the supreme of all emotions that binds the world together and goes far deeper than sympathy. It encompasses humanity and pervades the world. It makes us aware of the pain of not just humans but of all the creatures. Jami, often regarded as the last great mystical poet of Iran, coined a word '*Infiziyaat*' which is still used in Persian mysticism, albeit rarely. It is an equivalent of the Sanskrit word '*sahmarmita*' – sah+marm: co+marm; emotion that resides in the sanctum sanctorum of every heart.

Now the point is: What's empathy? Empathy is:
'You and I are no different
Each soul is me, each man's my friend.'
This sublime sense of interconnectivity is possible when the heart is mellowed with love and elevated with empathy; when everything's your reflection and vice versa. So, be an empathiser because empathy exceeds mere sympathy. While sympathy helps one relate to another person, empathy dissolves that 'otherness'.

In other words, empathy is alter-egoism. Pakistani Urdu poet Dilawar Figar puts it succinctly:

'Mujhmein, tujhmein na koi tafawatrahe
Yoon ek hon kena koi izaahatrahe.'

There mustn't be any difference between the two of us
Let's become one seamlessly.

Urdu-Persian poet Nashtar wrote:

'Koi khaamosh ashk bahaye koson dur
Meri ankhein geeli na hon, mujhe nahin Manzoor.'

Someone shedding tears far away
How can my eyes remain tearless?

Shed tears but not just for a specific person. Weep for all. Remember, men have shed more tears than all the waters lying in the great oceans. Someone laughing with you is no big deal. If eyes are tearful, when you weep, rest assured, your tears haven't gone in vain.

It's empathy that will enable humans to go beyond the self and merge the suffering of each and every individual. Much have we sparred over petty things like nation, colour, religion and sects. It's, therefore, time to allow empathy to permeate and suffuse mankind with a sense of Oneness.

A human being is part of the whole, called by us 'the universe'. We need to widen our circle of compassion to embrace all living creatures and the whole of nature in its beauty, pity and piety. The grief of every individual can be universalised through empathy because the universality of emotions lies in one and only emotion: empathy. Empathy is enlightened self-interest. To quote Roman poet Horace, 'When your neighbour's wall is burning, it becomes your business.' It's an all-embracing human spirit. We need empathy to evolve collectively. Empathy will help restore the estranged co-existence of yore.

Speaking Tree, Times of India, Nov 30, 2022

LESSONS ON PEACE AND PROSPERITY FROM DAVOS

By Gurudev Sri Sri Ravi Shankar

Returning to the World Economic Forum (WEF) after more than a decade, I see there is an emphasis on discussing the important role of mental wellbeing, resilience, reimagining globalisation, sustainability, sociocultural harmony, and happiness in economic and social development.

A peaceful society is the basis of a prosperous society, and I am happy that world leaders are placing a great deal of importance on recognising and addressing these issues.

The theme of this year's WEF is 'Cooperation in a Fragmented World'. The current perception of fragmentation is not new. We must know that conflict, division, chaos and confusion sprout in the minds of people. It has to be countered with commitment, caring and collective resolve. This can happen only when leaders cultivate the mind to be calm and take considered decisions. We all need to recognise that we live in an interconnected world. There is no substitute for cooperation for the general good of the world.

Economic ups and downs are a natural part of the world economic order and not all parts of the economy flourish at the same time. For example, the tourism industry reduced significantly during the pandemic, whereas the healthcare industry flourished. While the transportation industry suffered significantly, the medical supplies industry increased and as in-person physical conferences shut down, people adopted virtual conferences. The advancement of technology allowed governments and business leaders to rethink their strategies and made us more resilient. There is a lot of talk about leadership but who do you lead when there is so much attention deficit disorder? When uncertainty and anxiety have taken over the human psyche, leadership goes for a toss.

> Mental health is a huge crisis. We must address the root cause from a holistic perspective and explore breathing as a tool to manage the mind and emotions.

Mental health is a huge crisis. We must address the root cause from a holistic perspective and explore breathing as a tool to manage the mind and emotions. Yoga and meditation have proven to be the most effective tools to check attention deficit disorder, depression, anxiety and other challenges. Thanks to the initiatives of the government of India, yoga and meditation have been introduced in schools and colleges throughout the country. We are also taking *dhyan*, meditation, to every *ghar*, home.

