Unlocking India's RE and Green Hydrogen Potential

An Assessment of Land, Water, and Climate Nexus

Hemant Mallya, Deepak Yadav, Anushka Maheshwari, Nitin Bassi, and Prerna Prabhakar

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Council on Energy, Environment and Water
ISID Campus, 4 Vasant Kunj Institutional Area
New Delhi – 110070, India
+91 11 4073 3300

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

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

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Contents

Land often has community use such as for access to roads and cattle grazing, which can become sources of conflicts.

Image: Alamy

Executive summary

India has committed to achieving net-zero emissions by 2070. Renewable energy (RE), including solar and wind power, as well as green hydrogen, are expected to play a pivotal role in achieving this target. India also has nearer-term goals of achieving 50 per cent non-fossil fuel share in power generation capacity and deploying 500 GW of non-fossil power capacity by 2030 (PIB 2022). In the long run, the Council on Energy, Environment and Water (CEEW) estimates that India will need a solar capacity of over ~5,600 GW and a wind capacity of ~1,800 GW to achieve net-zero emissions by 2070 (Chaturvedi and Malyan 2022). Furthermore, the green hydrogen demand in India in sectors such as fertiliser, refinery, steel, and transportation is expected to reach ~30 million tonnes per annum (MTPA) by 2050 (Kowtham, Pranav, and Clay 2022).

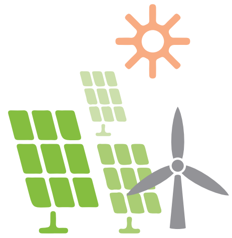
The study estimates India's RE potential at a resolution of 5 × 5 kilometre

However, large-scale RE and green hydrogen development entails challenges related to land and water access. While RE deployment depends on land availability, green hydrogen relies on water resources. These constraints hinder the full realisation of RE generation and green hydrogen production potential. Solar power, a major renewable source, requires extensive land resources. The current distribution of land use, as well as potential changes therein will determine whether sufficient land is available for widespread RE deployment. Additionally, the location of the available land is crucial, as end users prefer to deploy RE sources locally rather than transmitting power over long distances. Moreover, green hydrogen production requires access to water resources, known as uncommitted water, beyond what is already committed to the agricultural, industrial, domestic, and other sectors. The cost of land and availability of water directly influence the levelised cost of power and hydrogen. Therefore, to meet its net-zero targets, India needs to evaluate the overall potential for RE and green hydrogen and understand the challenges associated with realising this potential.

Our study estimates the potential for solar, wind, and green hydrogen at the national, state, and union territory level. The methodology involves dividing the Indian landmass into 5 × 5 kilometre rasters (or pixels) and evaluating the potential for RE and green hydrogen production in each raster and overlaying this data with land use categories such as crop-lands, mountainous terrain, water bodies, reserve forests, and sandy areas to determine the RE potential. Certain criteria, such as reserve forests, act as exclusion criteria and prevent the deployment of RE. Other criteria, like seismic activity and climate risks, act as constraints that do not prevent RE deployment but increase costs or social impact. We evaluate the RE potential after the application of exclusion criteria and limiting constraints. The RE potential is then layered with water-related constraints to evaluate the green hydrogen potential.

A. India has sufficient RE and green hydrogen potential to achieve net-zero emissions

Unlocking the potential for RE and green hydrogen production in India will require overcoming multiple challenges and constraints imposed by various social, climate, and commercial factors.



Out of 3,699 GW WSH potential, wind accounts for only 574 GW while the remaining is solar

RE potential in India and challenges to scaling up

As indicated in Figure ES1, our analysis shows that the bottom-up manufacturing cost of a PEM electrolyser is USD 359 per kW. The electrolyser stack constitutes about 40 per cent of the overall manufacturing cost, while the balance of plant (BoP) covers the remaining 60 per cent.

India has a significant RE potential of over 24,000 GW without applying any constraints. However, not all of this potential can be easily realised given the various constraints that limit deployment. A summary of RE potential and challenges to scaling up is provided below:

- **Onshore wind potential** – India has an onshore wind potential of 1,790 GW assuming a hub height of 100 metres and a plant load factor (PLF) equal to or greater than 30 per cent.
  - About 66 per cent of the onshore wind potential is concentrated in crop-lands, 27 per cent in rangelands, and only 7 per cent in bare ground. This indicates challenges in accessing land for large-scale wind generation.
- **Offshore wind potential** – India has an offshore wind potential of 2,435 GW, assuming a hub height of 100 metres and a PLF equal to or greater than 30 per cent.
  - Only 30 per cent of offshore wind is located in water less than 500 metres deep. Tapping into the rest of the potential may require floating wind turbine solutions.
- **Solar potential** – India has a solar potential of 20,270 GW for a PLF greater than 23 per cent (assuming 30 per cent oversizing).
  - **Seasonality in solar** – About 17,802 GW of solar capacity in the country experiences high seasonality – that is, more than three months with a PLF less than one standard deviation below the median values for the same location.
- **Wind–solar hybrid** (WSH) potential stands at 3,699 GW. Solar energy accounts for 84 per cent of the total WSH potential, at approximately 3,125 GW, while wind energy contributes the remaining 574 GW potential.
- **Earthquake zones** have minimal impact on RE potential, with 83 per cent of onshore wind potential and 77 per cent of solar potential located in low to moderate seismic zones (zone 2 or 3).
- **Population density** has a significant impact on RE potential. Only 29 per cent of onshore wind potential and 27 per cent of solar potential are located in areas with a population density lower than 250 people per square kilometre. However, social conflicts could arise even in areas with low population densities.

- **Land conflicts** can be a significant impediment to realising RE potential in the country. Only about 35 per cent of onshore wind potential and 41 per cent of solar potential are located in areas that have historically not experienced any land conflicts.

- **Climate risk and land prices** – Only 18 per cent of onshore wind potential and 22 per cent of solar potential are located in areas with low climate risks and low land prices.

The large-scale deployment of RE in India will require the careful selection of land parcels with minimal constraints and good quality RE.

Land policies and impact on RE

Favourable land policies and provisions are essential for the large-scale development of RE. A review of state-level RE policies indicates that there is no standard format for reporting land-related provisions.

- **Provisions for land-related issues in RE policies –** RE policies in some states lack provisions for land use conversion and land banks, creating an information gap in these states in terms of RE development.

- **Ease of doing business –** While provisions for deemed land use conversion are available in most states, the conversion still requires statutory approvals and fee payments.

- **Land transactions –** Most states have fully or partially exempted project developers from having to make stamp duty payments for purchasing land. However, of the 12 states analysed, only Jharkhand, Karnataka, Odisha, and Uttar Pradesh have provisions for land banks in their policies.

- **Wastelands –** While wastelands are an attractive option for project developers, the RE policies of most states do not include provisions for them.

Levelised cost of electricity for wind and solar generation

Although India has a large RE potential, the cost of power generation will significantly influence how much of it is eventually exploited. RE and green hydrogen have to compete with fossil fuels for widespread acceptance and minimal impact on economic growth. In this analysis, we used land costs and the RE PLF as variables to determine variations in the levelised cost of electricity (LCOE) across the country.

- Large solar potential exists in Rajasthan (6464 GW), Madhya Pradesh (2978 GW), and Maharashtra (2409 GW) at LCOEs lower than INR 2.8 kwh.

- Ladakh has a solar potential of ~625 GW at an LCOE lower than INR 2.5 kWh. However, unlocking this potential would be challenging due to the difficult terrain and a lack of power evacuation infrastructure.

- Karnataka (293 GW), Gujarat (212 GW), and Maharashtra (184 GW) have the largest wind potential in India at an LCOE lower than INR 3.25 per kwh.

- Tamil Nadu has a significantly lower cost of generation than in other states and union territories due to a high wind PLF, with a potential of 50 GW at an LCOE lower than INR 2.65 per kWh.

Only 41% of solar potential is located in areas that have historically not experienced any land conflicts

B. Green hydrogen potential: nexus with water and cost of production

Out of 80 MTPA green hydrogen production capacity in WSH areas, 56 MTPA do not face any significant water availability challenges

Green hydrogen capacity and water nexus

WSH provides a longer duration of power supply balancing the intermittency of solar and wind, thus increasing the efficiency of green hydrogen production and lower the costs. Hence, it is the preferred option for producing green hydrogen. Water is required for producing green hydrogen in electrolysers. Our analysis indicates that areas with WSH potential can produce about 80 MTPA of green hydrogen. Approximately 56 MTPA of hydrogen production capacity, mostly in western and southern India, can be realised in areas that do not face significant water availability issues. However, only 25 per cent of the surface water is available year-round, suggesting that storing monsoon water to ensure consistent year-round production would entail additional costs.

Levelised cost of hydrogen across the country

We estimate that India can produce about 40 MTPA of green hydrogen at a cost lower than USD 3.5 per kilogram. This cost is expected to decrease further in the coming years due to a decline in the cost of electrolysers and RE through the introduction of more efficient technologies.

- There is a significant green hydrogen production potential at a cost of less than USD 3.5 per kilogram in Gujarat (8.8 MTPA) and Karnataka and Maharashtra (5 MTPA each).
- Rajasthan has significant potential for producing 12 MTPA of green hydrogen, but the cost of production is much higher at USD 3.90 per kilogram, primarily due to the low capacity and PLF of wind power.

C. Challenges in achieving national RE and net-zero targets

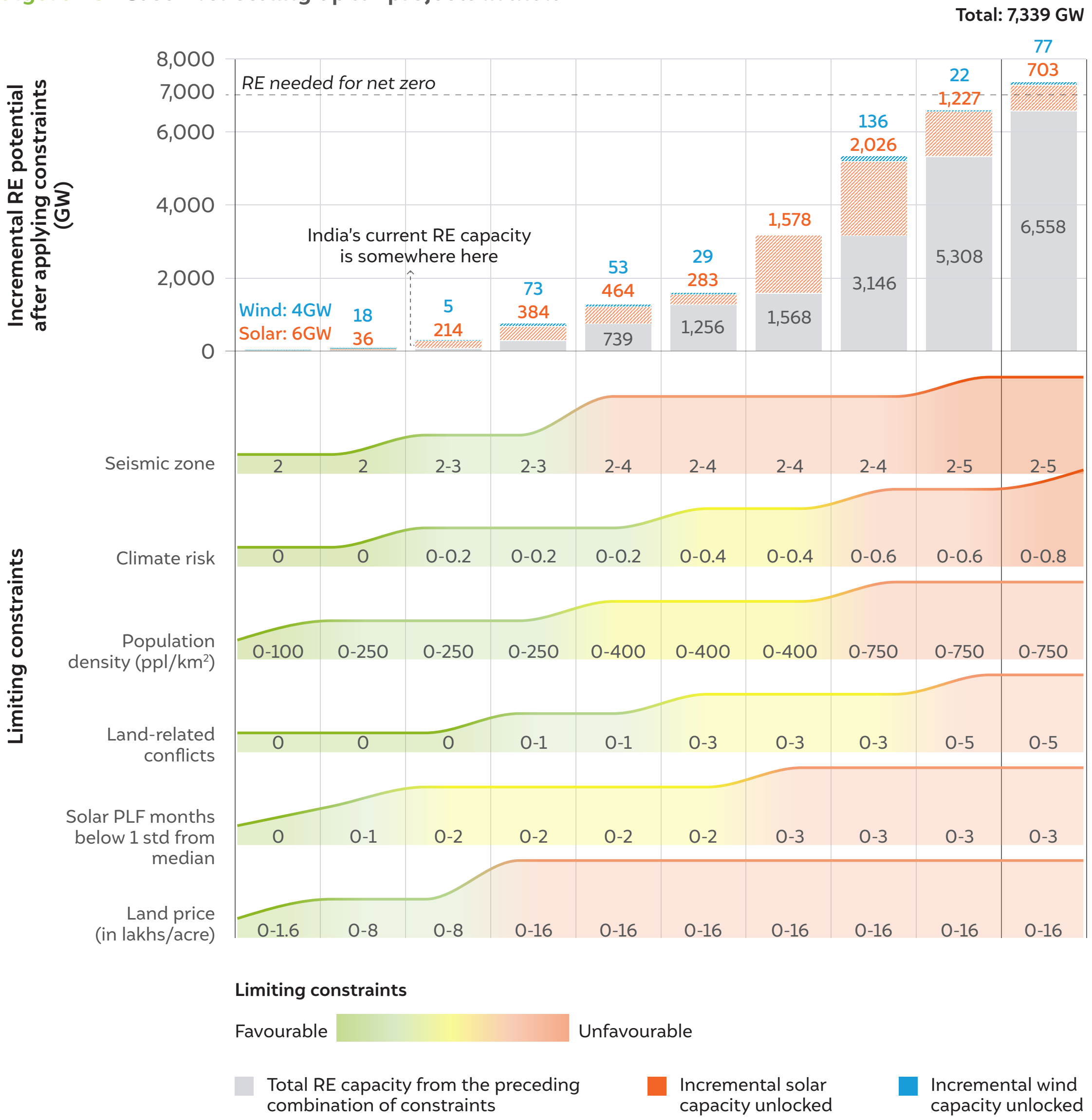
The significant RE potential in the country is limited by several constraints. Each location in the country has a different combination of constraints. To achieve net-zero emissions in India by 2070, it may be necessary to establish RE capacity of up to 7,000 GW. Multiple combinations of constraints need to be considered while establishing this generation capacity. We evaluated two such cases, depicted in ES Figures 1 and 2, where we consider the limitations posed by the constraints incrementally when scaling up RE deployment to 7,000 GW. The bars in the chart show the additional RE resulting from the tightening of each constraint and the cumulative RE for each combination of constraints. The constraints are listed to the left in the table below the chart in ES Figure 1, and the level of each constraint is provided below each bar.

