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Assessing the Impact of Green Hydrogen Production on India's Power System

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Executive Summary

Green hydrogen (GH2) is an essential component for the deep decarbonisation of the economy. India's *National Green Hydrogen Mission* targets the production of 5 million tonnes of GH2 per annum by 2030 to abate 50 million tonnes of greenhouse gas emissions, which is around 2 per cent of the energy sector emissions (National Green Hydrogen Mission 2022, MoEFCC 2023).

India's GH2 target will require a significant expansion of grid-connected renewable energy (RE), beyond the 500 gigawatts (GW) of non-fossil-based capacity target for 2030. Currently, over 80 per cent of RE capacity is concentrated in just six states.[1] However, the GH2 demand will be more dispersed, requiring the transmission of RE generation through the grid. This large-scale integration of RE will have implications for the electricity demand to be served, consumption patterns, transmission network planning, and power system operations.

We must answer the following key questions to plan for the emerging challenges and system needs: **What will be the most efficient and cost-effective approach to achieve the green hydrogen production target? What will be the optimal combination of RE resources and electrolysers? What will be the additional grid flexibility, transmission and storage requirements for integrating large-scale green hydrogen production?**

To answer these questions, we modelled India's power system for 2030 under different scenarios[2]:

1. **Business-as-Usual (BAU) scenario 2030:** This scenario assumes the 2030 electricity demand[3] as per the *20th Electric Power Survey Report* (Central Electricity Authority 2022), met with 500 GW of non-fossil-based capacity. We include measures such as thermal power plant flexibility, pumped storage hydro (PSH) and battery energy storage systems (BESS) to restrict the national RE curtailment to below five per cent.
2. **Green Hydrogen (GH2) scenario 2030:** This scenario estimates the additional electricity demand and RE capacity required for five million tonnes (MT) of GH2 production. Under this scenario, we model two possibilities:
    - **ISTS grid support to wheel RE power to other states for GH2 production (GH2 with ISTS support[4]):** Surplus RE power is utilised to meet the electricity demand. For GH2 production in non-windy states, wind power is wheeled from neighbouring wind-rich states. Additionally, the model allows surplus RE in other states, which would otherwise remain unutilised (curtailed), to be transmitted to states which can absorb the same for GH2 production.
    - **RE for GH2 production within a state (GH2 without ISTS support):** Surplus RE power[5] is not utilised to meet the demand.

Gujarat will contribute the highest share to GH2 production with 42 per cent of the national target catering to domestic (0.49 MT) and export demand (1.6 MT), followed by Tamil Nadu with 23 per cent (1.16 MT). Together, six states—Gujarat, Tamil Nadu, Maharashtra, Andhra Pradesh, Uttar Pradesh, and Odisha—will contribute around 90 per cent of the total GH2 production in 2030.

[1] The six states are Rajasthan, Gujarat, Tamil Nadu, Karnataka, Andhra Pradesh, Maharashtra.
[2] We modelled unit commitment dispatch simulation for 2030, limiting the RE curtailment to less than 5 per cent and unmet demand to less than 0.09 per cent.
[3] This does not consider GH2 demand, refer Box 1.0 in the Annexure 1 for details.
[4] ISTS stands for inter-state transmission system.
[5] Surplus RE power is that which is generated from RE resources (in GH2 scenario w/o ISTS support) which would have been curtailed if not utilised or absorbed.

A. Key Insights

Meeting the 2030 national green hydrogen production target with ISTS support will result in the following implications on power system planning and operations, relative to the BAU scenario:

1. National peak electricity requirement will increase by 67 GW

India will consume another 310 billion units (BU) of electricity to meet its 5 MT green hydrogen requirement by 2030. This will increase the peak electricity demand of the grid to 409 GW, up from 342 GW in the BAU scenario (CEA 2022).[6] More than 85 per cent of this 310 BU demand is likely to come from the states in the western and southern regions, namely, Gujarat, Madhya Pradesh, Maharashtra, Tamil Nadu, Andhra Pradesh, Karnataka, and Kerala, with a combined green hydrogen production capacity of 4.3 million tonnes by 2030.[7]

2. India will need to integrate 135 GW of additional RE capacity with the grid

This 310 BU of additional electricity requirement will be supplied by an additional 135 GW of RE capacity that would have to be integrated with the grid by 2030. This comprises 51 GW of solar and 84 GW of wind. Gujarat and Tamil Nadu will host 43 per cent and 24 per cent of the total incremental RE capacity.[8]

3. System will need to serve 74 GW of electrolyser capacity

The daily power requirement for an electrolyser will range from 45 GW to 74 GW.[9] Electrolysers can operate over a wide loading range and have good ramping capabilities, making them a valuable resource for grid flexibility.

4. Despite higher RE installed capacity, BESS requirement in the system will reduce by 6 GW

The required battery capacity will be 38 GW, down from 44 GW in the BAU scenario. This is because surplus renewable energy (27 BU) will be utilised for green hydrogen production instead of being stored or curtailed.

5. System flexibility requirement will quadruple between 2022 and 2030

The share of RE in the total generation mix will increase from 11 per cent in 2022 to 40 per cent in 2030, requiring nearly a fourfold increase in grid flexibility. The net load will need to ramp up/down at a faster rate to integrate this larger share of intermittent renewables.[10] This will increase the net load flexibility requirement from approx. 250 MW per minute to approx. 1,100 MW per minute for the top 10 per cent of hours.

6. Average cost of power generation will reduce by 2%

Increased contribution of cheaper RE sources to the generation mix will reduce the cost of power generation by 2 per cent to INR 3.76/kWh from INR 3.83/kWh in the BAU scenario. This will lead to savings of INR 18,800 crore (USD 2.3 billion[11]) to meet the GH2 demand.

7. INR 10.6 lakh crore (USD 129 billion) worth of investments will be required in the GH2 ecosystem

The deployment of 135 GW RE capacity will require a capital expenditure of INR 7.6 lakh crore (USD 92 billion), or 71 per cent of the total investment. Additionally, an electrolyser capacity of 74 GW will need an investment of INR 3.03 lakh crore (USD 37 billion), or 29 per cent of the total investment.

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[6] Observed on 7 June 2030 at 14:45 hrs in the BAU scenario, and on 5 June 2030 at 14:45 hrs in the GH2 scenario.

[7] Refineries are the primary hydrogen consumers in Gujarat, Tamil Nadu, Karnataka, and Kerala. In contrast, fertiliser production is a major hydrogen consumer in Maharashtra, Gujarat, Madhya Pradesh, and Andhra Pradesh.

[8] Gujarat and Tamil Nadu will require additional 58 GW and 33 GW of RE to meet 2 MT and 1.1 MT of GH2 demand.

[9] The CUF of the electrolyser is estimated to be 48 per cent.

[10] Net load is the resultant load after subtracting vRE (solar and wind) from the total demand.

[11] Exchange rate considered for all the conversions in this study is 82 INR/USD.

Table ES 1: National level dispatch for 2030 scenarios shows the positives of GH2 with ISTS support

Parameter	BAU scenario	GH2 scenario with ISTS support
RE capacity in GW (solar, wind)	425 (302, 123)	560 (353, 207)
RE share in generation (%)	33	40
NF capacity in GW (NF share in generation %)	518 (48)	653 (54)
LCOE[12] (INR/kWh)	3.83	3.76
Battery storage (GW)	44	38

Source: Authors' analysis

B. Impact of not utilising ISTS support on GH2 production

We modelled a second scenario that allows India to reach its GH2 target, but without leveraging the ISTS network and generating RE for producing GH2 within the same state. As one would expect, this led to suboptimal outcomes.

1. **Increased RE requirement:** The system will need 145 GW of additional RE, 10 GW more than in the scenario where ISTS support is available.
2. **Higher cost of hydrogen:** The levelised cost of hydrogen production will increase from USD 3.6/kg to USD 4.1/kg, leading to an additional cost of INR 20,500 crore (USD 2.5 billion).
3. **Increased battery storage requirement:** 3 GW of additional BESS will be required.
4. **Reduced electrolyser capacity:** This will reduce fall from 74 GW to 65 GW. Despite this reduction, the cost of GH2 production will increase.[13]
5. **Additional RE capacity will be needed for Punjab, Uttar Pradesh, and Haryana:** These states will need 5.3 GW of additional in-house RE capacity to produce the required GH2.

C. Recommendations

India should leverage its extensive electricity grid to achieve its green hydrogen production targets cost-effectively. Based on our findings, we recommend the following planning, regulatory, and policy measures.

1. Identify green hydrogen production hubs to guide national and state transmission planning

The activities under the *National Green Hydrogen Mission* should identify GH2 hubs in specific regions based on factors like RE potential, water availability, and land use for large-scale production and use of hydrogen. The Central Electricity Authority (CEA) must utilise this information to guide planning for intra and inter-state transmission networks. The Government of India must collaborate with states to develop transmission plans and consider expanding the *Intra-State Transmission System Green Energy Corridor* (InSTS GEC) schemes to other beneficiary states to attract investments. [14]

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[12] LCOE stands for levelized cost of electricity.

[13] Higher electrolyser requirement will be seen despite ISTS support because electrolysers will maximise their utilisation when free surplus RE (mostly solar) power is available for GH2 production.

[14] InSTS GEC-I and GEC-II schemes provided grants to Andhra Pradesh, Gujarat, Himachal Pradesh, Karnataka, Madhya Pradesh, Maharashtra, Rajasthan, Tamil Nadu, Kerala, and Uttar Pradesh.

2. Recognise electrolysers as a flexible resource under the Central Electricity Regulatory Commission (CERC) Ancillary Services Regulation, 2022

India will require 135 GW of additional vRE by 2030 to achieve its green hydrogen target. This will take India's total installed vRE capacity to 560 GW in 2030, implying high flexibility needs in the system. Electrolysers, with their higher ramping rates and wider load range, can provide flexibility and support grid balancing.[15] The CERC should recognise electrolysers as an eligible resource and set appropriate compensation norms to encourage their use for grid balancing.

3. Develop grid connectivity standards for electrolysers

Our study indicates that electrolyser capacity will increase to 74 GW by 2030. These capacities must adhere to robust technical standards to maintain grid safety and reliability. Hence, the CEA must introduce grid connectivity standards for electrolysers through an amendment to the *CEA (Technical Standards for Connectivity to the Grid) Regulations, 2007* (CEA 2020).

4. Facilitate the establishment of an industry-led consortium to pilot large-scale grid-connected GH2 projects

India's GH2 target can be achieved more cost-effectively under the GH2 scenario with ISTS support, saving INR 20,500 crores (USD 2.5 billion). However, at this nascent stage, developers are wary of the challenges, risks and uncertainties associated with large-scale GH2 projects. More importantly, offtake prospects for GH2 are uncertain, in absence of the developers' ability to guarantee a selling price. The *National Green Hydrogen Mission* should facilitate and support the creation of an industry-led consortium to address these issues. Such a consortium should establish a 'Green Hydrogen Development Fund' to finance multiple pilot demonstration projects in different sectors and geographies to de-risk investments and identify price ranges at which GH2 can be offered to potential buyers.[16] This fund could be capitalised by member industries, development finance institutions, and grants sanctioned under the *SIGHT programme*, among other appropriate sources. The experience and knowledge gained through the deployment of these projects should be shared through data publication on project planning, deployment, and performance. This will build confidence in the sector and expedite the development of green hydrogen projects.

[15] Load range of electrolysers can vary between 15% and 100%, and ramp rates could fall between 0.2% and 20% per second.
[16] The challenges of GH2 projects are sector and geography-specific.

1. Introduction

Image: iStock

India's commitment to a low-carbon pathway is reflected in its updated Nationally Determined Contributions (NDCs), which aim for a 45 per cent reduction in GDP emission intensity by 2030. Green hydrogen, produced using renewable energy, can play a crucial role in decarbonising the Indian economy and reducing dependence on imported hydrocarbon fuels. The country's target of 500 GW of non-fossil-fuel capacity by 2030 provides a strong foundation for building green hydrogen capacity.

India's *National Green Hydrogen Mission* aims to produce five million tonnes of GH2 annually by 2030. To achieve this, India will need to significantly expand its renewable energy capacity. The country produces and consumes around 5.6 MT of hydrogen annually in three sectors—fertilisers, refineries, and methanol (CEEW 2024). Green hydrogen will be produced in various regions, including states with port facilities, to meet both domestic demand and export targets. As of December 2022, over 80 per cent of RE capacity is concentrated in just six states—Gujarat, Tamil Nadu, Maharashtra, Andhra Pradesh, Uttar Pradesh, and Odisha. This means that GH2 production in regions with lower renewable energy potential or installed capacities will require the transmission of green power through the grid. The intermittent nature of renewable energy will introduce uncertainties in demand and supply, necessitating a thorough analysis of the implications on the power system and requirements for a successful transition.