The WEF has picked up several good projects that focus on protecting the environment. One of them is the Miyazaki diversity project. The Miyazaki method grows micro forests 10x faster, generates up to 100x more biodiversity, replaces water-guzzling lawns with native drought-tolerant plants, has a 95% survival rate, and empowers children to make a difference in a climate change solution. In California, the average height of the trees after just one year is 3 metres, 12 feet. As the world faces a biodiversity crisis, micro forests are serving as havens for local flora and fauna in underutilised micro-urban spaces.

The distant mountains surrounding Davos reflect the calm, beauty and peace inherent in nature – a reminder to the world that we need to maintain, protect and enjoy them for generations to come. Peace is the only way forward, without peace there is no prosperity, and without prosperity, there is no peace. And we need wisdom for both.

Times of India, Speaking Tree, 2023

7.6

Messages from Hon’ble Prime Minister of India, Shri Narendra Modi

Image Credit: PMO

‘This is not the era of war’

During a direct conversation with Vladimir Putin, Prime Minister Narendra Modi made it clear, in September 2022, that this is not a time for war, emphasising the importance of democracy, dialogue, and diplomacy. He also stated that the discussion would provide an opportunity to explore ways to advance the path of peace in the future.

‘Humanity’s challenges can’t be solved by fighting… but by acting together’

India assumed the G20 presidency on December 1, 2022. The previous 17 presidencies have produced significant results, such as ensuring macro-economic stability, rationalising international taxation, and relieving the debt-burden of countries. India plans to build upon these achievements but also hopes to catalyse a fundamental mindset shift that benefits humanity as a whole.

Throughout history, humanity has lived in scarcity, which has shaped our mindset. We have fought for limited resources, believing our survival depended on denying them to others. This mentality has led to confrontation and competition between ideas, ideologies, and identities becoming the norm. The question now is whether the G20 can go further in promoting a shift away from this scarcity mindset.

> For healing our planet, we will encourage sustainable and environment-friendly lifestyles, based on India’s tradition of trusteeship towards nature.

The unfortunate truth is that we are still stuck in the same zero-sum mindset today. This is evident when countries engage in disputes over territory or resources. It is also evident when essential goods are used as weapons or when a few nations hoard vaccines while billions of people remain vulnerable.

The theme of India’s G20 presidency is ‘One Earth, One Family, One Future’, which aims to promote a universal sense of oneness among all living beings and even inanimate things, based on the belief that they are composed of the same five basic elements of earth, water, fire, air, and space. The idea is to encourage harmony among these elements, which is essential for physical, social and environmental wellbeing. The theme also acknowledges recent changes in human circumstances that we have failed to appreciate. While some may argue that confrontation and greed are innate to human nature, the lasting appeal of spiritual traditions that advocate the fundamental oneness of all suggests otherwise.

The G20 priorities during India’s presidency will be developed through consultation with not only G20 members, but also countries in the global South whose perspectives are often overlooked. The priorities will be centred around promoting environmental sustainability and healing our planet, fostering unity and understanding among people, and ensuring a hopeful future for all.

- *For healing our planet, we will encourage sustainable and environment-friendly lifestyles, based on India’s tradition of trusteeship towards nature.*
- *For promoting harmony within the human family, we will aim to remove political barriers and ensure the equitable distribution of food, fertilisers, and medical products globally. We believe that prioritising the needs of the most vulnerable populations is imperative, just as we do within our own families.*
- *For imbuing hope in our future generations, we will encourage an honest conversation among the most powerful countries – on mitigating risks posed by weapons of mass destruction and enhancing global security.*

‘One Earth, One Family, One Future’

The theme of India’s G20 Presidency is *Vasudhaiva Kutumbakam*, which affirms the value of all life on our planet. More than 200 G20 meetings in India will surely provide momentum towards achieving Sustainable Development Goals, technological transformation, digital public infrastructure, and women-led development, among others. The goal is to achieve the theme of *One Earth, One Family, One Future*, as articulated by Prime Minister Modi, by joining together to make India’s G20 Presidency a presidency of healing, harmony, and hope. Let us work together to shape a new paradigm of human-centric globalisation.

The need today is for the benefits of development to be universal and all-inclusive. We must extend the benefits of development to all human beings with compassion and solidarity. Women’s participation is crucial for global development to be possible.

‘Developing nations want human-centric globalisation’

Prime Minister Modi said on January 14, 2023, that India and other developing countries are seeking a human-centric form of globalisation that brings prosperity and well-being to humanity as a whole, rather than one that creates a climate or debt crisis. He made these remarks while addressing what he described as the largest-ever

virtual gathering of the Global South, which saw participation by more than 120 countries.