Each combination trajectory provides different insights. However, based on the two cases evaluated in ES Figures 1 and 2, we observe some common patterns, as follows:

- The first 60 GW deployment has no significant constraints.
- Between 60 GW and 300 GW capacity, the intermittency of RE increases slightly, with locations experiencing two months of generation lower than one standard deviation from the median. Additionally, locations with existing conflicts will have to be used for RE deployment.

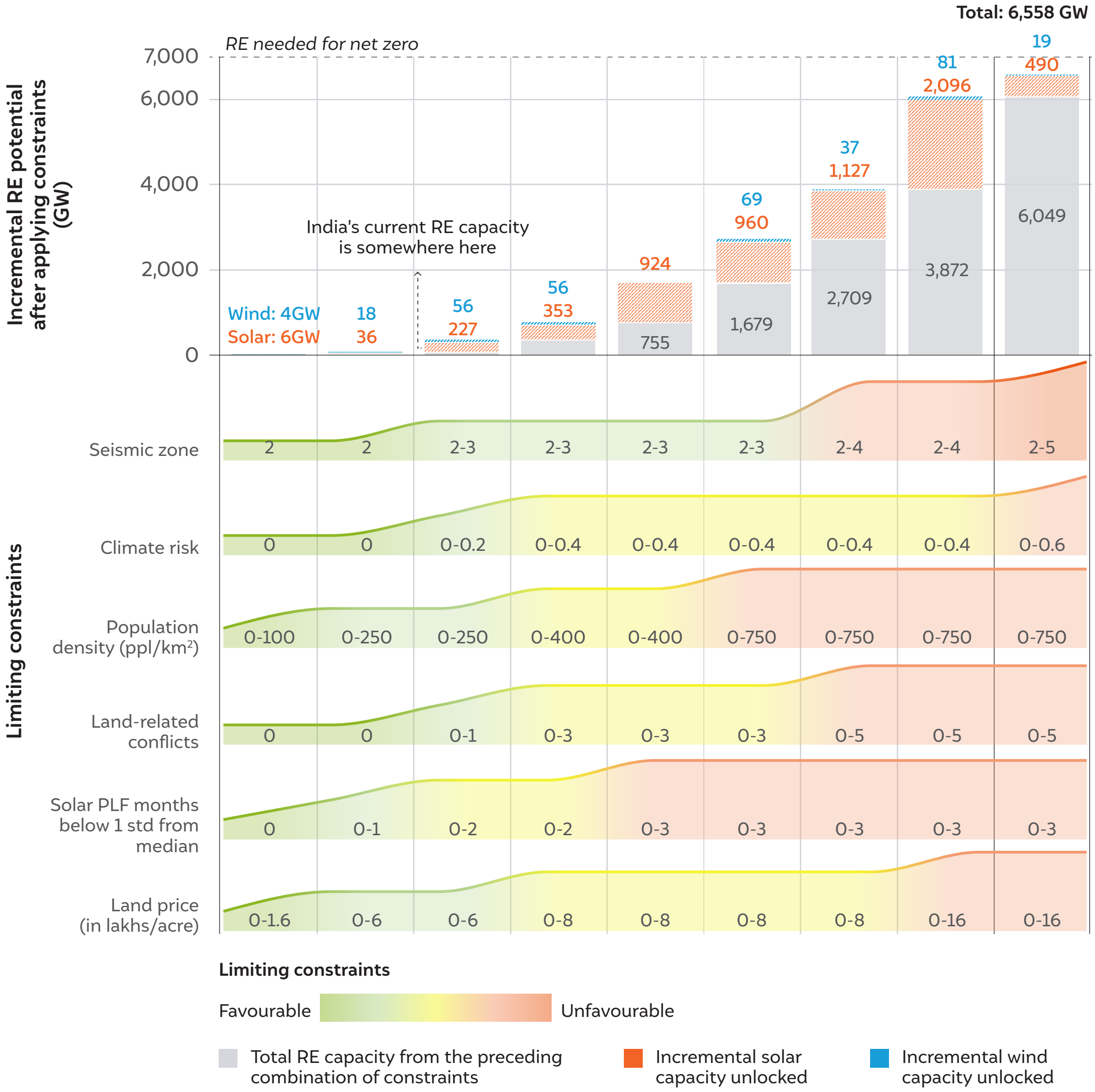
- In the 300–750 GW range, there is a trade-off between significantly higher land prices (between INR 8 and 16 lakhs per acre) and higher population density (between 250 and 400 people per square kilometre). Additionally, areas with higher population density are also associated with higher climate risk and conflicts. The climate risk also increases from 0.2 to 0.4.
- Beyond 750–1,500 GW, RE will need to be deployed in areas characterised as earthquake-prone zone 4 or in areas with higher seasonality, where generation is lower than one standard deviation from the median generation for three months. For the 1,500–3,000 GW range, we need to access high population density areas with 400–750 people per square kilometre. Unlocking the 3,000 GW RE potential will also require exploring land resources in high-conflict zones.
- And finally, beyond 3,000 GW, there is an increase in challenges associated with all constraints, from land price to population density and conflicts. At the extremity of more than 5,000 GW, we need to deploy RE in highly earthquake-prone zones. Additionally, climate risks are quite high in some areas as we reach higher capacity requirements.

Figure ES1 **Case 1 for scaling up RE projects in India**



Source: Authors' analysis

Figure ES2 Case 2 for scaling up RE projects in India



Source: Authors' analysis

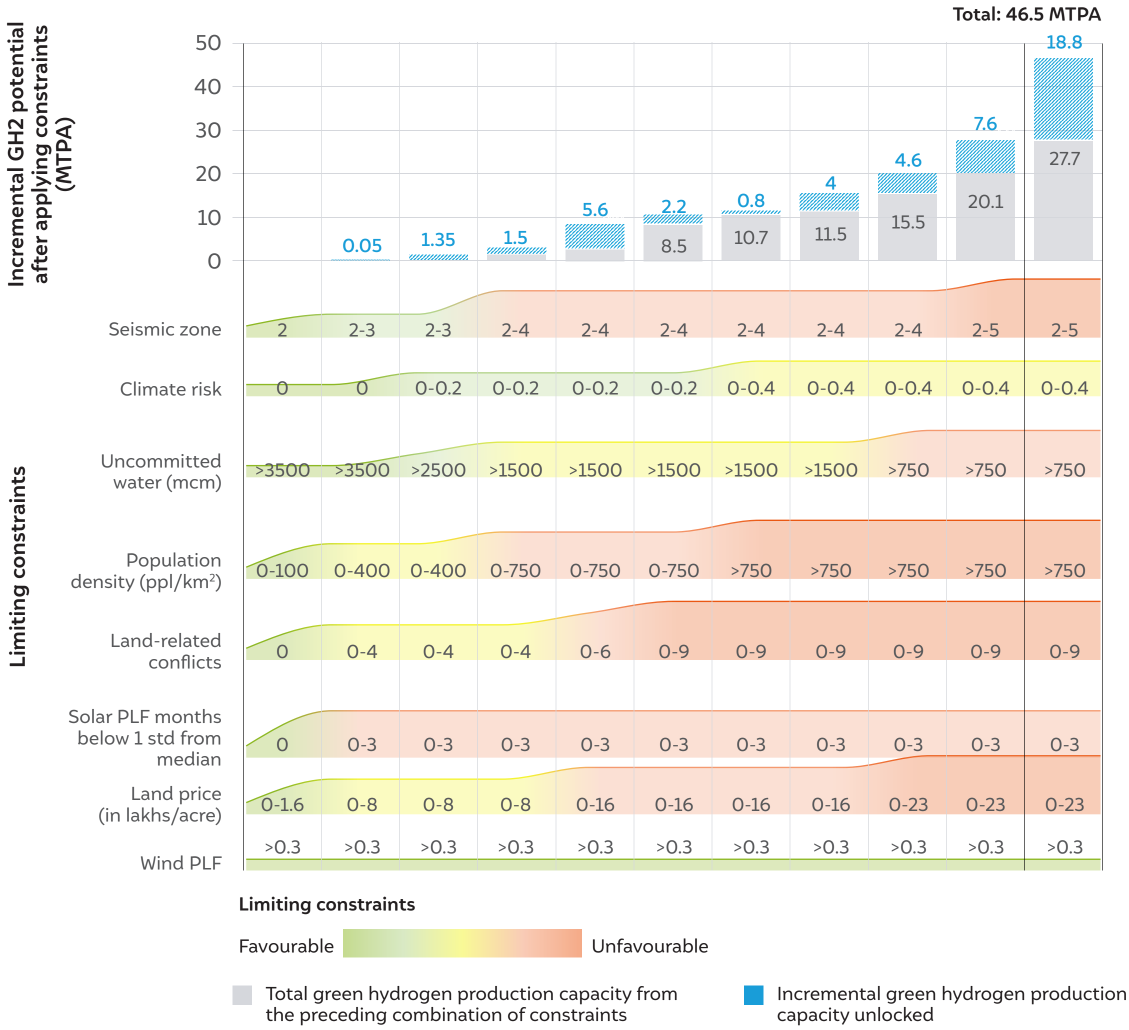
D. Challenges in realising the green hydrogen production potential in India

Similar to RE, we also evaluated the challenges posed by various constraints for scaling green hydrogen production. Since this is a burgeoning sector, we assessed the challenges up to a production volume of 50 MTPA, assuming that 5 MTPA will meet immediate domestic demand from existing hydrogen users, while the rest will be used for new applications such as steel production and export markets. We also assume that captive RE for hydrogen production through a WSH will be the predominant approach used for green hydrogen production, as power transmission open access charges and storage costs will make the transmission of RE for green hydrogen production commercially less competitive compared to captive RE.

It is assumed that green hydrogen projects will be set up only in WSH areas due to advantages related to low production costs. ES Figure 3 provides a summary of the incremental challenges associated with the growth of green hydrogen production. The key challenges are as follows:

- Land price is a challenge for most optimal WSH locations and will influence the levelised cost of hydrogen (LCOH).
- Most hybrid locations also have high variations in the solar PLF, with at least three months of solar generation that is lower than one standard deviation from the median value in a given year. However, these same locations mostly have a wind PLF higher than 30 per cent, which will likely compensate for the variation in solar generation.
- To achieve 1.5 MTPA through a hybrid RE arrangement, land with a population density of up to 400 people per square kilometre may need to be developed.
- To deploy between 1.5 and 8.5 MTPA potential, land with a population density up to 750 people per square kilometre may need to be used. Additionally, the amount of internal uncommitted water available decreases to 1,500 mcm. At higher volumes beyond 3 MTPA, the number of land conflicts increases to between four and six, and the RE must be deployed in areas with high land prices.
- To increase capacity to 8.5 to 15.5 MTPA annually, land with up to nine conflicts per district will have to be considered.
- To increase production beyond 15.5 MTPA, land with prices as high as INR 23 lakh per acre must be considered. Closer to 30 MTPA, green hydrogen projects will need to be developed in high-risk earthquake zones. The availability of internal uncommitted water decreases to 750 mcm, but it is still not a concern.

Figure ES3 **Scaling up of green hydrogen projects in India will need overcoming multiple challenges**



Source: Authors' analysis

The large-scale deployment of RE for power or green hydrogen will also require a significant amount of land. This could be anywhere between 5.54 and 6.31 per cent of India's landmass for RE power and 2.45 per cent for green hydrogen production. However, the utilisation of rooftop solar and agro-voltaics can, to some extent, mitigate the land usage issue. Furthermore, we expect photovoltaic (PV) panel efficiency to improve in the future, resulting in lower land requirements.