Objectives of the study

Large-scale green hydrogen production necessitates the integration of hundreds of gigawatts of electrolysers and renewable energy into the grid. This study aims to understand the temporal and spatial variations in the required renewable energy resource mix, and its impact on power system operations. We have assessed the power system operation for a green hydrogen scenario (power system operation with additional RE to meet the GH2 load) and a business-as-usual scenario (power system operation in 2030 without green hydrogen load) to address the following questions:

1. What would be the most cost-effective pathway to meet the GH2 production target?
2. What would be the optimal generation mix of RE sources?
3. Would the system costs increase or decrease?
4. What would be the storage requirements for managing intermittent renewables?
5. Could the surplus RE power (in the BAU scenario) be used to produce green hydrogen?
6. Would the thermal fleet need to demonstrate higher levels of flexibility?
7. Would the existing transmission infrastructure be enough to meet the green hydrogen load?
8. How much investment would India need?

2. Approach and methodology

This study assesses how power system operations will change with the additional electricity demand and altered supply mix due to green hydrogen production. By using a sub-hourly and disaggregated national-level power system production cost optimisation model, we aim to provide informed strategies for meeting electricity demand reliably and cost-effectively.

2.1. Methodology adopted

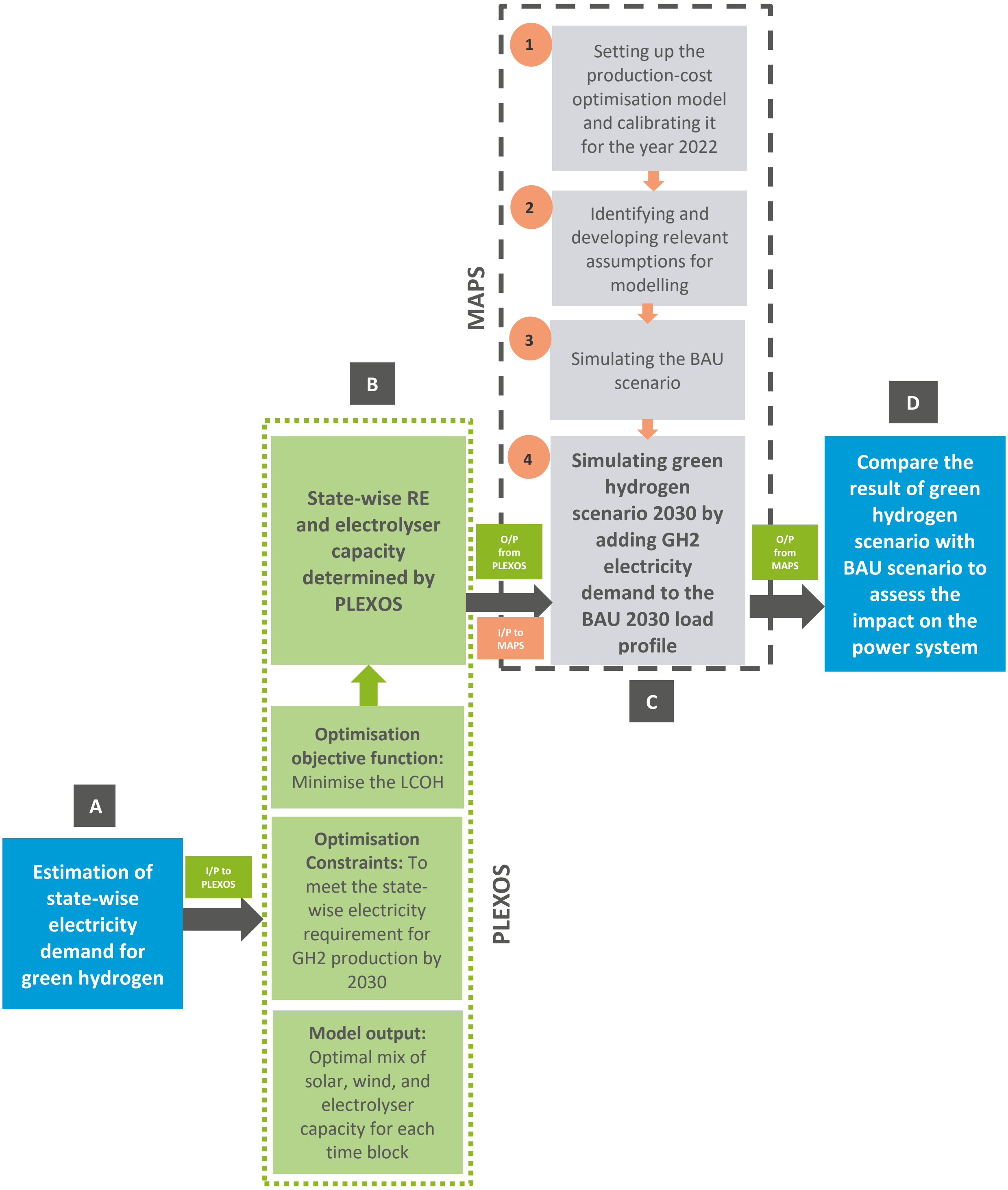
To assess the impact of green hydrogen electricity demand on power system operation, we have modelled two scenarios:

1. **Business-as-Usual (BAU) scenario 2030:** This assumes the electricity demand for 2030 will be as projected in the CEA's 20th Electric Power Survey report (CEA 2022), without considering additional demand for green hydrogen production. The supply side will include coal, nuclear, solar, wind, hydro and pump storage capacity additions and retirements as outlined in *National Electricity Plan, 2022* (CEA 2023), and CEA reports.
2. **Green Hydrogen (GH2) scenario 2030:** The green hydrogen scenario considers the additional electricity demand and RE capacity required to achieve the five million tonnes of GH2 production beyond the BAU scenario electricity demand projection.
    - **ISTS grid support to wheel RE power to other states for H2 production (GH2 with ISTS support:** Surplus RE power is utilised for green hydrogen production.
    - **RE for GH2 production within a state (GH2 without ISTS support):** Surplus RE power is not utilised for green hydrogen production.[17]

Our stepwise methodology for this study is depicted in Figure 1. First, we estimate the state-wise green hydrogen electricity demand (Step A) in 2030 to meet the five million tonne production target. This demand is used as input to PLEXOS[18] to determine the state-wise optimal mix of solar, wind, and electrolyser capacity to minimize the LCOH[19] (Step B). Next, we simulate the power system operation for GH2 scenario 2030 in MAPS[20] using the RE and electrolyser capacity determined in the previous step (Step C).[21] Finally, we compare the outputs of the BAU and GH2 scenarios to assess the impact on the power system.

[17] Surplus RE power is that generated from resources which would have been otherwise curtailed, if not utilised or absorbed.
[18] Refer to Annexure 3(E) for details on PLEXOS.
[19] LCOH stands for levelised cost of hydrogen.
[20] Refer to Annexure 1 for details on the MAPS.
[21] Stepwise approach in MAPS is depicted in the figure below. Annexure 1 provides details about these steps.

Figure 1: **Methodology to simulate India's power system with green hydrogen demand**



Source: Authors' analysis

In this study, we assume a Market-Based Economic Dispatch (MBED) approach, where the power generation is scheduled based on market prices to ensure the cheapest resources meet electricity demand in both the BAU and green hydrogen scenarios. We consider a unit cost commitment model without variable cost for RE, and inter and intra-state charges and losses for power transmission.

2.2. Approach to estimate state-wise green hydrogen production

The 2030 target for green hydrogen production of five million tonnes per annum (MTPA) is divided into domestic (30 per cent) and export (70 per cent) markets (Anand 2023). State-wise domestic green hydrogen production is projected based on the 2020 share of grey hydrogen production.[22] The remaining 3.5 million tonnes will cater to the export market, primarily Japan, South Korea, and the European Union (NITI Aayog 2022). Six port states—Gujarat, Tamil Nadu, Maharashtra, Odisha, Andhra Pradesh, and Kerala—are likely to produce green hydrogen for export. Based on policy and project announcements, each state's share of export demand has been estimated.[23]

2.3. Approach for estimating the green hydrogen scenario load profile

We scale up the block-wise (15-minute) load profile for each state in 2022 to project the 2030 load profile. The annual energy requirement and peak electricity demand for each state are taken from the 20th Electric Power Survey report to project the 2030 BAU scenario load profile without hydrogen electricity demand. We assume that the green hydrogen load profile will follow the renewable energy generation profile. The optimal solar, wind, and electrolyser capacity requirements to meet the states' green hydrogen electricity demand are obtained using an optimisation tool—PLEXOS.[24] Solar energy requirements are considered to be met through intra-state renewable energy resources in all states. However, the wind energy requirement is considered to be met through intra-state renewable energy resources for windy states, and from neighbouring windy states.[25] The load profile for the 2030 GH2 scenario is obtained by adding the green hydrogen profile to the states' BAU scenario load profile.

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[22] Refer to Annexure 3 for methodology to estimate the state-wise GH2 production capacities to meet domestic demand

[23] Refer to Annexure 3 for methodology to estimate the state-wise GH2 production capacities to meet export demand.

[24] Refer to Annexure 3(E) for details on PLEXOS.

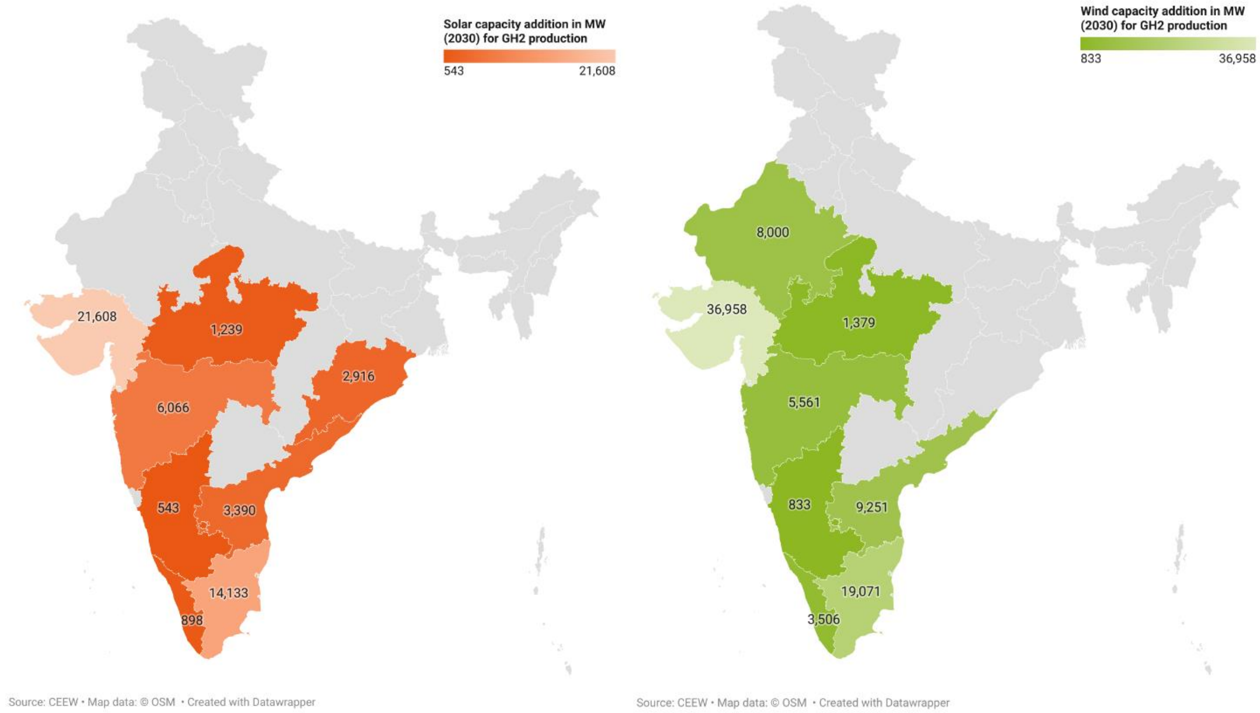
[25] To meet the wind energy requirement of Haryana (a non-windy state), the wind generation profile of Rajasthan is considered (Refer Annexure 3, Table A8).

3. Key findings

3.1. India will need 135 GW of additional grid-connected RE capacity to produce 5 MT green hydrogen by 2030

We assess that India will require additional 135 GW of RE capacity[26] (84 GW wind and 51 GW solar) to produce 310 BU[27] of green hydrogen electricity.[28] Over two-fifths of this capacity (59 GW) will be located in Gujarat, followed by Tamil Nadu with 34 GW.[29] Together, these five states—Gujarat, Tamil Nadu, Andhra Pradesh, Maharashtra, and Rajasthan—will need to host over 90 per cent of the total renewable energy capacity required for green hydrogen production in 2030.

