# Mainstreaming Decentralised Green Hydrogen in India

## A Compendium of Industrial, Commercial and Remote-Area Applications

**Hashvitha Rajakumaran, Hemant Prakash Singh, Karan Kothadiya, and Deepak Yadav**

Report | September 2024

Suggested citation: Rajakumaran, Hashvitha, Hemant Prakash Singh, Karan Kothadiya, Deepak Yadav. 2024. *Mainstreaming Decentralised Green Hydrogen Applications in India: Compendium of Industrial, Commercial and Remote-Area Applications.* New Delhi: Council of Energy, Environment and Water (CEEW)



Cover Image: iStock

Peer reviewers: Jasmeet Singh, Head - Dealer Development and Government & Defence Business, JCB India Limited; Gautham Jayashanker, Founder and CEO, Integrated Energy Solutions; Prof. R.S. Verma, Director - Technical, Integrated Energy Solutions; Dr. Sunil Kumar Pandey, Head - R&D, Integrated Energy Solutions; Priya Tayde, Programme Lead, CEEW.

Publication team: Kartikeya Jain (CEEW); Alina Sen (CEEW); The Clean Copy; Madre Designs and Friends Digital Colour Solutions

Acknowledgment: The Council on Energy, Environment and Water (CEEW) is privileged to be associated with the Ministry of New and Renewable Energy (MNRE), Government of India, as Knowledge Partner on this report.

We are grateful to Shri Ajay Yadav, Ex-Joint Secretary, MNRE; Shri Abhay Bakre, Mission Director, National Green Hydrogen Mission, MNRE; Shri Sujit Pillai, Scientist F, MNRE; Dr Prasad Chaphekar, Deputy Secretary, MNRE and Shri Deepak Rai; Programme Director (Policy), National Green Hydrogen Mission Secretariat, MNRE for entrusting CEEW with this study.

The authors would like to express their gratitude to Kalyan Bhattacherjee, Chief Sustainability Officer & Vice President Energy, Jindal Stainless Ltd; Jasmeet Singh, Head - Dealer Development and Government & Defence Business, JCB India Limited; Subrata Sarkar, General Manager, NTPC Energy Technology Research Alliance; Gaurav Agnihotri, General Manager – Business Development, Hygenco Green Energies Pvt Ltd; Gautham Jayashanker, Founder and CEO, Integrated Energy Solutions and Hemant Mallya, Fellow, CEEW for their contributions to the study.

Organisation: The Council on Energy, Environment and Water (CEEW) is one of Asia's leading not-for-profit policy research institutions and among the world's top climate think tanks. The Council uses data, integrated analysis, and strategic outreach to explain — and change — the use, reuse, and misuse of resources. The Council addresses pressing global challenges through an integrated and internationally focused approach. It prides itself on the independence of its high-quality research, develops partnerships with public and private institutions, and engages with the wider public. CEEW has a footprint in over 20 Indian states and has repeatedly featured among the world's best managed and independent think tanks. Follow us on X (formerly Twitter) @CEEWIndia for the latest updates.

COUNCIL ON ENERGY, ENVIRONMENT AND WATER (CEEW)
ISID Campus, 4 Vasant Kunj Institutional Area
New Delhi – 110070, India
+91 11 4073 3300

info@ceew.in | ceew.in | @CEEWIndia | ceewindia

नवीन एवं
नवीकरणीय ऊर्जा मंत्रालय
MINISTRY OF
NEW AND
RENEWABLE ENERGY

सत्यमेव जयते

# Mainstreaming Decentralised Green Hydrogen in India

## Compendium of Industrial, Commercial and Remote-Area Applications

**Hashvitha Rajakumaran, Hemant Prakash Singh, Karan Kothadiya, and Deepak Yadav**

Report
September 2024
ceew.in

# About CEEW

The Council on Energy, Environment and Water (CEEW) is one of Asia's leading not-for-profit policy research institutions and among the world's top climate think tanks. The Council uses **data, integrated analysis, and strategic outreach to explain — and change — the use, reuse, and misuse of resources**. The Council addresses pressing global challenges through an integrated and internationally focused approach. It prides itself on the independence of its high-quality research, develops partnerships with public and private institutions, and engages with the wider public. CEEW is a strategic/ knowledge partner to 11 ministries for India's G20 presidency.

The Council's illustrious Board comprises Mr Jamshyd Godrej (Chairperson), Mr S. Ramadorai, Mr Montek Singh Ahluwalia, Dr Naushad Forbes, Dr Janmejaya Sinha, Dr Suresh Prabhu, and Ms Vinita Bali. The 330+-strong executive team is led by Dr Arunabha Ghosh. CEEW has repeatedly featured among the world's best managed and independent think tanks.

**In over 14 years of operations**, The Council has engaged in 500+ research projects, published 460+ peer-reviewed books, policy reports and papers, created 220+ databases or improved access to data, advised governments around the world 1400+ times, promoted bilateral and multilateral initiatives on 160+ occasions, and organised 610+ seminars and conferences. In July 2019, Minister Dharmendra Pradhan and Dr Fatih Birol (IEA) launched the CEEW Centre for Energy Finance, which is now known as CEEW Green Finance Centre (CEEW-GFC). In August 2020, Powering Livelihoods — a CEEW and Villgro initiative for rural start-ups — was launched by Minister Piyush Goyal, Dr Rajiv Kumar (then NITI Aayog), and H.E. Ms Damilola Ogunbiyi (SEforAll).

**The Council's major contributions include:** Informing India's net-zero goals; work for the PMO on accelerated targets for renewables, power sector reforms, environmental clearances, *Swachh Bharat*; pathbreaking work for India's G20 presidency, the Paris Agreement, the HFC deal, the aviation emissions agreement, and international climate technology cooperation; the first independent evaluation of the *National Solar Mission*; India's first report on global governance, submitted to the National Security Advisor; support to the National Green Hydrogen and Green Steel Missions; the 584-page *National Water Resources Framework Study* for India's 12th Five Year Plan; irrigation reform for Bihar; the birth of the Clean Energy Access Network; the concept and strategy for the International Solar Alliance (ISA); the Common Risk Mitigation Mechanism (CRMM); India's largest multidimensional energy access survey (ACCESS); critical minerals for *Make in India*; India's climate geoengineering governance; analysing energy transition in emerging economies, including Indonesia, South Africa, Sri Lanka, and Viet Nam. CEEW published *Jobs, Growth and Sustainability: A New Social Contract for India's Recovery*, the first economic recovery report by a think tank during the COVID-19 pandemic.

**The Council's current initiatives include:** State-level modelling for energy and climate policies; consumer-centric smart metering transition and wholesale power market reforms; modelling carbon markets; piloting business models for solar rooftop adoption; fleet electrification and developing low-emission zones across cities; assessing green jobs potential at the state-level, circular economy of solar supply chains and wastewater; assessing carbon pricing mechanisms and India's carbon capture, usage and storage (CCUS) potential; developing a first-of-its-kind Climate Risk Atlas for India; sustainable cooling solutions; developing state-specific dairy sector roadmaps; supporting India's electric vehicle and battery ambitions; and enhancing global action for clean air via a global commission 'Our Common Air'.

**The Council has a footprint in over 20 Indian states**, working extensively with 15 state governments and grassroots NGOs. Some of these engagements include supporting power sector reforms in Uttar Pradesh, Rajasthan, and Haryana; energy policy in Rajasthan, Jharkhand, and Uttarakhand; driving low-carbon transitions in Bihar, Maharashtra, and Tamil Nadu; promoting sustainable livelihoods in Odisha, Bihar, and Uttar Pradesh; advancing industrial sustainability in Tamil Nadu, Uttar Pradesh, and Gujarat; evaluating community-based natural farming in Andhra Pradesh; and supporting groundwater management, e-auto adoption and examining crop residue burning in Punjab.

# Contents


**Decentralised green hydrogen systems enable a continuous, convenient and reliable off-grid energy supply.**

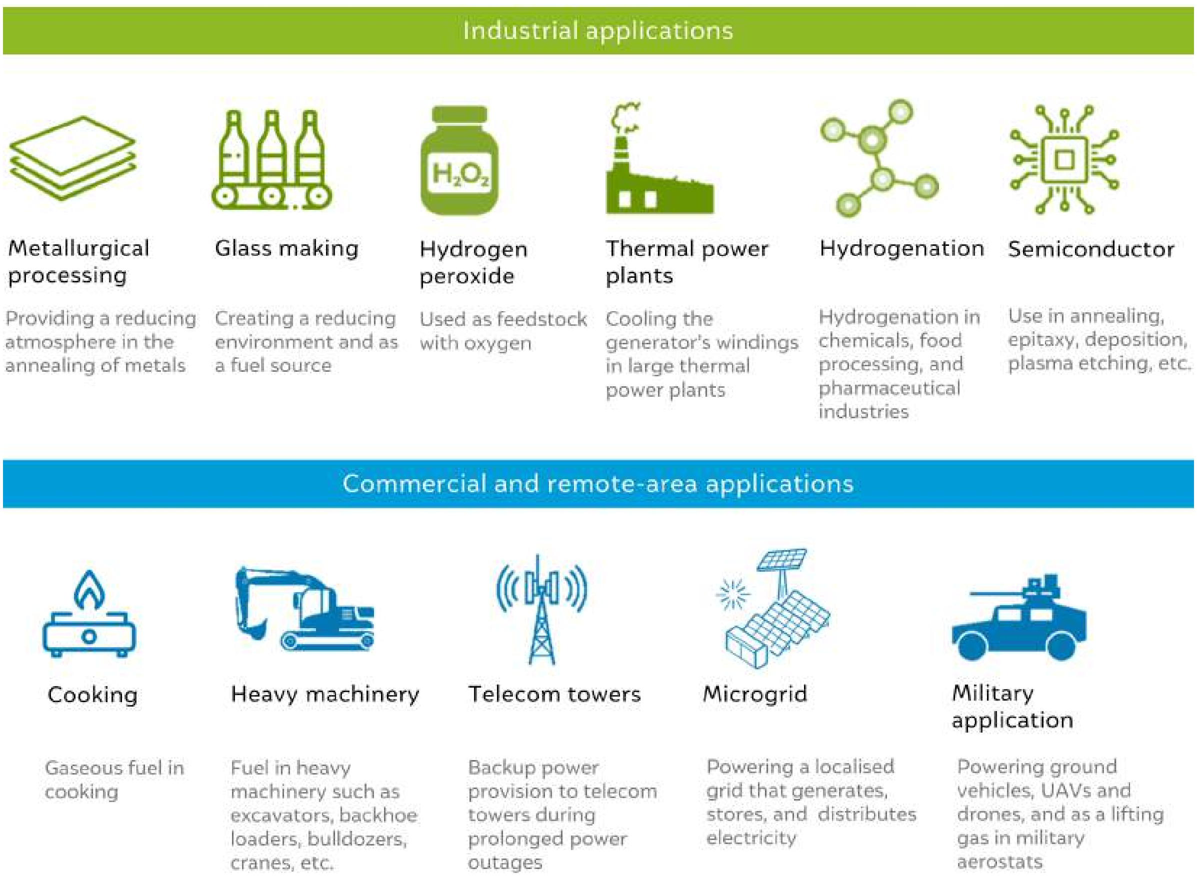
Image: iStock

# Executive summary

Green hydrogen, produced through water electrolysis using renewable energy (RE), is a clean energy carrier that has versatile uses, including as a feedstock, fuel, and energy carrier, in decarbonising hard-to-abate sectors. In decentralised green hydrogen systems, the production and use of green hydrogen are near the point of consumption, eliminating the need to transport it or transmit the RE required to produce it.

We find that unconventional decentralised green hydrogen applications in industries such as metallurgical processing, glass making, thermal power production, food processing, chemicals and pharmaceuticals, and semiconductor manufacturing could be already economically viable or close to viability. Furthermore, we find that applications in commercial and remote-area settings, such as its use as a cooking fuel, fuel for heavy machinery, a backup power source in telecom towers, and an energy source powering microgrids and military applications, could contribute to a substantial potential demand for green hydrogen in India, comparable to that for larger, more conventional green hydrogen applications, such as in the fertiliser, refining, and steel industries and long-haul heavy-duty road transportation. We present the use cases for green hydrogen in these applications in Figure ES1.

**Figure ES1** **Use cases of decentralised green hydrogen systems**




*Source: Authors' analysis*

In this report, we explore the unique advantages that decentralised green hydrogen systems offer and also discuss the challenges and constraints that they impose on producers and consumers. We quantify the potential demand for green hydrogen in India that would arise through these decentralised applications, the associated emissions mitigation potential, the breakeven cost of green hydrogen to compete against conventional fuels and commodities that it will replace, and the potential reduction in import expenditure with a transition to green hydrogen.

Beyond their ability to decarbonise applications, decentralised green hydrogen systems also offer several unique advantages:

- **A continuous, reliable, and convenient off-grid energy supply**: With decentralised green hydrogen systems, individuals and communities can take control of their energy supply, preventing disruptions and operational bottlenecks in their supply chains. This can be particularly useful in remote, inaccessible areas.
- **Higher energy efficiencies** are seen with the use of fuel cells and hydrogen-based technologies as compared to conventional diesel or biomass-based technologies.
- **The inherently higher purity** of green hydrogen compared to fossil-derived hydrogen is useful in industrial applications, to avoid contaminants and maintain process efficiencies.
- **Improvement in local air quality** is seen with a shift away from polluting fuels such as biomass and diesel to hydrogen-based cookstoves, microgrids, and heavy machinery.
- **Reduced transmission and distribution losses** and associated costs result in improved energy efficiency.
- **Reduction in greenhouse gas (GHG) emissions** of up to **221 million metric tonnes per annum (MTPA)** could be achieved with a complete transition to green hydrogen in the applications considered in this report, by our estimates. Green hydrogen use in cooking would account for around 209 MTPA of the total emissions mitigation potential due to the comparatively larger potential demand for it in this sector.
- **Reduction in energy import expenditure** of up to **INR 1.2 lakh crore (**around USD 15.3 billion) per year could be achieved by completely phasing out imported fuels such as liquefied petroleum gas (LPG), liquefied natural gas (LNG), and diesel, per our estimates.

In addition, we present certain application-specific advantages that decentralised green hydrogen systems offer in Table ES1.

**Table ES1 Unique application-specific advantages offered by decentralised green hydrogen systems**

| Sr. no. | Application | Specific advantages of green hydrogen |
|---|---|---|
| Industrial applications | | |
| 1 | Metallurgical processes | • High thermal conductivity leads to faster completion<br>• High purity of the gas eliminates contaminants<br>• On-site green hydrogen production ensures process continuity |
| 2 | Glassmaking | • High-purity gas leads to a smooth surface finish of the glass<br>• An oxy-hydrogen flame helps to achieve localised high temperatures in optic fibre production |
| 3 | Thermal power plants | • High thermal conductivity leads to reduced frictional heat losses in the process and rapid and uniform heat dissipation |

| Sr. no. | Application | Specific advantages of green hydrogen |
|---|---|---|
| Commercial and remote-area applications | | |
| 4 | Cooking fuel | • Zero particulate matter (PM) emissions<br>• Elimination of logistical bottlenecks in fuel procurement |
| 5 | Fuel in heavy machinery | • Higher tank-to-wheel efficiency<br>• High energy density ensures sufficient power delivery<br>• Refuelling convenience with on-site green hydrogen production |
| 6 | Backup power in telecom towers | • Higher efficiency compared to diesel generators<br>• Refuelling convenience with on-site green hydrogen production |
| 7 | Microgrids | • Seasonal long-duration storage capability in remote areas<br>• Portable energy generation source with small modular units<br>• Ability to use energy as electricity or fuel depending on the requirement |
| 8 | Military applications | • Tactical stealth advantages such as improved acoustic signatures, reduced infrared signatures, and extended fuel-use hours in vehicles<br>• Refuelling convenience with on-site green hydrogen production<br>• Portable energy generation source with small modular units |

*Source: Authors' analysis*

Note: There are no application-specific advantages in the industrial applications—hydrogen peroxide production, hydrogenation and semiconductor manufacturing

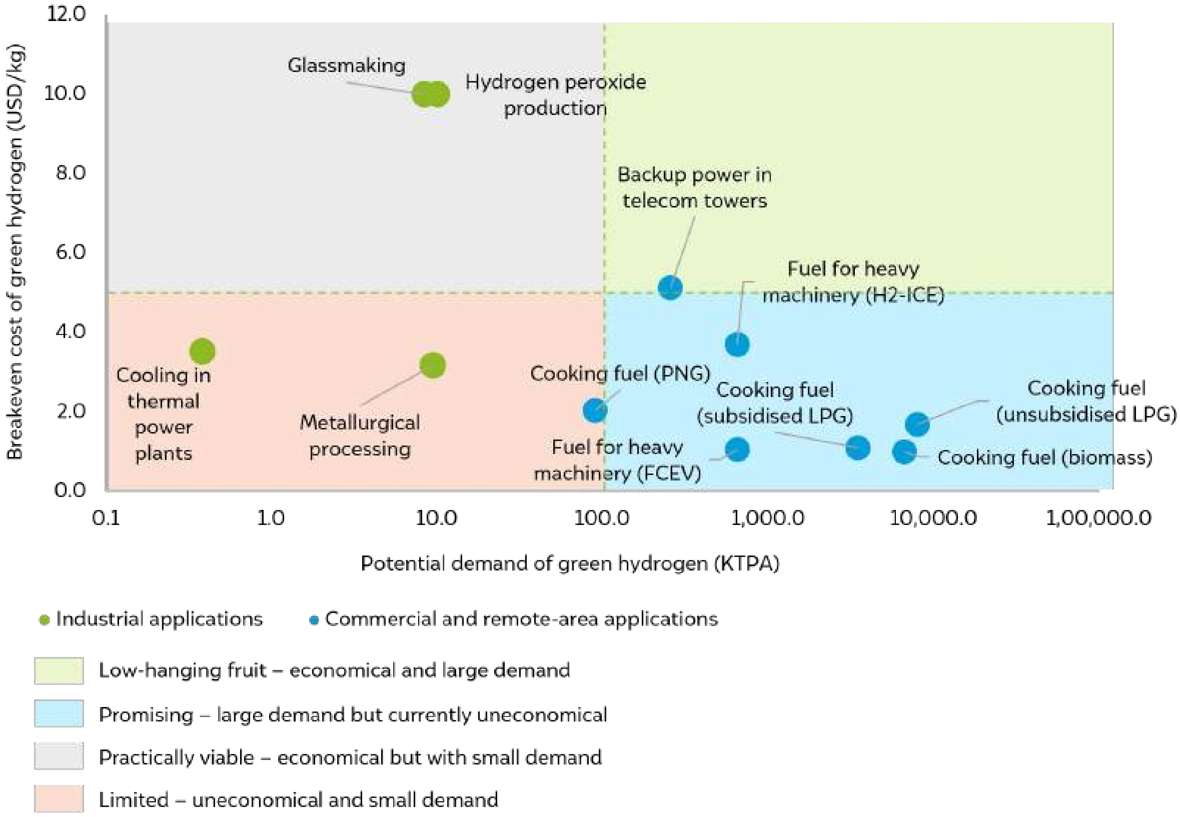
## Key estimation findings

We observe that the potential demand for green hydrogen is much higher in commercial and remote-area applications than in industrial applications. However, the lower break-even cost of most of these applications signifies a lack of economic viability.

We group the applications into four categories, as denoted in Figure ES2, assuming a demand potential higher than 100 kilo metric tonnes per annum (KTPA) to be large and a break-even cost higher than USD 5 per kg to be economical. The estimation results are as follows:

- **Low-hanging fruit:** Backup power provision in telecom towers is found to be the only economical application, with a break-even cost of USD 5.1 per kg and a large potential demand for green hydrogen of around 257 KTPA.
- **Promising:** Other commercial applications – cooking fuel and fuel for heavy machinery – have a larger potential green hydrogen demand of 18.1 MTPA and 650 KTPA, respectively, but the break-even cost ranges between USD 1.0 per kg and USD 3.7 per kg. These applications are termed promising because a trajectory of reducing green hydrogen costs could mean that they would become economically viable eventually.
- **Practically viable:** Hydrogen peroxide production and glassmaking have the highest break-even cost, ranging between USD 8 and USD 12 per kg, but the potential green hydrogen demand, at around 10.1 KTPA and 8.4 KTPA respectively, is much smaller than that for other applications.
- **Limited:** Metallurgical processing and thermal power plant cooling applications also have a small potential demand of around 9.5 KTPA and 0.4 KTPA, respectively. While they are near economic viability, with an estimated break-even green hydrogen cost of USD 3.2 per kg and USD 3.5 per kg, respectively, the overall impact of the transition to green hydrogen in this sector will be limited.

**Figure ES2 Most commercial applications have a high potential demand for green hydrogen but are currently uneconomical**




*Source: Authors' analysis*

By our estimates, a complete transition to green hydrogen in the applications considered in this report could reduce GHG emissions by up to 221 MTPA. Green hydrogen use in cooking would account for around 209 MTPA of the total emissions mitigation potential due to high demand in this sector. We find that industrial applications have a higher specific emissions mitigation potential associated with a green hydrogen transition than commercial and remote-area applications, albeit with a lower overall emissions mitigation potential due to correspondingly lower potential demand for green hydrogen. Metallurgical processing and cooling in thermal power plants are the outliers, with extremely high specific emissions mitigation potentials of around 65 kg-carbon dioxide equivalents ($CO_2$eq.) per kg-$H_2$ and 46.4 kg-$CO_2$eq. per kg-$H_2$, respectively. All other applications fall in the range of 10 kg-$CO_2$eq. per kg-$H_2$ to 20 kg-$CO_2$eq. per kg-$H_2$. It may be interesting to note that the difference in energy efficiencies of PNG, LPG, and biomass used as cooking fuels translates to a difference in the specific emissions mitigation of around 13 kg-$CO_2$eq. per kg-$H_2$ between the three fuels.