States and union territories should create graded land banks for RE and green hydrogen projects to accelerate India's energy transition

E. Limitations to the analysis

The accuracy of the analysis in this report depends on the quality and vintage of the data that was available in the public domain. There are several limitations to this analysis, as follows:

- **Hyperlocal land variables**: Cultural associations, social status and identity, and tenure can limit access to land. These hyperlocal issues were not captured in this study, although they may have a significant impact on land access for realising RE potential.
- **Land prices**: Land prices are available in the form of circle rates that do not directly reflect the market rate. Besides, there is no uniformity in how data is reported by each of the states and union territories. Hence, sampling circle rates and converting them to lease costs results in uncertainties that cannot be quantified.
- **Land use and land cover**: The land use and land cover (LULC) data come from multiple sources, mostly based on satellite data. However, land use has social nuances such as access and cattle grazing, which can only be captured at the ground level. Hence, the LULC in this analysis does not fully capture the availability of land for RE.
- **Lack of grid network information**: The spatial data for the power grid network is not in the public domain. Although this is perhaps the most important factor in developing RE at scale, we were not able to analyse the implications.
- **Green hydrogen costs**: The LCOH is estimated using a regression model that relies on a limited number of detailed model runs for specific locations across the country (Biswas, Yadav, and Guhan 2020). Conducting a detailed model run for every relevant raster across the country was not possible due to computing constraints. Consequently, there is uncertainty regarding green hydrogen production costs proportional to the error in the regression model. We also do not capture the increased construction costs in areas with higher seismic activity or elevated climate risks.

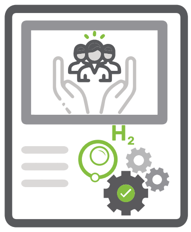
F. Recommendations

- **Validate RE and green hydrogen potential using better quality data and on-ground assessments**: The analysis in this report is limited by the quality of the data used. Land use is dynamic, and some of the data used in this analysis may not reflect current realities. Therefore, on-ground surveys and refinement of the data will yield accurate estimates of RE and green hydrogen potential.
- **Create graded land banks for RE and green hydrogen projects**: States and union territories should establish land banks based on on-ground validation to ensure rapid project development is not hampered to achieve the national targets set for RE and green hydrogen deployment. The land banks can be graded based on the quality of RE, water availability, and connectivity to the power grid and right-of-way (RoW) transport infrastructure such as roads, rail, and pipelines.
- **Encourage the utilisation of existing landholdings for RE development**: Several institutions such as the Indian Railways, public sector undertakings, port trusts, defence establishments, special economic zones, state industrial departments, private industries,

educational institutes, and private trusts hold significant land in the country. They can be encouraged to develop RE for their own use or for transmission to the grid.

- **Evaluate grid infrastructure where there is promising RE potential**: Large-scale deployment of RE may necessitate grid expansion and capacity enhancement. A detailed evaluation is needed to understand where there is promising RE and green hydrogen capacity and how the grid needs to evolve to meet growing power evacuation needs.
- **Evaluate offshore potential, especially for green hydrogen export**: The biggest challenge in tapping offshore wind potential is connecting to the onshore grid. One option to bypass this challenge is to produce green hydrogen and subsequently green ammonia offshore. The green ammonia can potentially be used as a bunkering fuel for ships or exported without the need for bringing it onshore.
- **Evaluate grid resilience and power storage requirements to address seasonality**: With the incremental scaling up of RE, locations with higher seasonality, especially in the case of solar energy, will need to be developed. This will directly impact grid resilience and necessitate storage for load balancing. The seasonality of RE and its implications should be evaluated thoroughly.
- **Evaluate the potential for agro-voltaics, especially in horticultural areas**: About 66,000 GW of solar power potential exists in crop-lands. Not all of these will be suitable for agro-voltaics, but even utilising a fraction of the crop-land for generating RE will substantially contribute to national targets. India had over 28 million hectares of land under horticulture in 2021 with a solar potential of 13875 GW. Agro-voltaics should be explored in crop-lands, particularly in horticultural areas, to increase generation capacity and farmer income (MoA&FW 2021).
- **Prevent desertification that will limit access to RE**: Over 16,980 square kilometres of land in Rajasthan, with the best RE potential of 832 GW, is desert. The expansion of deserts will be detrimental to the development of RE. Therefore, measures to halt the growth of desertification, such as the development of green walls or the remediation of wastelands adjoining deserts, should be considered.
- **Mechanism to address social impact**: More than half of the total onshore wind and solar potential is located in districts that have experienced at least one social conflict related to some form of development project. We can expect these conflicts to increase with larger-scale RE deployment. Therefore, a formal mechanism is needed to involve all stakeholders in project development to avoid conflicts.
- **Develop water management policies specifically for energy production**: Currently, there is no category for water allocation for energy production; it is instead captured under the industries category. Therefore, water allocation for green hydrogen production needs to be prioritised through a revision of existing water policies at the central, state, and union territory level.
- **Assess the need for developing surface water storage**: In districts where internal uncommitted surface water is available for transfer to green hydrogen plants, assessments are needed to determine whether water can be allocated from existing surface water storage facilities such as reservoirs. If not, additional storage facilities need to be created.

India has significant RE generation and green hydrogen production capacity to transition the country to net-zero and improve energy security. However, it will require careful long-planning and policy support to achieve this objective.



A formal mechanism to address social impact of RE and green hydrogen projects will help mitigate land and water conflicts

Green hydrogen will help India achieve the climate goal of net-zero emissions by 2070 and strategic goal of energy independence by 2047.

Image: Alamy

1. Introduction

As per its updated Nationally Determined Contributions (NDC), India aims to reduce the emissions intensity of its gross domestic product (GDP) by 45 per cent by 2030 from the 2005 level and achieve 50 per cent non-fossil installed capacity by 2030 (Government of India 2022). India has also committed to achieving net-zero emissions by 2070. Realising these climate goals will require significant decarbonisation of all end-use economic sectors, which can only be achieved through the use of alternative fuels and the deployment of RE. It is estimated that achieving net-zero emissions by 2070 will require a solar capacity of over 5,600 GW and a wind capacity of ~1,800 GW (Chaturvedi and Malyan 2022). In the short term, India has set a target of deploying 500 GW of non-fossil capacity by 2030 (PIB 2023). It also aspires to be energy-independent by 2047 (PIB 2021).

Land and water requirements for green hydrogen projects will have operational and social implications in India

Green hydrogen offers India an opportunity to reduce its dependence on imported fossil fuels, especially while decarbonising hard-to-abate sectors such as the steel and chemical industries, and to meet the energy demand with RE sources. The *National Green Hydrogen Mission* (NGHM) targets producing 5 MTPA of green hydrogen by 2030. Setting up 5 MTPA of green hydrogen projects is expected to require a RE capacity of 100–125 GW (Ministry of New and Renewable Energy 2023). Furthermore, India is expected to deploy ~30 million tonnes of green hydrogen production capacity by 2050 (Kowtham, Pranav, and Clay 2022).

Land is a key requirement for establishing RE plants, especially solar power projects. Green hydrogen is produced from water using RE. Therefore, in addition to land, water is also a critical resource that needs to be considered for the production of green hydrogen. Sourcing land for RE and green hydrogen production may be difficult in industrial areas, while water can be a constraint in arid and semi-arid areas that may have optimal RE. In this context, it is important to explore the RE–green hydrogen–land–water nexus, henceforth referred to as the 'nexus', so that stakeholders are aware of the operational and social implications of a transition to a green energy-driven economy. This study is an attempt to examine this nexus.

RE is key to India achieving its climate and strategic goals. Therefore, it is important to evaluate the total RE potential in the country before evaluating the nexus with land and water. While some studies have estimated the RE potential in India (Jain, et al. 2020; Deshmukh, et al. 2019), this study is distinct due to three factors. First, it goes beyond the technical and land availability aspects that were key driving parameters in earlier studies and focuses on other key parameters like climate risks and land prices that drive LCOE and LCOH. Second, the raster size used for the spatial analysis in this study (5 × 5 kilometres) is much more granular compared to other studies (100 × 100 kilometres). Third, this is the first study that uses RE potential estimates to evaluate green hydrogen production potential in the country.

In addition to land and water availability in India, which present their own challenges in meeting RE and green hydrogen production targets, social, economic, and topographic factors also necessitate serious trade-offs and considerations. For instance, there may be areas where land is available at affordable rates, but water availability for green hydrogen production is limited and vice versa. Similarly, affordable land may be located in flood-prone regions. Likewise, cheap land categorised as wastelands might actually have ecological or social significance. These trade-offs limit the effective availability of land and water, as was clearly seen in the case of Charanka Solar Park in Gujarat (Nair 2022), which faced a number of court petitions from communities whose livelihoods depended on the land that was categorised as government wasteland in official records.

The nexus analysis can serve as a guidebook for developing policies to mitigate risks with RE and green hydrogen projects

The nexus analysis is critical for understanding the various trade-offs that are likely to exist when setting up RE or green hydrogen plants in the country. This analysis will serve as a guidebook for all stakeholders, including central and state governments, in developing robust policies. It will also aid project developers in assessing and addressing the various challenges that might arise along with the RE and green hydrogen potential of their projects. It also identifies prospective districts that have relatively favourable conditions for deploying RE or green hydrogen projects.

In this report, Section 2 details the methodology used for estimating RE and green hydrogen potential, as well as the cost of producing power and green hydrogen. Sections 3, 4, and 5 explore the wind, solar, and wind–solar hybrid (WSH) RE potential in India, respectively. Section 6 discusses the land policies for RE projects across various states in India. Sections 7 and 8 provide insights into RE and green hydrogen production costs in India. Section 9 provides a detailed analysis of the nexus and its implications for achieving the country's RE and green hydrogen production targets. Section 10 deliberates on water policies across various states. Section 11 discusses the limitations of the study. Key recommendations are covered in Section 12.

2. Methodology

While solar panels can be installed in hilly areas, regions with slope greater than 20% have been excluded for estimating solar potential.

To fully evaluate the nexus, it is imperative that all relevant influencing parameters are identified and their impact on RE capacity and eventually green hydrogen production are examined. In this context, this study has four broad objectives, listed as follows:

1. Develop national-, state-, and union territory-level estimates of RE and green hydrogen production potential.
2. Evaluate the challenges associated with land availability for setting up or scaling up RE plants.
3. Evaluate water-related challenges and land availability for setting up green hydrogen projects.
4. Understand the confounding effects of various parameters such as climate risk and population density on the ability to develop RE and green hydrogen projects.

The methodology for estimating RE potential is predominantly divided into three parts. Section 2.1 provides key information on the parameters that influence the nexus; Section 2.2 discusses the Geographic Information System (GIS) methodology and how these parameters are spatially attributed; and Section 2.3 describes the methodology for the final data analysis to estimate the RE potential.

Exclusion parameters prevent the deployment while constraint parameters pose challenges for RE and green hydrogen projects

2.1 Parameter identification and description

A number of parameters influence the suitability of land for the commercial deployment of RE and green hydrogen. Some parameters limit deployment, while others pose challenges that increase commercial risks for projects. We have categorised the parameters into two groups as follows.

Group 1: Exclusion parameters

Factors such as land use land cover (LULC), eco-sensitive and military areas, and slopes (>20 per cent per raster) were used to exclude land parcels that are not feasible for the development of RE. Therefore, although these areas might have favourable wind or solar profiles, land in these categories is considered unfavourable for RE deployment, thereby reducing the overall national-, state-, and union territory-level RE potential.

Group 2: Constraint parameters

Land prices, land conflicts, climate risk exposure, seismic zones, and RE plant load factor (PLF) are considered to create various constraining scenarios for RE/green hydrogen projects. These variables, either individually or in combination, will limit the ease with which RE and green hydrogen projects can be deployed and also represent commercial risks for these projects.

Table 1 provides detailed information across five broad parameters: RE capacity, LULC, resource availability, economic aspects, and social aspects. These parameters influence the RE and green hydrogen potential in the country. The significance of each parameter indicates how it is being utilised in the analysis, and the data source identifies the source of the data. Finally, there is a flag indicating whether each parameter will restrict access to RE and green hydrogen resources or act as a constraint.

2.2 Spatial mapping and data extraction on GIS

For all the parameters mentioned in Table 1, pan-Indian data was collected at the district or plot levels (depending on availability) and further spatially mapped into various raster layers. A raster is an image with a two-dimensional rectangular matrix of equal-sized pixels, where each pixel attribute has a certain value. Values are aggregated at 0.01 decimal degrees (~1 kilometre) for consistency across the layers, which are available at more granular levels.