Figure 2: Gujarat requires an additional 59 GW of RE capacity to serve the green hydrogen load



Source: Authors' analysis

The Figure 3 shows the installed capacity and generation mix across various scenarios. In the BAU scenario, 843 GW of total installed capacity will meet 2,377 BU of demand[30] with RE capacity of 425 GW and non-fossil fuel-based capacity of 518 GW. In the GH2 scenario, 972 GW of installed capacity will meet 2,687 BU[31] demand with RE capacity of 560 GW and non-fossil-fuel-based capacity of 653 GW. This shows that RE and non-fossil-fuel-based generation contributions will increase from 33 per cent and 49 per cent in the BAU scenario to 41 per cent and 55 per cent in the GH2 scenario.

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[26] Capacity utilisation factors (CUFs) of 20 per cent for solar and 30 per cent for wind are considered due to technological advancement for new plants to be installed in this decade.

[27] Producing 5 MT GH2 will require 310 BU of electricity —Refer Annexure 3(C) for details.

[28] 'Green hydrogen scenario' means green hydrogen scenario with ISTS support, unless otherwise mentioned.

[29] Gujarat will have the highest share in GH2 production with 42 per cent of the national production capacity (0.49 MT domestic demand and 1.6 MT export demand), followed by Tamil Nadu with 23 per cent (0.09 MT domestic industrial demand and 1.07 MT export demand)—Refer Annexure 3 for details.

[30] 2,377 BU of demand as per EPS projection for 2030, with 1.9 BU unmet demand in BAU scenario.

[31] 2,687 BU of demand as per EPS projection for 2030, with 2.3 BU unmet demand in GH2 scenario.

Figure 3: RE share in the capacity and generation mix increases from 50% and 33% in the BAU scenario to 58% and 40% in the GH2 scenario

Source: Authors' analysis

3.2. India should meet GH2 target in a cost-effective way with large-scale grid-connected projects

We have modelled the GH2 scenario 2030 in two modes: a) **RE for H2 production within a state (GH2 without ISTS support)**, where surplus RE power is not used for green hydrogen production, and b) **ISTS grid support to wheel RE power to other states for H2 production (GH2 with ISTS support)**, where surplus RE power is used for green hydrogen production, subject to transmission availability.

We assess that the renewable energy requirement (solar) will decrease by 10 GW in the GH2 scenario with ISTS support. Additionally, battery storage requirements will also reduce by 3 GW in the GH2 scenario with ISTS support. This will result in a 12 per cent decrease in the levelised cost of hydrogen (LCOH) from USD 4.1/kg to USD 3.6/kg, saving INR 20,500 crore (USD 2.5 billion) in producing five million tonnes of green hydrogen.[32]

Table 1: LCOH and BESS requirement reduce by USD 0.5/kg and 3 GW respectively in the GH2 scenario with ISTS support

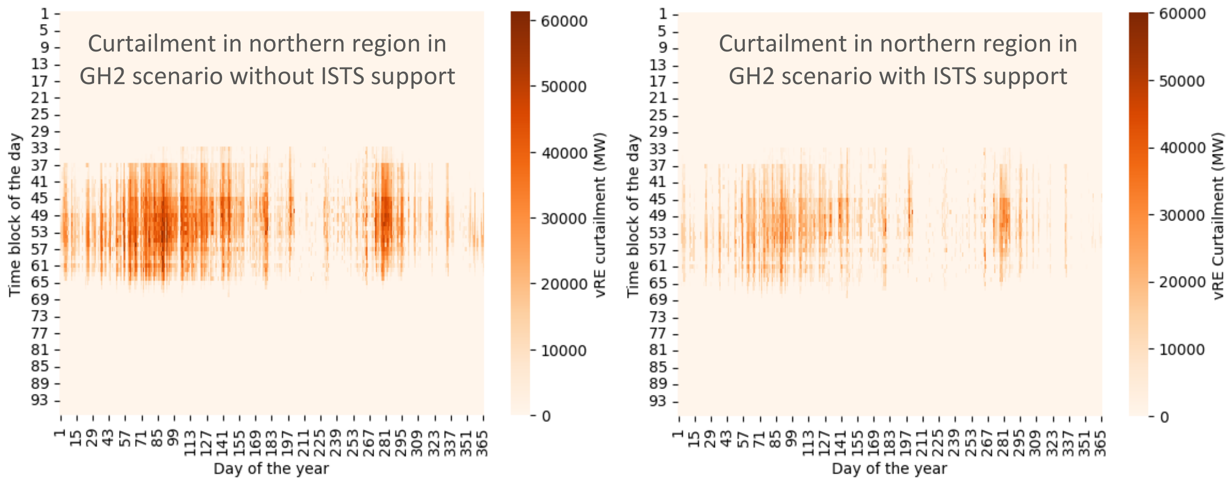
Parameter	GH2 with ISTS support	GH2 without ISTS support
Solar capacity (GW)	51	61
Wind capacity (GW)	84	84
vRE capacity (GW)	135	145
BESS capacity (GW)	38	41
LCOH (USD/kg)	3.6	4.1
Cost savings for GH2 generation in grid-support mode	INR 20,500 crore (USD 2.5 billion)	

Source: Authors' analysis

Figure 4 shows that curtailment in the northern India will be primarily observed during the solar hours. In the GH2 with ISTS support mode, this surplus solar power (around 22 BU)[33] in the northern region will be used to meet the green hydrogen electricity demand of Uttar Pradesh (UP), Punjab (PB) and Haryana (HR). This eliminates the need for additional RE capacity in these states, reducing the solar capacity requirement to 51 from 61 GW in the GH2 scenario with ISTS support.

[32] Saving of 0.5 USD/kg in grid-support mode for 5 MT GH2 production results in overall saving of INR 20,500 crore.
[33] Northern region observes 70 BU curtailment in GH2 scenario without ISTS support against only 48 BU in GH2 scenario with ISTS support.

Figure 4: **Solar curtailment absorbed in GH2 scenario with ISTS support reduces solar capacity requirement in northern region**



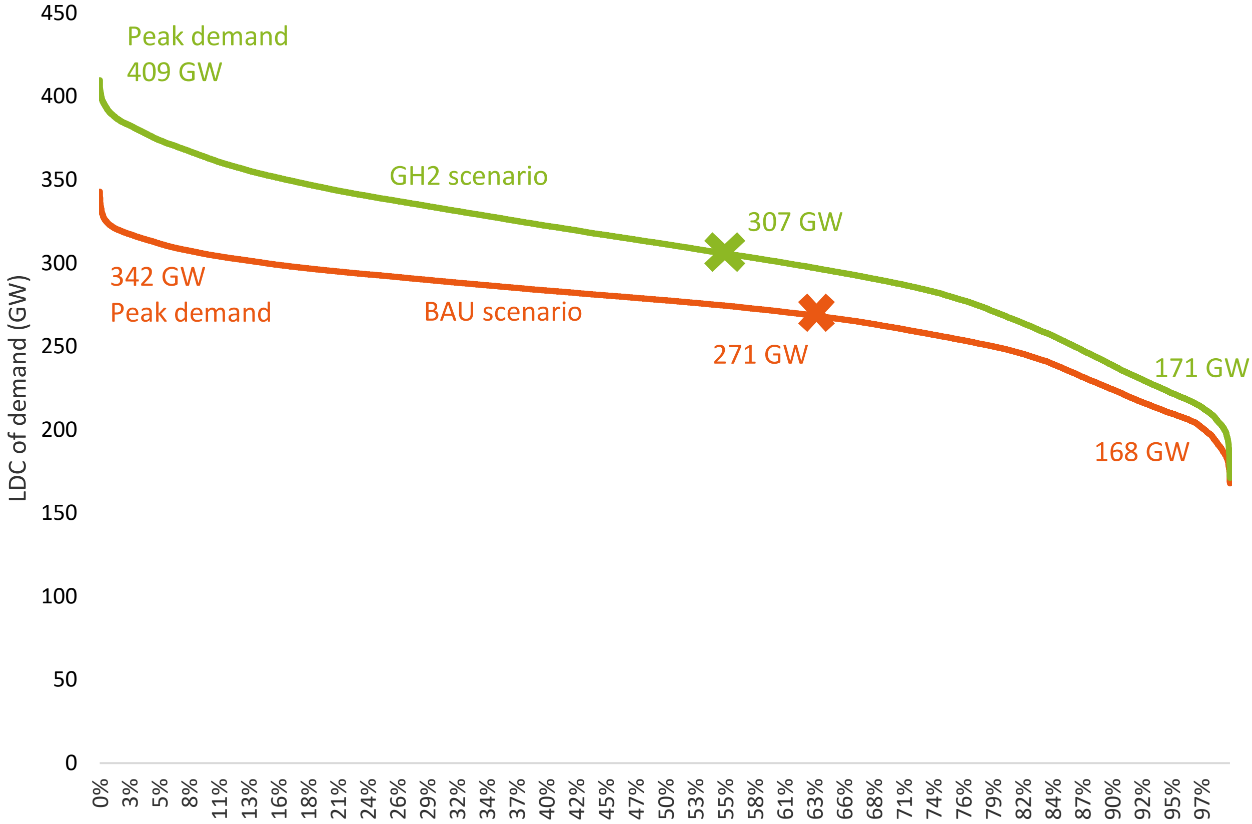
Source: Authors' analysis

3.3. India's peak demand will increase by 67 GW to serve the green hydrogen load in 2030

India's peak demand will increase by 67 GW, from 342 GW in the BAU scenario to 409 GW in the GH2 scenario. The peak demand will be observed in the same period in both scenarios.[34] Coal's contribution to the peak demand will decrease by 8 per cent (from 118 GW to 108 GW) in the GH2 scenario, which will be offset by the increased RE generation of 8 per cent (from 206 GW to 276 GW).

[34] Peak demand on 7 June 2030 at 14:45 hrs in BAU scenario, and on 5 June 2030 at 14:45 hrs in GH2 scenario.

Figure 5: **Peak demand increases to 409 GW to meet the green hydrogen load**



Source: Authors' analysis

Electrolyser load contributes 17 per cent (69 GW) to the peak demand.[35] To meet 310 BU of annual green hydrogen electricity demand, the maximum daily power requirement for an electrolyser will range from 45 GW to 74 GW. The electrolyser load will vary from 6 to 18 per cent (with an average of 11 per cent) of the total electricity demand. The daily electricity requirement for green hydrogen production will vary from 0.37 BU to 1.48 BU, adding to the total grid requirement of 5.3 BU to 8.8 BU (with hydrogen load).[36]

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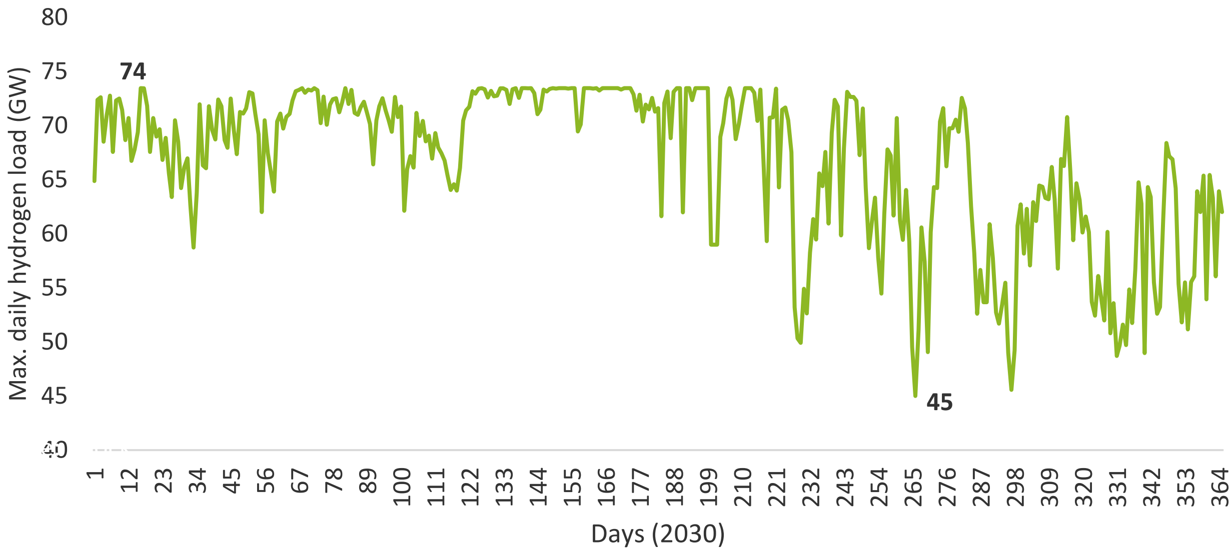
[35] Electrolyser load is also termed as hydrogen load.
[36] This study assumes electrolyser load profile follows RE generation profile.