## Policy recommendations

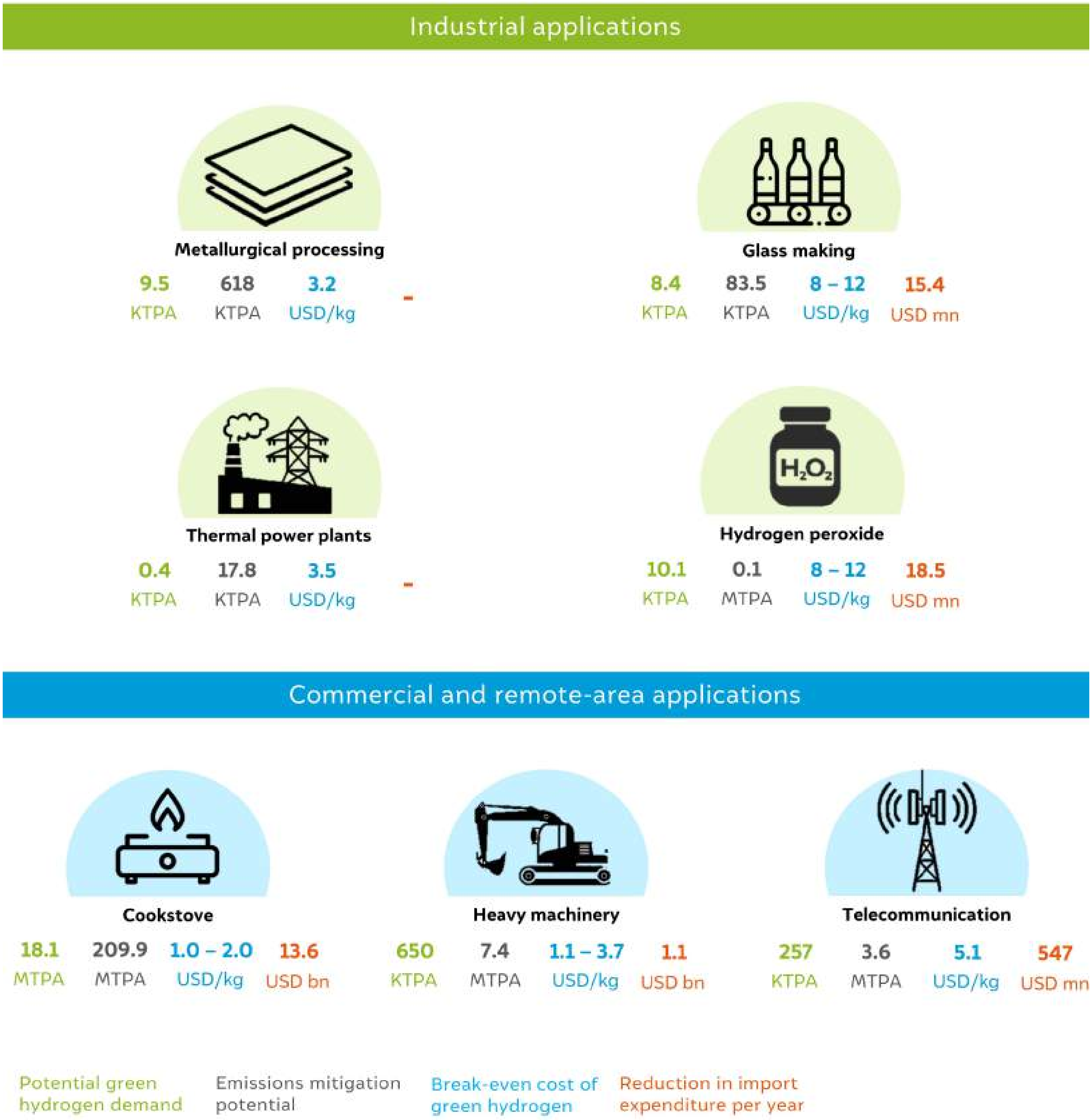
We find that decentralised green hydrogen systems are well positioned to serve multiple use-cases, offering unique application-specific advantages, in addition to decarbonising the applications. The economic, technological, and operational barriers to safe and scalable deployment of decentralised green hydrogen are common to most use cases. We outline the following policy recommendations to overcome these barriers:

- **Low-cost financing:** The high upfront investment required for decentralised green hydrogen applications is a common impediment, even in instances where they could be viable in the long run. Devising a financing programme for this, on lines similar to those of the *PM – Surya Ghar: Muft Bijli Yojana*, could help overcome this barrier.

- **Implement green public procurement strategies:** The government could preferentially procure green hydrogen–based systems in its undertakings – such as for heavy machinery for mining, construction, and manufacturing; hydrogen-based cookstoves and green hydrogen fuel for kitchens in government buildings and microgrids; and green hydrogen–operated devices for use in military operations – which would increase the demand and lead to consequent innovation on the part of suppliers in the ecosystem.
- **Explore biological green hydrogen production routes:** This can be done in applications that can leverage their organic waste streams to produce green hydrogen at low costs. The waste generated by the food-processing industry and the wet waste from residential communities could be utilised to produce and consume green hydrogen locally.
- **Utilisation of government land parcels for green hydrogen production:** The large land parcels available with government-controlled entities such as the armed forces, the public-sector industries, Indian Railways, and so on could be used for RE generation to produce and consume green hydrogen in a decentralised manner.
- **Strategic research and development (R&D) in military applications:** The defence research agencies in India could undertake special projects aimed at indigenising hydrogen-based military applications in consultation with the divisions of the armed forces operating in remote, inaccessible regions.
- **Budgeting a dedicated R&D allocation:** Allocating funds for research and pilot projects in decentralised green hydrogen applications will enable innovators building these technologies to access seed capital for their projects.
- **Develop safety standards:** While general safety standards for hydrogen production, storage, and use are in place, it is crucial to develop and enforce specific regulations tailored to various decentralised hydrogen applications, especially the consumer-focused ones.
- **Awareness building:** The government could organise exhibitions, trade shows, and demonstrations for the benefit of consumers to build awareness about the benefits and share the know-how regarding technology related to decentralised hydrogen applications.

Image: iStock

**Figure ES3** Overview of key estimation findings




*Source: Authors' analysis*

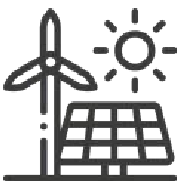
# 1. Introduction

Decentralised green hydrogen systems can be pivotal to India's energy transition. These systems involve producing and using green hydrogen near the point of consumption, typically in smaller quantities. This is in contrast to centralised systems in which hydrogen is either produced in large centralised facilities and transported to the end-use applications or the renewable energy (RE) required for producing green hydrogen is wheeled in from other places. Decentralised systems enable a continuous, convenient, and reliable off-grid energy supply; resolve operational bottlenecks in multiple use cases in urban, rural, and even remote areas; and reduce dependence on imported fossil fuels. Box 1 presents the overview and the significance of green hydrogen in different sectors.

**Box 1** **Overview of green hydrogen and its significance in the energy transition**

Green hydrogen, produced through water electrolysis using RE, is gaining traction globally. It is a clean energy carrier that does not contribute to greenhouse gas (GHG) emissions, unlike conventional hydrogen derived from fossil fuels. The associated use cases are versatile: as feedstock for industrial processes in hard-to-abate sectors like refineries and in steel and fertiliser production. It can also be used as a fuel for mobility applications, especially for heavy-duty long-distance transport like trucks and buses and in shipping and aviation vehicles. Green hydrogen and its derivatives like ammonia can be used as carriers for intercontinental movement of energy or can be blended in the natural gas grid. Green hydrogen also finds application in the seasonal long-duration storage of electricity.

Green hydrogen is also a strategic fuel for an energy import–dependent country like India. India imported INR 16.1 lakh crore (USD 200 billion) worth of fossil fuels in the financial year (FY) 2022–23 (Ministry of Petroleum & Natural Gas 2024). The use of green hydrogen across all sectors indicated in Figure 1 is expected to significantly reduce India's energy imports. Given that India has considerable solar and wind potential (Mallya et al. 2024), it is expected that a global transition to a green hydrogen economy will transform India from an importer of fossil fuels into an exporter of green fuels.



**Decentralised green hydrogen systems could enable a continuous, convenient, and reliable off-grid energy supply**

**Figure 1** Conventional use cases of green hydrogen in hard-to-abate sectors

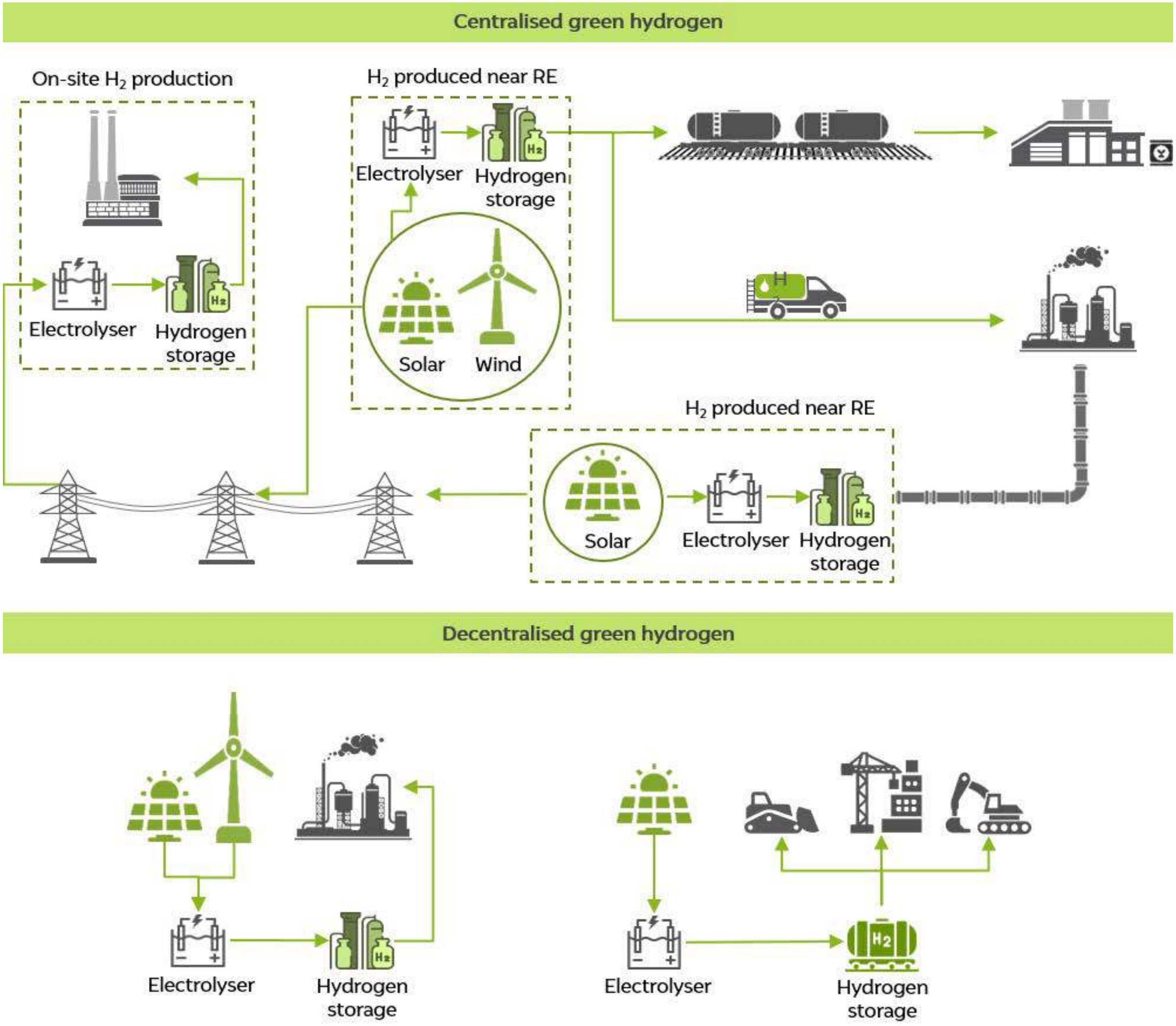

*Source: Climate Finance Leadership Initiative (CFLI) India and Council on Energy, Environment and Water (CEEW). 2024. Financing Green Hydrogen in India: Private Sector Considerations to Strengthen India's Enabling Environment for a Competitive Green Hydrogen Economy. New Delhi: CEEW*

## 1.1. Centralised versus decentralised green hydrogen

Centralised and decentralised green hydrogen production and usage routes can broadly be differentiated based on factors such as the quantum of hydrogen required, access to high-quality RE, geographical location, the end-use form of energy required, infrastructure availability, and economic considerations. The demand for decentralised applications is likely to be less compared to that for centralised ones like refineries and fertilisers.

Centralised hydrogen production generally involves large-scale plants in regions with abundant RE resources or access to low-cost electricity. As seen in Figure 2, in this route, either the RE required to produce green hydrogen is transmitted from where it is produced to the point of hydrogen production and consumption or hydrogen is produced far from the point of consumption and transported through pipelines or hydrogen storage containers. The cost per unit of hydrogen production in centralised set-ups has been historically found to be lower by 34 per cent to 50 per cent than in decentralised set-ups due to economies of scale (Jordan 2022; Sgarbossa et al. 2023). However, centralised systems require significant investment in supporting infrastructure and an operationally robust supply chain, which are not needed in decentralised systems.

**Figure 2** **Hydrogen pathways: centralised and decentralised green hydrogen**




*Source: Authors' analysis*

## 1.2. Advantages of decentralised green hydrogen applications

Decentralised green hydrogen set-ups offer several advantages within the hydrogen economy:

- **A continuous, reliable and convenient off-grid energy supply:** Energy gets democratised with decentralised green hydrogen systems, enabling individuals and communities to take control of their energy supply. Effectively, the risk from disruptions and operational bottlenecks in the supply chains and the reliance on imported fossil fuels is reduced. This can be particularly useful in remote, inaccessible areas. Refuelling becomes convenient in such systems, with the additional benefit of portability.
- **Higher energy efficiencies** are seen with the use of fuel cells and hydrogen-based applications as compared to conventional diesel or biomass-based technologies.
- **Inherently higher purity** of green hydrogen compared to fossil-derived hydrogen is useful in industrial applications to avoid contaminants and maintain efficiencies.

- **Improvement in local air quality** can be seen with a shift away from polluting fuels such as biomass and diesel to green hydrogen in applications such as hydrogen-based cookstoves, microgrids, and hydrogen-based heavy machinery.
- **Reduced transmission and distribution losses** and associated costs contribute to improved energy efficiency.

We also find certain application-specific advantages that decentralised green hydrogen systems offer, which we present in Section 2.

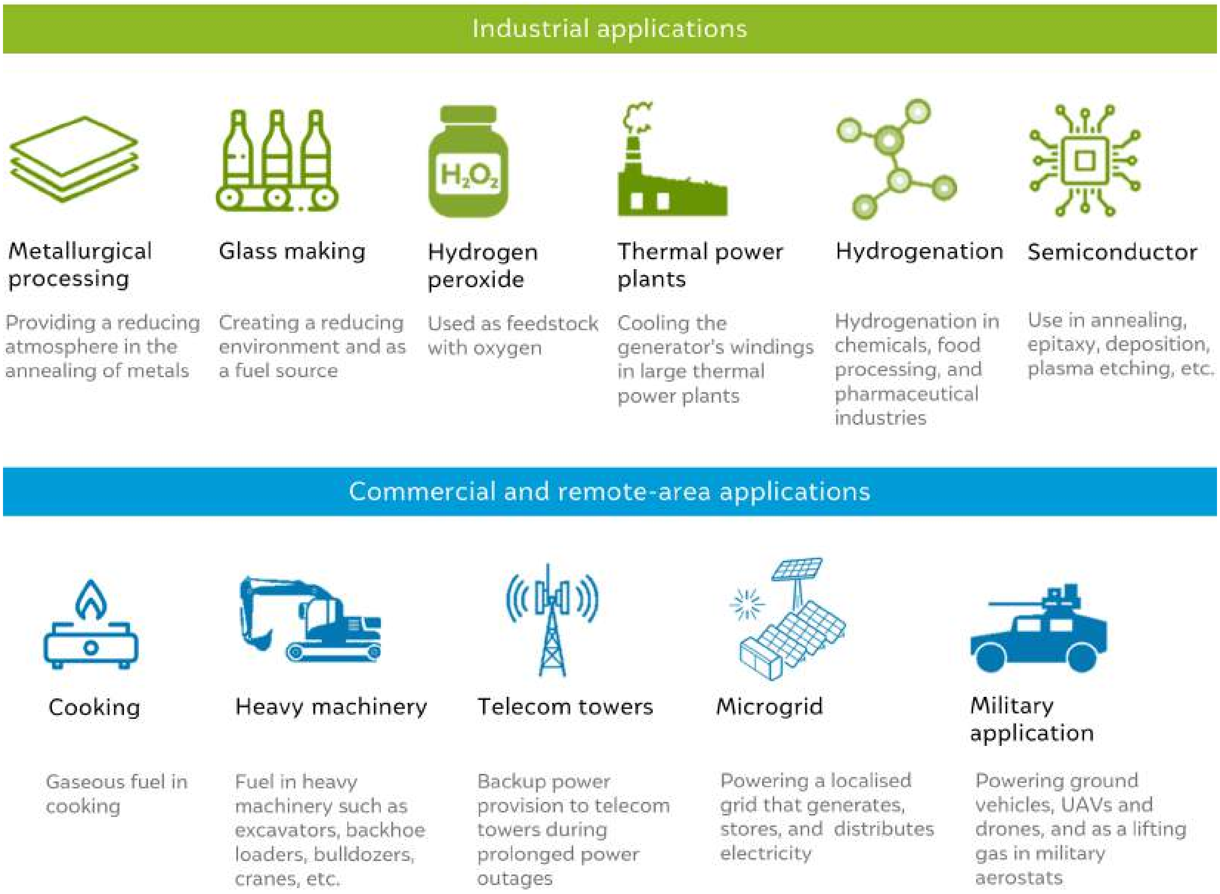
Through this report, we aim to profile various decentralised green hydrogen applications in industrial, commercial, and remote-area settings. We explore the unique advantages that they offer as well as the challenges and constraints that they impose on producers and consumers. We quantify the potential demand for green hydrogen in India through decentralised green hydrogen applications, the associated emissions mitigation potential, the fuels and commodities that they would replace, and the break-even cost of green hydrogen to compete against these fuels and commodities.

Image: iStock

# 2. Applications of decentralised green hydrogen

Decentralised green hydrogen systems find use cases in industrial processes, commercial applications and applications relevant to remote and inaccessible areas. Most of these applications have mature technology readiness levels (TRLs). Figure 3 indicates the various decentralised applications of green hydrogen in India.

**Figure 3 Industrial and commercial applications of green hydrogen**




*Source: Authors' analysis*

In general, decentralised green hydrogen can be used in industrial and commercial applications. Hydrogen derived from fossil fuels or produced through electrolysis using non-renewable electricity is already being used in industrial applications. In-house green hydrogen systems could fungibly replace this hydrogen and mitigate the emissions associated with it. In the industrial sector, decentralised green hydrogen use for metallurgical processing, glass making, thermal power production, food processing, chemicals and pharmaceuticals production, and semiconductor manufacturing might be already economically viable or close to viability.

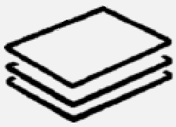
In commercial and remote-area applications, hydrogen-based technologies need to replace technologies that rely on energy sources such as diesel, biomass, and grid-connected electricity. We find that applications in commercial and remote-area settings, such as the use of green hydrogen as a cooking fuel, fuel for heavy machinery, a backup power source in telecom towers, or an energy source powering microgrids and military applications, could also translate to substantial potential demand for green hydrogen in India. Sections 2.1 and 2.2 discuss the applications of green hydrogen in the industrial and commercial sectors.

## 2.1. Industrial applications

Decentralised green hydrogen is a clean, alternative option in various industries such as metallurgical processing, glass manufacturing, semiconductor production, thermal power plants for cooling and food processing, and chemicals and pharmaceutical industries for hydrogenation. Fossil fuel–derived hydrogen is already used in these industries as a feedstock, fuel, and cooling agent or for creating a reducing environment. Decentralised green hydrogen can fungibly replace the grey hydrogen that these industries procure externally or produce through in-house electrolysers using captive power, albeit at a much smaller scale compared to its use in conventional hydrogen-consuming industries such as fertiliser production and refining.

We present a detailed analysis of all the industrial applications profiled in the report in the following sub-sections. The detailed calculations are presented in Annexure 1 to Annexure 7.

### 2.1.1.Metallurgical processes



Green hydrogen could replace fossil-derived hydrogen that is used for creating a reducing environment during annealing of metals

- **Technology readiness level:** 8–9
- **Energy source replaced:** Captive thermal power–driven electrolytic production

#### Process description

Annealing is a slow heat treatment process that increases ductility and reduces the hardness of metals, making them more pliant. The reducing environment created by hydrogen during annealing prevents metal oxidation–associated defects, resulting in a cleaner and smoother surface. Especially in stainless steels and flat steels, hydrogen is instrumental in enhancing surface quality, corrosion resistance, and overall material properties (Technotherma (India) Pvt. Ltd. 2023; Liu et al. 2018).

Conventionally, hydrogen may be used alone or combined with other inert gases, such as nitrogen or argon, for annealing. The primary benefit of hydrogen is its high thermal conductivity, which results in faster and more uniform heating. This characteristic reduces the processing time and improves the energy and fuel efficiency of the process when compared to the use of other inert media (Lu, Chen, and Hwang 2023). Using a 100 per cent green hydrogen atmosphere has additional advantages:

- **Elimination of contaminants:** Green hydrogen’s inherent purity eliminates contaminants that could otherwise compromise the annealing process, enhancing the quality of the final product.
- **Continuity in hydrogen supply:** An on-site hydrogen production and storage facility could support a continuous supply of high-purity hydrogen and ensure operational reliability.

#### Assumptions

Hydrogen demand in the stainless steel industry is estimated based on stainless steel production of 0.8 million metric tonnes per annum (MTPA) and hydrogen consumption of 353 tonnes per annum (TPA) by the Jindal Stainless steel unit at Hisar (Yadav 2024; Jindal Stainless Limited 2023). It is assumed that the specific hydrogen demand of 0.44 kg/tonne of stainless steel in this unit is applicable to all stainless steel production plants in India. Hydrogen is also used in the annealing process of cold-rolled steel, which is a process employed to manufacture steel with better surface finish, precise geometry, and increased strength (TATA Steel n.d.). In the absence of industry-specific data, it is assumed that the specific hydrogen consumption for cold-rolled steel is similar to that for stainless steel. Since integrated steel plants use captive power to meet the electricity demand in the plant, it is assumed that electrolytic hydrogen is obtained through captive thermal electricity. A detailed description of assumptions is provided in Annexure 1.

## Research insights

We estimate the potential demand for green hydrogen from metallurgical process industries in India to be 9.5 kilo metric tonnes per annum (KTPA), primarily for use in annealing stainless steel and cold-rolled steel. Here, hydrogen is not used as a feedstock but to maintain a reducing environment. Consequently, the demand for green hydrogen is estimated to be lower by two to three orders of magnitude compared to the potential demand in primary steel making. In addition to steel, hydrogen-based annealing units can also be used in other plants, such as those manufacturing copper, brass, and various non-ferrous metals. This is not considered here due to uncertainty in data.

**Figure 4 The transition to green hydrogen in metallurgical process industries is already economical**


*Source: Authors' analysis*

As shown in Figure 4, we estimate the emissions mitigation potential to be 618 KTPA. This estimation assumes that the electricity generated from the captive power plant at the steel facility is used to produce hydrogen through an in-house electrolyser. In this particular application, the specific carbon emission per kg of hydrogen is high, at 65 kg-carbon dioxide equivalents ($CO_2$eq.), primarily due to the high emissions per kilowatt hour in the captive plant of 1.3 kg $CO_2$/kWh (Elango et al. 2023).

The cost of hydrogen produced in these industries, estimated to be USD 3.18 per kg for a captive power cost of INR 3.72/kWh, is comparable to the cost of green hydrogen production. Therefore, adopting decentralised green hydrogen could be both economically and environmentally beneficial.

**Box 2** **HYGENCO's green hydrogen fuels; Jindal Stainless Limited's stainless steel future**


*Image received from Jindal Stainless Limited over email*

- Location: Hisar, Haryana, India
- Companies involved: Jindal Stainless Limited (JSL) and HYGENCO
- Status: Commissioned

## Project details:

The Jindal Stainless Hisar unit has a state-of-the-art, fully automated green hydrogen plant associated with Hygenco Green Energies Private Limited. The alkaline bipolar electrolyser, with a capacity of 350 $Nm^3$/hr, guarantees an average round-the-clock supply of 90 $Nm^3$/hr of green hydrogen using dedicated solar energy and storage.

This collaboration involves HYGENCO supplying continuous high-purity green hydrogen to JSL under a 20-year fixed-price offtake agreement. HYGENCO will operate the plant on a Build Own Operate (BOO) Model. The facility targets reducing approximately 2700 tonnes of $CO_2$ emissions per year and is based on a long-term off-take agreement. This is the first commercial-scale green hydrogen plant, powered by rooftop and floating solar panels.

Green hydrogen is used in the cold rolling division and bright annealing process lines, replacing forming gas (75% $H_2$, 25% $N_2$) produced by ammonia cracking. Increasing the $H_2$ concentration in the stainless-steel annealing atmosphere can produce superior end-product quality and increase productivity.