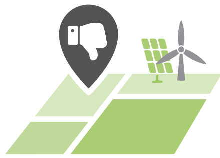
Aggregation is performed such that each cell gets the maximum occurring value from smaller cells. For example, consider an aggregated grid cell that contains 100 smaller divisions, of which 72 cells are categorised as built-up, 20 as bare ground, and 8 as trees. The aggregated cell (size 0.01 decimal degree) will receive the maximum occurring value, which is built-up in this case. Comprehensive steps for data processing in GIS are detailed in Annexure V. We also report a sensitivity analysis of other methods for resampling data in Annexure VI. These layers are then used to extract information for the parameters at 5 × 5 kilometre land parcels. This is the highest resolution possible without substantially increasing computing time requirements. However, we conducted sensitivity analysis at 100 × 100 metres resolution.

Table 1 **A number of exclusion and limiting constraints influence the nexus**

No.	Parameter	Significance	Data source	Exclusion / Constraint parameter
		RE capacity		
1.	Solar potential	The raw data obtained from the Global Solar and Wind Atlas (Annexure I) provides information on the RE PLF across the country.	Global Solar Atlas (n.d.)	NA
2.	Wind potential		Global Wind Atlas (n.d.)	NA
		Land characteristics		
3.	Land use land cover (LULC)	The LULC data is used to exclude land types that are not suitable for setting up RE and green hydrogen plants. These land types include built-up areas with existing infrastructure, snow, water bodies, tree cover, and flooded vegetation (Annexure II).	ESRI (n.d.)	Exclusion
4.	Slope	As RE infrastructure is difficult to install in hilly areas, regions with slopes greater than 20 per cent have been excluded. The slope is calculated based on the rate of change of the digital elevation model (DEM) cell.	USGS (2023)	Exclusion
5.	Ecological sensitive and defence no-go areas	This data is used to exclude areas in protected forests and areas reserved for defence purposes where RE development is not permitted.	DGH (2020)	Exclusion
6.	Seismic zone	Data related to seismic zones is used to identify and quantify RE and green hydrogen potential in areas with high seismic activity (Annexure III).	Institute of Engineers (2004)	Constraint
7.	Climate exposure zones	The climate exposure data is used to identify districts prone to floods or cyclones and assess the RE potential in addressing this challenge.	Mohanty and Wadhwan (2021)	Constraint
		Resource availability		
8.	Internal uncommitted water availability	Water is a key resource for green hydrogen production. Internal uncommitted water can be defined as the outflow from the landscape (basin, sub-basin, or administrative unit) after meeting all existing demands but it does not discounts for the downstream water requirements (Annexure IV). It should be noted that the water returned to the natural systems, such as groundwater and surface water sources, after meeting the sectoral demands (or consumptive part), needs to be treated before being reused.	Authors' estimation	Constraint
9.	Gas pipelines	Existing and under-construction gas pipelines will provide a right-of-way for transporting green hydrogen through these pipelines. The data helps identify access to gas pipelines (see Annexure III).	PNGRB (2021)	Constraint
		Economic factors		
10.	Land prices	Land prices determine the economic viability of RE projects. Circle rates are obtained from state and union territory's government websites and normalised against land prices in existing solar locations to obtain market values.	Respective state and union territory websites	Constraint
		Social factors		
11.	Population density	The potential for RE and green hydrogen will be constrained by population density. Areas with high population density will face resistance to RE and green hydrogen projects because people's lives and livelihoods will depend on the land.	MoHFW (2020)	Constraint
12.	Land-related conflicts	Areas with more land-related conflicts will encounter social challenges when establishing RE plants.	Land Conflict Watch (2022)	Constraint

Source: Authors' compilation

Individual criterion maps were then combined to create composite outputs that show the overall suitability of each location for setting up RE and green hydrogen plants.



RE potential is estimated by excluding land types not suitable for setting up solar and wind power plants

2.3 Data analysis

This subsection delves into the approach used for analysing the RE potential in the country. The research related to data analysis was divided into two stages. First, we used the RE potential data from the Global Solar (Global Solar Atlas n.d.) and Wind Atlas (Global Wind Atlas n.d.) and various exclusion layers to estimate the realisable or constrained RE potential in the country. Subsequently, we considered the constraints to understand their implications for the cost of producing RE and green hydrogen and assessed the nexus by considering other parameters such as climate risk.

RE potential calculation

The RE potential was obtained by excluding the land types unsuitable for setting up solar and wind power plants. The various steps involved in this exclusion process are listed as follows.

Step 1: The first step involved excluding no-go zones in the country. This included land areas in reserved and protected forests or military zones where development is restricted. This reduced the RE potential in the country. The state and union territory-wise solar and wind potential is indicated in Annexure VII.

Step 2: In the base case, we consider that wind projects are not commercially viable in areas with a PLF lower than 30 per cent. Therefore, the wind potential in the study corresponds to wind capacity with a PLF greater than 30 per cent, both for standalone wind potential and wind–solar potential. We also conducted a sensitivity analysis to estimate variations in wind potential with different cut-off PLFs (Annexure VIII).

Step 3: In this step, we excluded areas with LULC constraints, including water bodies, snow cover, flooded vegetation, cloud cover, and dense tree cover. Since the analysis focuses on large-scale RE projects, we did not consider rooftop potential and micro wind turbines, thereby excluding built-up areas. We also excluded desert areas in Rajasthan by removing the bare ground category in districts where sandy areas account for more than 90 per cent of the bare ground category.

Step 4: Finally, we excluded areas with slopes greater than 20 per cent to avoid hilly terrains as RE plants cannot be set up in these areas, and they pose challenges for developing and maintaining storage and transmission infrastructure.

This exclusion process resulted in the final land area available for setting up RE plants. This area was then multiplied by RE land requirement factors to determine the RE potential. The land use factors for solar and wind plants are 49 MW (SECI n.d.) and 9 MW (Deshmukh, et al. 2019) per square kilometre of land, respectively. A sensitivity analysis for alternative factors is provided in Annexure IX.

Step 5: Understanding the constraints on RE potential exploitation

The second stage includes understanding the impact of constraint parameters on RE potential. For some constraint parameters, such as seismic zones, population density, and land conflicts, RE potential was assessed for various values to understand the extent of the challenges these parameters pose. In another set of analyses, two constraint parameters—land prices and climate exposure—were jointly considered to understand the distribution of RE potential across the combination of different values of these two parameters. After excluding all the unsuitable land types, the resulting RE potential was plotted separately against land prices and climate risk. For each plot, inflection points were identified, and these parameters were divided into brackets, ensuring that all brackets have relatively equal RE potential. The details of this process are provided in Annexure X. These brackets are subsequently used to understand the constraints on RE potential within each bracket.

Land cost and solar/wind PLFs impact the cost of producing power and hydrogen across the country

2.4 Estimating levelised cost of electricity and levelised cost of hydrogen

The LCOE and LCOH will vary across India primarily due to changes in solar and wind PLFs and the cost of land. However, all other costs, such as solar PV module and engineering, procurement, and construction (EPC) costs, are considered to remain the same across different states and union territories. Variations in RE PLFs across the country is obtained from the Global Wind and Solar Atlas (Annexure I). The unavailability of land and high land prices are impediments to the rapid growth of RE in India. In this analysis, we use circle rates from state and union territory government portals (Annexure XI) and normalise them using land prices recorded for existing solar PV projects. For existing projects, we consider an average lease rate of INR 37,500 per acre with a 5 per cent escalation every year (Dutt, et al. 2021). The LCOE is obtained based on the solar and wind capital and the operational cost assumptions listed in Annexure XII. In addition to the CapEx and OpEx of solar and wind plants, the LCOE also depends on the RE PLF and the land cost, which are factored into the analysis.

To estimate the LCOH, we consider an islanded system without any grid interaction. Therefore, the hydrogen cost indicated in the study reflects the on-site production cost, excluding any open access charges or RE banking. The LCOH includes the cost of RE electricity, electrolysers, hydrogen storage units, and water. The cost of green hydrogen as a function of these variables is obtained based on insights from our previous study (Biswas, Yadav, and Guhan 2020). The LCOH at each location is best calculated using wind and solar profiles for 8,760 hours for the desired locations. However, given the large number of locations considered in the study and the challenges associated with heavy computational requirements, this study relies on a regression analysis that links the cost of green hydrogen with the LCOE, electrolyser cost, and other parameters. A detailed discussion is provided in Annexure XIII.

The water requirement for green hydrogen projects varies from 13 to 27 litres per kilogram of green hydrogen output (Ohmium 2022; Plug Power 2022). Water is also needed for cleaning the solar panels used for generating power for electrolysers. As a conservative estimate, we assume a water requirement of about 37 litres per kilogram of green hydrogen output. The methodology used for estimating the water requirement and its implications for green hydrogen production costs is discussed in Annexure XIV.

India has an offshore wind potential of 2,435 GW, of which only 737 GW is at depths less than 500 meters.

Image: Alamy

3. Wind potential

India is blessed with both onshore and offshore wind power. This section discusses the findings on India's wind potential after excluding the parameters indicated in Table 1.

India has an onshore wind potential of 1,790 GW for a hub height of 100m and PLF cut-off of 30%

3.1 Onshore wind potential

This section discusses various nuances of onshore wind potential. As discussed earlier, the distribution of wind PLF across the country is obtained from the Global Wind Atlas (Global Wind Atlas 2023). In the base case, we assume a hub height of 100 metres and a cut-off wind PLF of 30 per cent. We also separately indicate the variation in wind capacity with changing cut-off wind PLF (Annexure VIII).

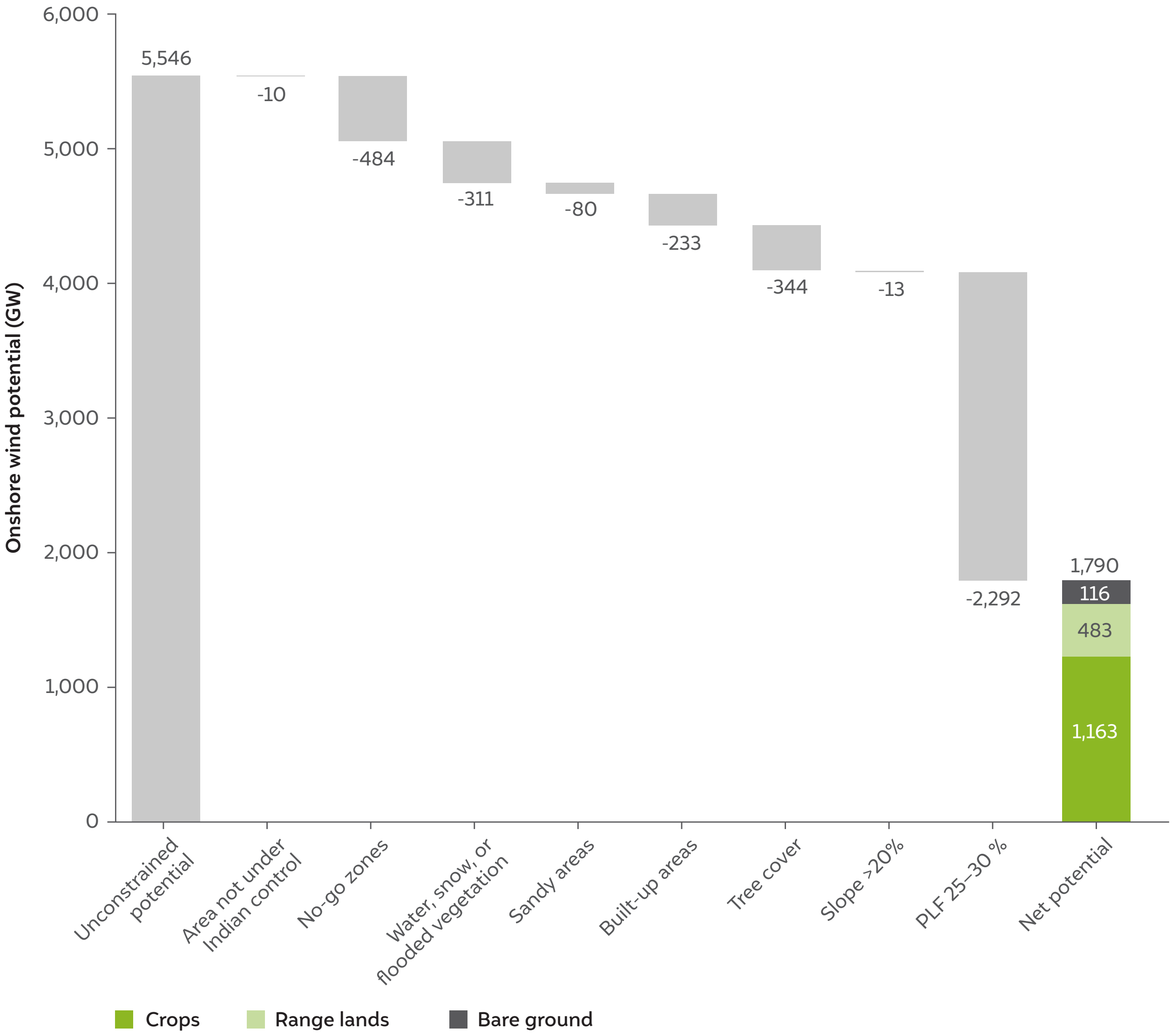
We find that India has an unconstrained wind potential of 5,546 GW. The wind potential in the country is derived after excluding Pakistan-occupied Kashmir and China occupied land in the Union Territory of Ladakh. After applying exclusion parameters such as no-go zones, areas under water/snow, built-up areas, tree cover, and steep slopes (more than 20 per cent), the net onshore wind potential in India is estimated to stand at 1,790 GW (Figure 1). The literature estimates wind potential to be around 3,102 GW (Jain, et al. 2020), which is higher than our estimate. This discrepancy can potentially be attributed to a wind PLF cut-off of 14 per cent, which is significantly lower than the 30 per cent considered in the study. Additionally, this potential is estimated for a hub height of 90 metres (compared to 100 metres in our estimate) and a land requirement of 85 acres per MW (compared to ~28 acres per MW in our estimate).