Speaking at the concluding leaders' summit, Prime Minister Modi noted that developing countries are also concerned about the increasing fragmentation of the international landscape and how these geopolitical tensions distract the Global South from focusing on their development priorities.

He added that these tensions cause sharp swings in the international prices of food, fuel, fertilisers, and other commodities. To address this geopolitical fragmentation, there's an urgent need for fundamental reform of major international organisations, including the UNSC and Bretton Woods institutions.

These reforms should focus on giving voice to the concerns of the developing world and reflect the realities of the 21st century. India's G20 Presidency will attempt to voice the views of the Global South on these important issues,' he said.

PM Modi announced that India would establish a Global-South Centre of Excellence that will conduct research on development solutions or best practices from any developing country that can be scaled and implemented in other Global South member countries. He also announced the launch of a Global-South Science & Technology Initiative to share India's expertise in space technology and nuclear energy with other developing nations.

Additionally, he announced a new project called *Aarogya Maitri*, under which India will provide essential medical supplies to any developing country affected by natural disasters or humanitarian crises.

Prime Minister Modi reiterated India's commitment to the principle of globalisation, emphasising that the developing world wants a globalisation that does not lead to an unequal distribution of vaccines or overconcentrated global supply chains.

'In its development partnerships, India's approach has been consultative, outcome-oriented, demand-driven, people-centric, and respectful of the sovereignty of partner countries,' he said. 'India will also establish Global-South Scholarships for students from developing countries to pursue higher education in India.'

Contributors

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Dr Jeewan Prakash Gupta is a widely travelled, skilled policy-maker and strategic planner. He has contributed widely towards policy-making in various companies and the government of India. He did his Ph.D. in Environmental Engineering from the University of Toronto, Canada, in 1985; M.Tech. in Process & Plant Design from IIT, Delhi, in 1971 (First Rank); and B.Tech. in Chemical Engineering from LIT, Nagpur, in 1969 (Gold Medallist). He has experience in the oil and gas sector, petrochemicals, polymers, specialty chemicals, sugar, distillery, fertilisers, pesticides, pharma, mechanical and processing equipment, water management, water treatment processes, environmental processes and environment impact assessment – water, air emissions and solid waste, apart from teaching and research. His skills are in the areas of formulation of policies and programmes, general management, strategic planning and management of large businesses, joint ventures, setting up of new businesses, greenfield projects, teaching, and research and development. Dr Gupta is engaged in the entire value chain of green hydrogen. His contributions in policy-making, safety and standards, setting up Centres of Excellence and JV for hydrogen production are globally recognised.

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Prior to the present assignment, he was in the Ministry of Petroleum & Natural Gas from 2016 to May 2022. He played a key role in bringing transformative policy reforms to facilitate investment in the oil and gas sector to increase production in the country. While at the Ministry of Petroleum and Natural Gas, he also served on the Board of ONGC and Oil India Ltd . He is a graduate in mechanical engineering from the National Institute of Technology (NIT), Kurukshetra, and holds an M.A in International Development Policy from Duke University, U.S.

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A chartered accountant, cost accountant and company secretary by profession, Mahendra Rustagi has worked in the corporate sector for over 35 years in top management positions (CEO/ COO) and is currently Chief Executive Officer at Kreston SNR, an ESG Service and Business advisory firm in New Delhi with branches at Pune and Bangalore.

Kreston SNR Advisors LLP is affiliated to Kreston Global, the 13th largest global accounting network firm with a presence in over 120 countries. This gives Kreston SNR easy access to global resources in any field be it financial, accounting, technological transfer, or ESS services. Kreston SNR is a JV partner with Greenstat, Norway, for ESG and carbon-offset services. Greenstat Norway is one of the leading green energy companies in Norway, helping the government of India and many large corporations in their green transition journey especially in the area of green hydrogen.

To his credit he has over three decades of professional experience including an entrepreneurial stint; strong experience in multiple functions across the lifecycle of a business including setting up the finance function, new projects (planning and execution0, managing operations, managing sales and marketing, managing stakeholders (investors, lenders, suppliers), fund raising (including managing IPOs), implementing business processes, and managing legal/arbitration matters. His relationship driven management style has allowed him to cultivate strong links across the banking fraternity and corporations.