Jindal Stainless has made significant strides in its decarbonisation efforts, as highlighted at the UN COP28 summit in Dubai. The company showcased its initiatives at the India Pavilion at the invitation of the Ministry of Steel, Government of India. With a substantial reduction of approximately 240,000 tonnes of $CO_2e$ over the past two fiscal years (FY22 and FY23), Jindal Stainless is well on its way to achieving its midterm goal of a 50% reduction in carbon emissions well ahead of the 2035 target year and Net Zero by 2050.

*Source: Information about the project received from Jindal Stainless Limited and Hygenco over email*

### 2.1.2. Glass manufacturing

Green hydrogen could be used in the float glass production process to create a reducing environment and as a fuel source in glass and optic fibre production

- **Technology readiness level:** 7–9
- **Energy source replaced:** Hydrogen derived from fossil-fuels or as a by-product from other industries

#### Process description

Hydrogen is used to create a reducing atmosphere in the glass manufacturing process. It is also used as a fuel in the oxy-hydrogen flame to manufacture optical fibres. This section details the use of hydrogen in the glass manufacturing sector, in the context of these two applications. While hydrogen can also offset the use of natural gas as an energy source for glass manufacturing, we do not consider this as an end-use hydrogen application in our assessment.

#### Thermal process

Hydrogen plays a crucial role as a protective gas in the manufacturing of float glass. As shown in Figure 5, manufacturers use mixture of hydrogen and nitrogen (5–10 per cent hydrogen and 90–95 per cent nitrogen) to create a reducing atmosphere within the tin bath (ITM n.d.). This mixture prevents the oxidation of molten tin onto which molten glass is poured to form flat glass. By maintaining a reducing environment, this gas helps produce smooth, impeccable sheets of glass, ensuring the final product's quality. Conventionally, the hydrogen used for this is bought from merchants and conveyed either in high-pressure cylinders or through pipelines.

#### Fuel source

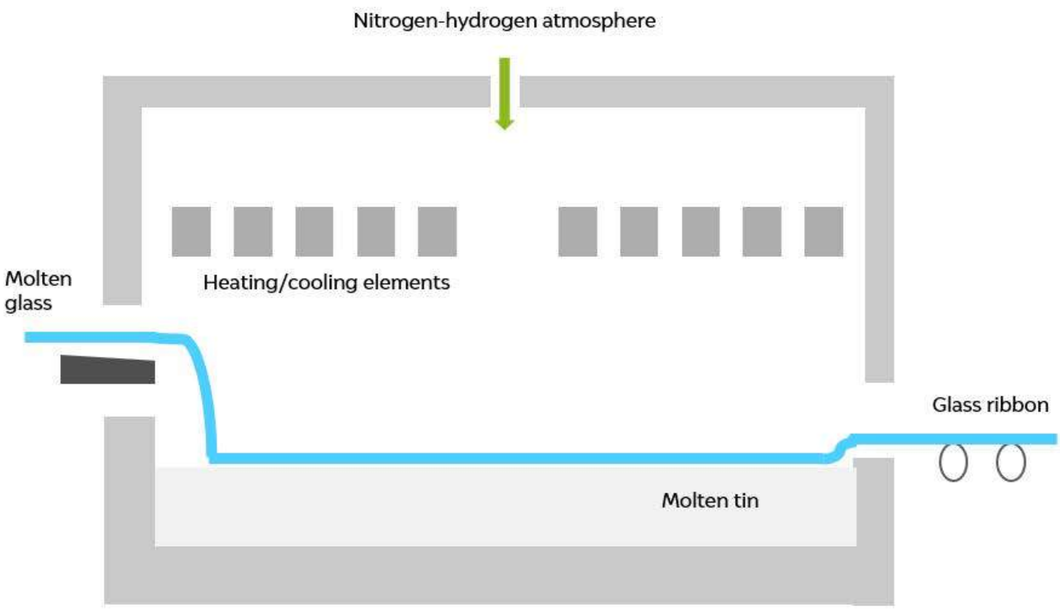
In addition to its use in float gas production, hydrogen is used in the oxy-hydrogen flame in the manufacture of optical fibres (STL 2023). The flame is also used in flame polishing the preform. This is done by localising the melting of the surface to smoothen it and remove any imperfections or dullness in the glass preform and the optic fibre (Gambling 2003).

The main advantage of green hydrogen is its inherently high purity, which eliminates the need for additional gas purification systems. The scalable deployment of green hydrogen in glass manufacturing requires a stable and uninterrupted hydrogen supply, as glass plants operate continuously, 24 hours a day, seven days a week. The intermittent nature of RE sources would necessitate oversizing RE assets, hydrogen storage infrastructure, or both.

#### Assumptions

We assume a typical hydrogen consumption rate of 2.98 kg/tonne of float glass manufactured, as reported by the industry (AIGMF 2017; Santhosh,Verma, and Dev 2024). However, due to the lack of publicly available data, we could not estimate the amount of hydrogen consumed in the manufacture of optic fibers. Furthermore, we assume that hydrogen is sourced in cylinders and is produced through a steam methane reforming process. Annexure 2 lists all the parameters considered for the analysis.

**Figure 5** **Hydrogen gas is used to obtain a smooth and high-quality glass**

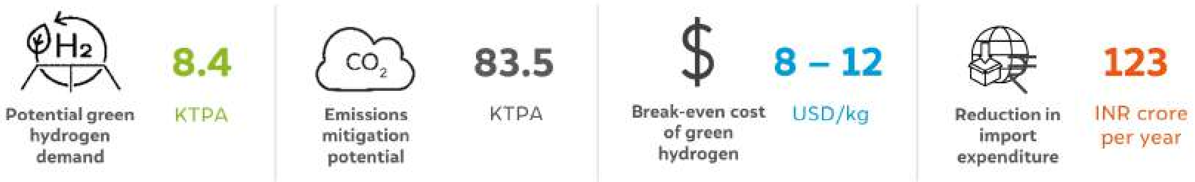



*Source: Oro et al. (2008)*

## Research insights

We estimate the hydrogen demand for float glass production to be 8.4 KTPA (Figure 6). The associated emissions mitigation potential is estimated to be 83.5 KTPA, assuming that 10 kg-$CO_2$eq. is mitigated per kg of grey hydrogen replaced. Assuming that the grey hydrogen being replaced is derived from natural gas, we estimate a potential reduction in import expenditure of INR 123 crore (USD 15.4 million) annually. This factors in the specific consumption of 3.4 kg of natural gas per kg of hydrogen produced (Collodi, Azzaro, and Ferrari 2017) and the average rate of natural gas import between the FYs 2019–20 and 2023–24 (Department of Commerce n.d.).

**Figure 6** **The transition to green hydrogen in the glass making industry is already economical**




*Source: Authors' analysis*

Industries that require hydrogen in relatively smaller quantities procure hydrogen externally at costs that can reportedly be as high as USD 12 per kg (Pillay 2023). Even assuming this cost to range between USD 8 per kg and USD 12 per kg, it is still much higher than the green hydrogen production cost, which ranges from USD 3.5 to USD 5 per kg (CFLI India and CEEW 2024). Consequently, commercial deployment of green hydrogen systems in this industry are already underway, as illustrated in Box 3.

**Box 3** **Commercialised use of hydrogen in the glass industry in India**

## Asahi India Glass

*Image: iStock*
Note: The image used is for illustrative purposes and is not related to the project described.

- Location: Soniyana, Rajasthan, India
- Companies involved: Asahi India Glass Limited (AIS) and INOX Air Products (INOXAP)
- Status: Commissioned

### Project details:

In May 2024, AIS entered into a 20-year offtake agreement with INOXAP to supply green hydrogen for its float glass manufacturing facility in Rajasthan. AIS will invest in a solar power plant to provide RE for green hydrogen production, and INOXAP will design, engineer, install, and manage the hydrogen plant. In the first phase, 95 TPA will be supplied to AIS (Asahi India Glass 2024).

## Project Photon Leap

*Image: iStock*
Note: The image used is for illustrative purposes and is not related to the project described.

Location: Aurangabad, Maharashtra, India
Companies involved: STL and HYGENCO
Status: Under construction
Use: Optical fibre – STL's glass preform plant

### Project details:

HYGENCO plans to use wind and solar energy to produce 200 plus TPA of hydrogen. It will build the hydrogen plant for STL on a Build Own Operate philosophy and it will be Maharashtra's First commercial Green Hydrogen plant. The hydrogen and oxygen will be transported to STL through a dedicated pipeline. STL states that this partnership will reduce carbon emissions by approximately 30 per cent annually (HYGENCO n.d.).

*Source: Information about project received from Hygenco over email*

### 2.1.3. Hydrogen peroxide production


Green hydrogen could be used as a feedstock to produce the hydrogen peroxide through the anthraquinone-autoxidation (AO) process

- **Technology readiness level:** 7–9
- **Energy source replaced:** Hydrogen derived from fossil-fuels or as a by-product from other industries

#### Process description

Hydrogen and oxygen are used as feedstock to produce hydrogen peroxide. It is mainly produced through the anthraquinone-autoxidation (AO) process, where palladium acts as a catalyst and anthraquinone derivative acts as a reaction carrier (Evonik n.d.) (Clifton 2019). Around 95 to 99 per cent of the global hydrogen peroxide production uses this production method (Gao, et al. 2020).

Hydrogen peroxide is a strong bleaching, disinfectant and oxidising agent used in multiple processes, including wastewater treatment, food processing, electronics manufacturing, pharmaceutical production, and many others (ChemAnalyst 2024).

#### Assumptions

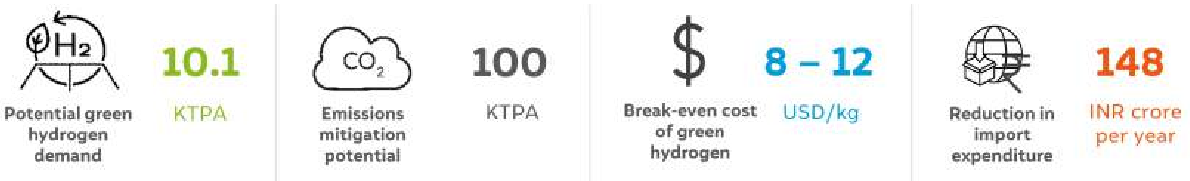
To estimate hydrogen demand, we assumed that India's total hydrogen peroxide market demand of 171 KTPA would be met domestically to avoid chemical imports (Ministry of Chemical and Fertilizers 2022).

We used a stoichiometric hydrogen requirement of 58.8 grams per kilogram of hydrogen peroxide production. The hydrogen needed for this process was assumed to be sourced from steam methane reforming (SMR) of natural gas, which requires 3.4 kg of natural gas to produce one kg of hydrogen (IEAGHG 2017). A proportion of the hydrogen consumed in hydrogen peroxide production is also sourced from other chemical industries, which produce hydrogen as a by-product in their processes. However, the information about this route is not available in public literature. A detailed description of assumptions for hydrogen peroxide production is listed in Annexure 3.

#### Research insight

As shown in Figure 7, we estimate the hydrogen demand for hydrogen peroxide production to be 10.1 KTPA. The associated emissions mitigation potential is estimated to be 0.1 MTPA, assuming a factor of 10 kg $CO_2$eq. mitigated per kg of grey hydrogen replaced. Assuming that the grey hydrogen being replaced is derived from natural gas, we estimate a potential reduction in import expenditure of INR 148 crore (USD 18.5 million) annually.

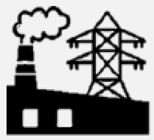
**Figure 7** **The use of decentralised green hydrogen could be economically beneficial**




*Source: Authors' analysis*

Similar to the glass industry the hydrogen required is assumed to be procured externally at costs ranging between USD 8 to USD 12 per kg (Pillay 2023). Thus, the deployment of decentralised hydrogen in this industry could be economically beneficial.

### 2.1.4. Cooling in thermal power plants



In large thermal power plants, green hydrogen could replace hydrogen that is used to cool the generator's windings

- **Technology readiness level:** 7–9
- **Energy source replaced:** Electrolytic hydrogen derived from coal-powered electricity

#### Process description

Hydrogen's low density and high heat transfer coefficient make it an optimal choice for use in this application. The gas reduces frictional heat losses within the turbine generator, improving fuel efficiency. Additionally, its high thermal conductivity enables rapid and uniform heat dissipation, which leads to a better process efficiency (Nel Hydrogen n.d.).

Hydrogen derived through water electrolysis is a highly pure gas. Ensuring hydrogen purity is essential for safety and efficiency, as the presence of any impurity or moisture can negatively affect thermal conductivity and lead to corrosion of internal components (PST n.d.). A continuous gas supply is required to maintain optimal pressure within the cooling system to prevent the formation of any potentially hazardous explosive mixtures.

#### Assumptions

It should be noted that trace amounts of hydrogen are required in the process to replace the gas escaping through the seals (Nel Hydrogen n.d.). Hydrogen consumption in thermal power plants also depends on the plant size. The consumption rate varies from 5 $Nm^3$/day for a 150-MW power plant to 1200 $Nm^3$/day for a 1200-MW system (VR Coolers 2023). Based on Central Electricity Authority (CEA) data (CEA 2023), we consider a total of 567 power plants in the country. A detailed description on assumptions for thermal power plants is listed in Annexure 4.

#### Research insights

As hydrogen is generally recycled, we estimate the overall potential demand for green hydrogen in power plants in India for cooling to be less than 400 TPA (Figure 8). This factors in the typical hydrogen replacement rates for plants with capacities ranging between 150 MW and 1.2 GW.

**Figure 8 Hydrogen produced by using electricity from thermal power plants has a significantly high emissions intensity**


*Source: Authors' analysis*

We estimate the breakeven cost of green hydrogen to be USD 3.5 per kg, factoring in the cost of electricity at INR 4.25/kWh that is generated from the power plant to produce hydrogen in addition to the cost of the electrolyser on a levelised basis (Shah 2021). A switch to green hydrogen is also unlikely to reduce any import dependency as thermal coal is abundantly available in India, notwithstanding the occasional shortage.

The specific emissions associated with this application are extremely high, at 46.5 kg-$CO_2$eq. per kg of hydrogen, owing to the high emission factor of thermal power plants. Although its specific emissions reduction potential is significantly high, the use of green hydrogen in thermal power plants might not materialise as electricity from thermal power plants is abundantly available. Furthermore, the total emissions mitigated through a transition to green hydrogen may be insignificant in comparison to the total emissions from the thermal power plant as hydrogen is only used in trace amounts. However, these power plants might be mandated to switch, if covered under the ambit of Indian Carbon Markets.

### 2.1.5. Hydrogenation process

Hydrogenation is a chemical process in which hydrogen molecules are added to unsaturated compounds, usually in the presence of a catalyst, to produce saturated compounds. This conversion reaction is widely used in various industries such as food production, petrochemicals, pharmaceuticals, and fine and speciality chemicals (Besora and Maseras 2021).

**Fine and speciality chemicals:** Hydrogenation is an important technique used in organic synthesis to reduce functional groups and alter the stereochemistry and properties of fine chemicals (Bonrath et al. 2012). It is essential for producing a wide range of speciality chemicals, polymers, fragrances, and agrochemicals, with sorbitol being a notable example (Behera et al. 2023).

**Food industry:** In the food industry, hydrogenation increases the melting point of unsaturated fats and converts them into solids or semi-solids. It also improves oxidative and thermal stability, increasing the shelf life of hydrogenated products. Margarine and shortening from vegetable oils are derivatives of this process (Orthoefer and List 2007).

**Pharmaceutical Industry:** The hydrogenation process is widely utilised in green chemistry to reduce specific compounds to produce pharmaceutical intermediates (the active pharmaceutical ingredient) with specific stereochemical properties. It is instrumental in the manufacture of various pharmaceuticals such as levofloxacin (antibacterial), carbapenem (antibiotic), glasdegib (cancer treatment), paroxetine (antidepressant), and numerous others (Behera et al. 2023).

The hydrogen consumption across these industries could not be estimated without a detailed assessment that would require extensive surveys to understand the processes of each industry.

### 2.1.6. Semiconductor industry

Hydrogen is extensively used in various stages of semiconductor manufacturing and plays a critical role because it has valuable properties like high thermal conductivity, reducing capability, and reactivity. Typical gas flow rates in these use cases could range between several hundred and several thousand standard cubic centimetres per minute (Cigal 2016). Hydrogen plays various roles across production stages:

- **Annealing** involves heating wafers to over 1000°C and cooling to repair crystal defects, relieve internal stress, and remove unwanted oxides. Hydrogen ensures uniform heating and cooling, which is critical for maintaining consistent material properties (Linde 2017).
- **Epitaxy** is a technique for growing thin layers of single-crystal film on a substrate. The silicon layers need to be grown in a desired and precise manner to produce defect-free film (Ji et al. 2023). In this

process, the gas acts as a reducing agent, reacting with oxygen and other impurities to prevent their incorporation into the growing silicon, silicon–germanium, or germanium films (Linde 2017). This process ensures the formation of high-quality thin films with the desired electrical and optical properties (Hansen and Kuech 2003).

- **Deposition** is a process by which hydrogen molecules disrupt the lattice structure of the wafers to alter their electrical properties, such as increasing resistivity (Linde 2017).
- **Plasma etching** is the process of removing material from the wafers to fabricate intricate circuits (Sukharev 2002). Among others, hydrogen and hydrides are also used to selectively remove unwanted thin films and deposits (Linde 2017).
- **Extreme ultra-violet lithography** is a technique used to print patterns on a wafer in which tin is used to generate the necessary radiation. In this process, hydrogen gas is used to remove tin residues and deposits (Linde 2017).

The upcoming semiconductor manufacturing units in India could emerge as industrial demand centres for green hydrogen. However, given the nascent stage of the semiconductor industry in India, we could not estimate the hydrogen demand for this sector.

## 2.2. Commercial and remote applications

Green hydrogen not only helps to reduce the carbon footprint, but also has unique properties that make it superior to conventional fuels for use in commercial applications, such as cooking fuel, heavy machinery, backup power in telecom towers, and microgrids. Green hydrogen also finds some important military applications that can help our defence forces strengthen their energy security. The decentralisation of green hydrogen in commercial applications allows energy to reach remote locations that are traditionally hard to access due to weather conditions or logistical constraints.

In contrast to most industrial applications, a green hydrogen transition in commercial applications would entail a redesign of the processes and equipment, as it would replace other energy sources such as diesel, liquefied petroleum gas, biomass, piped natural gas, or fossil fuel–derived electricity. To scale decentralised green hydrogen systems in commercial applications, governments will need to carefully evaluate them to place them suitably in the overall energy transition plan. In addition, private sector innovations and improvements in technology to address key challenges will be required.

We present a detailed analysis of all the commercial applications profiled in the report in the following subsections.

### 2.2.1. Cooking fuel in Indian households

Green hydrogen could replace LPG and biomass as fuel for cooking

- **Technology readiness level:** 6-7
- **Energy source replaced:** LPG, biomass

#### Green hydrogen as a cooking fuel

Green hydrogen has the potential to bring about significant changes in domestic cooking in rural and urban India. About 65 per cent of the country's population lives in rural areas (PIB Delhi 2023), and they depend primarily on biomass or fossil-based cooking fuels. Nearly half of the rural households rely on liquefied petroleum gas (LPG), while the rest depend on biomass (Ministry of Statistics and Programme Implementation

2023). Also, 89 per cent of urban households utilise LPG for their cooking needs, while only 1.2 per cent use piped natural gas (PNG) as their primary cooking source. The use of biomass pollutes the immediate environment and poses health risks to the population. Green hydrogen is a cleaner and more efficient cooking solution as it has a higher calorific value compared to conventional fuels as well as clean combustion attributes. The green hydrogen flame, with a temperature range of 1200°C to 1500°C, ensures efficient and rapid cooking (NTPC 2024).

Gaseous hydrogen could be supplied to specially designed hydrogen-based cookstoves through either of the two routes, as illustrated in Figure 9 and discussed below:

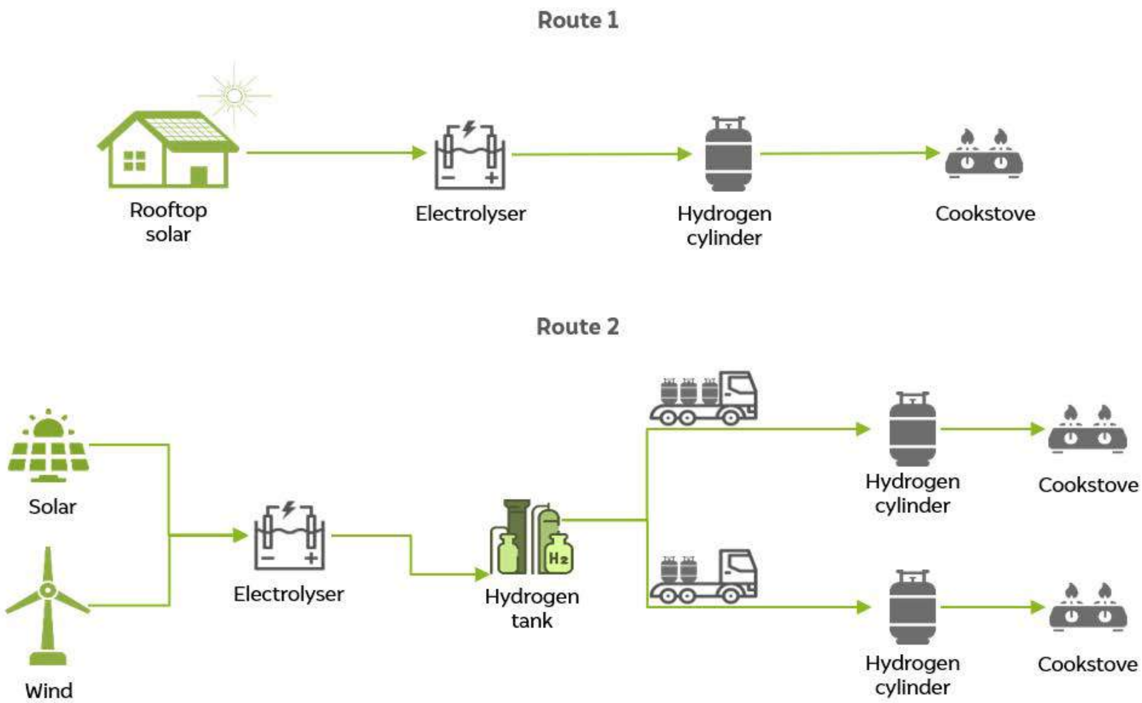
- Route 1: A truly decentralised setup could be employed, with stoves running on green hydrogen produced through an in-house electrolyser and electricity from rooftop solar panels.
- Route 2: High-pressure hydrogen gas cylinders could be used to procure hydrogen through a hub-and-spoke model. This will require small-scale centralised green hydrogen production facilities to be operated as a shared asset between communities.