About 66 per cent of the total onshore wind potential across different land types is in crop-lands. If this potential is to be exploited, then we need to be aware of the possible losses in food production and other agriculture-related activities. Despite the challenges in deploying infrastructure in crop-lands, we include wind potential in these areas, because wind turbines can coexist within cropped lands as their direct ground footprint is relatively smaller than their aerial footprint. This is followed by 27 per cent and 7 per cent potential in rangelands and bare ground, respectively. The theoretical definitions of these land categories are provided in Annexure II. While these are technical definitions, they might not reflect land tenure-related[1] aspects and could trigger disputes during land procurement if an adequate social impact assessment is not carried out.

1. Rules define the ways in which property rights to land are allocated, transferred, used, or managed in a particular society.

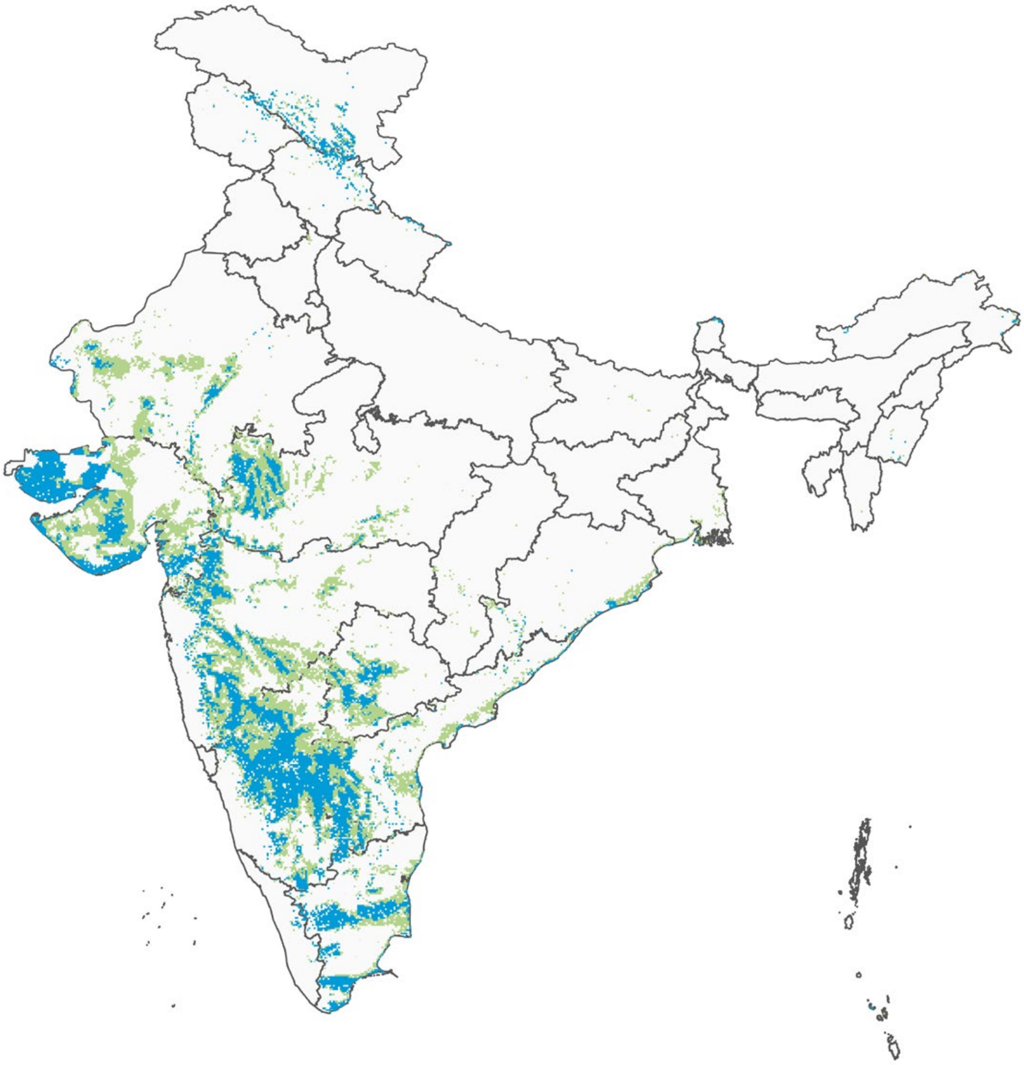
Figure 2 shows the spatial distribution of wind potential across the country. In India, wind potential is concentrated in the western and southern states. The highest wind potential is observed in Gujarat, followed by Karnataka, Maharashtra, Andhra Pradesh, and Tamil Nadu. The state and union territory-wise distribution of wind potential for select states and union territories is provided in Annexure VII. Our analysis indicates that the wind potential increases to 4,167 GW with a wind PLF cut-off of 25 per cent (Annexure VIII) as more land area becomes available.

Figure 1 Wind potential in India is 1,790 GW



Source: Authors' analysis

Figure 2 **Onshore wind potential in India is concentrated in the western and southern parts**



Wind potential above PLF 30%　　Wind potential between 25% and 30%

Source: Authors' analysis

Constraints in onshore wind potential exploitation

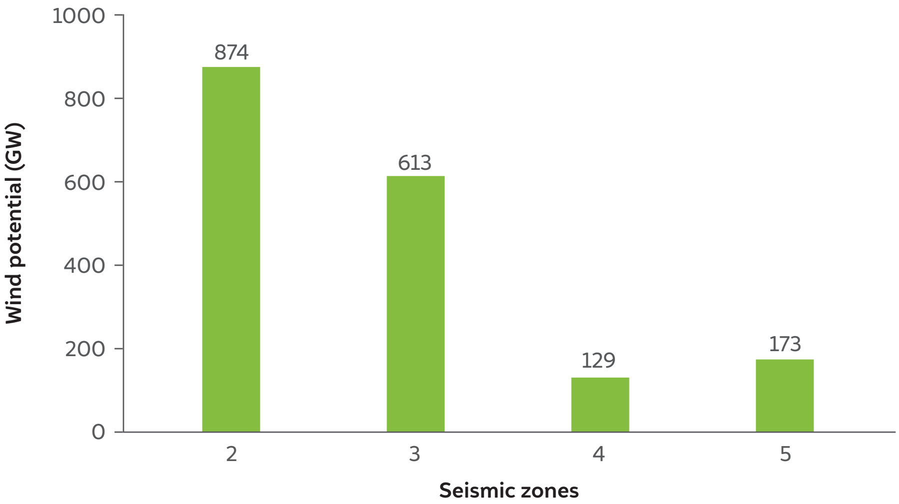
With an understanding of the theoretical net onshore wind potential in the country, this section delves into the constraining parameters, such as seismic risks, population density, and land conflict risks. We estimate that 173 GW of wind potential is in earthquake-prone areas (seismic scale 5[2]) (Figure 3), indicating potentially high infrastructure resilience–related costs in these regions. High population density can pose a greater risk of conflicts.[3] The analysis indicates that around 41 per cent of wind potential (732 GW) is in areas with a high population density of over 400 people per square kilometre, posing a potential risk of mobilisation against the development of wind power projects (Figure 4).

2. Seismic zones in India are divided across five zones with zone 5 having the most risk.
3. The population density brackets are estimated based on inflection points, and the details are mentioned in Annexure X.

Another constraint parameter considered in the analysis is the number of historical and ongoing land-related conflicts in the country, which serves as a proxy for potential future conflicts in those regions. Around 19 per cent of the total wind potential is located in high-conflict districts (Figure 5), which have experienced more than three conflicts.

An important point to note is that the absence of conflicts currently does not imply that there will be no conflicts in the future when the plants are installed. For instance, 31 per cent of existing wind plants in the country are in areas with three or more land conflicts. Therefore, we can expect an increase in conflicts as the scale of RE ramps up. The brackets for wind potential across various population zones and land conflicts were obtained from an inflection analysis that is explained in Annexure X.

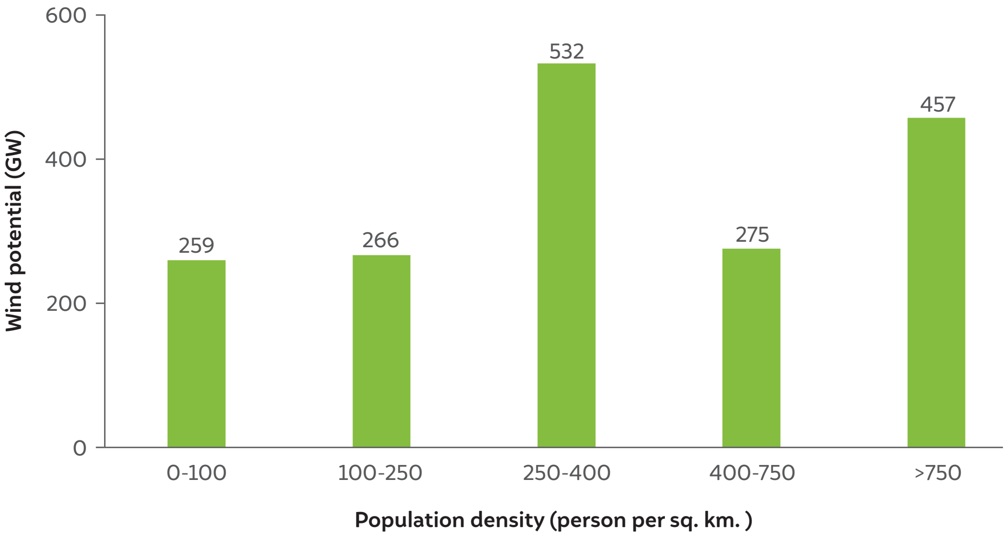
Figure 3 More than 83% of India's wind potential is in low seismic zones (GW)



Source: Authors' analysis

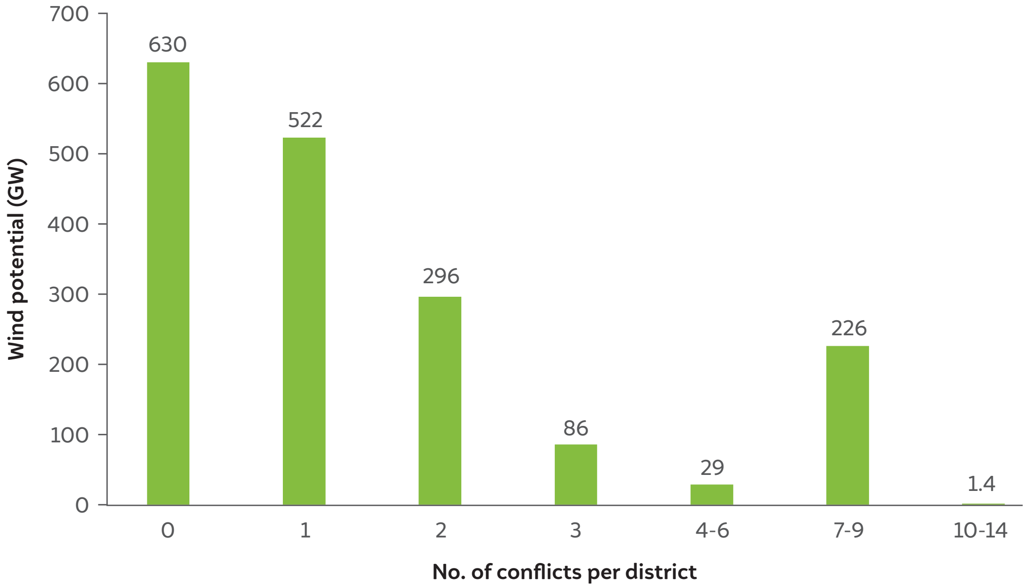
Note: India falls under only four seismic zones—2, 3, 4, and 5—and does not have any area classified as seismic zone 1.