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He has worked closely with the industry and the government through advisory and consultative processes on policy issues and campaigns, regulatory initiatives, and lobbying for policy changes to foster industry and economic growth and played a catalytic role in favourable policy implementation. He has also worked on projects with the government, multi/bilateral organisations, international agencies and think-tanks. He has written two books – *Towards Career Success* (Adarsh Publications) and *Way to Success Step-by-Step* (S. Chand Publications).

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Umesh Sahdev has more than five decades of experience in planning and development of industrial projects in a vast spectrum of industries, managing businesses of global companies, identifying business opportunities, and strategic planning of investment projects, carbon-offset projects, and also managed private equity and investments in sustainability and climate change mitigation projects. He has served as vice-chairman of Sindicatum Sustainable Resources, a Singapore-based principal finance and developers of clean energy and sustainability projects worldwide. Umesh was co-founder and director of LSE-listed Platinum Mining Company. He also served as CEO (Projects) of India's major merchant banking company Bajaj Capital Ltd. and Head of Merchant Banking Operations at Mefcom Capital Markets Ltd. He is working towards the development of a range of green hydrogen projects with-in the whole value chain and also supporting a highly innovative Indian company on low-cost membrane-less electrolyser in global commercialisation. He is also working on creating an IDO – investors-developers of hydrogen projects – a hydrogen offsets repository platform for stakeholders in the hydrogen value chain.

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Charly Berthod obtained his doctoral degree on the experimental study of temperature coefficients of multi-crystalline compensated silicon solar cells. He worked as a post-doctoral research fellow at the University of Agder for two years. He is now working with Greenstat Energy AS as CTO for solar energy for utility-scale solar parks and rooftop installations.

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He has over 200 research studies to his credit. He regularly participates in panel discussions on TV. Recently, he prepared the Economy GPS Index which provides an outlook of the Indian Economy.

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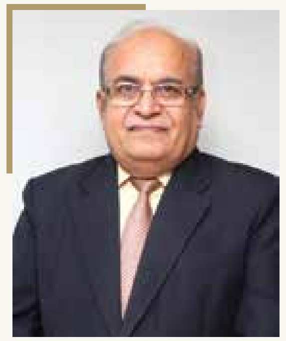
Alok Sharma is a chemical engineer and holds an M.Tech in chemical engineering from the Indian Institute of Technology, Delhi. He has over 31 years of experience at Indian Oil Ltd., including R&D & Refinery, process, projects and production. He has been instrumental in setting up hydro-processing, gasification, biofuels, hydrogen and fuel cell related facilities at Indian Oil R&D. An expert in hydro-processing, he has excellent knowledge of all aspects of energy transition.
He received World Petroleum Congress Excellence Award 2008 and was selected for Prestigious Endeavour's Awards in 2009. He was also awarded a Commonwealth Scholarship to CSIRO, Melbourne. He has over 30 granted patents in his name. He has guided two Ph.D. scholars and also successfully mentored two start-ups in the area of alternative energy. He is also a member of International Association of Hydrogen Energy (IAHE) and treasurer of the Hydrogen Association of India (HAI).



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Earlier he was director-general at the Federation of Indian Petroleum Industry from September 2015 to December 2021. Previously he was the chairman and director R&D at Indian Oil Corporation, the largest commercial enterprise of India where he spent 37 years. He has published/presented over 200 research papers and holds 138 patents in India and abroad.

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Siddharth R. Mayur is a first-generation social entrepreneur who founded h2e Power Systems Pvt. Ltd. (www.h2epower.net), India's first green hydrogen, electrolyser and fuel cell company, in 2009, to fulfil his vision of providing 24x7 clean, green, reliable and affordable energy to all.
Over the last 13 years h2e has developed partnerships with world leaders across the entire green hydrogen value chain and the company is now preparing to industrialise the fuel cell and electrolyser technology with a 1 GW/year manufacturing hub in India.
He has championed the cause of green hydrogen in India and has been instrumental in commissioning the first green hydrogen plant in the country. His company recently commissioned a hydrogen fuel cell bus.
He has over 24 years of experience in areas including international trade, entrepreneurship, green tech and social enterprise. *Swadeshi Urja* for a *Swawalambi Bharat* is the core to his vision and philosophy. Apart from energy he has made significant contributions in the field of chess and skill development.