## Advantages of green hydrogen as a cooking fuel

We can address both the practical and environmental concerns associated with traditional cooking fuels by shifting to green hydrogen, which has the following advantages:

- **Avoidance of harmful emissions**: The use of hydrogen as a fuel avoids emissions of particulate matter related to biomass-based cooking as well as $CO_2$, CO, $SO_2$, and volatile organic compounds. Thus, replacing traditional fuels like LPG and biomass with hydrogen will help improve air quality and public health in rural areas.
- **Reduces import dependency:** Switching to hydrogen for cooking needs can significantly reduce India's dependence on imported LPG and PNG. LPG is obtained from refining crude oil, and the country imports over 200 million metric tonnes (MT) of crude oil every year (Ministry of Petroleum & Natural Gas 2024). Moreover, we also import more than 15 MT of LPG annually. Likewise, PNG is derived from natural gas, a significant share of which is sourced as liquefied natural gas (LNG).
- **Reduces GHG emissions:** Green hydrogen, from production to combustion, has zero GHG emissions. In contrast, for LPG and PNG, the combustion process alone has high emission intensities of 63.1 and 56.1 g of $CO_2$ per MJ of fuel consumed, respectively (Gómez et al. 2006). These intensities increase even further when the efficiencies of their respective stoves are accounted for on the basis of per megajoules of energy delivered. The shift to green hydrogen can cut the emissions from the combustion of over 25 MT of LPG for cooking annually (Ministry of Statistics and Programme Implementation 2024).
- **Suitability to Indian cooking:** The acceptability of other clean cooking applications like electric cooking is low in India due to the perception that it is not suitable for the Indian style of cooking. Consequently, there is a significant reliance on flame-based cooking. Green hydrogen can support the transition to clean cooking without any change in cooking style as it is flame based and therefore seen as suitable for Indian cooking.
- **Elimination of frequent cylinder refills:** Green hydrogen produced through in-house electrolysers and rooftop solar panels (route 1) eliminates the hassle of frequent cylinder refills.

Figure 9 **Green hydrogen–based cooking could be operationalised through two routes**



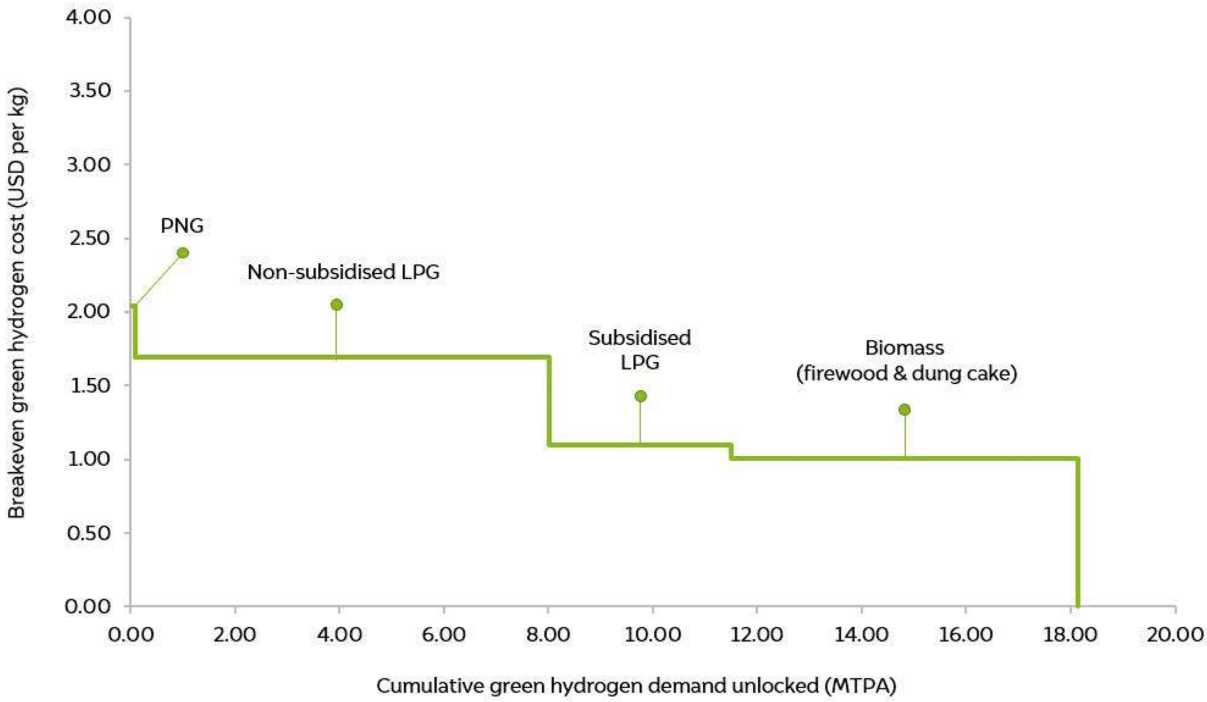

*Source: Authors' analysis*

## Challenges and constraints of green hydrogen as a cooking fuel

- **Economic feasibility:** The economic feasibility of deploying this technology for the target population is the primary hurdle. Currently, 49.7 per cent of rural households in India rely on biomass such as firewood and dung cakes for cooking (Ministry of Statistics and Programme Implementation 2023), primarily because these resources are available at almost no cost. Currently, green hydrogen production costs are estimated to range between USD 3.5 to 5 per kg (CFLI India and CEEW 2024). After accounting for burner efficiency of incumbent and hydrogen-based cookstoves (Annexure 5), we estimate the break-even costs of green hydrogen to replace biomass, subsidised LPG, non-subsidised LPG, and PNG for domestic cooking to be USD 1.0, USD 1.1, USD 1.7, and USD 2 per kg, respectively, as depicted in Figure 10. Therefore, making green hydrogen viable for consumers will require the central and state governments to include provisions for green hydrogen in the existing subsidy programmes for cooking fuels.

- **Need for a specialised burner:** Ensuring a stable and controlled combustion process is critical when using hydrogen as a cooking fuel. Specialised burners are required that can safely mix hydrogen and air at the point of combustion. This is because, unlike LPG, hydrogen cannot be premixed with air before combustion due to the risk of creating an explosive mixture (NTPC 2024). Also, if the flow rate of the hydrogen–air mixture is less than the flame velocity, there is a risk of burner damage. This necessitates the use of pressurised hydrogen or incorporation of a flame arrester (Mukelabai, Wijayantha, and Blanchard 2022).

**Figure 10 Replacing biomass with green hydrogen in cooking could lead to a large potential demand but at a steep economic premium**




*Source: Authors' analysis*

- **NOx emissions:** Although hydrogen combustion is generally clean, it can produce unwanted NOx due to the oxidation of nitrogen at high temperatures, typically above 1300°C (Clean Carbon Energy n.d.). The high flame temperature of hydrogen creates an environment conducive to NOx formation, which can contribute to air pollution and have adverse health effects.
- **Storage challenges**: Unlike LPG, storing hydrogen at a high pressure, as required in route 2, is difficult because it cannot be liquefied at room temperature and has to be stored as a gas. Even when stored at pressures of up to 20 times that of LPG storage pressures, the mass of hydrogen that can be contained in a cylinder of similar volume is substantially less. This limitation makes the use of hydrogen as a cooking fuel impractical, as it would require frequent refuelling and larger cylinders.
- **Renewable energy availability:** The feasibility of using green hydrogen in cooking through either of the routes is highly dependent on the availability of RE resources in the area. It is a challenge to uniformly implement this technology across the country, as the availability of RE varies widely. Furthermore, houses in urban India do not have enough space to install solar rooftop systems for meeting their cooking fuel requirements.
- **High emissions intensity for hydrogen production with grid electricity:** In the absence of access to rooftop solar energy or small-scale centralised production facilities, there are chances that households might be tempted to use grid power for electrolytic hydrogen production. This will significantly reduce any potential gains from using hydrogen for cooking applications as the power grid in India is highly carbon intensive and has an emissions intensity of 0.716 kg $CO_2$/kWh (CEA 2023). Table 1 compares the emissions intensity of incumbent cooking fuels with that of electrolytic hydrogen obtained from grid power. It is evident that the emissions intensity of fuel use per unit of energy delivered through hydrogen produced from electrolysis using grid-based electricity is the highest among all the fuels. This suggests that using hydrogen produced from grid electricity would be more detrimental to the environment than even biomass.

**Table 1 Use of hydrogen produced through electrolysis by using grid-based electricity for cooking could lead to the most emissions on a unit basis**

| Sr. No. | Fuel used | Emissions intensity of fuel per unit of energy content (g $CO_2$/MJ) | Emissions intensity of fuel per unit of energy delivered after accounting for burner efficiency (g $CO_2$/MJ) |
|---|---|---|---|
| 1 | LPG | 63.1 | 92.8 |
| 2 | Biomass | 44.1 | 294.0 |
| 3 | PNG | 56.1 | 102.0 |
| 4 | Electrolytic hydrogen obtained by using grid power | 301.0 | 519.5 |
| 5 | Green hydrogen | 0 | 0 |

*Source: Authors' analysis*

Note: The emissions intensity of biomass is based on a 30 per cent fraction of non-renewable biomass (fNRB)

## Key results

We estimate that the potential demand for green hydrogen to replace conventional cooking fuels in India could be as high as 18.1 MTPA, as depicted in Figure 10. We factor in the replacement of useful energy required for cooking in our estimation and compare the efficiency and the calorific values of green hydrogen, LPG, PNG, and biomass. Replacing LPG could unlock a potential demand of around 11.4 MTPA, almost two-thirds of the total potential demand. Half of the rural population still relies on biomass for their cooking needs, which leads to a further potential demand of 6.6 MTPA of green hydrogen. The demand for replacing PNG is the lowest among all the fuels, at just 0.1 MTPA, as only 0.5 per cent of households currently use PNG for cooking (Ministry of Statistics and Programme Implementation 2023).

The technical and economic input associated with a transition to green hydrogen, especially for the population that relies on biomass, could be onerous. Green hydrogen production costs would have to fall sharply to realise any portion of the potential demand. Our estimated breakeven cost of green hydrogen, ranging between USD 1.0 per kg and USD 2 per kg, suggests that commercial deployment without financial support from the government could be extremely challenging.

**Figure 11 Complete transition to green hydrogen as cooking fuel could lead to a potential demand of 18,100 KTPA**


*Source: Authors' analysis*

By our estimates, the associated emission mitigation potential of around 210 MTPA, as illustrated in Figure 11, could be as high as seven per cent of India's overall GHG emissions, which were around 3.1 billion tonnes of $CO_2$eq. per annum in 2019 (NITI Aayog 2024). In addition to emissions mitigation, the benefits due to improved air quality with reduced particulate matter emissions could be substantial. Replacing LPG could potentially reduce India's import expenditure by around USD 13.6 billion per year. The detailed calculations are presented in Annexure 5.

**Box 4** **The National Thermal Power Corporation (NTPC) demonstrated hydrogen cooking using a modified cookstove**


*Image: Image received from Integrated Energy Solutions over email*
Note: The image used is for illustrative purposes and is not related to the project described.

The R&D wing of National Thermal Power Corporation Ltd., NTPC Energy Technology Research Alliance (NETRA), recently demonstrated hydrogen cooking using a modified cookstove at its Greater Noida campus in January 2024 (NTPC 2024). Hydrogen produced from its existing green hydrogen plant using Ohmium's PEM electrolysers was used to fuel the modified cookstove (Ohmium 2024).

The project used a specialised burner capable of handling hydrogen's unique burning characteristics – high flame temperature and rapid flame propagation – and preventing premixing with air to avoid explosive mixtures (NTPC 2024). This demonstrates the technical feasibility of using hydrogen for everyday cooking.

## 2.2.2. Fuel in heavy machinery

Green hydrogen could replace diesel as a fuel for heavy machinery

- **Technology readiness level:** 6-7
- **Energy source replaced**: Diesel

### Green hydrogen uses in heavy machinery

Green hydrogen is emerging as a promising fuel for heavy machinery in the construction and manufacturing sectors. It is estimated that diesel-powered machines like excavators, backhoe loaders, bulldozers, cranes, and so on consume around 2.3 MT of diesel annually, representing 2.6 per cent of the country's total diesel consumption (CRISIL 2021). Internationally, leading companies like JCB, Liebherr, Volvo, and Komatsu have been actively developing hydrogen-powered machinery, exploring both hydrogen internal combustion engines ($H_2$-ICEs) and hydrogen-fuel-cell electric vehicles (FCEVs) with successful prototypes.

## Specific advantages of green hydrogen use in heavy machinery

- **No GHG emissions:** Hydrogen is a compelling alternative to diesel, with its **zero emissions profile**, in off-road heavy vehicles.
- **Higher tank-to-wheel (TTW) efficiency**: Both $H_2$-ICE vehicles and FCEVs offer higher TTWs than corresponding diesel vehicles (Lohse-Busch et al. 2018). The TTW efficiencies of both technologies vary with the vehicle's engine load. At a partial load of 40 per cent, FCEVs and $H_2$-ICEs achieve higher efficiencies of around 45 per cent and 35 per cent, respectively, compared to an efficiency of around 30 per cent for their diesel counterpart (Heid, Martens, and Orthofer 2021). At maximum load, $H_2$-ICEs offer a higher efficiency of around 45 per cent, surpassing both FCEVs and diesel vehicles, whose efficiencies are around 41 per cent and 38 per cent, respectively.
- **Reduces import dependency:** India consumed over 89 MT diesel in FY 2023-24 (Ministry of Petroleum and Natural Gas 2024). Almost all of this diesel is obtained from refining crude oil, of which India imports more than 200 MT every year. We can significantly reduce our reliance on fossil imports by switching to hydrogen-powered vehicles and ensuring independent energy access.

**Box 5** **$H_2$-ICEs versus FCEVs**

Hydrogen ICEs burn hydrogen in a manner similar to traditional gasoline engines by utilising spark ignition. While the engine architecture is similar to that of existing petrol and diesel engines, modern hydrogen engines are designed specifically to exploit the unique properties of hydrogen. Hydrogen fuel cells provide the necessary power to vehicles by converting hydrogen into electricity. Both $H_2$-ICEs and fuel cell–based technologies have distinct advantages and challenges across four key aspects:

- **Changes to the manufacturing process:** $H_2$-ICE vehicles can be produced and assembled in existing factories and using infrastructure that relies on familiar components and processes (Nebegall 2022). In contrast, fuel cell–based vehicles require distinct manufacturing infrastructure, including specialised parts and processes.
- **TTW efficiency**: Fuel-cell vehicles offer higher maximum TTW efficiency than $H_2$-ICE vehicles (Heid, Martens, and Orthofer 2021). But although fuel cells are highly efficient at lower loads, they are less efficient at higher loads. $H_2$-ICEs, on the other hand, operate more efficiently at higher loads (Heid, Martens, and Orthofer 2021), which aligns better with the demands of heavy machinery, which typically operate under such conditions. Although it is possible to oversize fuel cells to operate at their most efficient load, this approach would significantly increase the cost of the vehicle.
- **Cost differential:** FCEVs are expensive due to the use of catalysts and the energy-intensive production process required for fuel cells. On the other hand, $H_2$-ICE technology leverages existing suppliers and cost bases, resulting in costs similar to those of existing diesel engines, especially when production volume is high.

- **Emissions profile:** FCEVs produce no emissions other than water vapour. Hydrogen engines, while releasing near-zero[1] $CO_2$ emissions, can produce NOx gases (Nebegall 2022). However, the emissions are significantly lower than that of diesel engines, even without an after-treatment system.

$H_2$-ICE technology is better suited for heavy machinery due to its lower cost, compatibility with existing infrastructure, and better efficiency at operational loads. For FCEVs to become viable in this segment, significant reductions in fuel-cell costs and improvements in efficiency are needed. FCEVs may eventually prove to be more efficient for off-road vehicles that operate at lower loads, such as tow trucks or concrete mixers.

## Assumptions

To explore the potential for green hydrogen use in heavy machinery in India, we estimate its total potential demand with a complete transition to green hydrogen, the break-even cost of green hydrogen for it to be viable against diesel, and the associated benefits in terms of emissions mitigation and reduction in import expenditure.

TTW efficiency is a critical factor in the estimation, and it varies with engine load, particularly in heavy vehicle segments (Heid, Martens, and Orthofer 2021). We assumed a 60 per cent load factor for all three systems: diesel engine, hydrogen combustion engine, and fuel cell. To estimate break-even cost, we considered excavators as our benchmark. The detailed methodology and calculations are presented in Annexure 6.

## Key results

- We estimate the total potential demand for green hydrogen in heavy machinery to be around 650 KTPA, as illustrated in Figure 12, for a diesel consumption of 2.3 MT. It was determined by matching the useful energy obtained from the combustion of hydrogen and diesel in their respective engines by incorporating the energy content of fuels and losses due to engine inefficiencies.
- We estimate the breakeven cost of using green hydrogen, as availed at the tank inlet, to range between USD 1.1 to USD 3.7 per kg. This break-even cost of using green hydrogen was calculated by equating the total cost of ownership (TCO) of $H_2$-ICE, FCEV, and diesel-powered excavators. The wide range observed is primarily attributable to the difference in the purchase cost of $H_2$-ICE vehicles and FCEVs, which is a prominent factor in the TCO. It should be noted that the hydrogen refuelling station also has a levelised cost of USD 1.5 per kg to USD 2 per kg (Reddi et al. 2017). Therefore, the break-even cost of producing green hydrogen would reduce by around USD 1.5 per kg to USD 2 per kg, to account for the cost of the refuelling infrastructure.

[1] Trace amounts of $CO_2$ can be released due to the oxidation of carbon present in the lubricant.

**Figure 12** **Complete transition to green hydrogen in heavy machinery could lead to a potential demand of 650 KTPA**


*Source: Authors' analysis*

Note: The break-even cost of green hydrogen doesn't account for the additional cost of refuelling infrastructure, which could reduce the break-even cost further by USD 1.5 to USD 2 per kg according to estimates in the literature (Reddi et al. 2017)

- A complete switch to green hydrogen in heavy machinery could result in $CO_2$eq. emissions mitigation of up to 7.4 MTPA by our estimation. In addition to emissions mitigation, it could also reduce India's import expenditure on fossil fuels by an estimated USD 1.1 billion, considering the weighted average of the cost of directly imported diesel and the diesel obtained by refining imported crude oil between the financial years 2017-18 and 2022-23 (Ministry of Petroleum & Natural Gas 2024).

**Box 6** **JCB introduced its hydrogen ICE-powered backhoe loader, 3CX**

*Image received from JCB over email*

In 2021, JCB made a significant leap in sustainable construction machinery by unveiling the hydrogen combustion engine–powered version of its most popular backhoe loader, the JCB 3CX. The hydrogen engine's design is similar to that of diesel engines, with matching weight and other dimensions, allowing a seamless installation of the engine into existing machines without any structural modifications.

JCB developed a hydrogen engine that performs ultra-lean hydrogen combustion, resulting in low cylinder temperature and pressure. This helps the engine to achieve zero carbon emissions and easily comply with the European Union stage V NOx and particulate matter emissions standards even without an after-treatment system; this could be further reduced by 95 per cent through after-treatment.

The engine delivers performance on par with the diesel equivalent, matching power, torque, and an efficiency of ~40 per cent. In fact, it offers a higher peak thermal efficiency than conventional JCB diesel engines. The cost of manufacturing is only marginally higher as it leverages the existing infrastructure and supply chains of components. This could further reduce with economies of scale.

The machine made its Asian debut in a trade event, Excon, last year in India (NBM&CW 2024).

*Source: Information about project received from JCB over email*

## 2.2.3. Backup power provision in telecom towers

Green hydrogen–powered fuel cells can provide backup power to telecommunication towers during prolonged power outages

- **Technology readiness level**: 6–8
- **Energy source replaced:** Diesel

### Green hydrogen for the telecom sector

Disruptions in telecom services can have widespread consequences, affecting everything from personal communication to critical services. There are over 0.7 million towers in operation today in India (data.govin 2023), which may have multiple base transceiver stations (BTSs) on them. Each BTS typically consumes around 1.5 kW of power (Deevela, Kandpal, and Singh 2024). The overall power consumption of a tower, including the power consumed by auxiliary supporting units, varies with the number of BTSs that it hosts. Almost all towers today rely on electricity grids.

Despite the near-complete electrification of the country, many regions, particularly in northern India, still experience frequent and prolonged power cuts. The average time for which electricity is available daily is less than 20 hours even in urban areas of states like Uttar Pradesh, Bihar, Haryana, and Jharkhand (Agrawal et al. 2020). During these outages, diesel generators are commonly used to keep the towers operational, and telecom towers consume over 3.5 billion litres of diesel annually (Deevela, Kandpal, and Singh 2024), producing an estimated 9 MT of $CO_2$eq. emissions. By using hydrogen fuel cells, we can generate electricity from stored hydrogen to power the towers during outages, significantly reducing our reliance on diesel and mitigating the environmental impact.

### Advantages of green hydrogen in telecom towers

- **Higher efficiency:** Proton exchange membrane fuel cells (PEMFCs) used in hydrogen systems convert hydrogen into electricity with an efficiency of around 60 per cent (U.S. Department of Energy 2015), which is higher than the efficiency of 40 per cent typically seen in diesel generators (General Power n.d.).
- **Elimination of refuelling operations:** Given the low power requirements of telecom towers, green hydrogen can easily be produced on-site. This eliminates the need for regular refuelling that is required by diesel generators.

A key challenge in deploying green hydrogen fuel cells is the high upfront cost. A 10-kW PEMFC costs around INR 12.8 lakh (USD 16,000) (Yadav, Guhan, and Biswas 2021), far exceeding the purchase price of a similar 10-kW-rated diesel generator, which is around INR 2 lakh (around USD 2500) (Intelligent Energy 2012). Additionally, the costs of solar modules, electrolysers, and hydrogen storage systems add to the difference in capital costs.

**Box 7** **Battery energy storage solutions versus green hydrogen fuel cells**

Battery energy storage solutions as a backup source are also a possible alternative for telecom towers because they offer a higher energy efficiency of 90 per cent and instant power availability (EnerTech n.d.). However, batteries suffer from self-discharge over time and have a smaller storage capacity, which becomes an issue for long-duration backups. Batteries with larger capacities or oversizing of batteries will be required to ensure extended backup, which could become impractical and cost-prohibitive. Hydrogen fuel cells, on the other hand, can store energy without any loss of capacity. This ensures continuous operation during prolonged outages. Although they require a consistent hydrogen supply and have a brief start-up delay, their ability to provide sustained power makes them a favourable choice for remote locations, where outages can be prolonged. A detailed techno-economic analysis that considers the power outage frequency and profile along with RE availability can be used to arrive at an optimal share of battery storage and fuel cells. However, given the significant uncertainty and variability in data availability, we indicate the market size assuming a complete switch to green hydrogen–based fuel cells for telecom towers in India.

## Assumptions

The total hydrogen demand for mobile towers is obtained considering a BTS (4/4/4) configuration. The total load of 6 kW per tower includes the power consumed for the BTS system and balance of plant systems. We consider mobile towers in 10 states where the daily power outage exceeds four hours. We assumed an equal division of towers between rural and urban parts of a state for our estimations. Our analysis covers 260,288 telecom towers in the country. The total hydrogen requirement is obtained based on the total number of hours for which backup power has to be provided, which varies across states. A detailed discussion on methodology and assumptions is provided in Annexure 7.

## Key results

We estimate an economical breakeven green hydrogen production cost of around USD 5.1 per kg, as illustrated in Figure 13. The difference in efficiencies of hydrogen-based systems and diesel generators is primarily responsible for the high break-even cost of green hydrogen. The equipment costs, apportioned over respective lifetimes, constitute a much smaller share than the cost of fuel. We estimate the electricity cost from a diesel generator to be INR 23.1 per kWh for a diesel price of INR 87 per litre, significantly higher than that for other sources of electricity. The economics of hydrogen-fuel-cell systems vis-à-vis diesel generators make them a low-hanging fruit for deployment.

**Figure 13 The breakeven green hydrogen cost for use in backup power systems for telecom towers is USD 5.1 per kg, which is viable considering current green hydrogen production costs**


*Source: Authors' analysis*

We estimate a total potential green hydrogen demand of around 257 KTPA from telecom towers. The demand estimation considers towers in both urban and rural areas in states[2] with more than four hours of daily outage – Assam, Bihar, Chhattisgarh, Haryana, Jammu and Kashmir, Jharkhand, Karnataka, Ladakh, Madhya Pradesh, Rajasthan, and Uttar Pradesh (Agrawal et al. 2020). While a significant proportion of this demand

2 Only rural regions in Chhattisgarh, Haryana, Karnataka, Madhya Pradesh, and Rajasthan are considered, as urban areas in these states do not have outages exceeding four hours on a daily basis. Both urban and rural areas are considered in other states.

could be captured by battery energy storage solutions, hydrogen fuel cells could be more useful in certain remote locations with prolonged outages, as discussed above.