Figure 4 About 60% of India's wind potential is in areas with low population density



Source: Authors' analysis

Figure 5 **Significant wind potential exists in areas with fewer current land conflicts**

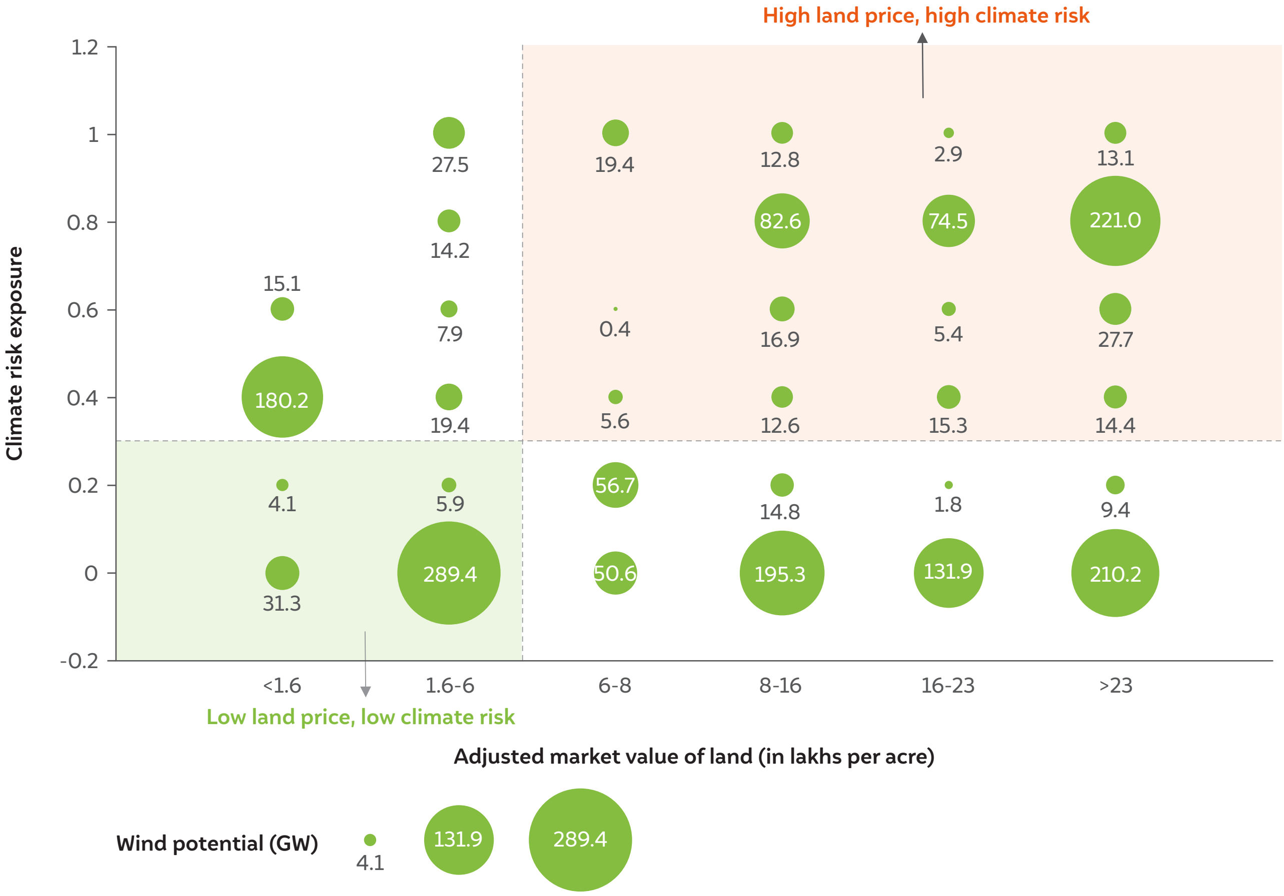


Source: Authors' analysis

Land price and climate risk will be the key constraints in realising the potential of onshore wind power in India. To assess the impact of these factors on onshore wind potential, we divide the two parameters into low- and high-value brackets. Land prices below INR 6 lakh per acre are considered in the low-value bracket, as they will have minimal implications for the cost of wind power generation. Similarly, climate risk values lower than 0.2 are considered to be in the low-value bracket. For context, a value of 0 indicates that the district has not been affected by any extreme weather events, in contrast to a value of 1, which indicates that the district has experienced the maximum number of such events in the past. More details are provided in Annexure III.

According to the analysis, only 331 GW of wind potential is in areas with low land prices and low climate risk (shaded in green) (Figure 6). Areas with high land prices and high climate risk (shaded in orange) account for 525 GW (29 per cent) of the total wind potential. However, a significant share of the wind potential in India is located in low climate risk zones. Therefore, realising this potential might not be a challenge from a climate risk perspective. However, the cost of generation might be an impediment due to higher land costs. It should be noted that the climate risk exposure cannot index cannot be a negative value and a negative axis is indicated only for better visibility of the bubbles shown in Figure 6.

Figure 6 **The wind potential, land prices, and climate risk exposure nexus indicate that 29% of the potential is in areas with both high land prices and high climate risk**



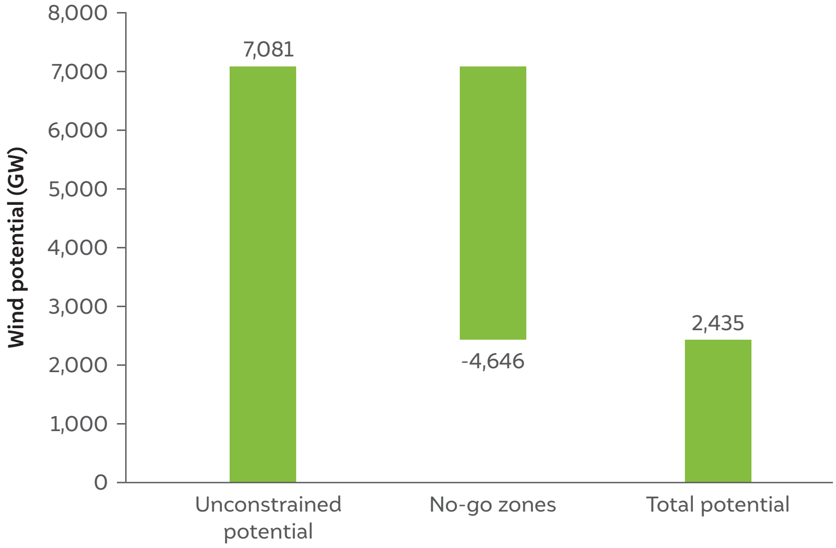
Source: Authors' analysis

3.2 Offshore wind potential

Offshore wind can prove to be more effective than onshore wind primarily due to a higher PLF. The offshore area within India's jurisdiction is defined by *Territorial Waters, Continental Shelf, Exclusive Economic Zone, and Maritime Zones Act, 1976*. The limit of this zone is 200 nautical miles from the coast. Therefore, in the study, we estimate India's offshore wind potential considering the 200-nautical-mile limit. We find that the total unconstrained offshore wind potential in India is around 7,081 GW. After excluding no-go zones (with around 4,646 GW potential), we estimate the offshore wind potential to be 2,435 GW (Figure 7).

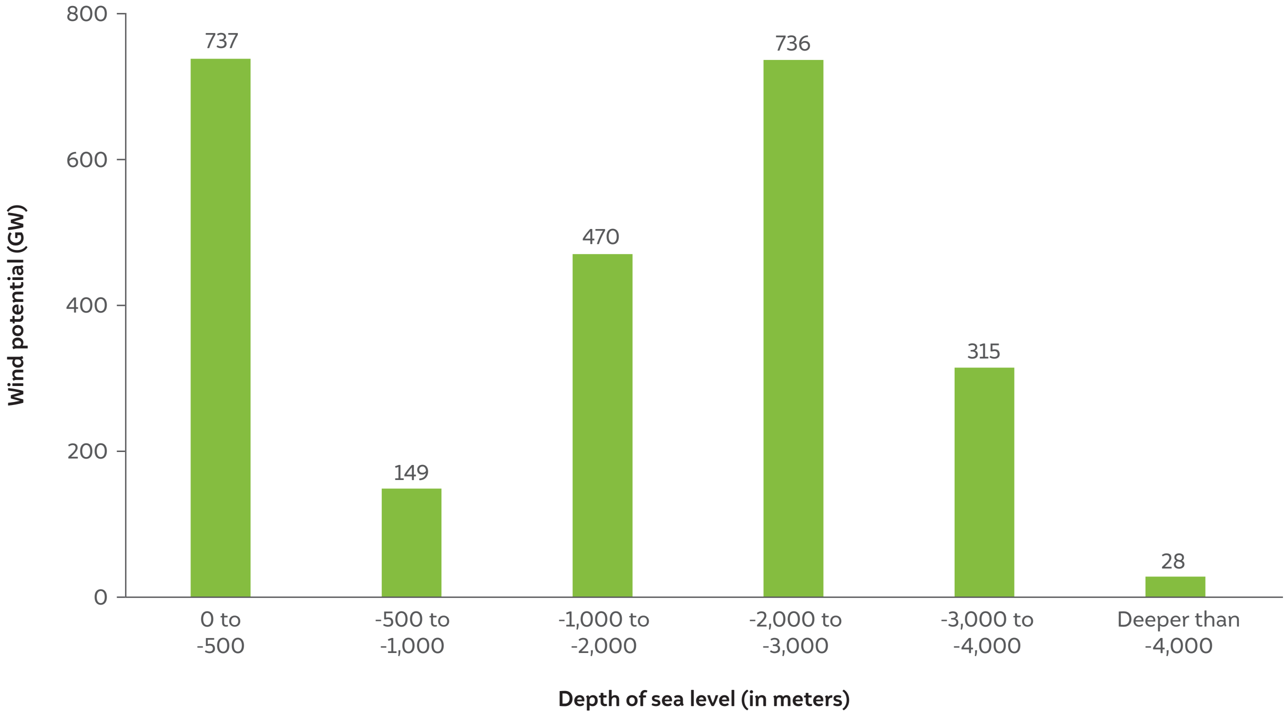
Offshore wind potential exceeds onshore potential, indicating the need for increased efforts and policies in this area. The higher offshore potential also suggests the possibility of producing green ammonia from wind energy offshore and subsequently transporting it via sea routes. It should be noted that around 737 GW of the constrained offshore potential is in shallow waters of less than 500 metres depth (Figure 8), indicating a relatively lower cost for exploiting this potential. As evident from Figure 9, the shallow seas are closer to the coast and therefore may also have lower power evacuation costs. However, one challenge that can limit this potential is fishing activity and the presence of ecologically sensitive zones in these regions. This can possibly conflict with fishing rights that communities might have in these areas.