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Santoshkumar D. Bhat's research interests are membrane electrolytes and electrocatalysts for polymer electrolyte fuel cells. He has more than 100 publications and three patents to his credit. He is a member of the Electrochemical Society (ECS). He was invited to Montreal, Canada, to talk on membranes for fuel cells during the ECS meeting. He is a recipient of the Outstanding Electrochemist award from Venus Research Foundation, Chennai. He is currently the programme co-ordinator of the Hydrogen Technology Mission project, a major initiative by CSIR, and leading the development of indigenous membrane electrolytes for fuel cells.

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After 37 years of corporate experience in the field of sales, business development and corporate strategy, and having travelled to about 25 countries and worked with global companies, Ravindra Vasisht has been able to create enduring relationships between Indian and global businesses by bridging the gap between management and leadership. He has wide industry experience in food, plastics, automotive, healthcare, defence and in the last 12 years, has been working in the natural gas and clean energy sectors with Hexagon Agility. At Hexagon, he introduced the concept of composite Type 4 CNG and hydrogen cylinders to India, and the first CNG bus with a range of over 1,000 km in the country. A voracious reader, he writes blogs, is active on social media, has a keen interest in defence, economics, business strategy and politics, has a good sense of humour, and enjoys traveling. He is available on Twitter and Instagram as rvasisht, and has a blog at rvasisht.blogspot.com
He now works as an independent consultant in the clean energy space with a focus on hydrogen and is currently working with Greenstat of Norway and also assisting Advantek India and Hexagon Agility, USA.

DEEPTI SHARMA DULLU

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Deepti Sharma Dullu is currently working as Senior Technical Officer at Innovation Management Directorate, CSIR headquarters, New Delhi. She joined CSIR in 2001 and has been working since then in the Division/Directorate, managing projects. She completed her M.Sc. in Chemistry from Delhi University. She is associated with coordination of R&D projects with the Directorate Team under various schemes of CSIR, which broadly includes facilitation and processing of R&D proposals. She is now associated with coordinating the CSIR Hydrogen Mission, CSIR CCUS Mission and CSIR Battery Mission.

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Mahesh Kumar is currently working as Senior Principal Scientist at Innovation Management Directorate, CSIR headquarters, and is Associate Professor at AcSIR. He has worked at CSIR-National Physical Laboratory for more than 15 years in the fields of surface science and ultrafast optoelectronics and terahertz photonics. Of late, he has been coordinating the CSIR Hydrogen Mission, CSIR CCUS Mission, CSIR Battery Mission and NMITLI projects. He has published two books, written three book chapters, and more than 140 papers that have been published in international journals. He has given more than 25 invited talks, developed technology of solid-state cooling-based vaccine refrigeration, and indigenously developed the PPE testing system during the COVID-19 pandemic.

KAMAL KISHORE PANT

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Kamal Kishore Pant received his Ph.D. in chemical engineering from the Indian Institute of Technology, Kanpur, in 1997. He took over as Director of the Indian Institute of Technology, Roorkee, on October 12, 2022. Previously, he held the position of Head of the Department of Chemical Engineering, and Dean, Faculty, at the Indian Institute of Technology, Delhi. He is Adjunct Faculty at the University of Saskatchewan in Canada.

He has published more than 230 articles in various journals and has got 12,665 citations with h-index 58. He has several national and international patents to his credit. He also serves as an editor for Chemical Engineering Science, Food and Bio-products Processing Journal and has been invited as an editor of special issues of various journals published by Wiley, Springer Nature and Elsevier. He is a fellow of several national and international academies such as the Royal Society of Chemistry, London (FRSC, London), the National Academy of Science, India (NASI), the Indian National Academy of Engineering (INAE), the Indian Desalination Association (InDA), the Biotech Research Society of India (BRSI), Institution of Engineers India, and the Indian Institute of Chemical Engineers. He has been awarded several national awards including Distinguished Alumni Award, HBTU, Kanpur; Prof. K. L. Chopra Applied Research Award by Indian Institute of Technology, Delhi; CHEMCON distinguished speaker award; Herdilia Award for Excellence in Basic Research in Chemical Engineering by Indian Institute of Chemical Engineers; Dr. A. V. Rama Rao award for best Ph.D. supervised; and the Gandhian Young Technological Innovation Award.

He is also an honorary Faculty at the University of Queensland (UQ), Australia and has been visiting professor at Auburn University, Tuskegee U.S., University of Saskatchewan, Canada, Aston University U.K., UNSW Australia, and University of Utah ,U.S.