The associated emissions mitigation potential is estimated to be 3.6 MTPA. We estimate a potential reduction in import expenditure to replace diesel to be around USD 0.55 billion per year.

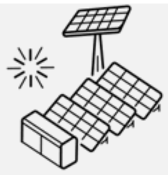
**Box 8** **Telstra, in partnership with Energys, deployed five hydrogen-fuel-cell generators at mobile towers in Australia**


*Image: Hydrogen News. 2024. "Energys & Telstra Launch Hydrogen Backup Generators in Victoria". 08 July. https://energys.com.au/green-hydrogen-news/hydrogen-generators-deployed-at-regional-mobile-towers-by-telstra-energys.*

In July 2024, Australian telecom company Telstra installed hydrogen generators at its five critical mobile towers in Victoria as a backup power source (Energys 2024). The sites were chosen due to their susceptibility to grid damage during storms. Telstra partnered with Energys, an Australian leader in hydrogen fuel cells and systems manufacturing, to design and produce 10-kW hydrogen-fuel-cell generators (Foley 2024) for the purpose. These generators can deliver a minimum of 72 hours of zero-emission power at full hydrogen capacity, ensuring reliable service during power outages (Foley 2024).

Indian companies like FC TecNrgy also offer similar hydrogen fuel cell–based backup solutions for telecom towers, providing power from 24 hours to 4 days, depending on the requirement (FC TecNrgy n.d.). Their systems are lightweight and are highly energy efficient compared to diesel generators..

## 2.2.4. Green hydrogen–based microgrids



A green hydrogen-based microgrid is a localised system that generates, stores, and distributes electricity using green hydrogen as its primary fuel.

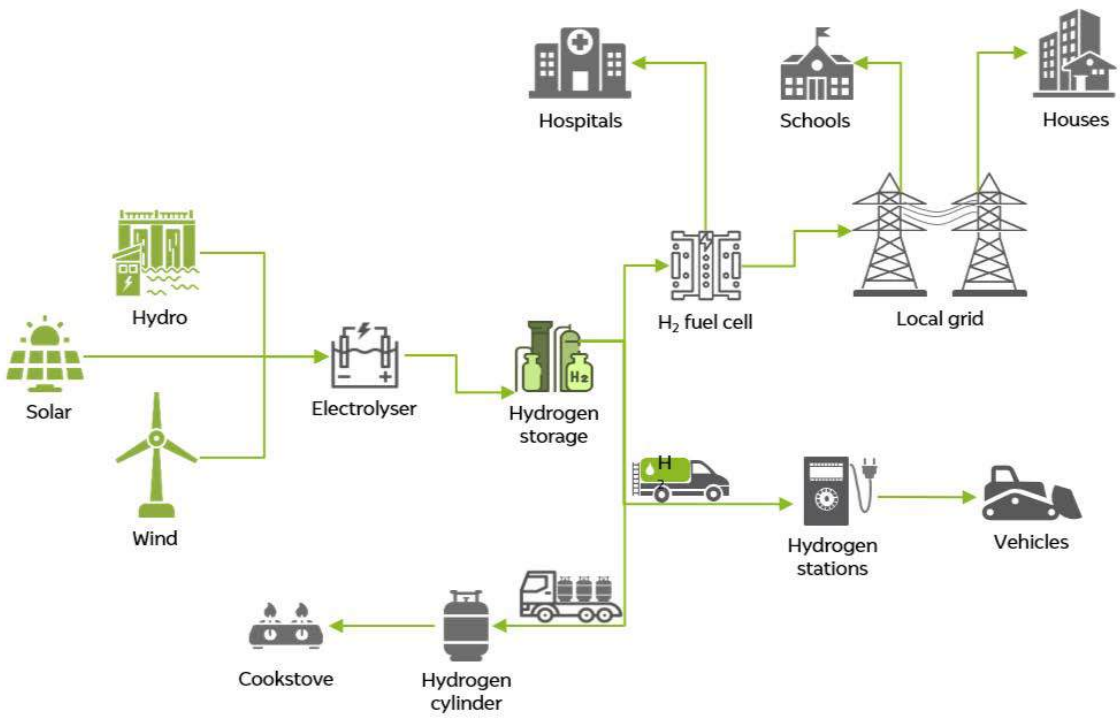
- **Technology readiness level:** 6-8
- **Energy source replaced**: Fossil fuel–powered generators

### Green hydrogen for improving energy access

Microgrids often function independently in island mode (Hasan et al. 2022) or can be integrated with the main grid, wherever available. As shown in Figure 14, the microgrid generates hydrogen through water electrolysis by utilising RE sources such as solar, wind, or hydro to produce electricity. The stored hydrogen can then complement battery storage by converting hydrogen back into electricity using fuel cells and distributing it through local grids to serve communities and critical infrastructure.

Green hydrogen–based microgrids could be particularly valuable for military use due to their ability to provide consistent power throughout the year in remote and off-grid locations. They can effectively power remote military bases, command posts, communication services, and so on. Such microgrids can also support small industries in isolated areas. The technology can reliably enable energy access in challenging environments.

**Figure 14 A decentralised green hydrogen–based microgrid could provide energy in multiple forms**




*Source: Authors' analysis*

## Advantages of green hydrogen–based microgrids

Green hydrogen–based microgrids offer several benefits that make them particularly valuable in remote areas. These advantages address the unique challenges of energy supply and distribution in such regions:

- **Seasonal storage capability:** Mountainous regions to the north and north-east in India experience low variability in solar output during summers and high variability during the rest of the year (Ghosh, Roy, and Chakraborty 2023). Green hydrogen can be stored indefinitely to address this seasonal variability in RE availability. Batteries could be impractical for long-duration energy storage due to limited capacities and the tendency to self-discharge, while green hydrogen, in contrast, could be a reliable energy source throughout the off-season.
- **Portability:** Microgrids can be built on modular platforms and transported via trucks, often called 'grids-on-a-skid' (Siemens Government Technologies n.d.). This portability can be helpful for disaster relief and emergency response, allowing for immediate power deployment to relief shelters and medical facilities.
- **Potential to supply energy in two forms:** Stored hydrogen can serve as both cooking and transportation fuel in its gaseous form, complementing the main use case of power generation in microgrids.
- **Lower transmission losses:** Microgrids reduce transmission losses by generating power near the point of consumption.
- **Energy exchange with main grids:** Microgrids can be connected to larger grids. This allows the entity to buy or sell energy to the main grid based on local generation and consumption levels.

## Challenges and constraints of green hydrogen–based microgrids

- **Requirement of a high RE potential:** The location must have high solar, wind, or hydro potential, for a significant part of the year to ensure reliable microgrid operation.
- **Oversizing to balance requirements between peak seasons and off-seasons:** The microgrid must be able to produce sufficient hydrogen during peak seasons to meet off-season requirements for continuous operation throughout the year.
- **Competition with battery–based microgrids**: Battery systems offer lower capital costs and higher efficiency. Green hydrogen systems are costlier due to expensive fuel cells and electrolysers. However, green hydrogen-based microgrids could be the only suitable option in certain regions due to the seasonal storage capability discussed above.

We do not quantify the green hydrogen demand, its breakeven cost, and the emissions mitigation potential for microgrids because India has already achieved near 100 per cent electrification of all its villages and towns in 2022 (PIB 2022), and while a niche market for microgrids exists, comprehensive data on the number of households that require power through microgrids is unavailable. It is important to note that the cost of electricity from profitable green hydrogen microgrids typically ranges from around INR 14 to INR 54 per kWh (USD 0.2 to USD 0.7) (Rey, Segura, and Andújar 2023), which is higher than the cost of power from central grids, which is less than INR 10 (around USD 0.1) per kWh in most of the states (NITI Aayog 2024). People living in remote and challenging areas might be unable to afford this premium. Furthermore, green hydrogen produced by the microgrid will complement the energy storage, and a dedicated study is required to optimise the configuration (Jacob, Banerjee, and Ghosh 2018).

**Box 9** **NTPC-NETRA achieves 25 kW continuous green power generation using hydrogen from sewage-treated water**

*Image received from NTPC-NETRA over email*

NTPC-NETRA has set up a demonstration green hydrogen-based microgrid in its Greater Noida campus that produces 25 kW of electricity round the clock using hydrogen from sewage-treated water. The campus's water treatment plant processes sewage water via Electrolysis Dialysis Reverse (EDS) with an impressive capacity of 24 tonnes per day and an overall 80 per cent yield. The treated water is purified to a 0.2 μs conductivity in the hydrogen production block and supplied to a PEM electrolyser and a high-temperature solid oxide electrolyser cell (HT-SOEC), both powered by solar PV panels. The PEM electrolyser is the first made-in-India PEM manufactured by Ohmium with a 6.5 kg $H_2$/hour capacity. The storage system secures 50 kg of hydrogen at 200 bar pressure, which is then utilised by fuel cells to deliver a consistent 25 kW of AC power.

*Source: Information about project received from NTPC-NETRA over email*

### 2.2.5. Military applications of green hydrogen

The use of green hydrogen in military applications could help in ensuring energy access and simplifying operations. Military operations rely heavily on imported fossil fuels to power everything from vehicles and aircraft to bases and operations in remote areas. Additionally, fuel transportation to remote places often poses logistical challenges, which could lead to disruptions in operations. The following are some specific military applications where green hydrogen could be used:

- **Ground vehicles:** Hydrogen can power all military vehicles, from combat to utility or logistics. Fuel-cell technology also offers a 75 per cent to 90 per cent improvement in the acoustic signature of the ground vehicle (DEVCOM – GVSC n.d.), with the potential to lower the infrared signature by half (Mills and Limpaecher 2021). This advantage is critical during stealth missions, allowing vehicles to remain undetected.
- **Hydrogen-powered unmanned aerial vehicles (UAVs) and drones:** The use of hydrogen as a power source is increasingly being explored in UAVs and drones, where conventional jet engines or batteries are being replaced with hydrogen fuel cells or combustion engines. The high energy density of hydrogen allows for extended flight times, which becomes crucial for missions involving surveillance and reconnaissance for long durations in the air (Khzouz et al. 2020). Fuel cells have already met target weight requirements in UAVs, offering a competitive advantage over traditional systems (Sobon et al. 2021).

- **Hydrogen-filled aerostats:** Hydrogen can be used as a lifting gas for military aerostats instead of helium. Aerostats are low-altitude 'lighter-than-air' balloons equipped with various sensors, such as radars and cameras, and are used for aerial surveillance and reconnaissance of wide areas. Today, helium is favoured over hydrogen because of its non-flammable nature. However, helium requires extraction from underground natural gas deposits and transportation to the point of use.
- **Hydrogen-based microgrids:** Green hydrogen–based microgrids can power remote military bases, command posts, camps, and so on, where power can be generated on-site through renewable sources and the energy stored in hydrogen. The portability of microgrids allows them to be easily moved around during critical missions, eliminating the logistical challenges of transporting fuel.

Advantages of green hydrogen in military applications:

- **On-site fuel production** through modular units could eliminate the logistical difficulties associated with transporting fuel to remote locations, especially during critical operations or missions.
- Green hydrogen systems lend **tactical advantages**, such as improved acoustic signature and the potential to lower the infrared signature by half in FCEVs and extended potential flight times in UAVs and drones.

We do not quantify the potential green hydrogen demand, the emissions mitigation potential, and the breakeven cost of green hydrogen as the data related to military applications is not publicly available. Furthermore, a detailed assessment of all the parameters, taking into account the specific requirements of the armed forces, is necessary to interpret the results and present a comprehensive analysis.

# 3. Key estimation results

In this section, we present a comparative overview of the green hydrogen demand, the break-even cost of green hydrogen, the emissions mitigation potential, and the potential reduction in import expenditure as estimated for each application in Section 2. We observe that the potential demand for green hydrogen is much higher in commercial and remote-area applications than in industrial applications, as illustrated in Figure 15. However, most of these applications also entail a low break-even cost of green hydrogen, signifying a lack of economic viability.

We group all applications into four categories, as denoted in Figure 15, assuming a demand potential higher than 100 KTPA to be large and a break-even cost higher than USD 5 per kg to be economical. The estimation results are as follows:

- **Low-hanging fruit:** Backup power provision in telecom towers is the only economical application, with a break-even cost of USD 5.1 per kg and a large potential demand for green hydrogen of around 257 KTPA.
- **Promising:** Other commercial applications – cooking fuel and fuel for heavy machinery – have a larger potential green hydrogen demand of 18.1 MTPA and 650 KTPA, respectively, but the break-even cost for them ranges between USD 1.0 per kg to USD 3.7 per kg. These applications are termed as promising because a trajectory of reducing green hydrogen costs could make them economically viable eventually.
- **Practically viable:** The break-even cost of green hydrogen is highest for hydrogen peroxide production and glass, ranging between USD 8 and USD 12 per kg, but the potential green hydrogen demand, at around 10.1 KTPA and 8.4 KTPA respectively, is much smaller when compared with the demand in other applications.
- **Limited:** Metallurgical processing and thermal power plant cooling applications also have a small potential demand of around 9.5 KTPA and 0.4 KTPA, respectively. While they are near economic viability, with estimated break-even green hydrogen costs of USD 3.2 per kg and USD 3.5 per kg, the overall impact of these applications in the transition to green hydrogen will be limited.

**Potential demand for green hydrogen could be much higher in commercial and remote-are applications than in industrial applications.**

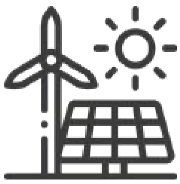
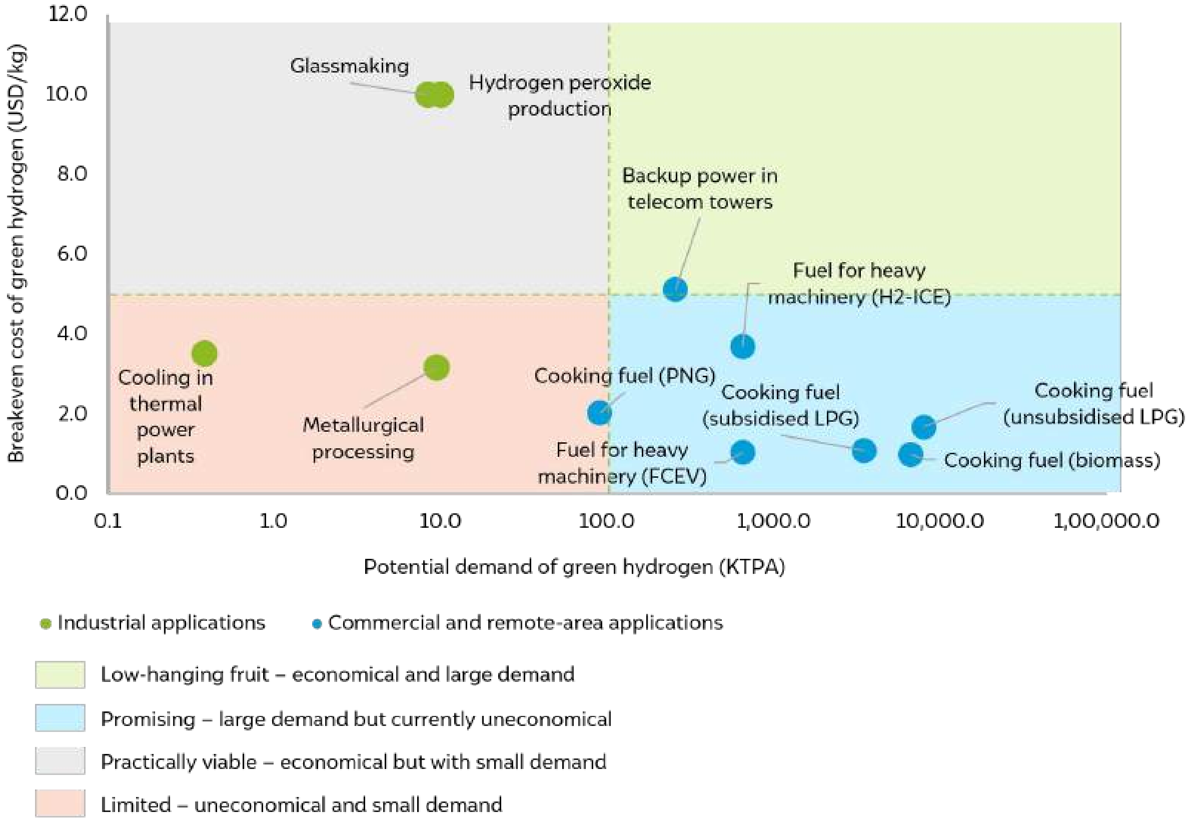


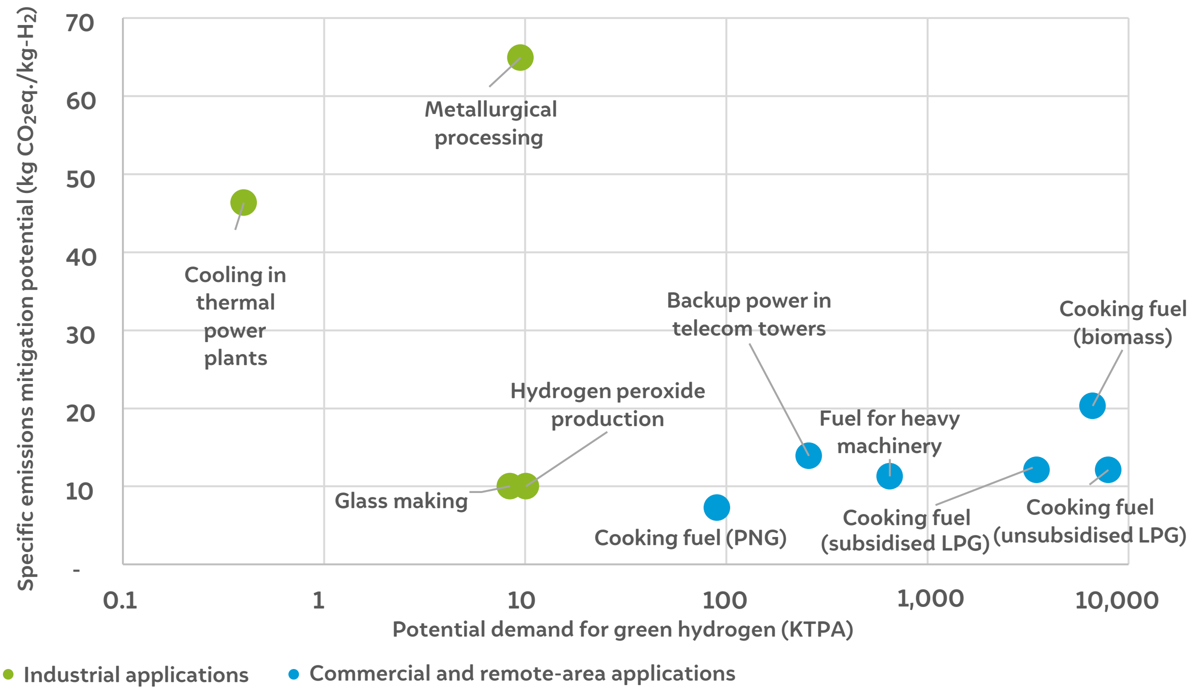
**Figure 15 Most commercial applications have a high potential demand for green hydrogen but are currently uneconomical**




*Source: Authors' analysis*

By our estimates, a complete transition to green hydrogen in the applications considered in this report could reduce greenhouse gas emissions by up to 221 MTPA. Green hydrogen use in cooking would account for around 209 MTPA of the total emissions mitigation potential due to its comparatively larger potential demand. Industrial applications have a higher specific emissions mitigation potential than commercial and remote-area applications, as illustrated in Figure 16. However, their overall emissions mitigation potential would be much lower due to the lower potential demand for green hydrogen in these applications. Metallurgical processing and cooling in thermal power plants are the outliers, with extremely high specific emissions mitigation potentials of around 65 kg-$CO_2$eq. per kg-$H_2$ and 46.4 kg-$CO_2$eq. per kg-$H_2$, respectively. All other applications fall in the range of 10 kg-$CO_2$eq. per kg-$H_2$ to 20 kg-$CO_2$eq. per kg-$H_2$. It may be interesting to note that the difference in energy efficiencies of PNG, LPG, and biomass used as cooking fuels translates to a difference in the specific emissions mitigation of around 13 kg-$CO_2$eq. per kg-$H_2$ between the three fuels.

**Figure 16 Industrial processes have a higher specific emissions mitigation potential than commercial and remote-area applications**




*Source: Authors' analysis*

Reduction in energy import expenditure of up to INR 1.22 lakh crore (around USD 15.3 billion) per year could be achieved by completely phasing out imported fuels such as LPG, LNG, and diesel, per our estimates. Table 2 presents the potential reduction in import expenditure for various applications with a transition to green hydrogen. As evident from the table, a transition to green hydrogen in cooking could lead to the highest reduction in import expenditure.

**Table 2 Reduced LPG consumption with a transition to green hydrogen use in cooking could lead to the highest reduction in import expenditure**

| Sr. no. | Application | Fuel replaced | Potential reduction in import expenditure in INR crore (USD million) |
|---|---|---|---|
| Industrial applications | | | |
| 1 | Glass making | Natural gas | 123 (16) |
| 2 | Hydrogen peroxide production | Natural gas | 148 (19) |
| Commercial and remote-area applications | | | |
| 3 | Cooking fuel | LPG | 108,500 (13,562) |
| 4 | Fuel for heavy machinery | Diesel | 9,045 (1,130) |
| 5 | Backup power in telecom towers | Diesel | 4,381 (548) |

*Source: Authors' analysis*


**The economic, technological, and operational barriers to safe and scalable deployment of decentralised green hydrogen could be overcome with policy support**

Image: iStock

# 4. Policy recommendations

We find that decentralised green hydrogen systems are well positioned to serve multiple use cases, offering unique advantages such as increased convenience, better energy efficiency, improvement in access to energy, and so on, in addition to minimising greenhouse gas emissions. The economic, technological, and operational barriers to safe and scalable deployment of decentralised green hydrogen are common to most use cases. We outline the following policy recommendations to overcome these barriers:

- **Low-cost financing:** The high upfront investment required for decentralised green hydrogen applications is a common impediment, even in instances where they could be viable on the basis of TCO. Devising a financing programme for decentralised green hydrogen applications on lines similar to the *PM – Surya Ghar: Muft Bijli Yojana* could help overcome this barrier.
- **Implement green public procurement strategies:** The government could preferentially procure green hydrogen–based systems in its undertakings: for heavy machinery in mining, construction, and manufacturing; using green hydrogen as fuel for kitchens and in cookstoves in government buildings and in microgrids; and using green hydrogen–operated devices in military operations. Such procurement could catalyse a larger demand and spur innovation by suppliers in the market.
- **Explore biological green hydrogen production routes:** Applications that can leverage their organic waste streams to produce green hydrogen at low costs could be the first movers to clean hydrogen. The waste generated by the food-processing industry and the wet waste from residential communities could be utilised to produce and consume green hydrogen locally. These applications may have abundant waste streams, which could be sufficient for green hydrogen production through enzymatic action at the required quantum.
- **Utilisation of government land parcels for green hydrogen production:** The large land parcels available with government-controlled entities such as the armed forces, the public-sector industries, Indian Railways, and so on could be used for RE generation to produce green hydrogen, which could be consumed in a decentralised manner.
- **Strategic R&D in military applications:** The defence research agencies in India could undertake special projects aimed at indigenising hydrogen-based military applications in consultation with the divisions of the armed forces operating in remote, inaccessible regions. A few applications might already be commercially viable in military bases in geographies like Ladakh.
- **Budget a dedicated R&D allocation:** Funds should be allocated for research and pilot projects in decentralised green hydrogen applications. This will enable innovators building these technologies to access seed capital for the projects. Without a dedicated budgetary allocation, R&D in these applications might get neglected in favour of the large-scale conventional applications of green hydrogen.
- **Develop safety standards:** Although general safety standards for hydrogen production, storage, and use are in place, it is crucial to develop and enforce specific regulations tailored to various decentralised hydrogen applications, especially the consumer-focused ones.
- **Awareness building:** The government could organise exhibitions, trade shows, and demonstrations to showcase the successful use of decentralised hydrogen applications. These initiatives can raise awareness of the benefits of decentralised hydrogen among consumers and provide technical know-how.