Figure 7 India has an offshore wind potential of 2,435 GW at a hub height of 100 metres and PLF >30%



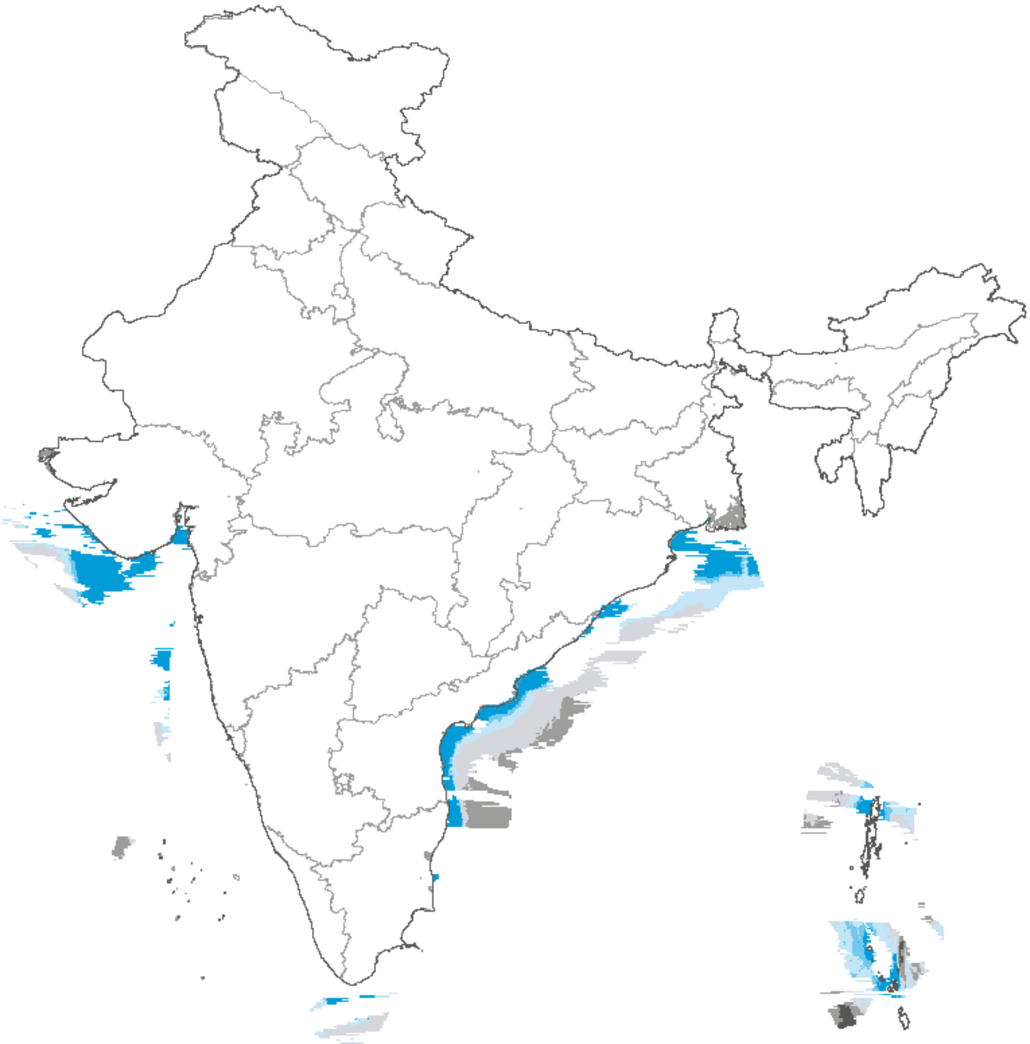
Source: Authors' analysis

Figure 8 Only 30% of offshore wind potential is at depths less than 500 meters

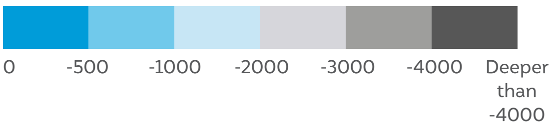


Source: Authors' analysis

Figure 9 **Gujarat and the east coast have significant offshore wind potential in the country**



Depth from sea level in meters



Source: Authors' analysis

4. Solar potential

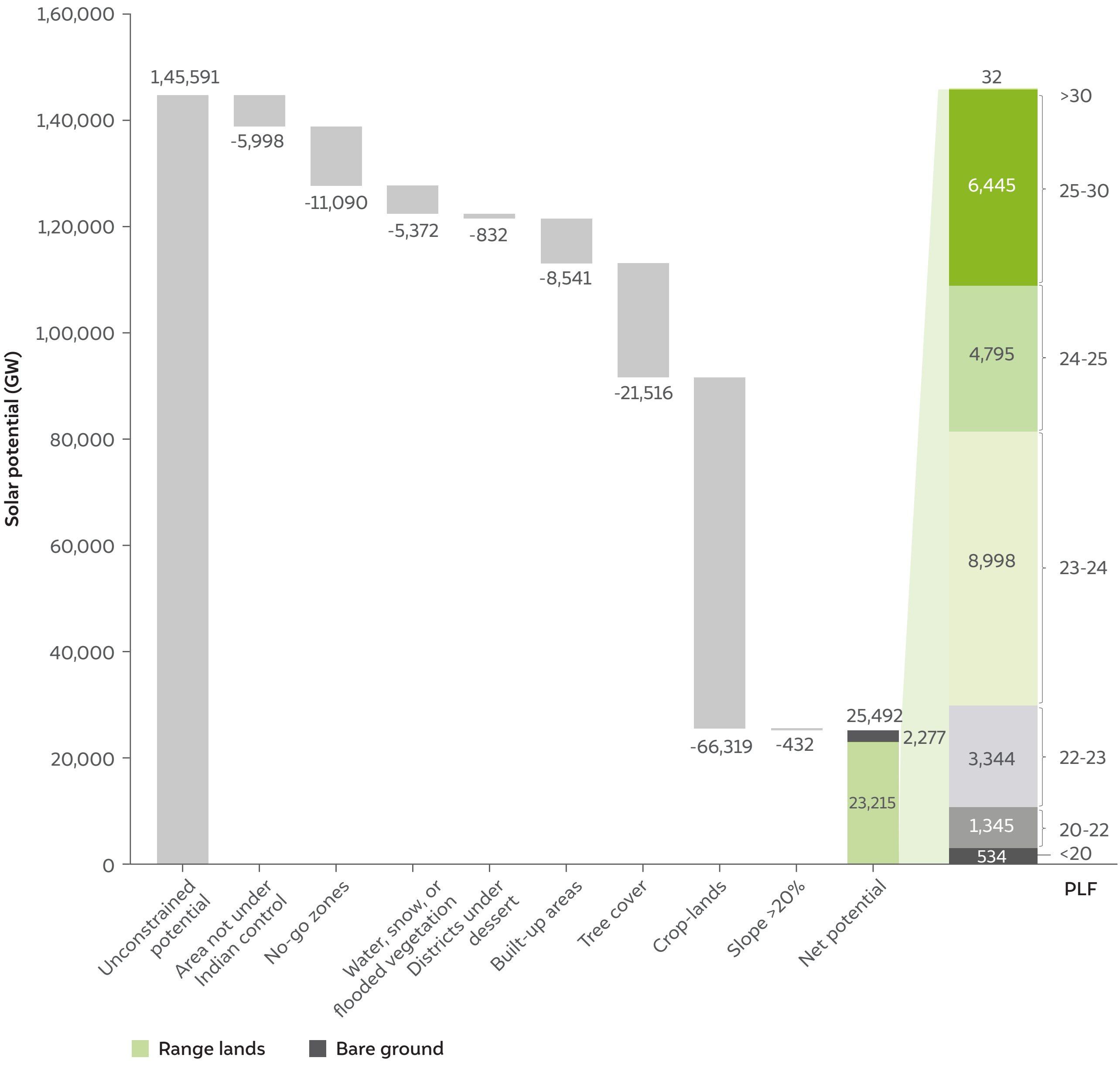
Solar power projects require large amounts of land - up to 5 acres/MW.

The PLF of solar power varies across the country. Information on spatial variations in solar PLF is obtained from the Global Solar Atlas (Global Solar Atlas n.d.). The solar potential in the country is derived after excluding Pakistan-occupied Kashmir and China occupied land in the Union Territory of Ladakh, no-go zones, water/snow-covered areas, forests, built-up areas, sandy regions, and crop-lands. We estimate the net solar potential in India to be 20,270 GW for a PLF greater than 23 (Figure 10). This solar PLF corresponds to a 30 per cent oversizing on the direct current (DC) side. Realising the solar potential of 20,270 GW would require approximately 13 per cent of the country's total land area.

The assessment indicates that rangelands account for 91 per cent of the net solar potential and are preferred for setting up solar power projects. Bare ground accounts for 9 per cent of the solar capacity. Rangelands include a large proportion of wasteland categories (for definitions, see Annexure II), which are defined as land that is currently lying unutilised due to different factors and is a preferred land type for RE developers. While rangelands account for most of the solar potential, it is important to ascertain the livelihood dependence of inhabitants on such lands to limit the likelihood of any conflicts during the acquisition process.

The state and union territory-wise potential shown in Figure 11 indicates that most of India's solar potential is found in Rajasthan, followed by Madhya Pradesh, Maharashtra, Odisha, and Gujarat. Additionally, Rajasthan's solar potential is the most clustered, making it the ideal state for setting up large-scale solar plants or parks. Details of the state and union territory-wise solar potential can be found in Annexure VII.

Figure 10 India has a solar potential of 20,270 GW with a PLF exceeding 23% (for 30% oversizing)

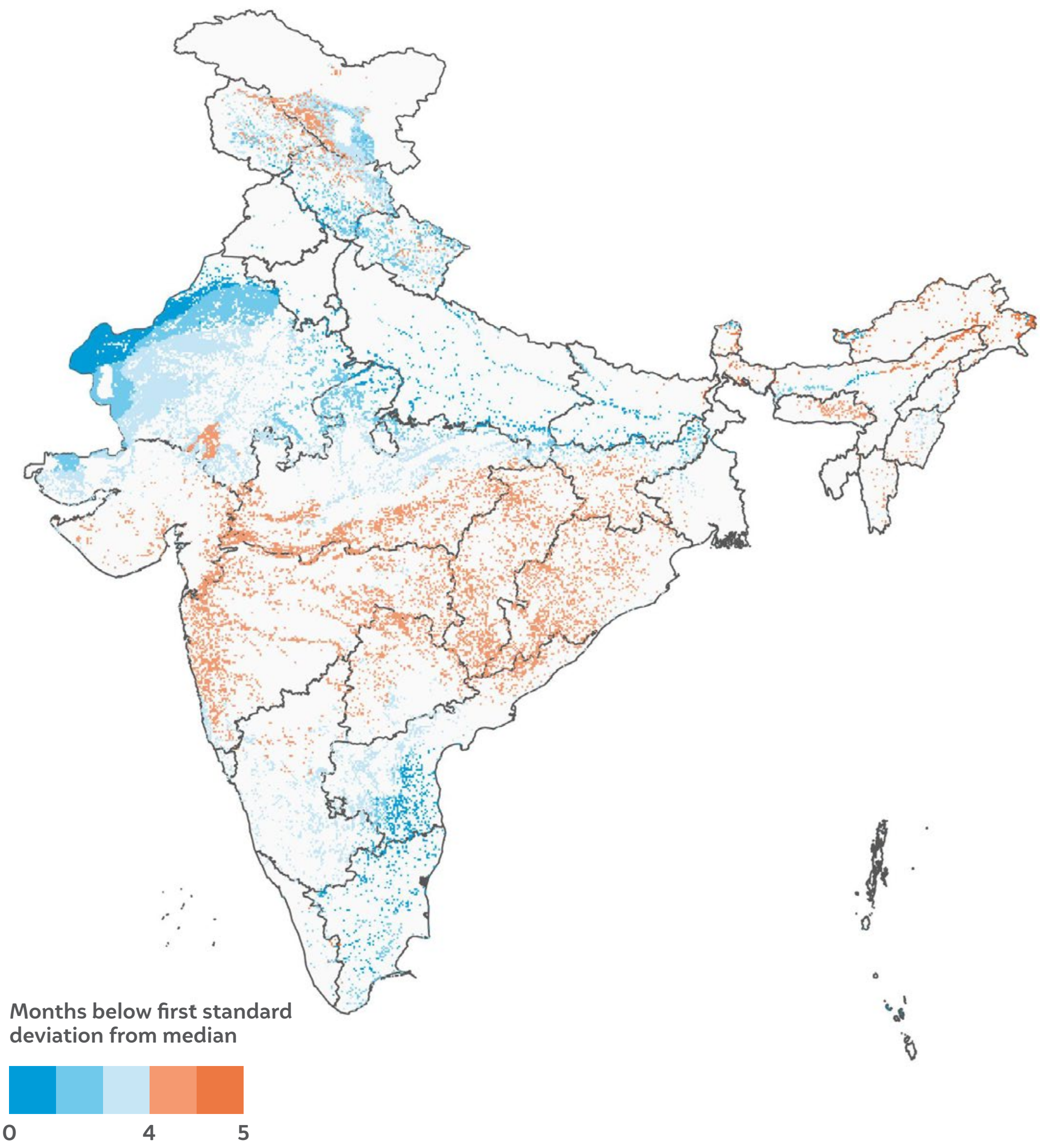


Source: Authors' analysis

Although solar power is available across most states and union territories in India, some regions experience significant seasonal variations in solar power output due to heavy monsoons (in southern and western India) or smog during winter (in northern India). Figure 11 shows that the entire solar potential in western, central, and eastern India faces high seasonality in the availability of solar power with 3 to 5 months in a year falling below the first standard deviation from the median PLF.