YOGENDRA (YOGI) SARIN

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To fulfil the sustainability gap existing in biofuels, ethylene and downstream petrochemical industry at the time, Yogi Sarin founded Petron Scientech in 1991 in New Jersey, U.S., with a focus on green and environment-focused technologies. (www.petronscientech.com).

He has more than 35 years of global experience in technology and catalyst development design, project execution/management of green and sustainable technologies in biofuels, chemicals, polymers, consumer products, and petrochemicals, having been involved in the conceptualisation, feasibility studies, design, technology development, technology transfer, operations, joint ventures, environmental leadership and initiatives in the U.S. and 15 other countries.

He holds a BS in chemical engineering from HBTI, India, MS in Chemical Engineering/research project to convert waste to syngas, from University of Idaho, U.S., and a post-graduate degree in petrochemical engineering from the postgraduate school in Milan, Italy. He has published papers in engineering and technology, holds patents, and has been invited as speaker at international conferences. He is also involved with continuing education of engineers and new ESG-focused technology developments.

AMOL NISAL

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Amol Nisal represents Praj Industries Ltd., India, a global leader in providing technology, equipment and services to the biofuels and agri-process industry for close to four decades, with over 1,000 customer references spanning over 100 countries.

He has been with Praj for close to 17 years and has handled functions of business development, strategy, technology sales, and project management in various regions for conventional as well as advanced biofuels. He has led the development of new business lines, new markets and geographies for he has a deep understanding of technology, markets and regulations for biofuels. He also has a keen interest in circular bio-economy, and lifecycle analysis.

Currently, he is leading Praj's efforts at developing technology and business solutions for SAF. He has actively contributed to various stakeholder forums and has written various articles and papers for commercialisation of SAF.

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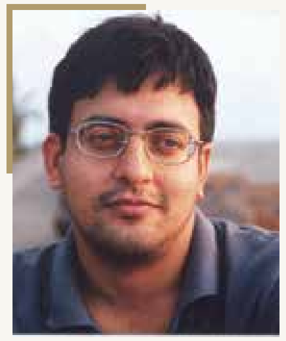
Anjan Ray holds a Ph.D. in chemistry from the University of Pennsylvania, U.S. and has worked for over 25 years in the chemical and energy industries across a wide range of functions. He took up his current position as Director, CSIR-Institute of Petroleum (CSIR-IIP), Dehradun, in November 2016.

His professional interests span fields as diverse as surfactants, lubricants, oleochemicals, cosmetics, pharmaceuticals, oil and gas, energy efficiency, biofuels, biotechnology, sustainable supply chains, and renewable energy policy.

He was a recipient of the Indian Federation of Green Energy Jury Choice Award for Outstanding Green Energy Activist in 2021, has been felicitated with the Uttarakhand Ratna Shri Award in 2022, and honoured recently with the Energy And Environment Foundation Global Excellence Award 2023 in the Bioenergy Sector.



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Rudrajyoti Palit obtained his Ph.D. in 2001 from Tata Institute of Fundamental Research, Mumbai. He was a Research Fellow at University of Frankfurt and then at GSI, Germany, during 2001-2004. He joined TIFR as faculty in 2004 where he is now a Professor(H). His research interests are in experimental nuclear physics, to explore the structure and dynamics of atomic nuclei through different nuclear reactions. He is also interested in the development of the associated instrumentation for accelerator-based nuclear physics experiments. He has over 100 articles published in journals. He is on various national committees including funding agencies.

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G. Hari Balamurali has 16 years of hands-on proven experience in all areas of process-plant operations. His major experience is in process design from concept till commissioning and product purity achievement. He is a dynamic process simulation expert and is also involved in large pipeline transient simulation studies. He is familiar with the concepts of process automation, process optimisation, yield accounting, PID-tuning, interlock/sequence/logic creation and plant trouble-shooting with major DCS/SCADA & PLC system.

He completed his B.Tech in chemical engineering in 2006. He started his career in plant operations. He worked for major process and pipeline transportation projects from public sector companies like GSPL, Gandhinagar; IOCL R&D Centre, Faridabad; and GAIL, Bhikaji Kama in India. He was involved with MNCs and Indian start-ups in design/simulation work for natural gas transportation, crude pipelines, FPSO design, LNG plant design, polymers, air separation cryogenic units, and pharmaceutical bulk-drugs.