# Annexure

## Annexure 1

The hydrogen consumption for annealing was estimated based on the specific requirements of JSL's Hisar plant. This value was then applied to India's total stainless and flat steel production to calculate the potential hydrogen demand.

To estimate the potential emission mitigation, we considered the typical emission factor of captive power plants in Indian steel plants and the electrolyser efficiency. The breakeven cost was calculated by summing the cost of the electrolyser and the electricity from a captive power plant, assuming an electrolyser efficiency of 50 kWh/kg hydrogen. Table A1 presents all the underlying assumptions for the estimation.

**Table A1 Key assumptions in estimating green hydrogen demand, potential emission mitigation and breakeven cost of green hydrogen production for metallurgical applications**

| Particular | Unit | Value | Source |
|---|---|---|---|
| Metallurgical Application | | | |
| JSL (Hisar plant) hydrogen requirement | TPA | 353 | (S. Yadav 2024) |
| JSL (Hisar plant) stainless steel output | MTPA | 0.8 | (Jindal Stainless Limited 2023) |
| Hydrogen consumption per tonne of stainless steel produced | kg $H_2$/ tonne steel | 0.44 | Calculation |
| Cold-rolled steel production in India | MTPA | 19.05 | (Joint Plant Committee 2023) |
| Stainless steel production India | MTPA | 2.5 | (Ministry of Steel 2023) |
| Stainless and cold rolled steel production in India | MTPA | 21.5 | Calculation |
| Potential emission mitigation | | | |
| Emission captive power plant | kg $CO_2$/kWh | 1.3 | (Elango, et al. 2023) |
| Electrolyser efficiency | kWh/kg $H_2$ | 50 | (Groenemans, et al. 2022) |
| Breakeven cost of green hydrogen production | | | |
| Electrolyser cost for PLF 74 per cent | USD/kg $H_2$ | 1.09 | (CFLI India and CEEW 2024) |
| Electrolyser cost for PLF 95 per cent | USD/kg $H_2$ | 0.85 | Calculation |
| Captive power plant electricity cost | INR/kWh | 3.72 | (Elango, et al. 2023) |
| USD:INR exchange rate | USD:INR | 1:80 | Assumption |

## Annexure 2

To estimate the hydrogen demand for float glass production in India, we utilised the Taloja Plant of Asahi Float Glass as a standard. By applying the plant's specific hydrogen consumption rate to the total annual production capacity of the Indian float glass industry, we calculated the industry's overall hydrogen demand. Given the relatively low volume of hydrogen required, we assumed that manufacturers would primarily procure grey hydrogen produced through steam methane reforming (SMR) at USD 12 per kilogram (Pillay 2023).

To assess the potential reduction in import expenditure, we assumed that all the natural gas consumed in SMR for hydrogen production is imported. Using data from the Indian Department of Commerce and Trade, we determined the average import cost of natural gas per unit quantity for the last financial year. Using this, we estimated the potential savings in import expenditure as shown in Table A2.

**Table A2 Key assumptions in estimating green hydrogen demand, potential emission mitigation and breakeven cost of green hydrogen production for float glass production**

| Particular | Unit | Value | Source |
|---|---|---|---|
| Float glass manufacturing | | | |
| Taloja plant Asahi float glass capacity | Tonnes/day | 550 | (AIGMF 2017) |
| Taloja plant Asahi float glass hydrogen demand | MT | 0.0006 | ( Santhosh, Verma and Dev 2024) |
| Specific hydrogen demand | kg $H_2$/tonne glass | 2.99 | Calculation |
| Installed float glass capacity | Tonnes/day | 7,650 | (Oberoi n.d.) |
| Potential emission mitigation | | | |
| SMR hydrogen emission factor | kg $CO_2$/kg $H_2$ | 10 | (IEA 2023) |
| Breakeven cost of green hydrogen production | | | |
| Hydrogen procurement cost | USD/kg $H_2$ | 12 | (Pillay 2023) |

Table A3 shows the LNG imports by cost and by quantity which was obtained from the Indian Department of Commerce and Trade webpage to determine the cost per unit kilogram over the past five financial years. By calculating the average per-unit cost of LNG in USD/kg and USD/MMBtu, we estimated the potential savings in import expenditure.

**Table A3 Import value and quantity of LNG in India**

| Financial year | Import value of LNG (USD million) | Import quantity of LNG (KTPA) | Cost of imported LNG (USD/kg) | Cost of imported LNG (USD/MMBtu) |
|---|---|---|---|---|
| 2019-2020 | 9,662.8 | 24,416 | 0.40 | 7.91 |
| 2020-2021 | 7,880.7 | 25,055 | 0.31 | 6.29 |
| 2021-2022 | 13,472.2 | 23,417 | 0.58 | 11.51 |
| 2022-2023 | 17,113.6 | 19,852 | 0.86 | 17.24 |
| 2023-2024 | 13,404.7 | 23,996 | 0.56 | 11.17 |

*Source: (Department of Commerce n.d.)*

## Annexure 3

To estimate hydrogen demand, we assumed that India's total hydrogen peroxide market demand of 171 KTPA would be met domestically to avoid chemical imports (Ministry of Chemical and Fertilizers 2022).

We used a stoichiometric hydrogen requirement of 58.8 grams per kilogram of hydrogen peroxide production to estimate the total demand. To estimate the potential emission mitigation, we considered the hydrogen needed for this process to be sourced from steam methane reforming (SMR) at a cost of 12 USD/kg $H_2$ (Pillay 2023). We assume that all natural gas used in SMR for hydrogen generation is imported to assess the potential reduction in import expenditure. Using the data from the Indian Department of Commerce and Trade, we determined the average import cost of natural gas per unit quantity for the last five financial years, as shown in Table A4.

**Table A4 Key assumptions in estimating green hydrogen demand, potential emission mitigation and breakeven cost of green hydrogen production for hydrogen peroxide production**

| Particular | Unit | Value | Source |
|---|---|---|---|
| Hydrogen peroxide manufacturing | | | |
| Hydrogen peroxide consumption | KTPA | 171.3 | (Ministry of Chemical and Fertilizers 2022) |
| $H_2$ requirement for 1 kg $H_2O_2$ | Grams | 58.8 | Calculation |
| Potential emission mitigation | | | |
| SMR $H_2$ Emission factor | kg $CO_2$/kg $H_2$ | 10 | (IEA 2023) |
| Breakeven cost of green hydrogen production | | | |
| Hydrogen procurement cost | USD/kg $H_2$ | 12 | (Pillay 2023) |

## Annexure 4

The total number of power plants of various sizes was obtained from the Central Electricity Authority of India's website. We assumed all power plants with a capacity exceeding 150 MW employ hydrogen as a cooling agent.

We used the known hydrogen consumption rates for different plant sizes to estimate the total hydrogen demand for cooling these thermal power plants, as seen in Table A5. The potential emission mitigation was calculated by considering the emission factor of a thermal power plant as 0.93 kg $CO_2$/kWh and 50kWh/kg $H_2$ as the electrolyser efficiency (Mallapragada , et al. 2019) (Groenemans, et al. 2022).

Similar to its metallurgical application, the breakeven cost was determined by using the cost of the electrolyser and the electricity from a thermal power plant, assuming an electrolyser efficiency of 50 kWh/kg $H_2$.

**Table A5 Key assumptions in estimating green hydrogen demand, potential emission mitigation and breakeven cost of green hydrogen production for thermal power plants**

| Particular | Unit | Value | Source |
|---|---|---|---|
| Thermal power plant application | | | |
| Number of power plants with a capacity of 150MW | Units | 11 | (Central Electricity Authority 2023) |
| Number of power plants with capacity >=250 | Units | 249 | |
| Number of power plants with capacity >=700 | Units | 307 | |
| Hydrogen consumption for 150 MW | $Nm^3$/day | 5 | (VR Coolers 2023) |
| Hydrogen consumption for 250 MW | $Nm^3$/day | 16 | |
| Hydrogen consumption up to 1200 MW | $Nm^3$/day | 25 | |
| Total hydrogen consumption | $Nm^3$/year | 42,75,610 | Calculation |
| Density of hydrogen | kg/$m^3$ | 0.089 | (Hydrogen Europe 2021) |
| Potential emission mitigation | | | |
| Emission factor for thermal power generation | kg $CO_2$/kWh | 0.93 | (Mallapragada , et al. 2019) |

| | | | |
|---|---|---|---|
| Electrolyser efficiency | kWh/kg $H_2$ | 50 | (Groenemans, et al. 2022) |
| Breakeven cost of green hydrogen production | | | |
| Coal-fired power plant cost | INR/kWh | 4.25 | (Shah 2021) |
| USD:INR exchange rate | USD:INR | 1:80 | Assumption |
| Electrolyser cost for PLF 74 per cent | USD/kg $H_2$ | 1.09 | (CFLI India and CEEW 2024) |
| Electrolyser cost for PLF 95 per cent | USD/kg $H_2$ | 0.85 | Calculation |

# Annexure 5

We estimated the emission intensity of burning each fuel during cooking by determining the $CO_2$ released per unit of fuel combustion on an energy basis and incorporating the cookstove efficiencies. We only considered the $CO_2$ emissions to calculate the intensities. Additionally, the emission intensity of biomass is based on a 30 per cent fNRB. All the required values are shown in Table A6.

**Table A6 Key assumptions to estimate emission intensity of fuels during cooking**

| Particular | Unit | Value | Source |
|---|---|---|---|
| LPG | | | |
| Emission intensity on LPG combustion in residential sector | kg $CO_2$ emitted per TJ of fuel burnt | 63,100 | (Gómez, et al. 2006) |
| Efficiency of LPG cookstove | Percentage | 68% | (Ministry of Petroleum & Natural Gas 2011) |
| Biomass | | | |
| Gram $CO_2e$ emissions per megajoules of energy delivered by wood-based cookstove (for 30% fNRB) | g $CO_2e$/MJ | 294.0 | (Kar, et al. 2023) |
| Efficiency of traditional solid biomass cookstove | Percentage | 15% | (Suresh, et al. 2016) |
| LNG | | | |
| Emission intensity on natural gas combustion in residential sector | kg $CO_2$ emitted per TJ of fuel burnt | 56,100 | (Gómez, et al. 2006) |
| Efficiency of PNG stove | Percentage | 55% | (PIB 2021) |
| Electrolytic hydrogen produced using grid power | | | |
| Emission intensity of electricity generation in India | kg $CO_2$/kWh of electricity produced | 0.716 | (Central Electricity Authority 2023) |
| Electricity requirement to produce per kg hydrogen using electrolyser | kWh/kg $H_2$ | 50.5 | (CFLI India and CEEW 2024) |
| Net calorific value of hydrogen | MJ/kg | 120 | (U.S. Department of Energy n.d.) |
| Efficiency of hydrogen cookstoves | Percentage | 58% | (Schöne, Dumitrescu and Hein 2023) |

The potential demand of green hydrogen as cooking fuel was estimated by considering the distribution of different fuels used in India, particularly the rural households, for cooking, and equating the useful energy from these fuels with that of hydrogen. We assumed that each household requires the same useful energy and only relies on their primary cooking source for all their cooking needs throughout the year. We estimated individual hydrogen demand for LPG, biomass (firewood and dung cakes) and PNG, where LPG was further distributed into subsidised and non-subsidised categories using the data on the number of subsidies given under PMUY (Press Information Bureau 2023).

We calculated the potential emissions mitigation on replacing LPG, biomass and PNG with hydrogen, by factoring in the $CO_2$eq. emissions from combustion of these fuels on the basis of per MJ of useful energy delivered by their respective stoves.

To estimate the breakeven cost of green hydrogen production for it to be viable to replace biomass, LPG and PNG, we assumed that only the operational cost of fuels would be the differentiating factor and the difference in initial purchase cost of a LPG stove and a specialised hydrogen cookstove would become insignificant over a period of 15 years which is usually how long they last. Table A7 shows all the key assumptions and values used in the estimation.

**Table A7 Key assumptions in estimating green hydrogen demand, potential emission mitigation, breakeven cost of green hydrogen production and potential reduction in country's import expenditure for hydrogen cookstoves**

| Particular | Unit | Value | Source |
|---|---|---|---|
| Potential green hydrogen demand | | | |
| Annual domestic distribution of LPG in India | Kilo tonnes | 25,381.6 | (Ministry of Statistics and Programme Implementation 2024) |
| Share of households using LPG as primary source for cooking in India | Percentage | 62% | (Ministry of Steel 2023) |
| Share of households using firewood as primary source for cooking in India | Percentage | 33.8% | |
| Share of households using dung cakes as primary source for cooking in India | Percentage | 2.2% | |
| Share of households using PNG as primary source for cooking in India | Percentage | 0.5% | |
| Share of households using other sources as primary source for cooking in India | Percentage | 0.8% | |
| Share of households with no cooking arrangement in India | Percentage | 0.7% | |
| Total number of LPG connections in India | Crore | 31.36 | (Press Information Bureau 2023) |
| Number of LPG connections subsidised under PMUY | Crore | 9.58 | |
| Net calorific value of LPG | MJ/kg | 46.0 | (Energypedia n.d.) |
| Net calorific value of hydrogen | kWh/kg | 33.3 | (U.S. Department of Energy n.d.) |
| Efficiency of LPG cookstoves | Percentage | 68% | (Ministry of Petroleum & Natural Gas 2011) |

| | | | |
|---|---|---|---|
| Efficiency of hydrogen cookstoves | Percentage | 58% | (Schöne, Dumitrescu and Hein 2023) |
| **Potential emission mitigation** | | | |
| Share of households using LPG as primary source for cooking in India | Percentage | 62% | (Ministry of Steel 2023) |
| Share of households using firewood as primary source for cooking in India | Percentage | 33.8% | |
| Share of households using dung cakes as primary source for cooking in India | Percentage | 2.2% | |
| Share of households using PNG as primary source for cooking in India | Percentage | 0.5% | |
| Gram $CO_2e$ emissions per megajoules of energy delivered by wood-based cookstove | g $CO_2e$/MJ | 294.0 | (Kar, et al. 2023) |
| Gram $CO_2e$ emissions per megajoules of energy of LPG | g $CO_2$/MJ | 63.1 | (Gómez, et al. 2006) |
| Gram $CO_2e$ emissions per megajoules of energy of natural gas | g $CO_2$/MJ | 56.1 | (Gómez, et al. 2006) |
| Efficiency of LPG cookstoves | Percentage | 68% | (Ministry of Petroleum & Natural Gas 2011) |
| Efficiency of PNG stove | Percentage | 55% | (PIB 2021) |
| **Breakeven cost of green hydrogen production** | | | |
| Net calorific value of hydrogen | kWh/kg | 12.64 | (U.S. Department of Energy n.d.) |
| Efficiency of hydrogen cookstoves | Percentage | 58% | (Schöne, Dumitrescu and Hein 2023) |
| Market price of firewood chips | INR/kg | 3.0 | (IndiaMART n.d.) |
| Net calorific value of wood pellets (10 % moisture content) | kWh/kg | 4.8 | (Forest Research n.d.) |
| Efficiency of traditional solid biomass cookstove | Percentage | 15% | (Suresh, et al. 2016) |
| Cost of non-subsidised LPG in India | INR per 14.2 kg cylinder | 855 | Assumed based on market trends |
| Subsidy on LPG given to PMUY beneficiaries | INR per 14.2 kg cylinder | 300 | (PIB Delhi 2024) |
| Efficiency of LPG cookstoves | Percentage | 68% | (Ministry of Petroleum & Natural Gas 2011) |
| Cost of PNG | INR/SCM | 48.5 | (Indraprastha Gas Limited n.d.) |
| Net calorific value of PNG | kcal/SCM | 9000 | (Bharat Petroleum n.d.) |
| Efficiency of PNG stove | Percentage | 55% | (PIB 2021) |
| USD:INR exchange rate | USD:INR | 1:80 | Authors' analysis |

India meets its LPG needs by both directly importing it and through crude oil refining. Of the total crude oil India processes each year, 87.4 per cent is imported, and only 12.6 per cent is obtained through Indigenous sources (Ministry of Petroleum and Natural Gas 2024). Table A8 and Table A9 present the quantity and corresponding value of crude oil and LPG imported by India from FY 2017-18 to FY 2022-23, respectively. Additionally, Table A10 shows the total annual production of petroleum products through crude oil refining, highlighting the production of LPG which is roughly 5 per cent of total crude oil processed. We estimated the possible reduction in the import value of LPG when it is replaced with green hydrogen by considering the weighted average of the cost of directly imported LPG and the LPG obtained through refining imported crude oil. We assumed that the cost of obtaining per tonne of LPG from crude oil is the same as the cost per tonne of imported crude oil. No refining expenditure was included in the estimation.

**Table A8** **Import value and quantity of crude oil in India**

| Financial year | Import value of crude oil (USD million) | Import quantity of crude oil (KTPA) | Cost of imported crude oil (USD/tonne) |
|---|---|---|---|
| 2017-18 | 87,803 | 2,20,433 | 398.3 |
| 2018-19 | 1,11,915 | 2,26,498 | 494.1 |
| 2019-20 | 1,01,376 | 2,26,955 | 446.7 |
| 2020-21 | 6,22,48 | 1,96,461 | 316.8 |
| 2021-22 | 1,20,675 | 2,12,382 | 568.2 |
| 2022-23 | 1,57,531 | 2,32,700 | 677.0 |

*Source: (Ministry of Petroleum and Natural Gas 2024)*

**Table A9** **Import value and quantity of LPG in India**

| Financial year | Import value of LPG (USD million) | Import quantity of LPG (KTPA) | Cost of imported LPG (USD/tonne) |
|---|---|---|---|
| 2017-18 | 5,849 | 11,380 | 514.0 |
| 2018-19 | 7,178 | 13,235 | 542.3 |
| 2019-20 | 7070 | 14,809 | 477.4 |
| 2020-21 | 7,242 | 16,476 | 439.5 |
| 2021-22 | 12,235 | 17,043 | 717.9 |
| 2022-23 | 13,344 | 18,335 | 727.8 |

*Source: (Ministry of Petroleum and Natural Gas 2024)*

**Table A10** **Annual production of all petroleum products and LPG through crude refining in India**

| Financial year | Total production of petroleum products (KTPA) | LPG production (KTPA) | Percentage of LPG obtained from crude oil (percentage) |
|---|---|---|---|
| 2017-18 | 2,54,405 | 12,380 | 4.9% |
| 2018-19 | 2,62,361 | 12,786 | 4.9% |
| 2019-20 | 2,62,940 | 12,823 | 4.9% |
| 2020-21 | 2,33,513 | 12,072 | 5.2% |
| 2021-22 | 2,54,305 | 12,238 | 4.8% |
| 2022-23 | 2,66,542 | 12,832 | 4.8% |

*Source: (Ministry of Petroleum and Natural Gas 2024)*

# Annexure 6

Table A11 presents the key assumptions used to estimate the green hydrogen demand, potential emission mitigation, and breakeven cost of green hydrogen production for deploying hydrogen as vehicle fuel in heavy machinery in India.

Green hydrogen demand was estimated by equating the useful energy obtained from the combustion of hydrogen and diesel in their respective engines, considering the TTW efficiencies to incorporate energy losses and the energy content of fuels. TTW is a critical factor in the estimation that shows variation with engine load, particularly for heavy vehicle segments (Heid, Martens, and Orthofer 2021). We assumed a 60 per cent load factor for all three systems: diesel engine, hydrogen combustion engine, and fuel cell.

The potential emissions that could be mitigated by replacing diesel with hydrogen were determined by considering the emission factor on diesel combustion in vehicles from Gómez, et al. 2006. The breakeven cost of green hydrogen was calculated by matching the TCO of diesel-powered, $H_2$-ICE and FCV excavators. As per our analysis, the breakeven cost is intricately linked to the price of the vehicle. The higher the cost of the diesel-powered vehicle, the lower the breakeven cost. We assumed a 20 and a 80 per cent mark-up on diesel counterparts for $H_2$-ICE and FCEV, respectively.

**Table A11 Key assumptions in estimating green hydrogen demand, potential emission mitigation and breakeven cost of green hydrogen production for heavy machinery**

| Particular | Unit | Value | Source |
|---|---|---|---|
| Potential green hydrogen demand estimation | | | |
| Total annual diesel consumption in India (2023-24) | Kilo tonnes | 89,653 | (Petroleum Planning and Analysis Cell 2024) |
| Share of diesel used annually in machinery for industrial purposes | Percentage | 2.6% | (CRISIL 2021) |
| TTW efficiency of diesel engines (at 60% load) | Percentage | 34% | Authors' analysis of (Heid, Martens and Orthofer 2021) |
| TTW efficiency of hydrogen combustion engines (at 60% load) | Percentage | 44% | |
| TTW efficiency of hydrogen fuel cell engines (at 60% load) | Percentage | 42% | |
| Net calorific value of hydrogen | MJ/kg | 120.0 | (U.S. Department of Energy n.d.) |
| Net calorific value of diesel | MJ/kg | 42.6 | |
| Potential emission mitigation | | | |
| Emission factor for diesel combustion in commercial sector | kg $CO_2$ emitted per TJ of fuel combusted | 74,100 | (Gómez, et al. 2006) |
| Total annual diesel consumption in India (2023-24) | Kilo tonnes | 89,653 | (Petroleum Planning and Analysis Cell 2024) |
| Share of diesel used annually in machinery for industrial purposes | Percentage | 2.6% | (CRISIL 2021) |

| | | | |
|---|---|---|---|
| Net calorific value of diesel | MJ/kg | 42.6 | (U.S. Department of Energy n.d.) |
| Breakeven cost estimation of green hydrogen production | | | |
| Net calorific value of diesel | MJ/litre | 36.2 | (U.S. Department of Energy n.d.) |
| Net calorific value of hydrogen | MJ/kg | 120 | |
| TTW efficiency of diesel engines (at 60% load) | Percentage | 34% | Authors' analysis of (Heid, Martens and Orthofer 2021) |
| TTW efficiency of hydrogen combustion engines (at 60% load) | Percentage | 44% | |
| TTW efficiency of hydrogen fuel cell engines (at 60% load) | Percentage | 42% | |
| USD:INR exchange rate | USD:INR | 1:80 | Authors' analysis |
| Diesel engine excavator | | | |
| Typical ex-showroom price of diesel-engine excavator in India | INR | 54,00,000 | (Infra Junction n.d.) |
| Lumpsum tax applicable on excavator | Percentage | 6% | (Government of Haryana 2017) |
| Share of amount borrowed as loan | Percentage | 80% | Assumption |
| Loan repayment period | Years | 5 | |
| Annual interest rate | Percentage | 12% | |
| Annual depreciation rate | Percentage | 10% | |
| Annual discount rate | Percentage | 10% | |
| Total lifespan of excavator | Hours | 10,000 | (Louisiana CAT n.d.) |
| Total years of vehicle ownership | Years | 12 | Assumption |
| Annual operation of excavator | Hours | 833.3 | Calculation |
| Diesel consumption rate of engine | Litre/hour | 15.1 | Authors' analysis of (Volvo n.d.) |
| Diesel price in India | INR/litre | 87.0 | Assumed based on market trends |
| $H_2$-ICE excavator | | | |
| Typical ex-showroom price of $H_2$-ICE excavator in India | INR | 64,80,000 | Assumption of a 20 per cent mark-up on diesel counterpart for prototypes |
| Lumpsum tax applicable on excavator | Percentage | 6% | (Government of Haryana 2017) |
| Share of amount borrowed as loan | Percentage | 80% | Assumption |
| Loan repayment period | Years | 5 | |
| Annual interest rate | Percentage | 12% | |
| Annual depreciation rate | Percentage | 10% | |
| Annual discount rate | Percentage | 10% | |
| Total lifespan of excavator | Hours | 10,000 | (Louisiana CAT n.d.) |
| Total years of vehicle ownership | Years | 12 | Assumption |

| | | | |
|---|---|---|---|
| Annual operation of excavator | Hours | 833.3 | Calculation |
| Hydrogen consumption rate of $H_2$-ICE for same net output as diesel engine | kg/hour | 3.5 | Calculation |
| FCEV excavator | | | |
| Typical ex-showroom price of FCV excavator in India | INR | 97,20,000 | Cost ratio of FCEV:ICE assumed from (Gerrard 2023) |
| Lumpsum tax applicable on excavator | Percentage | 6% | (Government of Haryana 2017) |
| Share of the amount borrowed as loan | Percentage | 80% | Assumption |
| Loan repayment period | Years | 5 | |
| Annual interest rate | Percentage | 12% | |
| Annual depreciation rate | Percentage | 10% | |
| Annual discount rate | Percentage | 10% | |
| Total lifespan of excavator | Hours | 10,000 | (Louisiana CAT n.d.) |
| Total years of vehicle ownership | Years | 12 | Assumption |
| Annual operation of excavator | Hours | 833.3 | Calculation |
| Hydrogen consumption rate of FCV for same net output as diesel engine | kg/hour | 3.7 | Calculation |

We used the crude oil and diesel import data from (Ministry of Petroleum and Natural Gas 2024), as shown in Table A8 and Table A12, to determine the average cost of importing per tonne of crude oil and diesel in India. It should be noted that a tiny proportion of diesel consumed annually is directly imported; most of it is refined from imported crude oil. Table A13 highlights the annual production of HSD in India which is around 42 per cent of total petroleum products produced. We determined the annual diesel produced from imported crude oil by taking 42 per cent of the total crude imported each year. A similar methodology (Annexure 5) was followed to estimate the reduction in import value of diesel on switching to hydrogen as fuel by taking the weighted average of the cost of directly imported diesel and the diesel obtained by refining imported crude oil. The cost of obtaining per tonne of diesel from imported crude oil is assumed to be the same as per tonne cost of imported crude oil, with no additional cost due to refining.

