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Green Hydrogen: Understanding Techno-Economic Viability for Industries

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Abstract: Green hydrogen is being touted as the ultimate decarbonisation tool. It is the most versatile fuel and can be used for multiple applications but has a strong use case in hard to abate sectors including refineries, fertilisers, cement and steel. But the commercial viability of the fuel is still uncertain. There is still a hesitation among the market to deploy and scale it which can be attributed to its high cost. Renewable power accounts for more than 85% of the cost of green hydrogen and high cost of renewable power generation and transmission makes it financially unattractive in comparison to grey hydrogen. Technology viability of green hydrogen market is also still evolving. Technology like Alkaline electrolysers are cheaper in comparison but not as efficient as other technologies including proton exchange membrane and solid oxide electrolysers. Notwithstanding, the market is extremely hopeful about the prospects of green hydrogen, but this paper concludes that current policy initiatives are inadequate to make a material change. There is a need for more concerted support from the government in the form of capital subsidies, waivers in grid charges for renewable power, strong R&D boost and demand side measures like mandatory purchase obligation on refineries to help the green hydrogen market take off. This paper evaluates techno-commercial viability, policy framework and global developments related to green hydrogen to understand its status of adoption.

Keywords: Electrolysers, green hydrogen, refineries, technological viability, policy and regulatory framework

Introduction

Hydrogen is a versatile energy carrier which can be used across for a wide range of applications. Green hydrogen offers several advantages over other conventional fuels which includes higher specific energy consumption (energy content per unit mass), ability to be stored for longer durations and produces zero carbon emissions (RMI, 2022). It can be used as a fuel in transport, feedstock in refining, fertilisers, plastics, steel and glass or as a heating source in industry including steel, cement (Abdin, 2023). It can also be used to build net-zero commercial and residential buildings by providing a reliable source of heating and power (Hydrogen Europe, 2022). Considering intermittency of renewable power, there is an urgent need for various storage technologies and hydrogen is one of the most effective alternatives to store power (Egeland-Eriksen, 2021).

Hydrogen is one of the most abundant elements in the universe but not available in its elemental form, thus needs to be extracted from other hydrogen containing compounds. Efficient hydrogen extraction is crucial as it directly impacts the fuel's carbon emissions, influencing its overall environmental footprint (see table 1). Hydrogen produced through water electrolysis emits the least amount of carbon emissions, rendering it the most environmentally friendly pathway to produce hydrogen.

Table 1: Emissions from different hydrogen production pathways

Pathways	Global warming potential (kg CO2 eq/ kg of H2)
Steam methane reforming (SMR)	12.13
Coal gasification	24.2
SMR with CCS	3.4
Gasification with CCS	4.08
Water electrolysis	2.21

Source: World Resources Institute, 2022

Use of different processes and inputs determine the colour of hydrogen (see table 2).

Table 2: Colours of hydrogen

Colours of hydrogen	**Black/ brown hydrogen**	**Grey hydrogen**	**Turquoise hydrogen**	**Blue hydrogen**	**Pink hydrogen**	**Green hydrogen**
Inputs	Coal	Natural gas	Natural gas	Natural gas	Nuclear	Renewables
Process	Coal gasification	Steam methane reforming	Pyrolysis	Reforming with carbon capture and storage	Electrolysis	Electrolysis

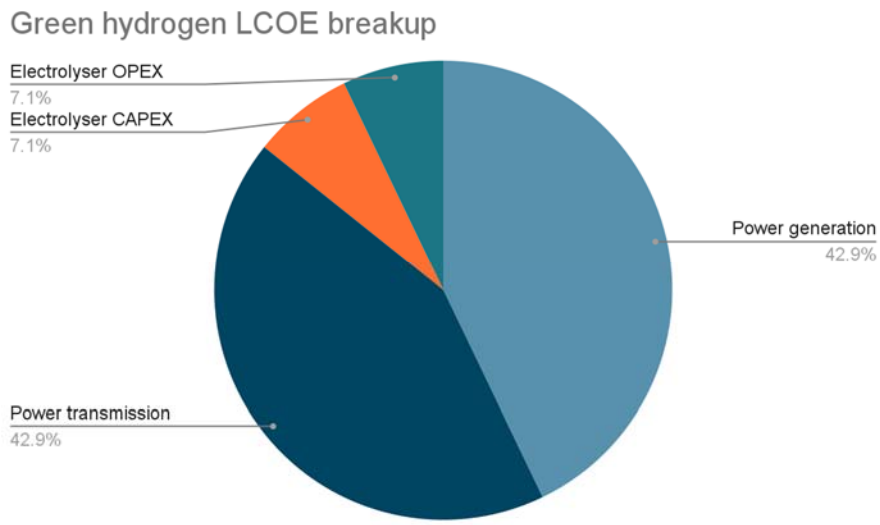
Source: (Ajanovic et al., 2023)