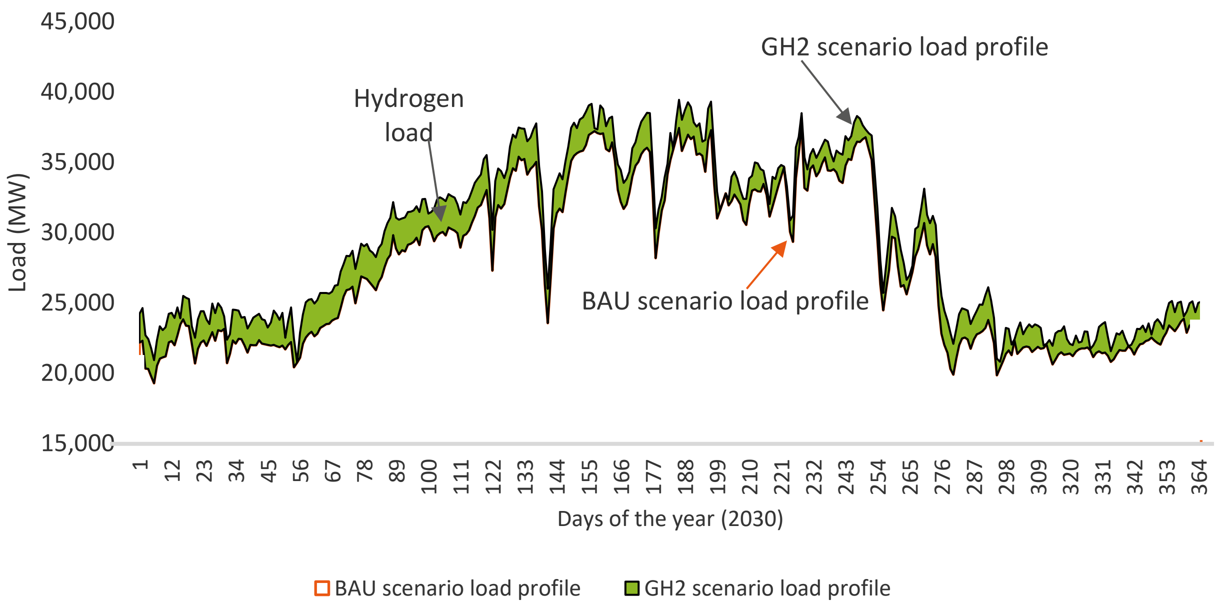
Figure 6: **Maximum daily power requirement for electrolyser varies significantly across the year**



Source: Authors' analysis

In Uttar Pradesh, the daily average load varies from 19 GW to 37 GW in the BAU scenario. With the addition of the hydrogen load, the demand increases up to 3 GW. Figure 7 illustrates the load profiles for both scenarios, demonstrating the 3 GW demand increase caused by green hydrogen production.

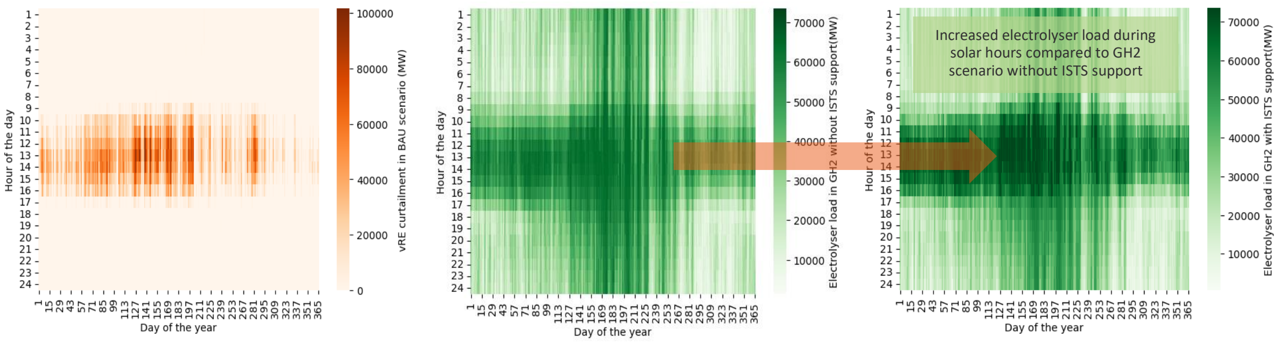
Figure 7: **Daily average load increases up to 3 GW in Uttar Pradesh to meet the GH2 demand**



Source: Authors' analysis

The electrolyser capacity requirement will increase from 65 GW in the GH2 scenario without ISTS support to 74 GW in the GH2 scenario with ISTS support, a difference of 9 GW. This increase shall occur because electrolysers will maximise their utilisation when free surplus RE (mostly solar) power is available for green hydrogen production (Figure 8).[37] This will lead to the overall reduction in utilisation from 55 per cent to 48 per cent in the GH2 scenario with ISTS support.

Figure 8: Electrolyser load increases with the absorption of surplus RE in the GH2 scenario with ISTS support



vRE curtailment (MW)
BAU scenario

Electrolyser load (MW)
GH2 scenario without ISTS support

Electrolyser load (MW)
GH2 scenario with ISTS support

Source: Authors' analysis

3.4. Green hydrogen scenario with ISTS support leads to a 5 per cent reduction in curtailment and a 6 GW reduction in storage requirements compared to BAU scenario

In the GH2 scenario, renewable energy curtailment decreases by 5 percentage points—from 12.6 per cent to 7.9 per cent—compared to the BAU scenario, even with the addition of 135 GW of renewable energy capacity. This reduction in curtailment will be due to absorption of RE at the national level[38] to meet green hydrogen demand, thus, leading to a 6 GW decrease in battery storage requirements from 44 GW to 38 GW.[39]

Out of this 6 GW BESS reduction, 3 GW will be due to 27 BU of surplus RE being absorbed with the ISTS support when compared to without ISTS support. More than 80 per cent (22 BU) surplus RE will be absorbed in the northern region, which will eliminate the need for additional RE capacity in Punjab, Haryana, and Uttar Pradesh to meet the green hydrogen demand.

Table 2: 27 BU of surplus vRE is absorbed for GH2 production in the GH2 with ISTS support mode

All India level	BAU Scenario	GH2 scenario without ISTS support (145 GW)	GH2 scenario with ISTS support (135 GW)
vRE generation (BU)	817	1,144	1,128
Without BESS deployment			
vRE curtailment (BU)	103	**117**	**90**
vRE curtailment (%)	12.6	10.2	7.9
With BESS deployment			

37 Surplus RE power is considered a free resource in the model.

38 Difference in curtailment in GH2 scenarios (without and with ISTS support) before BESS deployment (117 BU – 90 BU = 27 BU).

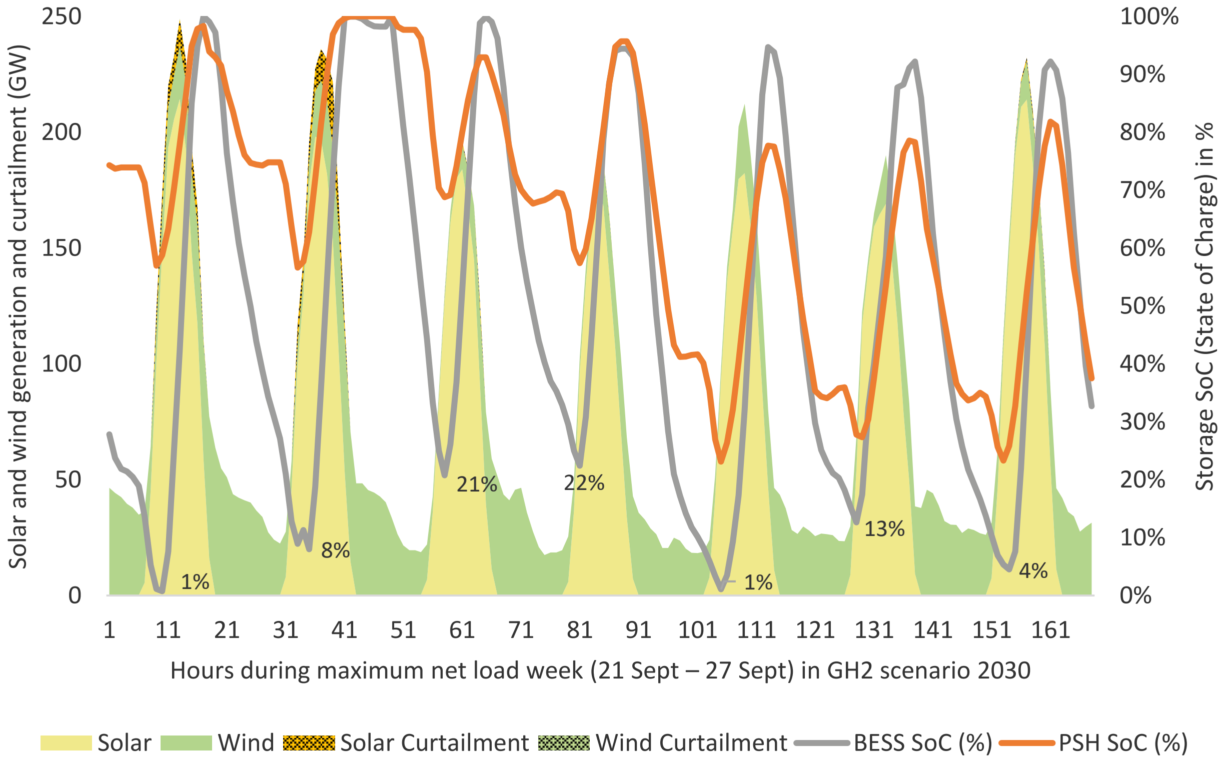
39 Keeping the vRE curtailment below 5 per cent.

All India level	BAU Scenario	GH2 scenario without ISTS support (145 GW)	GH2 scenario with ISTS support (135 GW)
Battery storage (GW)	44	41	38
vRE curtailment (BU)	35	55	35
vRE curtailment (%)	4.3	4.8	3.1

Source: Authors' analysis

Battery storage will absorb surplus RE produced during the day to meet demand during non-solar hours. Figure 9 shows the operation of battery storage. This will discharge twice a day, during night hours (between midnight and 8:00 a.m.) and during evening hours (between 5 p.m. and 11:45 p.m.). Charging occurs during solar hours (between 8 a.m. and 5 p.m.). Pumped hydro storage, suitable for longer durations, discharges less than battery storage during day-to-day operations.

Figure 9: Diurnal discharge operation of BESS during maximum net load week in 2030



Source: Authors' analysis

3.5. Grid flexibility requirements increase fourfold in green hydrogen scenario 2030 compared to 2022

The total installed vRE capacity will increase to 560 GW in 2030 to meet the green hydrogen load. This will increase the RE penetration from 11 per cent in 2022 to 40 per cent in the GH2 scenario and 33 per cent in the BAU scenario 2030.

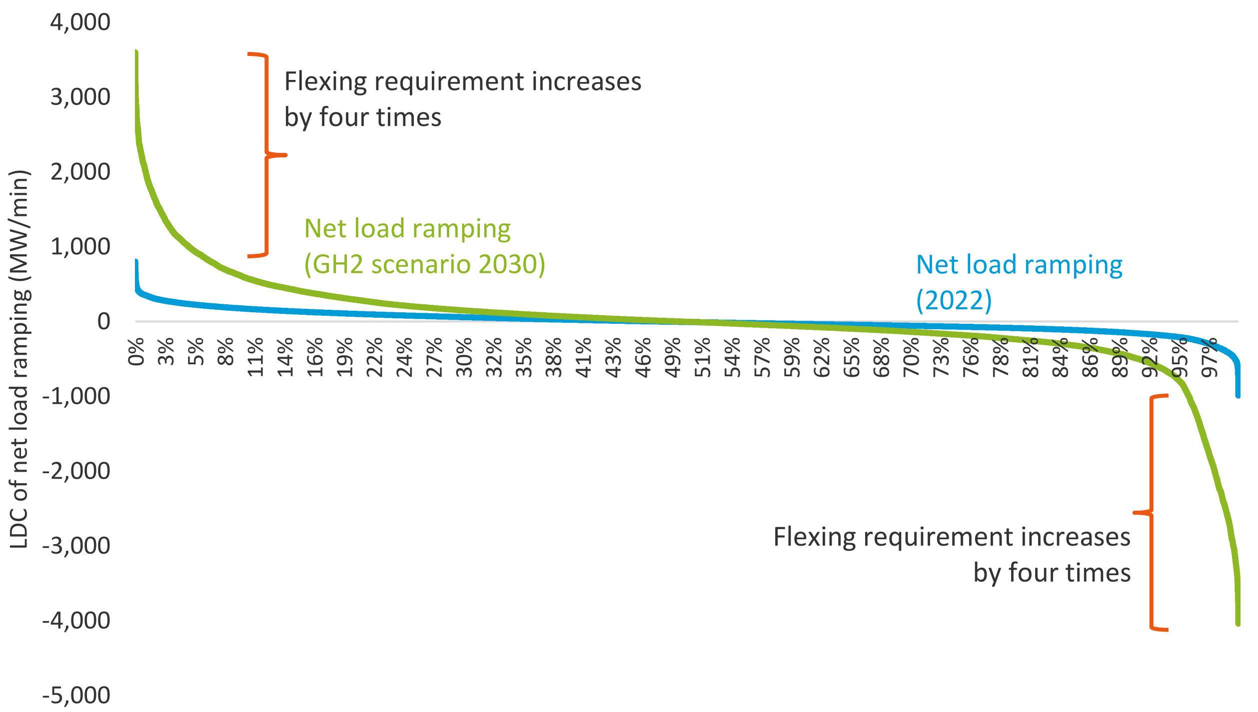
Table 3: **Increasing penetration of RE in the BAU and GH2 scenarios 2030 compared to 2022**

Parameter	2022	BAU scenario 2030	GH2 scenario 2030
Non-fossil contribution to total generation (%)	27	4	54
Solar and wind contribution to total generation (%)	11	33	40
Daily vRE share contribution (% of total load)	5–18	18–48	22–59

Source: Authors' analysis

This higher RE penetration will require nearly a fourfold increase in grid flexibility in 2030 compared to 2022 (Figure 10).