PRAKASH DHONDIRAM CHAVAN

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Gasification & Catalysis Research Group
CSIR-Central Institute of Mining & Fuel Research

Prakash Dhondiram Chavan is currently working as a Chief Scientist and Head, Gasification & Catalysis Research Group, CSIR-Central Institute of Mining & Fuel Research. He completed his Ph.D. in 2013 from IIT-ISM, Dhanbad, in the area of gasification. He worked on dynamic R&D activities in coal/biomass gasification and syngas utilisation, development of 1.5 TPD oxy-blown PFBG & 0.5 TPD airblown PFBG pilot plants, development of gasification R&D facilities like thermo gravimetric reactor, and fixed bed reactor to study gasification reactivity/kinetics of coal, biomass and petcoke, gasification potential mapping of MCL, CCL & ECL areas under the aegis of NITI Aayog, and hazardous chemicals/waste incineration system. He also worked as a member of the Technical Standing Group for Indian Coal Gasification Mission under NITI Aayog.

JAMES KHONG

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James Khong is co-founder and Chief Operating Officer of Galaxy FCT, a hydrogen technology company which has a patented process (issued and worldwide pending) which allows rapid and efficient release of H_2 gas from solid feedstock – a process which opens the pathway for evolution of a parallel clean energy logistics ecosystem based on Solid H_2.

He has extensive work experience in energy and infrastructure project development and project financing in various capacities, having worked as a business development director for the AES Corporation, as an investment banker with Barclays DeZoete Wedd (Corporate & Project Finance), Tokyo Mitsubishi International (Singapore), & CIMB Investment Bank (Equity Capital Markets & Structured Products) as well as legal counsel (Privatisation, Infrastructure and Project Financing) with Zaid Ibrahim & Co (ZICO Law). Over the years, he also made direct principal investments in several different businesses/companies including two in the oil and gas support services sector and subsea services, participated actively in management, and subsequently exited those investments through trade sale/ IPO. He holds a Master of Laws (LLM, Cambridge, St Johns College), a Bachelor of Laws (LLB, Malaya) and had qualified as a CFA (Chartered Financial Analyst) Charter holder in 2001.

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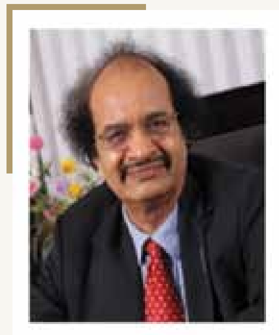
Chitra Rajagopal is a distinguished scientist and former Director General, DRDO (till December 2020). She is also INAE AICTE Distinguished Visiting Professor, and adjunct faculty at IIT Madras and IIT Delhi. An outstanding scientist and Director, Centre for Fire, Explosive & Environment Safety (CFEES), till January 2017, she holds bachelor's degree in chemical engineering from DCET and a Ph.D. in heat transfer from IIT Delhi.
Her research contributions cover a number of areas including environment, explosives, process, chemical and fire safety, qualitative risk assessment, systems safety analysis, and disaster management. Her siting includes eco-friendly and clean energy technologies, sustainable development and systems analysis, hazchem and hazWaste management, and EIA.



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Ganapati D. Yadav is a highly prolific and accomplished engineering-scientists in India. He is the National Science Chair, government of India, which is a very prestigious national honour and is Emeritus Professor of Eminence and former vice chancellor of the Institute of Chemical Technology, Mumbai. As the VC he took ICT to a spot on international rankings with the establishment of two new campuses in Bhubaneswar and Jalna, creation of 23 new programmes, several centres of excellence and five new departments. He has been internationally recognised with over 125 prestigious and rare awards as an academician, researcher and innovator, for his seminal contributions to education, research and innovation in green chemistry and engineering, catalysis, chemical engineering, energy engineering, biotechnology, nanotechnology, and development of clean and green technologies. He was conferred a Padma Shri in 2016 for his outstanding contributions to science and engineering. He has been awarded two honorary doctorates and has addressed six convocations of renowned universities. He has been elected to the fellowship of all science and engineering academies in India, TWAS, RSC (U.K.), and IChemE (U.K.) among others. He was elected to two prestigious foreign academies: the U.S. National Academy of Engineering (only 23 living Indians were elected to this academy), and as a Fellow of the U.S. National Academy of Inventors in 2022 (the second Indian to be so honoured).