Use in industries

Industries have been using hydrogen for decades, but increasing penetration of renewable power and available at lower costs has renewed interest in green hydrogen. India is aiming to become a green hydrogen hub because of the unique advantages it enjoys. Given that renewable power accounts for over 85% of the levelized cost of green hydrogen (refer to figure 1), the pivotal factor influencing the location of green hydrogen production is the affordability of power. India has one of the lowest levelised cost of round-the-clock renewable power, 27% lower than China. Round-the-clock power is preferred for green hydrogen production facilities as 100% dependence on storage technologies shall take a few years to become commercially viable (Economic Times, 2023, GS). India also ranks at 3rd position in renewable attractiveness index, attributing to its geographical position, availability of natural resource, policy and regulatory framework and costs, making it extremely attractive for green hydrogen production (EY, 2023).

India announced its Green Hydrogen Mission in early 2023 after much anticipation. A massive target of 5 MMT by 2030 was announced which can reduce 50 MMT of CO2 emissions. Roughly, one kg of green hydrogen requires 50 kWh of renewable power which means, 5 MMT of green hydrogen production capacity shall require 125 GW of renewable power capacity to be built by 2030. It is important to note that India already has a target of reaching 500 GW of renewable capacity by 2030, while India has a total renewable installed capacity of 132 GW excluding large hydro as of November 2023 (MNRE, 2023).

Figure 1: Levelised cost of green hydrogen breakdown



Source: Bridge to India

Industries account for more than 65% of emissions in India (GHG Platform, 2019). Across all applications, demand in refining and ammonia production is the highest (Manna et al., 2021). India is the third largest consumer of hydrogen in the world, after the US and China. Refineries and fertilisers are the major consumers of green hydrogen with an estimated demand of 6 MMT per annum. While fertilisers account for 55% of the demand, refineries consume the rest 45% (Vasudha Foundation, 2022). These sectors are traditionally dependent on conventional sources of fuel and have limited low carbon options to decarbonise. Refining industries are expected to play a key role in energy transition and are showing willingness to energy proof their businesses by switching from conventional fuel business to low carbon business. Most refining industries have announced climate targets and are on path to find low carbon options to decarbonise. Some of the biggest refineries including Bharat Petroleum Corporation Limited (BPCL), Hindustan Petroleum Corporation Limited (HPCL) and Oil India have pledged to become net zero by 2040 (Economic Times, 2022, Pathak, 2023, Reuters, 2023) and Indian Oil has set a further date of 2046 (Indian Oil, 2022). While ONGC has pledged to achieve net neutrality by 2038 and shall invest more than USD 24 billion on clean energy projects (Verma, 2023). Considering the emission reduction potential within the refinery sectors and the imperative to decarbonize, the most compelling argument arises for the adoption of green hydrogen in this industries.

Refining industries also have made announcements of venturing into green hydrogen business and various projects being undertaken by them. IOCL and HPCL are building a plant in Haryana and Andhra Pradesh respectively with a capacity of 7 KT H2 per annum each which will be completed by 2025-26. While BPCL is building a plant of 10 KT H2 capacity by 2030. In total all state-run refineries are setting up projects with a cumulative capacity of 30.8 KT H2 by 2030 (ET Energy World, 2023). ICF estimates India's green hydrogen demand is expected to reach 15-20 MMT by 2040 which is expected to be concentrated in the fertilizer and refinery industry. The market size is expected to reach USD 30-35 by 2035-40 under best case scenario (Asia Clean Energy Forum, 2023). Hydrogen consumption shall be mostly by refineries and fertilisers for captive demand and for export markets. There are already discussions underway with France, Italy, Germany for exporting green hydrogen (India Shipping News, 2023). But viability of export and consumption by industries shall be contingent upon techno-commercial viability of the fuel in the country.