Figure 10: **Net load ramping requirement increases fourfold in GH2 scenario 2030 vis-a-vis 2022**



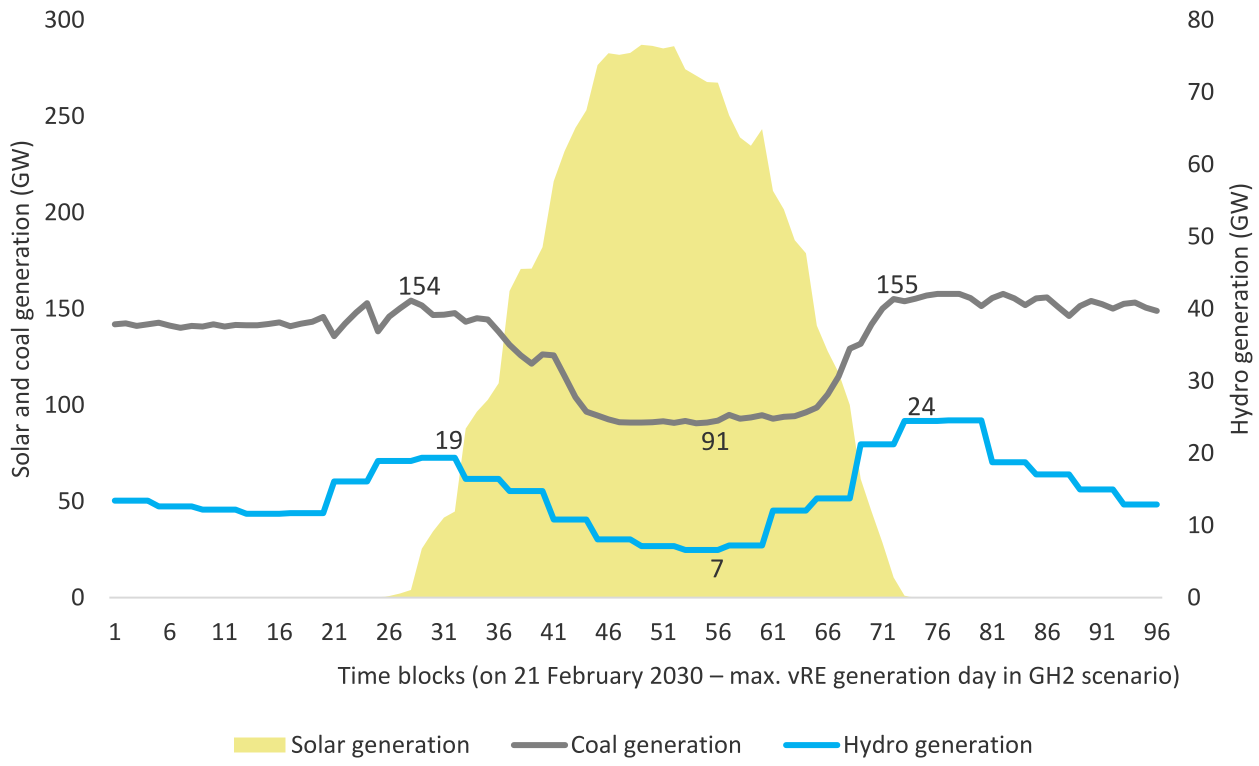
Source: Authors' analysis

Grid flexibility requirements will increase significantly on certain days in 2030. On the day with maximum vRE generation[40], RE will contribute up to 66 per cent of generation, leading to steeper flexibility needs. Coal and hydro resources will meet these flexibility requirements. Coal plants must ramp down from 154 GW to 91 GW in about five hours during the solar hours, and then ramp up from 99 GW to 155 GW in two hours to

[40] In GH2 scenario, maximum vRE generation day is observed on 21 February 2030.

offset the decline in solar generation in the evening hours.[41] Hydro capacity will ramp down from 19 GW to 7 GW in four hours (during solar hours) and then ramp up from 7 GW to 24 GW in three hours in the evening. This flexibility of coal and hydro will enable smooth integration of variable solar generation.

Figure 11: Flexibility requirements on maximum vRE generation day are provided by coal and hydro plants



Source: Authors' analysis

In addition to coal and hydro resources, electrolysers can provide grid flexibility in 2030. They offer higher ramping rates, lower start-up time, and a wider load range, making them a suitable resource for grid flexibility (IRENA 2018).

Table 4: Higher ramping rates and lower start-up time make electrolysers a better choice to meet flexibility needs

Parameter	Alkaline electrolyser	PEM electrolyser
Load range	15-100% of nominal load	0-160% of nominal load
Start-up time	1-10 minutes	1 - 5 seconds
Ramp up/down rate	0.2–20% per second	100% per second

Source: Data from Hydrogen from renewable power 2018, IRENA

Our analysis shows no significant changes in source-wise ramping requirements between the GH2 scenario and the BAU scenario 2030.[42] The maximum ramp-up requirement remains in the range of 2,500-2,900

[41] Solar generation starts at 0600 hrs, reaches its peak of 287 GW at 1200 hrs, and drops to zero at 1815 hrs.

[42] The flexibility requirements will change if the hydrogen load profile is considered differently. In this analysis, we assumed the green hydrogen load profile follows the RE generation profile.

MW/min for both scenarios. Although Table 5 shows similar ramp-up and ramp-down requirements for coal, gas, and hydro sources in both scenarios, grid flexibility needs in 2030 will increase significantly compared to 2022. Therefore, leveraging electrolyser capacity to meet these grid flexibility needs will be crucial to managing grid operations.

Table 5: Ramping requirements do not change significantly in the GH2 scenario

Ramping source	BAU scenario and GH2 scenario Maximum ramp up/down rate (MW/min)
Net load	2,500-2,900
Coal	1,200-1,400
Hydro	500-700
Gas	130-150

Source: Authors' analysis

3.6. Increased cheaper RE penetration in green hydrogen scenario will lead to 2 per cent reduction in system cost compared to BAU scenario

The GH2 scenario will lead to a 2 per cent reduction in system cost or levelised cost of electricity (LCOE) from INR 3.83/kWh to INR 3.76/kWh. This is due to the increased contribution of cheaper renewable energy sources to the total generation mix. This will lead to a savings of INR 18,800 crore (USD 2.3 billion) to meet the GH2 demand.

Table 6: System cost reduces by 2% in the GH2 scenario due to increase in the share of cheaper RE sources

Source	Source-wise LCOE (INR/kWh)	LCOE (INR/kWh)	
		BAU scenario	GH2 scenario with ISTS support
Solar	2.44	3.83	3.76
Wind	3.70		
Nuclear	3.53		
Coal	4.43		
Hydro	2.98		
Bio	6.18		
Gas	8.44		
BESS	3.84		
PSH	4.60		

Source: LCOE for solar, wind and BESS is as per authors' analysis. LCOE for nuclear, coal, hydro is as per CEA's rate of sale of power for year 2022-23. Biomass LCOE is as per Karnataka's generic tender. Gas LCOE is as per the Merit India portal, and the LCOE for PSH is as per ICRA's 2023 hydro power report.

Note: LCOEs in the BAU and GH2 scenarios are calculated based on source-wise generation and CUFs.

3.7. Congestion will increase by 2 per cent of the hours in Uttar Pradesh, Punjab, and Haryana to meet the green hydrogen electricity demand

We observe an increase in congestion hours, i.e., around 2 per cent of total hours in a year in Uttar Pradesh, Punjab, and Haryana in the GH2 scenario compared to the BAU scenario. These are non-windy states and will import wind power from neighbouring windy states to meet their green hydrogen electricity demand. To reduce congestion in these states, we need to enhance transmission capability (ATC limits[43]) of both inter-state and intra-state networks. The government should collaborate with states to develop transmission plans and consider expanding InSTS GEC schemes beyond current beneficiary states[44] to attract investments in necessary infrastructure.

Table 7: **No further relaxation of state-wise ATC limits is needed in GH2 Scenario 2030, as only a slight increase is observed in congestion hours**

State	ATC as of 2022	ATC for 2030	ATC relax-ation	Congested hours		Congested hours (percentage of total hours)		Congestion hours compared to BAU scenario
				BAU Scena-rio*	GH2 scena-rio*	BAU scena-rio	GH2 scena-rio	
Rajasthan	7,000	7,100	100	1,381	158	16%	2%	↓
Uttar Pradesh	14,500	14,500	0	201	374	2%	4%	↑
Punjab	8,900	15,000	6,100	69	239	1%	3%	↑
Haryana	8,500	15,000	6,000	63	229	1%	3%	↑
Maharashtra	9,760	9,904	144	1,540	1,361	18%	16%	↓
Gujarat	12,450	12,450	0	122	172	1%	2%	
Madhya Pradesh	10,751	10,924	173	0	0	0%	0%	
Kerala	2,812	3,550	738	2,685	2,644	31%	30%	↓
Karnataka	3,500	3,500	0	1,508	964	17%	11%	↓
Andhra Pradesh	6,000	6,000	0	8	8	0%	0%	

[43] Available Transfer Capacity (ATC) limits determine the import capability of the states as published by the Grid controller of India in the monthly ATC inter-regional reports. The ATC limits for some states (PB, HR, KL, MP, MH, RJ) are relaxed to meet the BAU scenario demand (2,377 BU) and reduce the unserved energy. The cumulative ATC limits are increased by 14 per cent from 98,000 MW to 112,000 MW.

[44] InSTS GEC-I and GEC- II schemes provided grants to Andhra Pradesh, Gujarat, Himachal Pradesh, Karnataka, Madhya Pradesh, Maharashtra, Rajasthan, Tamil Nadu, Kerala and Uttar Pradesh.

Tamil Nadu	10,450	10,450	0	28	218	0%	2%
Odisha	3,743	3,743	0	0	2	0%	0%

Legend:

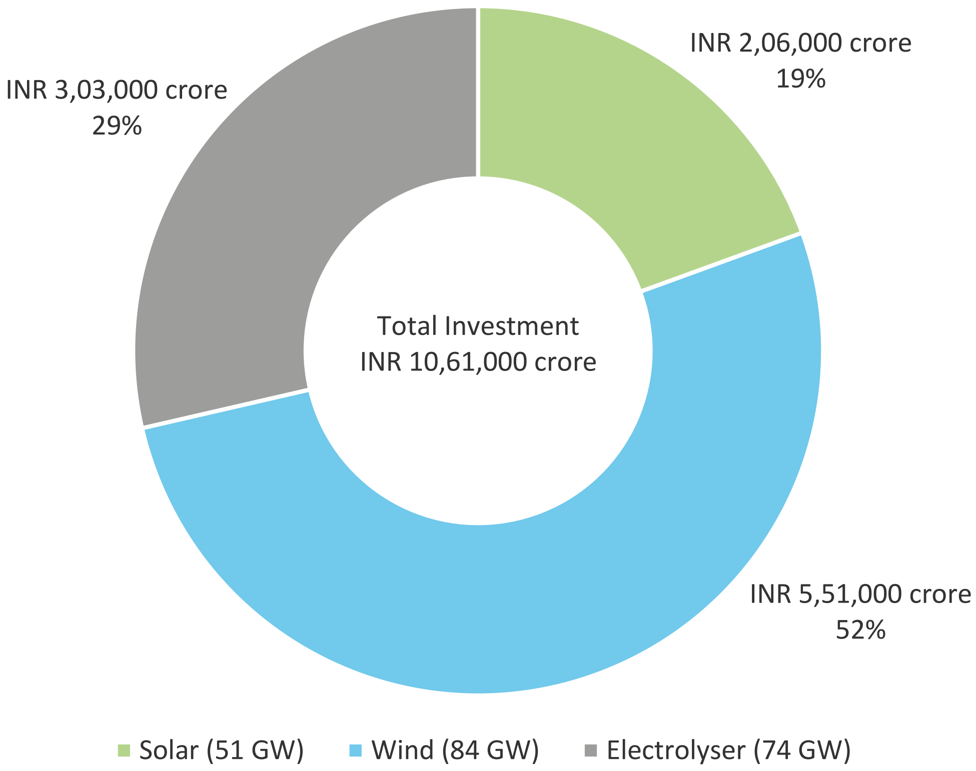
(light blue)	ATC limit relaxed
↑	Increase in congestion hours compared to BAU scenario
↓	Decrease in congestion hours compared to BAU scenario

Source: Author's analysis
Note: *The values of congestion in both scenarios are after the BESS deployment

3.8. Investment of INR 10.6 lakh crore (USD 129 billion) is required to meet national green hydrogen target

India will need the total investment of **INR 10.6 lakh crore** (USD 129 billion) to deploy the RE capacity (solar 51 GW, wind 84 GW) and electrolyser (74 GW) to achieve its 5 MT green hydrogen production target by 2030. Around 29 per cent of the investment will be required for electrolyser development, whereas the remaining 71 per cent will be needed for RE deployment.