**Table A12 Import value and quantity of diesel in India**

| Financial year | Import value of diesel (USD million) | Import quantity of diesel (KTPA) | Cost of imported diesel (USD/tonne) |
|---|---|---|---|
| 2017-18 | 660 | 1,361 | 484.9 |
| 2018-19 | 360 | 555 | 648.6 |
| 2019-20 | 1,632 | 2,796 | 583.7 |
| 2020-21 | 265 | 648 | 409.0 |
| 2021-22 | 34 | 43 | 790.7 |
| 2022-23 | 454 | 322 | 1,409.9 |

*Source: (Ministry of Petroleum and Natural Gas 2024)*

**Table A13 Annual production of all petroleum products and diesel through crude refining in India**

| Financial year | Total production of petroleum products (KTPA) | Diesel production (KTPA) | Percentage of diesel obtained from crude oil (percentage) |
|---|---|---|---|
| 2017-18 | 2,54,405 | 1,07,904 | 42.4% |
| 2018-19 | 2,62,361 | 1,10,535 | 42.1% |
| 2019-20 | 2,62,940 | 1,11,221 | 42.3% |
| 2020-21 | 2,33,513 | 1,00,441 | 43.0% |
| 2021-22 | 2,54,305 | 1,07,175 | 42.1% |
| 2022-23 | 2,66,542 | 1,13,775 | 42.7% |

*Source: (Ministry of Petroleum and Natural Gas 2024)*

## Annexure 7

We estimated the hydrogen demand as backup source to power telecom towers by taking into account the annual backup required by all the towers and BTSs in India with an average daily power outage of at least 4 hours. We assumed that load of all auxiliary components at an outdoor tower site is independent of number of BTS units installed there, and each BTS has 4+4+4 TRX configuration. An equal division of towers in rural and urban parts of any state was considered for calculations.

We used the emission factor for diesel combustion to estimate the emission mitigation potential of replacing diesel generators by hydrogen fuel cells at these tower sites. The breakeven cost of green hydrogen was calculated by matching the levelised cost of electricity for both the technologies over their lifetime. All the assumption and key steps are presented in the Table A14.

The import value reduction of diesel when replaced with hydrogen was estimated using crude oil and diesel import data, as shown in Table A8 and Table A12. We followed a similar methodology, presented in Annexure 5 and Annexure 6, to determine the weighted average cost of diesel from direct import and from refining imported crude oil, using Table A13. We estimated the total annual energy requirement by all targeted towers to calculate the annual diesel requirement to provide backup power during outages.

**Table A14 Key assumptions in estimating green hydrogen demand, potential emission mitigation and breakeven cost of green hydrogen production for backup power in telecom towers**

| Particular | Unit | Value | Source |
|---|---|---|---|
| Potential green hydrogen demand | | | |
| Typical power requirement of BTS (4/4/4) | kW | 1.5 | Based on (Deevela, Kandpal and Singh 2023) |
| Typical power requirement for other loads (microwave units, aviation lamps, fans, etc.) at tower site | kW | 4.5 | |
| Number of BTSs in Assam | Units | 61,414 | (Indiastat 2023) |
| Number of BTSs in Bihar | Units | 1,25,291 | |
| Number of BTSs in Chhattisgarh | Units | 15,299 | |
| Number of BTSs in Haryana | Units | 91,100 | |
| Number of BTSs in Jammu and Kashmir | Units | 38,868 | |
| Number of BTSs in Jharkhand | Units | 56,341 | |

| | | | |
|---|---|---|---|
| Number of BTSs in Karnataka | Units | 1,70,957 | |
| Number of BTSs in Madhya Pradesh | Units | 1,35,445 | |
| Number of BTSs in Rajasthan | Units | 1,47,656 | |
| Number of BTSs in Uttar Pradesh | Units | 3,40,303 | |
| Number of towers in Assam | Units | 17,490 | |
| Number of towers in Bihar | Units | 41,084 | |
| Number of towers in Chhattisgarh | Units | 48,919 | |
| Number of towers in Haryana | Units | 17,490 | |
| Number of towers in Jammu and Kashmir | Units | 10,823 | (visualize.data.govin 2023) |
| Number of towers in Jharkhand | Units | 21,046 | |
| Number of towers in Karnataka | Units | 47,490 | |
| Number of towers in Madhya Pradesh | Units | 38,423 | |
| Number of towers in Rajasthan | Units | 40,147 | |
| Number of towers in Uttar Pradesh | Units | 90,421 | |
| Average daily electricity availability in rural part of Assam | Hours | 18 | |
| Average daily electricity availability in urban part of Assam | Hours | 20 | |
| Average daily electricity availability in rural part of Bihar | Hours | 16 | |
| Average daily electricity availability in urban part of Bihar | Hours | 20 | |
| Average daily electricity availability in rural part of Chhattisgarh | Hours | 20 | |
| Average daily electricity availability in rural part of Haryana | Hours | 17 | |
| Average daily electricity availability in rural part of Jharkhand | Hours | 16 | (Agrawal, et al. 2020) |
| Average daily electricity availability in urban part of Jharkhand | Hours | 19 | |
| Average daily electricity availability in rural part of Karnataka | Hours | 20 | |
| Average daily electricity availability in rural part of Madhya Pradesh | Hours | 20 | |
| Average daily electricity availability in rural part of Rajasthan | Hours | 20 | |
| Average daily electricity availability in rural part of Uttar Pradesh | Hours | 16 | |
| Average daily electricity availability in urban part of Uttar Pradesh | Hours | 20 | |
| Average daily power outage in Jammu and Kashmir | Hours | 8 | Assumption |

| | | | |
|---|---|---|---|
| Total annual energy requirement to power towers during power outages | TWh | 5.1 | Calculation |
| Net calorific value of hydrogen | kWh/kg | 33.3 | (U.S. Department of Energy n.d.) |
| Hydrogen to electricity efficiency of PEMFC | Percentage | 60% | (U.S. Department of Energy 2015) |
| Potential emission mitigation | | | |
| Rating of diesel generator set | kVA | 10 | (Intelligent Energy 2012) |
| Required power from generator | kW | 6 | (Deevela, Kandpal and Singh 2023) |
| Diesel consumption rate at 75% load | Litre/hour | 1.56 | (Blue Diamond Machinery 2023) |
| Net calorific value of hydrogen | kWh/kg | 33.33 | (U.S. Department of Energy n.d.) |
| Density of diesel (at 15 °C) | kg/litre | 0.85 | (U.S. Department of Energy n.d.) |
| Efficiency of generator | Percentage | 38.4% | Calculation |
| Total annual energy requirement to power towers during power outages | TWh | 5.1 | Calculation |
| Emission factor for diesel combustion in commercial sector | kg $CO_2$ emitted per TJ of fuel combusted | 74,100 | (Gómez, et al. 2006) |
| Breakeven cost of green hydrogen production | | | |
| Average daily backup required (by including all the considered states) | Hours | 5.39 | Calculation |
| USD:INR exchange rate | USD:INR | 1:80 | CEEWs' analysis |
| Diesel generator set | | | |
| Apparent power rating of diesel genset | kVA | 10 | (Intelligent Energy 2012) |
| Power factor of diesel genset | | 0.8 | (Top One Power 2020) |
| Real power rating of diesel genset | kW | 8 | Calculation |
| Cost of 10 kVA diesel genset | INR | 2,00,000 | (Intelligent Energy 2012) |
| Life span of diesel generator | Hours | 30,000 | (Petersen 2020) |
| | Years | 15.25 | Calculation |
| Discount rate | Percentage | 10% | Assumption |
| Capital recovery factor | Percentage | 13.1% | Calculation |
| Diesel consumption rate at 75% load | Litre/hour | 1.56 | (Blue Diamond Machinery 2023) |
| Diesel price in India | INR/litre | 87.0 | Assumed based on market trends |
| PEMFC | | | |
| Power rating of fuel cell | kW | 10 | Authors' analysis |
| Required power from fuel cell | kW | 6 | Authors' analysis |

| | | | |
|---|---|---|---|
| Per kW cost of PEMFC | USD/kW | 1,600 | (Yadav, Guhan and Biswas 2021) |
| Cost of 10 kW PEMFC | USD | 16,000 | Calculation |
| Life span of PEMFC stack | Hours | 60,000 | (Yadav, Guhan and Biswas 2021) |
| | Years | 30.5 | Calculation |
| Discount rate | Percentage | 10% | Assumption |
| Capital recovery factor | Percentage | 10.6% | Calculation |
| Hydrogen to electricity efficiency of PEMFC | Percentage | 60% | (U.S. Department of Energy 2015) |
| Net calorific value of hydrogen | kWh/kg | 33.3 | (U.S. Department of Energy n.d.) |
| Hydrogen consumption rate for 6 kW output | kg/hour | 0.3 | Calculation |
| Total annual energy requirement to power towers during power outages | TWh | 5.1 | Calculation |

# Acronyms

| | |
|---|---|
| **AIS** | Asahi India Glass AP |
| **BTS** | base transceiver station |
| **$CO_2$** | carbon dioxide |
| **$CO_2$eq.** | carbon dioxide equivalents |
| **FCEV** | fuel-cell electric vehicle |
| **fNRB** | fraction of non-renewable biomass |
| **GHG** | greenhouse gas |
| **GW** | gigawatt |
| **$H_2$** | hydrogen gas |
| **$H_2$-ICE** | hydrogen internal combustion engine |
| **INOXAP** | INOX Air Products |
| **INR** | Indian National Rupee |
| **JSL** | Jindal Stainless Limited |
| **KTPA** | kilo metric tonnes per annum |
| **kW** | kilowatt |
| **kWh** | kilowatt-hour |
| **LNG** | liquified natural gas |
| **LPG** | liquified petroleum gas |
| **MT** | million metric tonnes |
| **MTPA** | million metric tonnes per annum |
| **MW** | megawatt |
| **$N_2$** | nitrogen gas |
| **NETRA** | NTPC Energy Technology Research Alliance |
| **$NO_x$** | nitrogen oxides |
| **NTPC** | National Thermal Power Corporation |
| **PEMFC** | proton exchange membrane fuel cell |
| **PMUY** | *Pradhan Mantri Ujjwala Yojana* |
| **PNG** | piped natural gas |
| **R&D** | research and development |
| **RE** | renewable energy |
| **TCO** | total cost of ownership |
| **TPA** | tonnes per annum |
| **TTW** | tank-to-wheel |
| **UAV** | unmanned aerial vehicle |
| **USD** | United States dollar |

# References


AGC. 2023. "AGC Achieves Success in Demonstration Test of Glass Production Using Hydrogen as Fuel." October 26, 2023. https://www.agc.com/en/news/detail/1205304_2814.html.

Agrawal, Shalu, Sunil Mani, Abhishek Jain, and Karthik Ganesan. 2020. State of Electricity Access in India. New Delhi, India: Council on Energy, Environment and Water (CEEW).

Airbus. n.d. "ZEROe – Towards the World's First Hydrogen-Powered Commercial Aircraft." Accessed September 3, 2024. https://www.airbus.com/en/innovation/energy-transition/hydrogen/zeroe.

All India Glass Manufacturers' Federation (AIGMF). 2017. "Glass News Oct Dec 2017." Accessed September 3, 2024. https://aigmf.com/Glass_News_Oct_Dec_2017.pdf.

Asahi India Glass. 2024. "Asahi India Glass & INOXAP Collaborate for an Industry Pioneering Initiative for Off-Take of Green Hydrogen at Asahi India's New Greenfield Float Glass Plant at Soniyana (Dist. Chittorgarh), Rajasthan." Accessed September 3, 2024. https://www.aisglass.com/wp-content/uploads/2024/05/Press-Release-INOXAP-Asahi-Green-Hydrogen-07-05-2024.pdf.

Behera, Priyanka, Duggirala S. Ramakrishna, Manchikanti M. Chandrasekhar, and Sridhar Reddy Kothakapu. 2023. "A Concise Review on Recent Advances in Catalytic Asymmetric Hydrogenation." Chirality 35 (8): 477–97. https://doi.org/10.1002/chir.23559.

Besora, Maria, and Feliu Maseras. 2021. "Computational Insights into Metal-Catalyzed Asymmetric Hydrogenation." Advances in Catalysis 68:385–426.

Bharat Petroleum. n.d. "Natural Gas Conversions." Bharat Petroleum. Accessed July 23, 2024. https://www.bharatpetroleum.in/images/files/Natural%20Gas%20Conversions-11-july-22.pdf.

Blue Diamond Machinery. 2023. "Diesel Generator Fuel Consumption Guide." June 7, 2023. https://www.bluedm.com.au/blog/diesel-generator-fuel-consumption-guide-/.

Bonrath, Werner, Jonathan Medlock, Jan Schu ̈tz, Bettina Wu ̈stenberg, and Thomas Netscher. 2012. "Hydrogenation in the Vitamins and Fine Chemicals Industry – An Overview." In Hydrogenation, edited by Iyad Karamé, chap. 3. London, UK: IntechOpen.

BV Glas. 2022. "BV Glas and GWI Complete Their HyGlass Project." September 5, 2022. https://www.bvglas.de/en/detail/news/bv-glas-and-gwi-complete-their-hyglass-project/.

Central Electricity Authority (CEA). 2023. "List of Thermal Power Stations as on 31.03.2023." Accessed September 3, 2024. https://cea.nic.in/wp-content/uploads/pdm/2023/05/List_of_Power_Stations_31.03.2023.pdf.

Central Electricity Authority. 2023. "CO2 Baseline Database for the Indian Power Sector." Central Electricity Authority. December. https://cea.nic.in/wp-content/uploads/baseline/2024/04/User_Guide__Version_19.0.pdf.

ChemAnalyst. 2024. "India Hydrogen Peroxide Market Analysis."

Clifton, Jessica. 2019. How is Hydrogen Peroxide Made? 13 March. Accessed 2024. https://www.chemicals.co.uk/blog/how-hydrogen-peroxide-made#:~:text=While%20the%20overall%20equation%20for,(H2O2).

Climate Finance Leadership Initiative (CFLI) India and Council on Energy, Environment and Water (CEEW). 2024. Financing Green Hydrogen in India: Private Sector Considerations to Strengthen India's Enabling Environment for a Competitive Green Hydrogen Economy. New Delhi: CEEW.

Cigal, Jean-Charles. 2016. "Expanding Use of Hydrogen." Linde. Accessed September 3, 2024. https://assets.linde.com/-/media/global/global-gases/global-industrial-gases/documents/industries/electronics/expanding-use-of-hydrogen-in-the-electronics-industry-gasworld-november-2016_tcm17-419014.pdf.

Clean Carbon Energy. n.d. "NOx Emissions from Diesel Engines – Clean Carbon Energy." Accessed September 3, 2024. https://clean-carbonenergy.com/nox-emissions.html#:~:text=Why%20are%20NOx%20gases%20produced%3F&text=High%20temperature%20combustion%20of%20fuels,in%20air%20to%20NOx%20gases.

Collodi, Guido, Giuliana Azzaro, and Noemi Ferrari. 2017. "Techno-Economic Evaluation of SMR Based Standalone (Merchant) Plant with CCS." February 1, 2017.

CRISIL. 2021. All-India Study on Sectoral Demand for Petrol and Diesel. New Delhi: Petroleum Planning & Analysis Cell (PPAC).

data.govin. 2023. “State/UT-Wise Details of Mobile Towers Installed by Various Telecom Service Providers (TSPs) across the Country as on 31-01-2023.” June 21, 2023. https://www.data.gov.in/resource/stateut-wise-details-mobile-towers-installed-various-telecom-service-providers-tsps-across.

Deevela, Niranjan Rao, Tara C. Kandpal, and Bhim Singh. 2024. “A Review of Renewable Energy Based Power Supply Options for Telecom Towers.” Environment, Development and Sustainability 26:2897–964.

Department of Commerce. n.d. "Export Import Data Bank Version 7.1 – TRADESTAT." Accessed January 16, 2024. https://tradestat.commerce.gov.in/eidb/.

Destinus. n.d. Mastering Aviation. Combination of the Most Advanced Aerospace Technologies. Accessed September 3, 2024. https://www.destinus.com/hypersonic.

DEVCOM Ground Vehicle Systems Center. n.d. “U.S. Army Combat Capabilities Development Command.” Accessed September 3, 2024. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/htac_mar19_07_centeck.pdf?Status=Master.

Elango, Sabarish, Kartheek Nitturu, Deepak Yadav, Pratheek Sripathy, Rishabh Patidar, and Hemant Mallya. 2023. Evaluating Net-Zero for the Indian Steel Industry: Marginal Abatement Cost Curves of Carbon Mitigation Technologies. New Delhi: Council on Energy, Environment and Water.

Energypedia. n.d. s.v. Liquefied Petroleum Gas (LPG). https://energypedia.info/wiki/Liquefied_Petroleum_Gas_(LPG).

Energys. 2024. Energys & Telstra Launch Hydrogen Backup Generators in Victoria. Accessed September 3, 2024. https://energys.com.au/green-hydrogen-news/hydrogen-generators-deployed-at-regional-mobile-towers-by-telstra-energys.

EnerTech. n.d. How Battery Energy Storage System Can Revolutionize Your Energy Efficiency. Accessed September 3, 2024. https://enertechups.com/blog/how-battery-energy-storage-system-can-revolutionize-your-energy-efficiency/#:~:text=Ans%3A%20The%20efficiency%20of%20a,trip%20efficiency%20often%20exceeding%2090%25.

Evonik. n.d. Hydrogen peroxide. Accessed September 2024. https://active-oxygens.evonik.com/en/products-and-services/hydrogen-peroxide/general-information#:~:text=The%20chemical%20peroxide%20hydrogen%20is,acts%20as%20%22reaction%20carrier%22.

FC TecNrgy. n.d. “Backup Power for Mobile Telecom Towers and Repeater Stations.” https://www.fctecnrgy.com/telecom/.

Foley, E. V. 2024. “Remote Telecom Towers Powered by 10 kW Hydrogen Generators.” Accessed September 3, 2024. https://www.pv-magazine.com/2024/07/05/remote-telecom-towers-powered-by-10-kw-hydrogen-generators/.

Forest Research. n.d. “Typical Calorific Values of Fuels.” Accessed July 20, 2024. https://forestresearch.gov.uk/tools-and-resources/fthr/biomass-energy-resources/reference-biomass/facts-figures/typical-calorific-values-of-fuels/.

Gao, Guohua , Yanan Tian, Xiaoxiao Gong, Zhiyong Pan, Keyong Yang, and Baoning Zong. 2020. “Advances in the production technology of hydrogen peroxide.” Chinese Journal of Catalysis 1039-1047.

Gambling, W. A. 2003. “Optical Fibers, Fabrication and Applications.” In Encyclopedia of Physical Science and Technology (Third Edition), edited by Robert A. Meyers, 295–313. Cambridge, MA: Academic Press.

General Power. n.d. “Diesel Generator vs. Gas Generator: Which Is More Efficient?” Accessed September 3, 2024. https://www.genpowerusa.com/blog/diesel-generator-vs-gas-generator-which-is-more-efficient/#:~:text=Typically%20a%20diesel%20generator%20will,losses%20from%20heat%20and%20friction.

Gerrard, Neil. 2023. “Will Hydrogen Fuel Cells Make It into Construction Equipment?” November 10, 2023. https://www.constructionbriefing.com/news/will-hydrogen-fuel-cells-make-it-into-construction-equipment-/8032708.article.

Ghosh, Saikat, Jatindra Nath Roy, and Chandan Chakraborty. 2023. “Exploring the Merits of Geographical Diversification of Solar PV Power Plants for a Resilient PV-Dominated Electricity Grid in India.” CleanEnergy 7 (4): 885–910. https://doi.org/10.1093/ce/zkad024.

Gobain, Saint. 2023. “Saint Gobain Achieves the First Flat Glass Production Using More than 30% Hydrogen.” March 30, 2023. https://www.saint-gobain.com/sites/saint-gobain.com/files/media/document/20230330_Herzogenrath_VA.pdf.

Gómez, Darío R., John D. Watterson, Branca B. Americano, Chia Ha, Gregg Marland, Emmanuel Matsika, Lemmy Nenge Namayanga, Balgis Osman-Elasha, John D. Kalenga Saka, and Karen Treanton. 2006. “Chapter 2: Stationary Combustion.” In National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf.

Government of Haryana. 2017. “Non Transport Vehicles (One Time Tax).” Accessed September 3, 2024. https://haryanatransport.gov.in/en/content/non-transport-vehicles-one-time-tax.

Groenemans, Hugo, Genevieve Saur, Cortney Mittelsteadt, Judith Lattimer, and Hui Xu. 2022. “Techno-Economic Analysis of Offshore Wind PEM Water Electrolysis for $H_2$ Production.” Current Opinion in Chemical Engineering 37:100828.