Considering the potential of green hydrogen in industries, this research was conducted with the objective to understand current market status, analyse challenges related to technology and economic viability, analyse government initiatives by central and state governments and their potential impact and provide policy recommendations to policymakers that can help provide a boost to the green hydrogen sector.

Technological viability

Multiple electrolyser technologies are available today to produce green hydrogen, however all of them are at different stages of development. Most popular and widely discussed technologies are alkaline electrolysers, proton exchange membrane (PEM) electrolysers, solid oxide electrolysers and anion exchange membrane. As seen in the renewable sector, with technology advancements and increase in adoption scale, it takes several years to realise the lowest cost possible. Improvements in various parameters, as discussed in table 3 shall help in reducing cost of electrolysers.

Table 3: Comparison between electrolyser technologies

	Alkaline electrolysers	**PEM electrolyser**	**Solid oxide electrolyser**	**Anion exchange membrane**
Technology maturity	Highly mature	Demonstration stage	R&D stage	R&D stage
Working temperature, degree celsius	60-80	50-80	900-1000	40-60
Stack life (hours)	60,000-100,000	50,000-90,000	20,000-90,000	30,000
Energy consumption (kWh/ kg of H2	55-60	50-55	45-44	57-69
Start up time	30-60	15-28	>60	>30
Use of rare and earth materials	Platinum (Pt), Ruthenium (Ru),	Platinum (Pt) and iridium (Ir)	Zirconium (Zr), samarium (Sm), and lanthanum (La)	None
Capital cost of stack (USD/ kW)	270-450	400-870	690-2,000	>177

Source: Oxford Institute for Energy Studies, 2022, Peng, 2021

Alkaline electrolysers are the most techno-commercially viable technology. IEA estimates global electrolyser manufacturing capacity at 11 GW, where China and Europe account for more than 60% of this capacity. Predominantly, alkaline electrolysers account for most of this capacity followed by PEM. Conversations regarding solid oxide technology are still in nascent stages, given its ongoing development, and the actual technological parameters are expected to undergo changes. Conversations regarding solid oxide technology are still in nascent stages, given its ongoing development, and the actual technological parameters are expected to undergo changes.

As discussed above, renewable power accounts for a significant portion of total cost of green hydrogen, thus reducing energy consumption to produce per unit of H2 can reduce costs significantly. SOEC uses the least amount of renewable power, while alkaline electrolysers use less power than PEM as it operates at high pressure, sometimes above 80 bar which avoids the challenge of handling high pressure oxygen.

Response time of electrolysers is one of the most critical performance parameters due to the variable nature of renewable power. Electrolysers should have the ability to respond to intermittent supply of power. Alkaline electrolysers have been used traditionally as they have been using grid power but their ability to respond to renewable power is relatively poor. The system may require up to an hour to cold start, resulting in increased energy consumption and associated costs. Alternatively, it requires a temporary shutdown until a reliable and stable power supply is available to maintain an operable working range.This directly impacts the utilisation factor of the system and ultimately higher costs. There are already issues reported by green hydrogen producers for their alkaline electrolysers which had an operating range of 30-100% as promised by Chinese electrolyser suppliers. But as tested on ground, producers reported that actual working range is 50-100% which means until a sufficient supply of renewable power is not available to produce at least 50% of maximum output, electrolysers will not work. This has directly influenced the cost economics of their projects, which were already in a precarious state (Collins, 2023). PEM technologies are considered to be the most suitable to be used with intermittent renewable power as its response time is in seconds and can be cold-started within 15 minutes.

One of the main challenges preventing PEM becoming dominant technology is its reliance on rare metals and associated high costs. There have been several studies on finding replacements, but most of them have proven to be futile. Eliminating or reducing use of these metals shall be critical to help this technology become commercially viable.

Longer stack lifetime helps to avoid the cost of stack replacement, a notably expensive component incurring substantial costs. As PEM and SOE work at high temperatures and high pressure, durability of these technologies are also affected. On the other hand, alkaline electrolysers have a better stack lifetime.

Based on announcements on capacity expansion, new global capacity shall be mostly for alkaline and PEM (IHS Markit, 2023). Rystad estimates that India shall reach 8 GW capacity by 2025 based on announcements by Adani, Reliance-Stiesdal, Ohmium, H2e Power, L&T-HydrogenPro and John Cockerill and Greenko ZeroC. These manufacturers are working on all three technologies, alkaline, PEM and SOEC. (Gupta, 2022).