Figure 12: More than one-third of the investment for green hydrogen production is required for RE deployment



Source: Author's analysis
Note: Based on stakeholder consultations and reviewed studies, solar and wind capex are considered USD 493/kW and USD 800/kW respectively, while electrolyser capex is considered USD 500/kW.

4. Recommendations


Image: iStock

India must utilise its vast electricity grid to meet its green hydrogen production targets cost-effectively. Thus, we recommend the following planning, regulatory, and policy measures based on our findings:

4.1. Identify green hydrogen production hubs to guide national and state transmission planning

Under the *National Green Hydrogen Mission*, specific regions in different states must be identified as green hydrogen hubs. This would involve the identification of suitable sites for setting up green hydrogen capacities on key factors such as RE potential, water availability, land-use type, and population density. Information on prospective sites and the associated RE capacity must inform the intra and inter-state transmission planning for 2030.

For instance, initial green hydrogen plants in Uttar Pradesh, Punjab and Haryana, will import wind power from nearby windy states. These states will require relaxation in import transfer capabilities to reduce the likely congestion in the inter-state network. Similarly, intra-state networks will also need capacity enhancements. The Government of India must collaborate with these states to develop perspective transmission plans which, in turn, will be essential to attract investments in the desired infrastructure. It must consider extending InSTS GEC beyond current beneficiary states.

4.2. Recognise electrolysers as a flexible resource under the Central Electricity Regulatory Commission (CERC) Ancillary Services Regulation, 2022

We find that India will require an additional 135 GW of grid-connected vRE capacity to meet its GH2 target. This will take India's total installed vRE capacity to 560 GW in 2030, implying high flexibility needs in the system.[45]

Electrolysers have higher ramping rates, lower start-up time, and can operate in a wider load range. Load range varies between 15 per cent and 100 per cent of the nominal load, and ramp rates could fall between 0.2 per cent and 20 per cent per second (IRENA 2018).

Our assessment shows that 74 GW of electrolyser capacity will be grid-connected by 2030, capable of providing flexibility and fast-response services to the grid. The CERC must recognise electrolysers as an eligible resource through an amendment to its *Ancillary Services Regulations, 2022.*[46] It must identify appropriate compensation norms in consultation with GH2 developers. This intervention will encourage plants to operate electrolysers for grid balancing, besides meeting the industrial demand for green hydrogen.

4.3. Develop grid connectivity standards for electrolysers

Electrolyser capacity will increase to 74 GW by 2030. These capacities must adhere to robust technical standards to maintain grid safety and reliability. Hence, the CEA must introduce grid connectivity standards for electrolysers through an amendment to *its Technical Standards for Connectivity to the Grid Regulations, 2007* (CEA 2020).

4.4. Facilitate establishment of an industry-led consortium to pilot large-scale grid-connected GH2 projects

Our assessment highlights that meeting India's green hydrogen target through grid-connected renewable energy will lower the production cost by 2 per cent, resulting in an overall cost savings of INR 20,500 crore (USD 2.5 billion).

However, at this nascent stage, realising these savings is fraught with a set of challenges, risks and uncertainties. Developers are wary of operational, technological, regulatory, and other infrastructure-related challenges associated with large-scale grid-connected GH2 projects.

We recommend that Government of India should facilitate the creation of a consortium of industry partners. This consortium must establish a corpus, or a 'Green Hydrogen Development Fund' (GHDF), by pooling resources from all the participating member industries, concessional lines of credit from development banks, and the *NGHM SIGHT programme* (with an approved outlay of INR 1,466 crore for pilot projects) to mitigate such risks and challenges. The consortium must collaboratively identify key problem statements or challenges that need to be solved, and support relevant demonstration projects through well-established processes in different sectors and geographies. The experience and knowledge gained through the deployment of these projects should be shared through data publication on project planning, deployment, and performance. This will build developer confidence and expedite green hydrogen projects.

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[45] In the green hydrogen scenario, the average net load ramp-up rate goes up from 107 MW/min in 2022 to 385 MW/min, while the average net load ramp-down rate goes up from 96 MW/min in 2022 to 376 MW/min.

[46] Battery energy storage systems have high ramping capability and are eligible to provide secondary reserve ancillary service to manage the grid operations, under the *Ancillary Services Regulations, 2022.*

5. Limitations

The study's results are based on certain assumptions and limitations:

1. Our results assume that the electrolyser load profile follows the hybrid renewable energy generation profile. However, the results may vary depending on different electrolyser or green hydrogen load profiles.
2. The study's results are based on a specific methodology used to estimate state-wise green hydrogen production for 2030 (as discussed in Chapter 3). However, different methodologies could lead to varying results.
3. Solar and wind capacity is assumed to be intra-state for meeting the green hydrogen load. For non-windy states, wind capacity is sourced from neighbouring windy states.
4. Intra-state and inter-state charges and losses are not considered in this modelling exercise.
5. The study uses a unit cost commitment model that excludes the power cost for renewable energy. However, the capital expenditure (CAPEX) of renewable energy power is included in the levelised cost of hydrogen (LCOH) estimation.
6. The study does not consider load shift or demand-side measures that could affect the load profile for 2030.

The resource requirements will vary depending upon the type of electrolyser profile considered for the analysis. A detailed assessment is required to analyse the variations in RE and electrolyser capacity, storage requirements, and transmission requirements based on various electrolyser profiles, such as flat, stepped, solar-following, etc.

Annexure

Annexure 1: Modelling the power system

Modelling Tool

Production-cost optimisation model uses the GE MAPS software, *Multi-Area Production Simulation software*. The model simulates grid operation while minimizing system costs. The MAPS software integrates detailed representations of system load, generation, and transmission into a single simulation, enabling the calculation of production costs considering transmission system constraints on economic dispatch. The simulation adheres to defined operational constraints like technical minimums, ramp rates for different sources, reserve margins, and planned and forced outages in grid operation planning. Load profiles are adjusted to meet the monthly or annual peak and energy forecasts input to the model.

A.1. Model Setup

The base year 2022 is considered to set up the model, and the model outputs are calibrated with the actual power system operation results. The model is then run for 2030 for both BAU and GH2 scenarios. The data inputs to the model are:

a. Supply Side Inputs

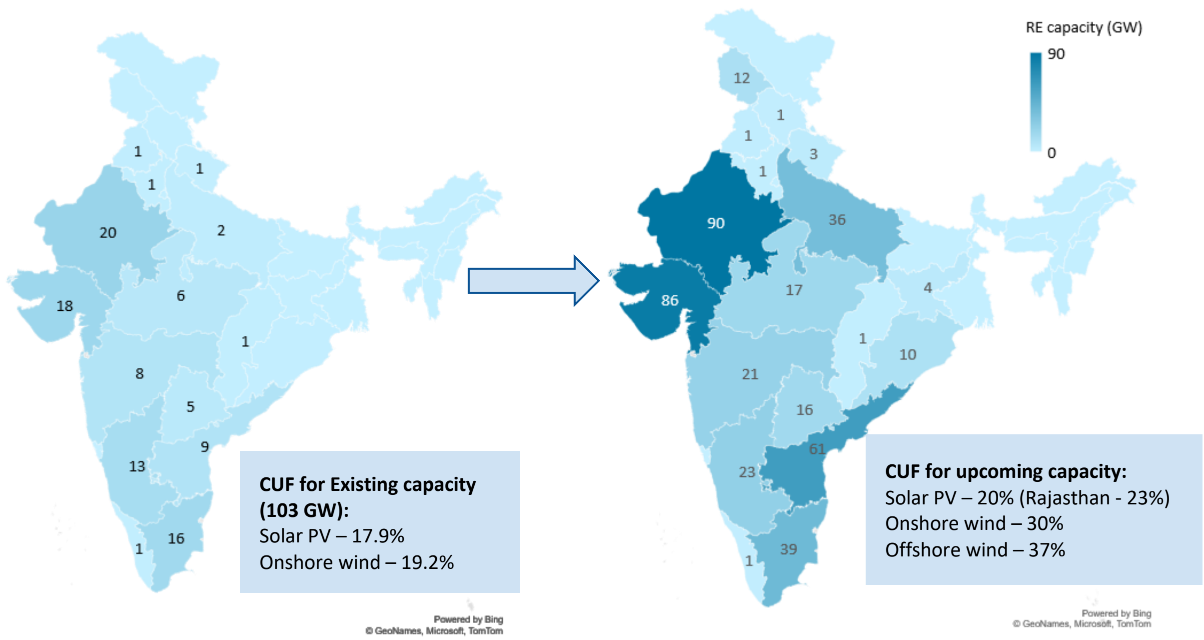
1. Installed RE capacity for 2022 and 2030: Installed RE Capacity for 2022 is based on CEA data. For 2030, the state-wise installed RE capacity is considered from the recent announcements on state RE policies *(Sr. no. 1 to 8 in Table A1 in annexure*) and for the other states *(Sr. no. 9 to 25 in Table A1 in annexure*) CEA report (CEA 2022) is referred to.

2. Installed non-RE capacity addition for 2030: Coal, nuclear, hydropower, and pump storage are considered based on the National Electricity Plan 2022 (CEA 2023) and CEA reports for under-construction hydro and pump-storage projects (refer to Table A2 in the *annexure for further details).*

3. State-wise Additional RE Capacity for GH2 in 2030: Annexure 2 outlines the additional RE required to meet the green hydrogen requirement of 5 million tonnes by 2030.

4. RE site selection and generation profiles: District-level multiple RE (solar and wind) generation profiles are considered to build a particular state's RE generation profile. For example, five different solar profiles for different districts such as Banaskantha, Amreli, Anand, Kutch, and Patan are considered to build Gujarat's generation profile. The figure below shows the solar and wind capacity utilisation factors (CUFs) considered for 2022 and 2030. Due to technological advancement in the future, higher CUFs for upcoming RE capacity are considered.

Figure A1: **Northern, western, and southern regions host most of the upcoming VRE capacity in 2030**



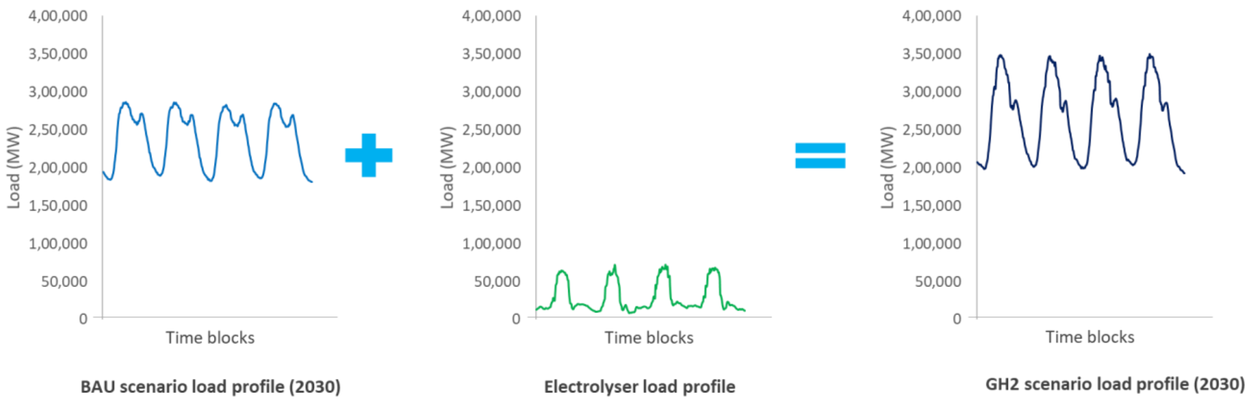
Source: Authors' compilation based on CEA reports and state RE policies

b. Demand Side Inputs

1. Load profile for BAU scenario 2030: The state-wise actual load profile for 2022 is used to project the 2030 BAU scenario load profile based on the 20th electric power survey report by CEA. The base load requirement for 2030 is 258 GW, with a peak demand of 343 GW.