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Navin Gopinathan is an assistant professor in the Department of Chemical Engineering at the Indian Institute of Technology, Ropar. He obtained his Ph.D. from the University of Bath and completed a postdoctoral fellowship from the University of Nottingham. He subsequently undertook a research associateship with HP Green R&D before returning to academia. He possesses expertise in the structural characterisation of porous materials using classical methods such as adsorption, liquid intrusion, etc., and advanced NMR based methods. He also has a keen interest in separation processes, equipment design, process intensification and chemical process safety.

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SECTION 1

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SECTION 2

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SECTION 7

7.1 Learning from Nature – the Regenerative Perspective on Business and Leadership

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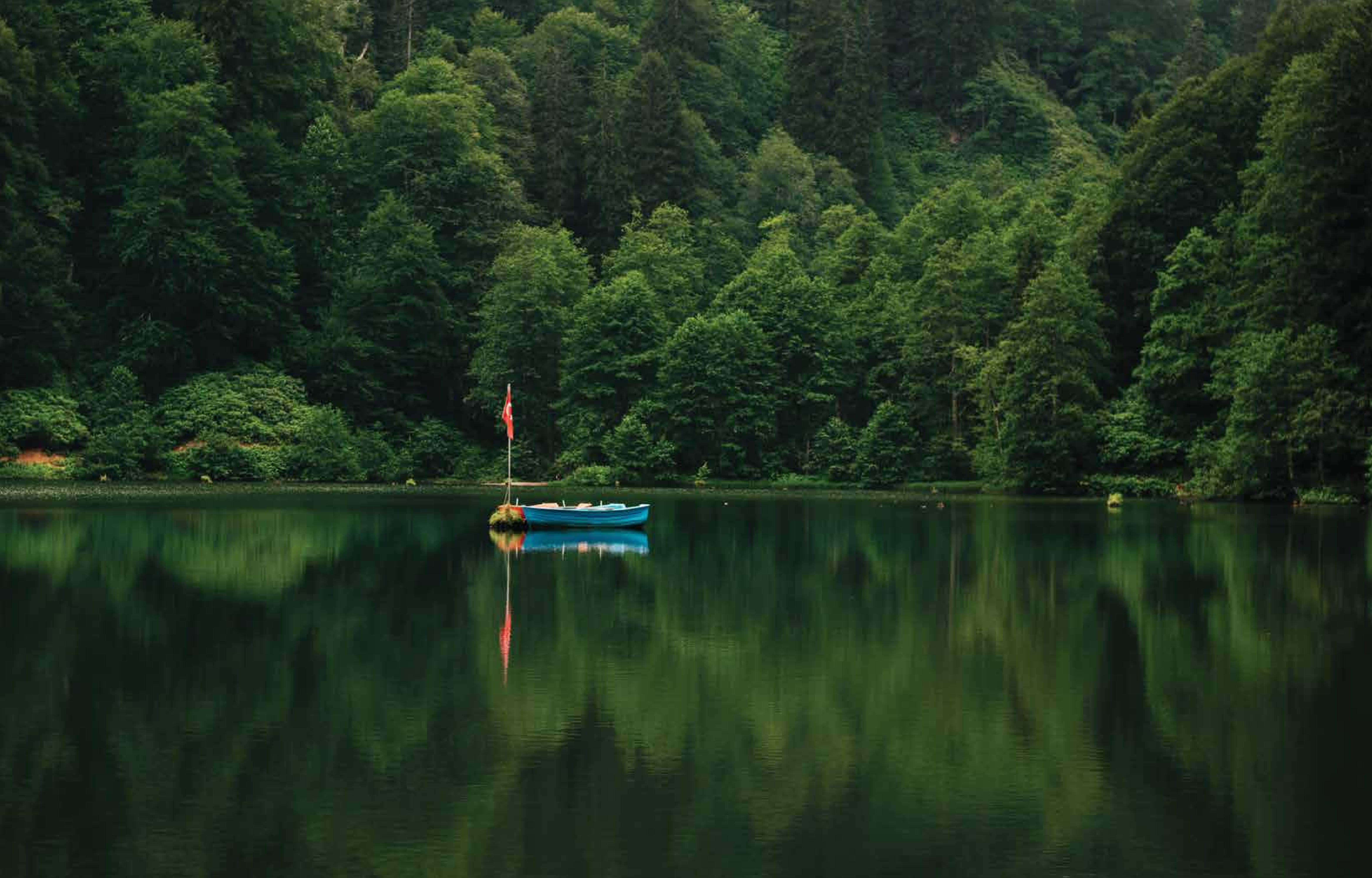

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