Policy and regulatory framework

Green Hydrogen Policy

The Ministry of Power issued the Green Hydrogen Policy in 2022 for procurement of renewable power to produce green hydrogen and green ammonia. Renewable power can be procured through DISCOMs or open access routes. Cost of power procured from DISCOMs shall not exceed tariff discovered in auction, wheeling charge and a margin approved by state regulator. Open access connectivity approval shall be provided within 15 days and monthly banking facility shall be available on power procured for green hydrogen production. Banking charge shall not exceed the difference of average renewable power procurement cost and monthly average clearing price in day-ahead market. ISTS charges shall also be 100% waived off for ISTS renewable projects for 25 years commissioned before 31 December 2030 and then it will be levied in a staggered manner (Joshi, 2023). This in contrast to other ISTS solar, wind and hydro projects where charges shall be levied after 2025. It was done keeping in mind that green hydrogen facilities and associated renewable plants shall take more years to become commercially viable.

National Green Hydrogen Mission

The mission proposed an implementation plan in two parts, phase I from 2023 to 2026 and phase II from 2027 to 2030. Several initiatives for creating demand through export markets and mandating use in industries, pilot projects for use in steel production, mobility sector and shipping industry, building green hydrogen hubs, support for infrastructure development and developing a framework for standards, R&D activities, public outreach and awareness programmes were announced.

The main highlight of the mission was the “SIGHT” programme which stands for Strategic Interventions for Green Hydrogen Transition. This programme has a total fund allocation of INR 175 billion. The programme was started with two key objectives to support green hydrogen production and building domestic capabilities for electrolyser manufacturing so as to reduce dependence on imports. Under this programme, MNRE announced subsidies for green hydrogen production and electrolyser manufacturing capacity in 2023 with total financial outlay of INR 130 billion and INR 44 billion respectively with an aim of subsiding 450,000 MT of green hydrogen production and building 1.5 GW of electrolyser manufacturing capacity. Consequently, SECI issued tenders for both the programmes in July 2023. Other details of the programme are as below:

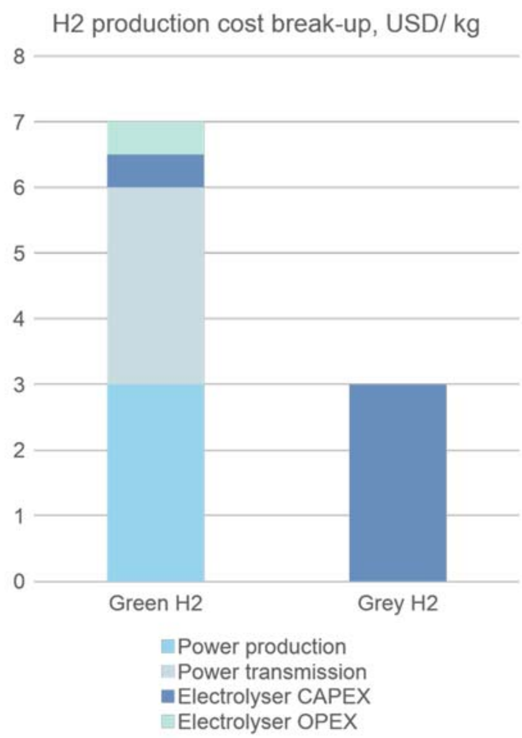
Subsidy for green hydrogen production

Under the program, a direct incentive in INR /kg of green hydrogen production will be provided for a period of 3 years. The incentives will have an upper limit of INR 50/ kg in the first production year, INR 40/ kg in the second year, and INR 30/ kg in the third year. Beneficiaries shall be selected through a competitive bidding process based on the least averaged incentives quoted by the bidder (SECI, 2023).

There are two buckets - tranche 1 (technology-agnostic pathway) has a total bidding capacity of 4,10,000 tons per annum and tranche 2 (biomass-based pathway) has a total capacity of 40,000 tons per annum. The maximum and minimum bid size was at 90,000 tons and 10,000 tons respectively in Tranche 1 and 4000 tons and 500 tons in Tranche 2. SECI shall be entitled to 0.5% of the disbursed incentive amount as administrative charges on an annual basis (SECI, 2023). This scheme will only subsidise 9% of the total 2030 target.