2. Load Profile for GH2 scenario: The load profile for GH2 scenario 2030 is obtained by adding the load profile of green hydrogen or electrolyser to the BAU scenario 2030 demand. The electrolyser load profile for a particular state is assumed to be similar to the hybrid RE (solar + wind) generation profile. The optimal requirement of RE and electrolyser capacity are derived from the optimisation (PLEXOS) model.

Figure A2: **Representative load profiles**



Source: Authors' analysis

Box 1.0. Green hydrogen electricity demand to be considered over and above the 20th EPS demand projection for 2030

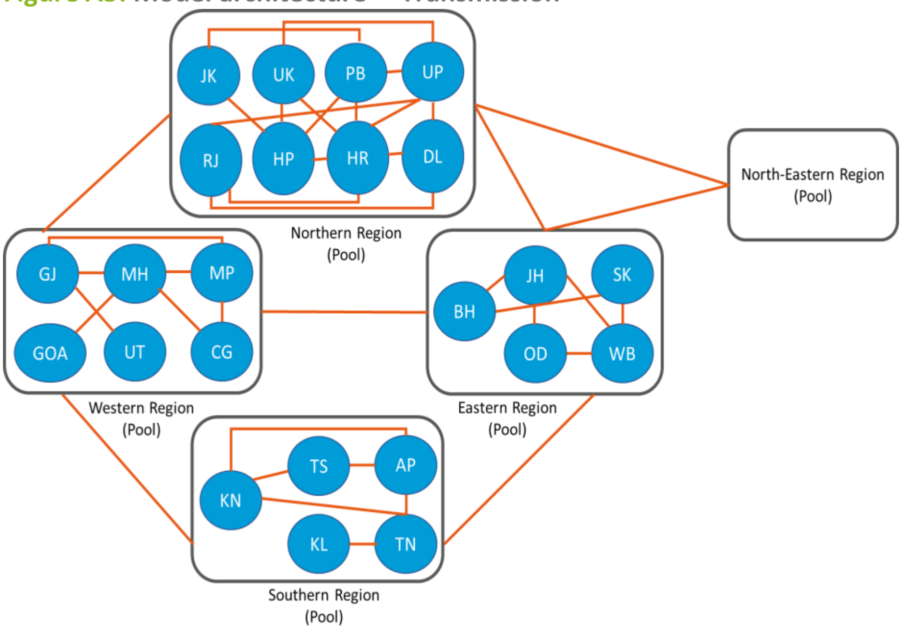
The EPS has projected a demand of 2377 billion units for 2030, including 250 billion units for green hydrogen production of 5 million tonnes. However, for this study, we consider the demand of 2377 billion units as the base case demand without factoring in green hydrogen load due to the following reasons:

- The EPS has projected a demand of 10 million tonnes of green hydrogen by 2031-32, assuming 5 million tonnes will be produced in the HT industries category and 5 million tonnes will be produced in the captive mode. Since we are focusing on grid electricity demand, we assess whether the 5 million tonnes green hydrogen load (250 billion units) has been factored into the EPS projection or not.
- The rooftop solar power of 55 billion units in 2031 will reduce electricity consumption in Domestic (18 billion units), Commercial (6 billion units), LT (5 billion units), and HT industries (26 billion units) sectors based on their respective consumption ratios (as per the EPS methodology).
- The net increase in HT consumption from the grid to accommodate green hydrogen demand would be 224 billion units (=250-26). Excluding the net impact due to rooftop solar power and green hydrogen load on HT consumption, the HT consumption compounded annual growth rate will only be 3 per cent from 2021 to 2031.
- The industrial consumption growth rate has been higher in the last decade at 5.8 per cent. Considering economic growth aspirations and industrial electrification, electricity demand in industries may grow faster (than 3 per cent) in the future

c. Transmission Side Inputs

Each state in the region (load and generation) is modelled as a distinct node. Interstate transmission links are modelled separately, each emulating the electrical characteristics including line loading capacity. Within the state, a copper plate model is assumed, allowing unrestricted energy flow from one corner to another. The states in the northern region are pooled together to form a single node.

Figure A3: Model architecture —Transmission



Source: Authors' analysis

A.2. Assumptions and constraints considered for modelling different scenarios

Broad Assumptions

- Market-Based Economic Dispatch (MBED), i.e., where the power generation is scheduled based on market prices to ensure the cheapest resources meet electricity demand.
- Unit cost commitment model without variable cost for RE is considered.
- No charges and losses to wheel the power from one location to another are considered.

Cost Assumptions

- 1 per cent annual cost escalation is assumed for domestic and imported coal plants.
- Natural Gas price projections are projected as per the World Bank Commodity price index.
- Fuel cost and heat rate are considered to model the variable cost. Benchmarking is done based on the MERIT portal and daily coal reports from the national power portal.

Operational Constraints

- Operating reserves are modelled as 5 per cent of the load for each region.
- Ramp rates of 1 per cent per minute and 3 per cent per minute for coal and gas plants respectively.
- Planned maintenance and forced outages are based on technology and the capacity of individual plants. Unavailability variation is considered between 9 and 15 percent.
- Minimum Technical Level (MTL) operation of 40 per cent is considered for the selected coal units. The selection criterion for coal plants is discussed in detail below (Refer to Box 2.0).

Box 2.0. Selection criterion for coal plants to operate at 40% MTL

As per ***'CEA's Draft Phasing Plan for achieving 40% Minimum Technical Load (MTL)'*** around **199 GW** of coal capacity has been selected for MTL lowering to 40% by 2030 but we have adopted a more nuanced approach for selection of units for MTL lowering.

We have selected around **80 GW** of coal capacity (143 units) for **MTL lowering from 55% to 40% by 2030** such a that optimum benefit is derived out of such lowering. This criterion includes:

- Selection of the coal capacity in the states (/nodes) where maximum vRE curtailment is happening
- Selection of the coal plants in these states (/nodes) which are running at lower Plant Load Factor (PLF) during vRE curtailment hours

23 BU of otherwise curtailed vRE is absorbed due to MTL lowering of these selected units. This nuanced selection helps in **smooth grid integration** of increasing RE by 2030.

Annexure 2: Installed capacity considerations: 2022 and 2030

Table A1: Considering the current plans, northern, western and southern regions will host most of the vRE in 2030

Sr. No.	State	2022 Installed Capacity (GW)			Incremental Addition by 2030 (GW)			Final Installed Capacity by 2030 (GW)		
		Wind	Solar	Total	Wind	Solar	Total	Wind	Solar	Total
1	Rajasthan	5	15	**20**	10	60	**70**	15	75	**90**
2	Karnataka	5	8	**13**	5	5	**10**	10	13	**23**
3	Gujarat	10	8	**18**	36	32	**68**	45	40	**86**
4	Uttar Pradesh	0	2	**2**	0	34	**34**	0	36	**36**
5	Jharkhand	0	0	**0**	0	4	**4**	0	4	**4**
6	Odisha	0	1	**1**	0	10	**10**	0	11	**11**
7	Tamil Nadu	10	6	**16**	3	20	**23**	13	26	**39**
8	Uttarakhand	0	1	**1**	0	3	**3**	0	3	**3**
9	Andhra Pradesh	4	5	**9**	18	34	**52**	22	38	**61**
10	Telangana	0	5	**5**	3	9	**12**	3	14	**16**
11	Madhya Pradesh	3	3	**6**	3	8	**12**	6	11	**17**
12	Maharashtra	5	3	**8**	4	9	**13**	9	12	**21**
13	JK & Ladakh	0	0	**0**	0	11	**11**	0	12	**12**
14	Himachal	0	0	**0**	0	1	**1**	0	1	**1**
15	Kerala	0	1	**1**	0	0	**0**	0	1	**1**
16	Bihar	0	0	**0**	0	0	**0**	0	0	**0**
17	Chhattisgarh	0	1	**1**	0	0	**0**	0	1	**1**
18	Delhi	0	0	**0**	0	0	**0**	0	0	**0**
19	Goa	0	0	**0**	0	0	**0**	0	0	**0**
20	Haryana	0	1	**1**	0	0	**0**	0	1	**1**
21	North East (Agg)	0	0	**0**	0	0	**0**	0	0	**0**
22	Punjab	0	1	**1**	0	0	**0**	0	1	**1**
23	Sikkim	0	0	**0**	0	0	**0**	0	0	**0**
24	West Bengal	0	0	**0**	0	0	**0**	0	0	**0**
25	UT_West	0	0	**0**	0	0	**0**	0	0	**0**
	India	**42**	**61**	**103**	**82**	**241**	**323**	**123**	**302**	**425**

Legend:

Upcoming RE capacity as per state policy/announcements (Sr. No. 1–8)

Upcoming RE capacity as per CEA Report (Sr. No. 9–25)

Source: Authors' compilation based on individual state RE policies for capacities from Sr. No. 1 to 8, and on CEA report for Sr. No. 9 to 25

Table A2: Non-RE capacity addition till 2030 (MW)

Coal-based plants			
Region	**Area**	**2030**	**Total**
Southern	Andhra Pradesh	1,600	10,640
	Tamil Nadu	3,440	
	Telangana	5,600	
Northern	Uttar Pradesh	6,600	6,600
Western	Maharashtra	660	660
Eastern	Bihar	2,640	9,000
	Odisha	1,320	
	Jharkhand	4,380	
	West Bengal	660	
Total		**26,900**	**26,900**
**Note – Coal capacity of 4.69 GW is retired by 2027 (as per NEP, 2022)*			
Nuclear plants			
Region	**Area**	**2030**	**Total**
Southern	Karnataka	1,400	5,900
	Tamil Nadu	4,500	
Northern	Uttar Pradesh	0	4,200
	Rajasthan	1,400	
	Haryana	2,800	
Western	Gujarat	1,400	2,800
	Madhya Pradesh	1,400	
Total		**12,900**	**12,900**
Hydro power plants			
Region	**Area**	**2030**	**Total**
Southern	Kerala	40	1,000
	Andhra Pradesh	960	
Northern	Uttarakhand	1,271	6,046
	Himachal Pradesh	2,010	
	Jammu & Kashmir	2,560	
	Punjab	206	
Western	Madhya Pradesh	400	400
Eastern	West Bengal	620	1,157
	Sikkim	500	
North-Eastern		2,120	2,120
Total		**10,723**	**10,723**

Pumped storage hydro			
Region	**Area**	**2030**	**Total**
Southern	Karnataka	9,150	14,410
	Andhra Pradesh	3,260	
	Tamil Nadu	2,000	
Northern	Uttarakhand	1,000	1,000
Eastern	West Bengal	1,420	2,420
	Odisha	1,000	
Western	Maharashtra	80	1,520
	Madhya Pradesh	1,440	
Total		**19,350**	**19,350**

Source: Authors' compilation based on National Electricity Plan, 2022 for coal and nuclear projects, and CEA Reports for under-construction hydro and pumped storage hydro projects

Annexure 3: Electricity demand for green hydrogen

A. State-wise green hydrogen production to meet domestic demand in 2030

India's domestic green hydrogen demand is considered to be 1.5 million tonnes, which is thirty per cent of the national green hydrogen production target of 5 million tonnes in 2030. State-wise domestic green hydrogen production to meet the domestic demand in 2030 is projected based on the current share (as of 2020) of grey hydrogen production in the states. The methodology to estimate the sectoral grey hydrogen production is explained below.

Estimation of sectoral hydrogen production

Gujarat will contribute to more than 40 per cent of the hydrogen production in the refineries sector. To estimate hydrogen production in refineries, the study "*Opportunities for Green Hydrogen Production in India*" (Manna et al. 2021) and NITI Aayog's report on *"Harnessing Green Hydrogen"* (NITI Aayog 2022) were referred. Total hydrogen production in the refineries is estimated to be 2.5 million tonnes, about two-fifths of the total hydrogen production *(refer to Table A4).*

The Department of Fertilizers annual reports (2021-22) provide data on the production of different types of urea and non-urea (DAP and complex fertilizers). This data is correlated with the stoichiometric requirement to estimate hydrogen production in the fertilizer sector. Of the estimated 3 million tonnes of hydrogen production in the fertilizer sector, around 26 per cent is produced in Uttar Pradesh, followed by Gujarat.

The conversion factor used to calculate the hydrogen requirement is outlined in Table A3.