Hansen, D. M., and Kuech T. F. 2003. “Epitaxial Technology for Integrated Circuit Manufacturing.” In Encyclopedia of Physical Science and Technology (Third Edition), edited by Robert A. Meyers, 641–52. Cambridge, MA: Academic Press

Hasan, Tanvir, Kianoush Emami, Rakibuzzaman Shah, N. M. S. Hassan, Jake Anderson, Dane Thomas, and Alan Louis. 2022. “A study on green hydrogen-based isolated microgrid.” Energy Reports 8 (15): 259–67.

Heid, Bernd, Christopher Martens, and Anna Orthofer. 2021. “How Hydrogen Combustion Engines Can Contribute to Zero Emissions.” June 25, 2021. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/how-hydrogen-combustion-engines-can-contribute-to-zero-emissions.

Hydrogen Europe. 2021. “HYDROGEN EUROPE – TECH [Overview}.” Hydrogen Europe. https://hydrogeneurope.eu/wp-content/uploads/2021/11/Tech-Overview_Hydrogen-Transport-Distribution.pdf.

Hydrogen News. 2024. “Energys & Telstra Launch Hydrogen Backup Generators in Victoria.” July 8, 2024. https://energys.com.au/green-hydrogen-news/hydrogen-generators-deployed-at-regional-mobile-towers-by-telstra-energys.

HYGENCO. n.d.a “Photon Leap – for Sustainable Optical Fibre Production.” Accessed September 3, 2024. https://www.hygenco.in/project-photon-leap.html.

HYGENCO. n.d.b “Steel One – Commercial Project.” Accessed September 3, 2024. https://www.hygenco.in/project-steel-one.html.

HyNet. n.d. “HyNet Industrial Fuel Switching.” Accessed September 3, 2024. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1119899/phase_3_hynet_industrial_fuel_switching.pdf.

IamRenew. 2024. “JSL Hisar Green Hydrogen Plant Hygenco Renewable Energy.” Accessed September 3, 2024. https://www.iamrenew.com/green-energy/stainless-steel-sectors-first-green-hydrogen-unit-installed-at-jsl/attachment/jsl-hisar-green-hydrogen-plant-hygenco-reneawble-energy/.

IEA. 2023. *Towards hydrogen definitions based on their emissions intensity*. Paris: IEA

IndiaMART. n.d. "Firewood Chips". Accessed July 22, 2024. https://www.indiamart.com/proddetail/firewood-chips-26862530948.html.

Indiastat. 2023. "Selected State-wise Number of Base Transceiver Stations (BTSs) in India (as on 30-06-23)." Accessed August 15, 2024. https://www.indiastat.com/table/telecommunication/selected-state-wise-number-base-transceiver-statio/1450944.

Indraprastha Gas Limited. n.d. PNG Price. Accessed July 23, 2024. https://www.iglonline.net/png-price#:~:text=In%20Delhi%20%3A%20Rs.,48.59%20per%20SCM.

Infra Junction. n.d. "Volvo EC200D." Accessed August 20, 2024. https://infra.tractorjunction.com/en/volvo-construction-equipments/ec200d.

Intelligent Energy. 2012. “The True Cost of Providing Energy to Telecom Towers in India.” Accessed September 3, 2024. https://www.gsma.com/get-involved/gsma-membership/wp-content/uploads/2013/01/true-cost-providing-energy-telecom-towers-india.pdf.

ITM. n.d. “Green Hydrogen for Glass: Providing a Zero Emissions Method of Creating Uniform Glass.” Accessed September 3, 2024. https://itm-power.com/markets/hydrogen-for-glass.

Jacob, Ammu Susanna , Rangan Banerjee, and Prakash C. Ghosh. 2018. “Sizing of hybrid energy storage system for a PV based microgrid through design space approach.” Applied Energy 640-653.

JCB. n.d. “Hydrogen: Building a Greener Future.” Accessed September 3, 2024. https://www.jcb.com/en-in/campaigns/hydrogen.

Ji, Jongho, Hoe-Min Kwak, Jimyeong Yu, Sangwoo Park, Jeong-Hwan Park, Hyunsoo Kim, Seokgi Kim, Sungkyu Kim, Dong-Seon Lee, and Hyun S. Kum. 2023. “Understanding the 2D-Material and Substrate Interaction During Epitaxial Growth Towards Successful Remote Epitaxy: A Review.” Nano Convergence 10:49.

Jindal Stainless Limited. 2023. “Manufacturing Strengths.” Accessed September 3, 2024. https://www.jindalstainless.com/annualreport-2023/corporate-overview/manufacturing-strengths.php#:~:text=The%20Hisar%20plant%2C%20with%20its,tonnes%20per%20annum%20(MTPA).

Jordan, Thomas. 2022. “Hydrogen Technologies.” In Hydrogen Safety for Energy Applications, edited by Alexei Kotchourko and Thomas Jordan, 25–115. Oxford, UK: Butterworth-Heinemann.

Kar, Abhishek, Roshan Wathore, Arunabha Ghosh, Shruti Sharma, Emily Floess, Andrew Grieshop, Rob Bailis, and Nitin Labhasetwar. 2023. “Promoting the Use of LPG for Household Cooking in Developing Countries.” Accessed September 3, 2024. https://t20ind.org/research/promoting-the-use-of-lpg-for-household-cooking-in-developing-countries/.

Khzouz, Martin, Evangelos I. Gkanas, Alessandro Girella, Thomas Statheros, and Chiara Milanese. 2020. “Sustainable Hydrogen Production via LiH Hydrolysis for Unmanned Air Vehicle (UAV) Applications.” International Journal of Hydrogen Energy 45 (8): 5384–94.

Linde. 2017. “Hydrogen in Electronics: Growing Applications and Consumption.” Accessed September 3, 2024. https://assets.linde.com/-/media/global/global-gases/global-industrial-gases/documents/industries/electronics/hydrogen-in-electronics-silicon-semiconductor-march-2017_tcm17-419023.pdf.

Liu, Xiaohong, Li Xiao, Chunhua Wei, Xiuxia Xu, Minghuan Luo, and Weilin Yan. 2018. “Effect of Multi-Directional Forging and Annealing on Abrasive Wear Behavior in a Medium Carbon Low Alloy Steel.” Tribology International 119:608–13.

Lohse-Busch, Henning, Michael Duoba, Kevin Stutenberg, Simeon Iliev, and Mike Kern. 2018. Technology Assessment Of A Fuel Cell Vehicle: 2017 Toyota Mirai. Technical, Argonne National Laboratory.

Louisiana CAT. n.d. “The Average Lifespan of Construction Equipment.” Accessed August 20, 2024. https://www.louisianacat.com/our-company/blog/lifespan-of-heavy-equipment/.

Lu, Nan Hua, I-Chun Chen, and Rey-Chue Hwang. 2023. “Prediction of Hydrogen Concentration in Annealing Furnace.” Sensors and Materials 33 (7): 2671–80. https://doi.org/10.18494/SAM4240.

Mallapragada, Dharik S., Indraneel Naik, Karthik Ganesan, Rangan Banerjee, and Ian J. Lauren. 2019. “Life Cycle Greenhouse Gas Impacts of Coal and Imported Gas-Based Power Generation in the Indian Context.” Environmental Science and Technology 46 (2): 539–49.

Mallya, Hemant, Deepak Yadav, Anushka Maheshwari, Nitin Bassi, and Prerna Prabhakar. 2024. Green Hydrogen-Renewable Energy-Land-Water Nexus in India: Unlocking Renewable Energy and Green Hydrogen Potential in India. New Delhi: Council of New and Renewable Energy (CEEW).

Mills, Walker, and Erik Limpaecher. 2021. “The Promise of Hydrogen: An Alternative Fuel at the Intersection of Climate Policy and Lethality.” December 27, 2021. https://mwi.westpoint.edu/the-promise-of-hydrogen-an-alternative-fuel-at-the-intersection-of-climate-policy-and-lethality/.

Ministry of Chemical and Fertilizers. 2022. “Chemical and Petrochemical statistics at a glance - 2022.”

Ministry of Petroleum & Natural Gas. 2011. “LPG Gas Stoves.” December 1, 2011. https://pib.gov.in/newsite/PrintRelease.aspx?relid=78057#:~:text=The%20BIS%2D%20marked%20LPG%20stoves,reply%20in%20Lok%20Sabha%20today.

———. 2024. Indian Petroleum and Natural Gas Statistics 2022-23. New Delhi: Ministry of Petroleum & Natural Gas. https://chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://mopng.gov.in/files/TableManagements/IPNG-2021-22_L.pdf.

Ministry of Statistics and Programme Implementation (MOSPI). 2023. Multiple Indicator Survey in India: NSS 78th Round (2020–2021). New Delhi: MOSPI. https://www.mospi.gov.in/sites/default/files/publication_reports/MultipleIndicatorSurveyinIndiaf.pdf.

———. 2024. Energy Statistics India 2024. New Delhi: MOSPI. https://mospi.gov.in/publication/energy-statistics-india-2024-1.

Ministry of Steel. 2023. Annual Report 2022–23. New Delhi: Ministry of Steel. https://steel.gov.in/sites/default/files/MoS%20AR%202022-23.pdf.

Mukelabai, Mulako D., K. G. U. Wijayantha, and Richard E. Blanchard. 2022. “Hydrogen for Cooking: A Review of Cooking Technologies, Renewable Hydrogen Systems and Techno-Economics.” Sustainability 14 (24): 16964. https://doi.org/10.3390/su142416964.

National Thermal Power Corporation (NTPC). 2021. “NTPC Awards India’s First Green Hydrogen Microgrid Project.” December 15, 2021. https://ntpc.co.in/index.php/media/press-releases/ntpc-awards-indias-first-green-hydrogen-microgrid-project.

———. 2024. “NTPC demonstrates zero emission ‘Hydrogen Cooking’.” January 15, 2024. https://ntpc.co.in/media/press-releases/ntpc-demonstrates-zero-emission-hydrogen-cooking.

NBM&CW. 2024. “JCB Introduces Hydrogen Powered 3DX Backhoe Loader.” Accessed September 3, 2024. https://www.nbmcw.com/equipment-machinery/construction-equipments/earthmoving-equipment/jcb-introduces-hydrogen-powered-3dx-backhoe-loader.html.

Nebegall, Jim. 2022. “Hydrogen Internal Combustion Engines and Hydrogen Fuel Cells.” January 27, 2022. https://www.cummins.com/news/2022/01/27/hydrogen-internal-combustion-engines-and-hydrogen-fuel-cells.

Nel Hydrogen. n.d. “Generator Cooling.” Accessed September 4, 2024. https://nelhydrogen.com/glossary/generator-cooling/#:~:text=Hydrogen%20is%20used%20to%20cool,heat%20capacity%20and%20low%20density.

New and Renewable Energy Department, Government of Madhya Pradesh. 2022. “Madhya Pradesh Renewable Energy Policy.” https://rumsl.mp.gov.in/wp-content/uploads/government_policy/2022/08/English-Policy.pdf.

Nippon Electric Glass. 2022. “Nippon Electric Glass Succeeds in Melting Glass with Combustion Technology Using a Hydrogen-Oxygen Burner.” April 19, 2022. https://www.neg.co.jp/en/news/20220419-4693.html.

NITI Aayog. 2024. “Economy-Wide Emissions.” Accessed September 4, 2024. https://iced.niti.gov.in/climate-and-environment/ghg-emissions/economy-wide.

NITI Aayog. 2024. Overview- Power Distribution in India. Accessed August 25, 2024. https://iced.niti.gov.in/energy/electricity/distribution.

Oberoi, Sanjeev. n.d. “Indian Float Glass Market.” Accessed September 4, 2024. https://www.aigmf.com/docs/Float%20glass%20segment.pdf.

Ohmium. 2024. “Ohmium Celebrates Lohri Festival with Green Hydrogen Clean Cooking Demonstration at NTPC NETRA Campus.” January 18, 2024. https://www.ohmium.com/news/ohmium-celebrates-lohri-festival-with-green-hydrogen-clean-cooking-demonstration-at-ntpc-netra-campus.

Oro, Jesús Manuel Fernández, K. M. Argüelles Diaz, Carlos Santolaria, and A. F. Cobo Hedilla. 2008. “Multiphase Modelling of Pouring Glass Over the Spout Lip of an Industrial Float in the Flat Glass Forming Process.” International Journal for Numerical Methods in Fluids 58 (10): 1147–77.

Orthoefer, Frank T., and Gary R. List. 2007. “Initial Quality of Frying Oil.” In Deep Frying (Second Edition), edited by Michael D. Erickson, 33–48. Champaign, IL: AOCS Press.

Petersen, Conrad. 2020. “6 Signs It’s Time to Replace Your Standby Generator.” December 29, 2020. https://goemc.com/2020/12/29/6-signs-its-time-to-replace-your-standby-generator/#:~:text=Depending%20on%20the%20quality%20and,how%20well%20it%20is%20maintained.

Petroleum Planning and Analysis Cell. 2024. “Domestic Consumption of Petroleum Products (P).” https://ppac.gov.in/consumption/products-wise.

PIB Chennai. 2023. “Pradhan Mantri Ujjwala Yojana Fuels LPG Revolution Nearly 17 Crore LPG Consumers Added in Last 9 Years.” April 20, 2023. https://pib.gov.in/PressReleasePage.aspx?PRID=1918364#:~:text=Pradhan%20Mantri%20Ujjwala%20Yojana%20Fuels,added%20in%20last%209%20years&text=India%20has%20achieved%20significant%20growth,crore%20as%20of%20March%202023.

PIB. 2021. “"New Gas Stove for Domestic PNG".” Press Information Bureau. 13 December. https://pib.gov.in/PressReleasePage.aspx?PRID=1780895.

—. 2022. “"100% Village Electrification Achieved in India".” Press Information Bureau. 27 July. https://static.pib.gov.in/WriteReadData/specificdocs/documents/2022/jul/doc202272774301.pdf

PIB Delhi. 2023. “Economic Survey Highlights Thrust on Rural Development.” January 31, 2023. https://pib.gov.in/PressReleasePage.aspx?PRID=1894901.

———. 2024. “Cabinet Approves Continuation of Rs.300 Targeted Subsidy to PM Ujjwala Yojana Consumers.” March 7, 2024. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=2012354#:~:text=The%20Union%20Cabinet%20chaired%20by,)%20during%20FY%202024%2D25.

Pillay, Amritha. 2023. “Indian Steel, Cement Makers Face Uphill Task in Quest to Go Green.” https://www.moneycontrol.com/news/business/companies/indian-steel-cement-makers-face-uphill-task-in-quest-to-go-green-10739271.html#google_vignette.

PowerCell. n.d. “World’s First Zero-Emission Hauler.” https://powercellgroup.com/worlds-first-zero-emission-hauler/.

Process Sensing Technologies (PST). n.d. “Maintaining Hydrogen Purity in Turbine Power Generators.” Accessed September 4, 2024. https://www.processsensing.com/en-us/blog/maintain-hydrogen-purity-turbine-power-generators.htm.

Raczon, Frank. 2023. “JCB Adds Hydrogen Combustion Engine Along Its ‘Road to Zero’.” January 18, 2023. https://www.constructionequipment.com/sustainability/news/21545778/jcb-adds-hydrogen-combustion-engine-along-its-road-to-zero.

Reddi, Krishna, Amgad Elgowainy, Neha Rustagi, and Erika Gupta. 2017. “Impact of Hydrogen Refueling Configurations and Market Parameters on the Refueling Cost of Hydrogen.” International Journal of Hydrogen Energy 42 (34): 21855–65. https://doi.org/10.1016/j.ijhydene.2017.05.122.

Rey, Jesús, Francisca Segura, and José Manuel Andújar. 2023. “Profitability of Hydrogen-Based Microgrids: A Novel Economic Analysis in Terms of Electricity Price and Equipment Costs.” Electronics 18.

Santhosh, Apoorva, Kalyan Verma, and Vishal Dev. 2024. Green Hydrogen Demand Assessment For C&I Consumers in India. New Delhi: WWF India.

Schöne, Nikolas, Raluca Dumitrescu, and Boris Hein. 2023. “Techno-Economic Evaluation of Hydrogen-Based Cooking Solutions in Remote African Communities—The Case of Kenya.” Energies 16 (7): 3242. https://doi.org/10.3390/en16073242.

SCHOTT. 2024. “Premiere: SCHOTT Produces Optical Glass with 100 Percent Hydrogen.” April 16, 2024. https://www.schott.com/en-in/news-and-media/media-releases/2024/schott-produces-optical-glass-with-100-percent-hydrogen.

Servotech India Limited. n.d. “Vanaspati/Hydrogenation Plant.” Accessed September 4, 2024. https://www.servotech-india.com/index.php/vanaspati-hydrogenation-plant.html.

Sgarbossa, Fabio, Simone Arena, Ou Tang, and Mirco Peron. 2023. "Renewable Hydrogen Supply Chains: A Planning Matrix and an Agenda for Future Research." International Journal of Production Economics 255:108674. https://doi.org/10.1016/j.ijpe.2022.108674.

Shah, Kashish. 2021. New Coal-Fired Power Plants in India: Reality or Just Numbers? Cleveland, OH: Institute for Energy Economics and Financial Analysis. https://ieefa.org/wp-content/uploads/2021/05/New-Coalfired-Power-Plants-in-India_Reality-or-Just-Numbers_June-2021.pdf.

Siemens Government Technologies. n.d. "Mobile Microgrids: The Ultimate Emergency Backup Power Source for Critical Government and Defense Operations." Accessed September 4, 2024. https://www.siemensgovt.com/insights/articles/article-mobile-microgrids.

Singh, Braj N., Tripti Ratn, and Prakash Jha. 2024. India's Green Hydrogen Revolution: An Ambitious Approach. New Delhi: Ministry of New and Renewable Energy. https://static.pib.gov.in/WriteReadData/specificdocs/documents/2024/may/doc2024510336301.pdf.

Sobon, Andrzej, Daniel Slys, Mariusz Ruszel, and Alicja Wiacek. 2021. "Prospects for the Use of Hydrogen in the Armed Forces." Energies 14 (21): 7089. https://doi.org/10.3390/en14217089.

STL. 2023. "STL among the First Indian Optical Companies to Transition to Green Hydrogen for Sustainable Operations." October 12, 2023. https://stl.tech/press-release/stl-among-the-first-indian-optical-companies-to-transition-to-green-hydrogen-for-sustainable-operations/.

Sukharev, V. 2002. "Multiscale Modeling of Plasma Etch Processing." Vacuum 65 (3–4): 281–89. https://doi.org/10.1016/S0042-207X(01)00432-8.

Suresh, R., V. K. Singh, J. K. Malik, A. Datta, and R. C. Pal. 2016. "Evaluation of the Performance of Improved Biomass Cooking Stoves with Different Solid Biomass Fuel Types." Biomass and Bioenergy 95:27–34. https://doi.org/10.1016/j.biombioe.2016.08.002.

TATA Steel. n.d. Hot-Rolled Steel vs Cold-Rolled Steel. Accessed August. https://digeca.tatasteel.com/resources/blogs/hot-rolled-steel-vs-cold-rolled-steel.

Technotherma (India) Pvt. Ltd. 2023. "H2 Hydrogen Bell Annealing Furnace." August 16, 2023. https://www.technotherma.com/blog/h2-hydrogen-bell-annealing-furnace.html.

The Federation of Indian Petroleum Industry. 2023. "Hydrogen Market Report." The Federation of Indian Petroleum Industry. October. https://www.fipi.org.in/assets/pdf/downstream-report/Hydrogen%20Market%20Report.pdf.

Top One Power. 2020. "Power Factor of Diesel Generator Sets." July 31, 2020. https://www.topone-power.com/power-factor-of-diesel-generator-sets/#:~:text=The%20value%20of%20Power%20Factor%20ranges%20from%200%20to%201.&text=To%20maximise%20the%20performance%2C%20the,0.8%20for%20their%20generator%20units.

U.S. Department of Energy. 2015. "Fuel Cells Fact Sheet." Accessed September 4, 2024. https://www.energy.gov/eere/fuelcells/articles/fuel-cells-fact-sheet.

Volvo. 2022. "Volvo CE Starts Testing of the World's First Prototype Hydrogen Articulated Hauler." June 13, 2022. https://www.volvoce.com/global/en/news-and-events/news-and-stories/2022/volvo-ce-starts-testing-of-the-worlds-first-prototype-hydrogen-articulated-hauler/.

———. n.d. "Fuel Efficiency Guarantee." Accessed August 20, 2024. https://www.volvoce.com/united-states/en-us/volvo-services/fuel-efficiency-services/fuel-efficiency-guarantee/.

VR Coolers. 2023. "Why the Hydrogen Is Used for the Cooling of Large Generators Instead of Air?" March 13, 2023. https://www.vrcooler.com/news/why-the-hydrogen-is-used-for-the-cooling-of-la-65472580.html.

Yadav, Deepak, Ashish Guhan, and Tirtha Biswas. 2021. Greening Steel: Moving to Clean Steelmaking Using Hydrogen and Renewable Energy. New Delhi: Council on Energy, Environment and Water. https://www.ceew.in/sites/default/files/ceew-study-on-clean-and-carbon-neutral-hydrogen-based-steel-production.pdf.

Yadav, Subhash. 2024. "Stainless Steel Sector's First Green Hydrogen Unit Installed at JSL." March 6, 2024. https://www.iamrenew.com/green-energy/stainless-steel-sectors-first-green-hydrogen-unit-installed-at-jsl/#:~:text=Hydrogen%20plays%20a%20crucial%20role,a%20fixed%2Dprice%20offtake%20contract.

# The authors

**Hashvitha Rajakumaran**
hashvitha.rajakumaran@ceew.in

Hashvitha is a Research Analyst with the Industrial Sustainability team at The Council. Her work focuses on the decarbonisation of various industries, with a primary interest in exploring the potential of green hydrogen for industry-specific applications. Hashvitha holds a dual master's degree in Sustainable Energy Systems from KTH Royal Institute of Technology, Sweden, and Aalto University, Finland.

**Hemant Prakash Singh**
hemant.singh@ceew.in

Hemant is a Research Analyst with the Industrial Sustainability team at The Council. His work focuses on advancing low-carbon pathways for India's major industrial sectors, with a primary interest in exploring decarbonisation strategies for petroleum refineries through the integration of emerging technologies such as green hydrogen, CCU and biofuels. Hemant is an engineer by education, having graduated from IIT Delhi with a dual degree (BTech + MTech) in Chemical Engineering.

**Karan Kothadiya**
karan.kothadiya@ceew.in

Karan is a Programme Associate at The Council in the Industrial Sustainability Team. He studies decarbonisation pathways that find applications in hard-to-abate sectors of the economy. His primary areas of interest are clean hydrogen technologies and technological carbon capture and storage. Before joining The Council, Karan worked as a management consultant. Karan graduated from IIT Bombay with a dual degree (BTech + MTech) in Metallurgical Engineering and Materials Science.

**Deepak Yadav**
deepak.yadav@ceew.in

Deepak is a Programme Lead at CEEW and has expertise in green hydrogen, carbon capture, and utilisation and the steel sector. He has over eight years of experience in renewable energy, alternative fuels, and industrial sustainability. He is also a BEE-certified energy auditor and has published his research in leading international journals and conferences. Deepak holds a doctorate and a master's degree from the Department of Energy Science and Engineering, IIT Bombay.

Scan to download the study


**COUNCIL ON ENERGY, ENVIRONMENT AND WATER (CEEW)**

ISID Campus, 4 Vasant Kunj Institutional Area
New Delhi - 110070, India
T: +91 11 4073 3300

info@ceew.in | ceew.in | @CEEWIndia | ceewIndia

**MINISTRY OF NEW AND RENEWABLE ENERGY (MNRE)**

Atal Akshay Urja Bhawan, Lodhi Road,
New Delhi - 110070, India

mnre.gov.in | @mnreindia | mnreministry