In terms of subsidy, the impact on total cost of green hydrogen production averaged out over 10 years (assuming minimum life of 10 years for a facility) shall be only USD 0.15/ kg which is miniscule in comparison to incentives available in US and EU (BRIDGE TO INDIA, 2023). The cost of green hydrogen is not expected to decrease to a level that would make it competitive with grey hydrogen. Assuming cost of renewable power production and transmission at USD 0.056/ kWh and power transmission cost at USD 0.11/ kWh and electrolyser CAPEX and OPEX at USD 1/ kg (Bridge to India, 2023). In order to be commercially viable, green hydrogen must be cost competitive with grey hydrogen which costs around USD 1.92-3.00/ kg, based on natural gas price of USD 9-12/ MMBTu (ICF, 2023).

Figure 2: Cost of green hydrogen and grey hydrogen, USD/ kg



Source: ICF, Bridge to India

The US has announced generous incentives on green hydrogen through the Inflation Reduction Act (IRA). There are multiple incentives available across the green hydrogen value chain which provides a total benefit of more than USD 3/ kg. There is a clean hydrogen credit which is a production tax credit (PTC) that is available for a 10 year period for facilities that will start construction by 31 Dec 2032. Entities can also choose investment tax credit (ITC) which is available up to 6% of the total capital cost for green hydrogen facilities. There are additional multipliers available if the producers shall meet certain conditions with respect to construction of the facility within a time period and meeting certain labour and wage conditions (EY, 2022). On the other hand, the EU provides a much more generous incentive of USD 4.78/ kg in the form of green hydrogen production credit for a 10 year period, through its Innovation Fund to launch the European Hydrogen Bank which has a total allocation of USD 3.18 billion.

A total of 14 companies submitted bids for setting up green hydrogen production facilities which included several renewable developers, existing green hydrogen consumers (refineries). Understandably, renewable developers are interested in transitioning to the green hydrogen business owing to their experience in renewable power, a key ingredient to green hydrogen. The list of participants include ACME Cleantech, Torrent Power, UPL Limited, GH4 India (joint venture of ReNew, L&T and Indian Oil), Aneeka Universal, Sembcorp Green Hydrogen, Greenko ZeroC, CESC Projects, JSW Energy, Welspun New Energy, Avaada GreenH2, Reliance Green Hydrogen and Green Chemicals Limited and HHP in bucket I and single bid from BPCL for bucket II. For bids invited for a total 450,000 MT production capacity, bids for 553,730 MT were received (Business Standard, 2023).

Subsidy for electrolyser manufacturing capacity

PLI scheme for electrolyser manufacturing with total allocation of INR 44 billion for five years of production. There are certain performance parameters and multipliers associated with it. A manufacturer falling in the highest category for local value addition and specific energy consumption shall be selected. Highest incentive of INR 4,440/ kW shall be available in year 1 and incentive shall taper down to INR 1,480/ KW by year 5 (Agarwal & Sharma, 2023). The PLI will support building 1.5 GW of manufacturing capacity which is 1.2% of electrolyser capacity that is required to be built to achieve the 2030 target.

In electrolyser manufacturing tender, total bids for 3.5 GW capacity were received from Hild Electric, Ohmium, John Cockerill, Waaree Energies, Jindal India, Adani New Industries, L&T Electrolysers, Avaada Electrolysers, Green H2 Network, Reliance Electrolyser manufacturing, Avadit Infratech, ACME Cleantech, Oriana Power, Matrix Gas and HHP Seven in bucket I and HomiHydrogen, BHEL, NewTrace, C.Doctor & Company, Partishna Energies and LiveHy Energies in bucket II (Business Standard, 2023).

Ohmium is the only manufacturer in the country with a domestic manufacturing capacity of 500 MW for PEM electrolysers and plans to expand its capacity to reach 2 GW. The company has already signed one of the biggest deals with NTPC to supply electrolysers for 400 MW project over two years until May 2025 (Hazarika, 2023). There are no other manufacturers in India.

Total incentive payout is expected to be only about 8% of the capital cost of electrolysers, resulting in a marginal reduction in the ultimate cost of green hydrogen at only USD 0.05/kWh. This reduction is too small to significantly stimulate demand. Additionally, when considering the 7.5% basic customs duty, the proposed subsidy lacks substantial efficacy in safeguarding against imports from China. (Bridge to India, 2023).