Table A3: Conversion factor to calculate hydrogen requirement in the fertilizer sector

	Urea	DAP	OCF
Kg NH3/t	570	230	240
Kg H2/t NH3	180		
Kg H2/t	102.6	41.4	43.2

Source: Fertiliser Association of India 2020

Table A4: More than half of the grey hydrogen is consumed in the fertilizer sector in 2020

State	Refinery (Kilo Tonnes)	Fertilisers (Kilo Tonnes)	Methanol (Kilo Tonnes)	Total H2 Production (Kilo Tonnes)
Gujarat	1,109	496	99	1,704
Uttar Pradesh	80	805	-	885
Maharashtra	126	277	16	418
Rajasthan	-	375	-	375
Madhya Pradesh	117	210	-	327
Tamil Nadu	166	137	-	303
Andhra Pradesh	66	187	-	253
Haryana	190	58	-	248
Karnataka	145	46	-	192
Odisha	62	127	-	189

State	Refinery (Kilo Tonnes)	Fertilisers (Kilo Tonnes)	Methanol (Kilo Tonnes)	Total H2 Production (Kilo Tonnes)
Punjab	75	112	-	188
Kerala	144	37	-	182
West Bengal	104	29	-	132
Assam	83	13	39	135
Bihar	46	49	-	96
Goa	-	62	-	62
Total	**2,515**	**3,020**	**153**	**5,687**

Source: Authors' analysis

Note: India's total grey hydrogen demand in 2020 stood at 8 MTPA, of which 5.6 MTPA was met by domestic production and the remaining 2.4 MTPA by imports (CEEW 2024).

We estimate the state-wise green hydrogen production to meet the domestic demand in 2030 by assuming that 1.5 million tonnes of green hydrogen will be produced in the states in the same proportion as the current hydrogen production.

Table A5: **Gujarat and Uttar Pradesh will cater to 50% of the domestic green hydrogen demand**

State	Present H_2 production (MT)	Share of current hydrogen production (%)	GH2 Production to meet domestic demand (2030) in MT
Gujarat	1.7	32	0.49
Uttar Pradesh	0.9	17	0.25
Maharashtra	0.4	7	0.12
Rajasthan	0.4	7	0.11
Madhya Pradesh	0.3	6	0.09
Tamil Nadu	0.3	6	0.09
Andhra Pradesh	0.3	5	0.07
Haryana	0.3	5	0.07
Karnataka	0.2	4	0.05
Odisha	0.2	4	0.05
Punjab	0.2	4	0.05
Kerala	0.2	3	0.05
Total	**5.6***	**100**	**1.5 (30% of 5 MT)**

Source: Authors' analysis

Note: States of West Bengal, Assam, Bihar, and Goa are included for *grey hydrogen production, but have not been considered for GH2 production as there has been no visible policy development in these states for GH2 production till 2030.

B. State-wise green hydrogen production to meet export demand in 2030

The export demand is expected to be met by production in six port states: Gujarat, Tamil Nadu, Maharashtra, Odisha, Andhra Pradesh, and Kerala. The share of export demand to be met by each of the port states is estimated based on policy and project announcements for green hydrogen and green ammonia projects.

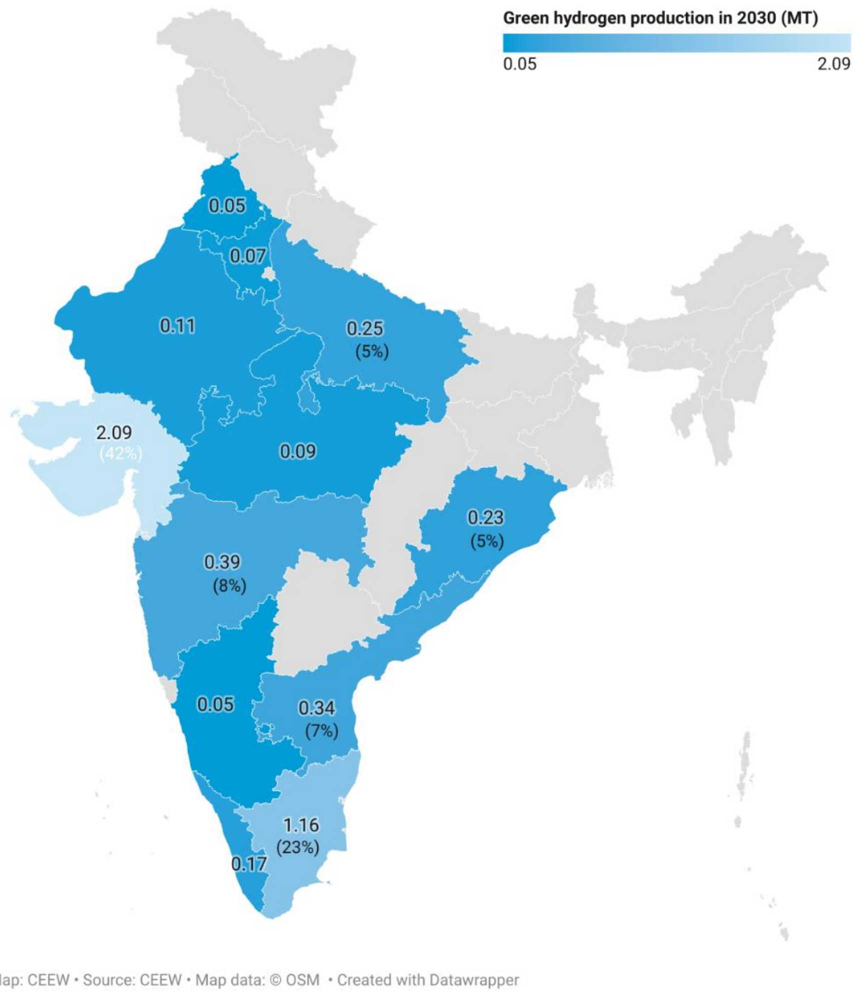
Table A6: **Gujarat and Tamil Nadu will meet three-fourths of the green hydrogen export demand**

State	Announced green hydrogen/ green ammonia Capacity (MT)	GH2 Production to meet export demand (2030) in MT
Gujarat	3.0	1.6
Tamil Nadu	2.0	1.0
Maharashtra	0.5	0.3
Andhra Pradesh	0.5	0.3
Odisha	0.3	0.2
Kerala	0.2	0.1
Total	**6.5**	**3.5 (70% of 5 MT)**

Source: Authors' compilation based on state green hydrogen policies and recent project announcements

The state-wise green hydrogen production to meet the national target is represented below:

Figure A4: **Gujarat will contribute to 42% of the green hydrogen production**



Source: Authors' Analysis

Note: GH2 production in states here is the total of GH2 produced to meet both export and domestic demand

C. Electricity requirement for green hydrogen production

Based on various consultations and literature (H2B2 Tech 2022) (Hydrogen tools n.d.), we assume 62 kWh of electricity will be required to produce 1 kilogram of green hydrogen. Thus, the total electricity required for the production of 5 tonnes of green hydrogen is estimated to be 310 billion units (BU).

Table A7: 310 BU of electricity demand will be required for 5 MT GH2 production in 2030

State	GH2 production in MT (Share in %)	Energy requirement in billion units (BU) for GH2 Production
Gujarat	2.1 (42)	130
Tamil Nadu	1.1 (23)	72
Maharashtra	0.4 (8)	24
Andhra Pradesh	0.4 (7)	21
Uttar Pradesh	0.2 (5)	16
Odisha	0.2 (5)	14
Kerala	0.1 (3)	11
Rajasthan	0.1 (2)	7
Madhya Pradesh	0.1 (2)	6
Haryana	0.05 (1)	4
Punjab	0.05 (1)	3
Karnataka	0.05 (1)	3
Total	**5.0**	**310**

Source: Authors' analysis

D. Wind Profile considerations for green hydrogen production

Table A8: Non-windy states import wind energy from neighbouring windy states to serve GH2 load

State	Windy/Non-windy state	Wind Profile considered to meet the GH2 demand
Odisha	Non-windy	Andhra Pradesh
Uttar Pradesh	Non-windy	Rajasthan
Haryana	Non-windy	Rajasthan
Punjab	Non-windy	Rajasthan
All the remaining states	Windy	Intra-state

Source: Authors' assumptions as per solar and wind generation data

E. PLEXOS: Optimization tool

In this study, we use PLEXOS to optimize RE (solar, wind) and electrolyser capacity in the states to meet the green hydrogen electricity demand with the objective to achieve the minimum cost of hydrogen.

PLEXOS (Energy Exemplar n.d.) is an energy simulation software that helps unify data streams across electric, water and gas energy systems into a single unified modelling and forecasting platform. PLEXOS estimates the cost savings due to intra-hourly operation for new generic resources. It helps for long, medium and short-term energy market analysis. PLEXOS can capture specifics of short-term operational limits, as well as the effects of system expansion.

The cost assumptions considered for RE and electrolyser mentioned below:

Build Cost ($/kW) = **493**
WACC (%) = 10
Life (Years) = 25
O&M charges ($/kW/Year) = 9.86
O&M Escalation (%) = 2

Build Cost ($/kW) = **800**
WACC (%) = 10
Life (Years) = 25
O&M charges ($/kW/Year) = 16
O&M Escalation (%) = 2

Build Cost ($/kW) = **500**
Replacement Cost ($/kW) = 150
WACC (%) = 10
Life (Years) = 25
O&M charges ($/kW/Year) = 10
O&M Escalation (%) = 2

Annexure 4: Resource requirement for GH2 production

Table A9: 145 GW of RE and 65 GW of electrolyser capacity is required for GH2 production without ISTS support

GH2 production without ISTS support (145 GW RE)						
State	Solar Installed Capacity (GW)	Wind Installed Capacity (GW)	Electrolyser Installed Capacity (GW)	Electrolyser Capacity Factor (%)	H_2 Gen. (Ktonns)	LCOH ($/kg)
Gujarat	23	37	25	58%	2,090	4.0
Tamil Nadu	16	19	16	52%	1,160	4.2
Maharashtra	6	6	6	50%	390	4.1
Andhra Pradesh	5	9	5	51%	340	4.1
Uttar Pradesh	4	0	3	53%	250	4.2
Odisha	3	0	3	51%	230	4.2
Kerala	1	4	2	63%	170	3.9
Rajasthan	1	8	1	58%	110	3.8
Madhya Pradesh	1	1	1	53%	90	4.1
Haryana	1	0	1	56%	70	4.1
Punjab	1	0	1	55%	50	4.1
Karnataka	1	1	1	58%	50	4.0
India	**61**	**84**	**65**	**55%**	**5,000**	**4.1**

Source: Authors' analysis

Note: Refer to Table A9 in Annexure 5 for state-wise curtailment figures.

Table A10: A 10 GW reduction in RE requirement and a 9 GW increase in electrolyser requirement is observed in the GH2 production with ISTS support

GH2 production with ISTS support (135 GW RE)						
State	Solar Installed Capacity (GW)	Wind Installed Capacity (GW)	Electrolyser Installed Capacity (GW)	Electrolyser Capacity Factor (%)	H_2 Gen. (Ktonns)	LCOH ($/kg)
Gujarat	22	37	26	58%	2,089	4.0
Tamil Nadu	14	19	16	51%	1,160	4.1
Maharashtra	6	6	6	50%	389	4.2
Andhra Pradesh	3	9	5	48%	339	4.1
Uttar Pradesh	0	0	8	22%	250	2.8
Odisha	3	0	3	50%	228	4.1
Kerala	1	4	2	63%	170	3.9
Rajasthan	0	8	3	26%	109	2.3

State	Solar Installed Capacity (GW)	Wind Installed Capacity (GW)	Electrolyser Installed Capacity (GW)	Electrolyser Capacity Factor (%)	H_2 Gen. (Ktonns)	LCOH ($/kg)
Madhya Pradesh	1	2	1	1	90	4.1
Haryana	0	0	2	0	70	2.4
Punjab	0	0	2	0	50	2.7
Karnataka	1	1	1	1	49	4.0
India	**51**	**84**	**74**	**48%**	**4,993**	**3.6**

Source: Authors' analysis

Table A11: Northern region observes a reduction in curtailment by one-third in GH2 scenario with ISTS support compared to without ISTS support

	Curtailment (BU) in GH2 scenario (*Without BESS deployment)*		Curtailment absorbed (BU)
Region	Without ISTS support (145 GW)	With ISTS support (135 GW)	
Northern	70	48	22
Western	27	24	3
Southern	20	18	2
All India	**117**	**90**	**27**

Source: Author's Analysis

Note: No curtailment is observed in the eastern region.

Acronyms

BAU	Business-as-usual
BU	billion unit
BESS	battery energy storage system
CEA	Central Electricity Authority
DAP	diammonium phosphate
GH2	Green hydrogen
GW	giga watt
INR	Indian Rupee
MT	million tonnes
MTL	minimum technical load
MTPA	million tonne per annum
MW	mega watt
NGHM	*National Green Hydrogen Mission*
OCF	other chemical fertilisers
PSH	pumped storage hydro
vRE	variable renewable energy
USD	United States Dollar

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