R&D support

National Hydrogen Mission allocated INR 15 billion for pilot projects and INR 4 billion (total USD 23 million) for R&D. There is a comprehensive R&D plan also issued which focuses on initiatives across the value chain (MNRE, 2023). Effective implementation of the plan and funding shall be critical for the growth of the green hydrogen sector. While the financial support provided by the US Department of Energy is double (USD 59 million) of support provided by the Indian government. Considering green hydrogen requires intensive R&D efforts and pilot and demonstration projects to make it cost competitive with conventional fuels, more incentive shall be required on R&D. Transportation and storage infrastructure is not available in the country and also requires an immense amount of research and development (US DOE, 2023).

GH2 standards

MNRE issued green hydrogen standards which provided much required clarity on definition of "green hydrogen". Similar standards have been already notified by other countries. In India, emissions from green hydrogen production must not exceed 2 kgCO2/ kg of H2 to be called green hydrogen. Standards exclude pre and post-production emissions and only include production related emissions (*India Announces Definition of Green Hydrogen*, n.d.). Standards set by the EU, Japan and US are much more stringent compared to Indian standards. As per EU standard, emissions must not exceed 3.4 kg CO2 but it includes emissions from the entire lifecycle including power generation until end use (*Delegated Regulation for a Minimum Threshold for GHG Savings of Recycled Carbon Fuels and Annex*, n.d.). The US emission threshold is relaxed at 4 kg CO2 but includes well to gate emissions. Incentives under Inflation Reduction Act are linked with emissions. Green hydrogen produced with an emission rate of 4 kg shall be only eligible for 25% of the incentive and for full credit, emission rate should be equal to or less than 0.45 kg CO2 (*DOE Announces $59 Million to Advance the National Clean Hydrogen Strategy*, n.d.). UK and Japan emission rates are 3.4 kg CO2 and 2.4 kg CO2 respectively for green hydrogen standard (Bridge to India, 2023). Divergence in green hydrogen standards worldwide is poised to present challenges.

Conclusion

Climate action and emission reduction are becoming one of the top priorities of nations and industries. Green hydrogen is a versatile fuel with use cases across a wide range of sectors and being considered by several industries to reduce emissions. The most established use case for green hydrogen is in refineries which is one of the key consumers of hydrogen. However, green hydrogen must be cost competitive to traditional fuel, in case of refineries grey hydrogen. Refining industry is already looking to build clean businesses and want to reduce their dependence on conventional fuels.

India is serious about the green hydrogen sector and has been prompt in taking steps to build the required policy and regulatory ecosystem. But the incentives provided shall be inadequate to provide a boost to the sector. The cost of green hydrogen is double of its grey counterpart and shall require more financial subsidies to reduce the gap.

Considering high costs of green hydrogen, it is anticipated that initially most of the green hydrogen produced quantum shall be exported due to high costs for the domestic market. Around 3.5 MT kg H2 per annum (70% of the targeted capacity) shall be exported to different countries. Plans to deploy required shipping infrastructure on the ports are already being made. Shipping Ministry is already developing infrastructure including storage and refuelling facilities on key ports of Kandla, Paradip and Tuticorin, which is expected to be completed by 2030 and similar infrastructure shall be developed on the remaining ports (India Shipping News, 2023).

Incentives available in the market shall not be able to provide the adequate support required to meet the 2030 target of 5 MMT green hydrogen production capacity.

Power production and transmission costs account for the highest chunk of the levelized cost of green hydrogen. Power transmission costs can be easily reduced by providing grid charge waivers. Renewable power supplied by DISCOMs are already at a premium over already high grid charge, and costlier than renewable power through open access. Round the clock renewable power is a much more expensive option than vanilla renewable power, but it is the only other route to ensure a firm and stable power supply. Incentives for energy storage technologies shall help to reduce the cost of round the clock power and simultaneously provide a boost to the storage market.

There is also a need for more incentives to build domestic manufacturing capacity for electrolysers. India is extremely dependent on China for solar PV modules which is a result of late action by the government to build a domestic ecosystem for module manufacturing. Later it was followed by stringent trade restrictions which directly affects solar capacity addition. It is important to ensure the same story is not repeated again with electrolysers and the green hydrogen market.

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