Figure 12 plots the number of months falling below the first standard deviation from the median solar PLF for each raster. It can be observed that significant solar capacity across various PLFs is three or more months below the first standard deviation from the median PLF. This implies that these areas experience considerable variations in solar power output throughout the year. This will have additional repercussions for grid balancing. Power generators and discoms will have to consider seasonal variations in addition to diurnal variations in solar power output.

Figure 11 Most states and union territories in India have significant solar potential, but states like Maharashtra, Telangana, Chhattisgarh, and Odisha face high seasonality in solar PLF



Source: Authors' analysis

Note: This figure represents the total solar potential of 25,492 GW without considering any PLF cut-off criteria.

Figure 12 **17,802 GW of solar capacity in the country experiences significant seasonality (more than three months with PLF below one standard deviation from the median PLF)**

Source: Authors' analysis

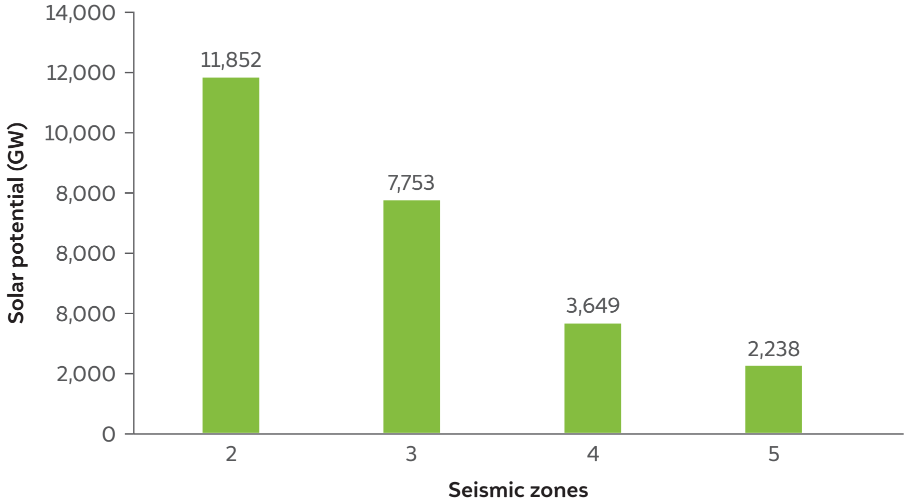
Note: This figure represents the total solar potential of 25,492 GW without considering any PLF cut-off criteria.

4.1 Constraints in solar potential exploitation

This section focuses on understanding the constraints in realising the solar potential across the country. The mapping of solar potential across different seismic zones shows that around 8.8 per cent (2,238 GW) is in seismic zone 5 (Figure 13), indicating a high risk of earthquakes. This includes areas in Gujarat (1,329 GW) with significant solar potential. However, more than 19,000 GW of solar potential is in areas categorised as seismic zones 2 and 3. Therefore, while high seismic zones do constrain the solar potential in India, they will not be an impediment for India to achieve its net-zero goals.

Regarding the nexus between population density and solar potential, the analysis shows that India has a solar potential of over 6,700 GW in areas with a population density below 250 people per square kilometre (Figure 14). These assessments are based on the 2023 population projections from the National Commission on Population, Ministry of Health & Family Welfare (MoHFW 2020), and the population in the country is expected to continue increasing for a few more decades. Nevertheless, as India strives to meet its climate goals, accessing areas with low population density will be challenging for setting up solar power projects due to limited access to land resources.

Figure 13 More than 19,000 GW of solar potential is located in seismic zones 2 and 3

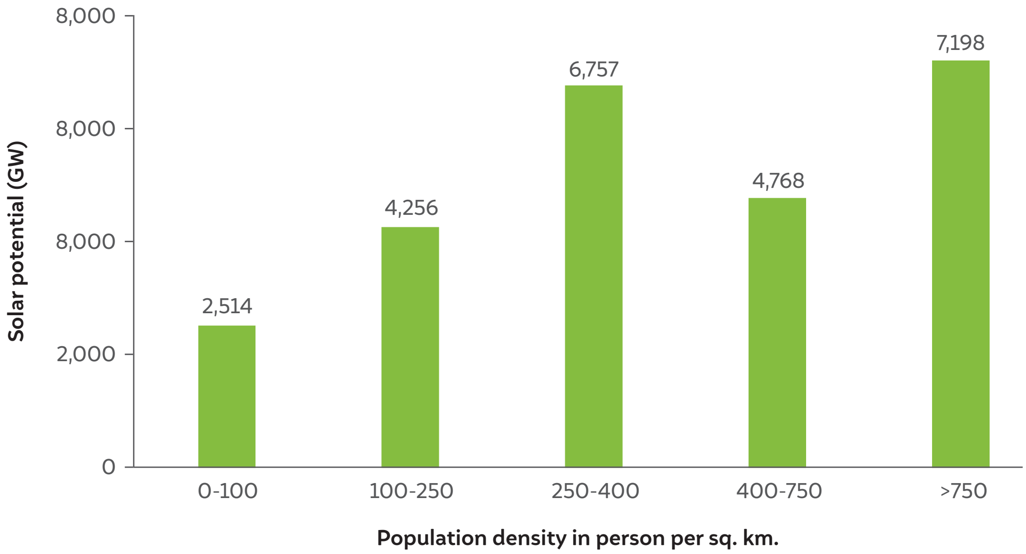


Source: Authors' analysis

Note:

i. India falls into only four seismic zones—2, 3, 4, and 5—and does not have any areas in seismic zone 1.
ii. This figure represents the total solar potential of 25,492 GW without considering any PLF cut-off criteria.

Figure 14 Over 6,700 GW of solar potential in areas with a population density below 250 people per square kilometre

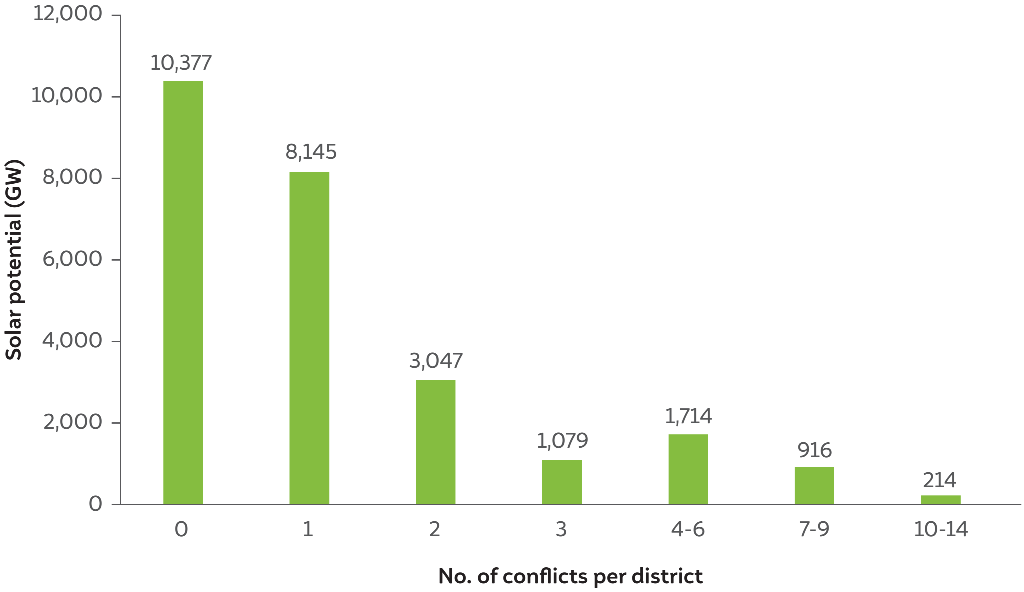


Source: Authors' analysis

Note: This figure represents the total solar potential of 25,492 GW without considering any PLF cut-off criteria.

Regarding land conflicts, the analysis shows that 40 per cent of the total potential is in districts with no ongoing land conflicts, while 15 per cent of the potential is in high-conflict areas (with more than three conflicts) that might pose a challenge for scaling up solar power plants (Figure 15). Although land conflicts may not be a significant impediment for setting up solar power plants today, fewer conflicts in high-potential areas cannot be taken as a conclusive trend and do not imply that these areas will always be free of conflicts. As solar project development scales up in these potential areas, new conflicts may arise. A closer look at existing plants reveals that approximately 12 per cent of the total existing solar plants in India are located in high-conflict zones, with more than three conflicts, which might increase in the future.

Figure 15 Over 15% of India's solar potential is in high land conflict areas



Source: Authors' analysis

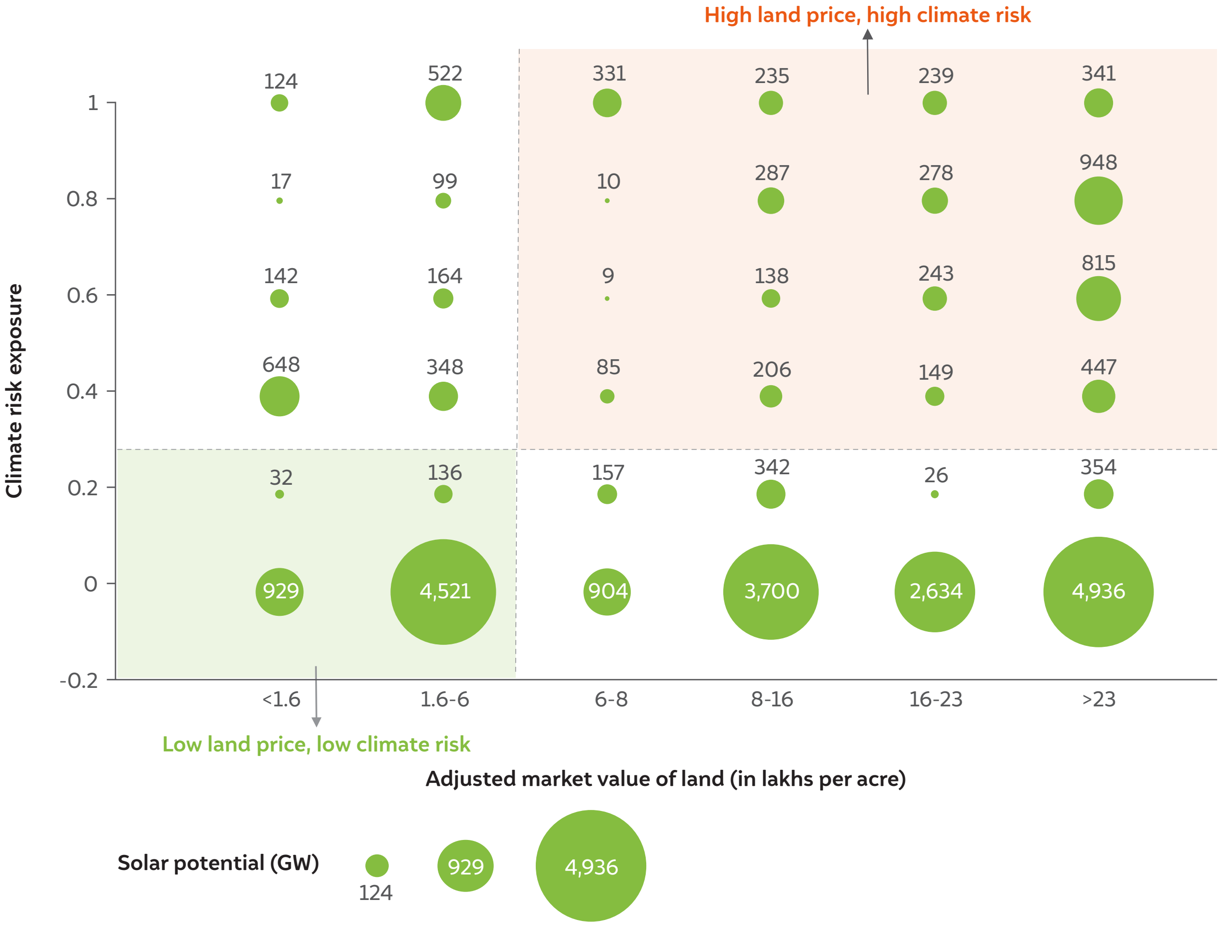
Note: This figure represents the total solar potential of 25,492 GW without considering any PLF cut-off criteria

Land prices and climate risk pose significant challenges for setting up solar power projects in the country. To further understand this nexus, the distribution of theoretical solar potential was assessed across these parameters, as shown in Figure 16. The solar potential distribution across these brackets is obtained from an inflection analysis. As the first step, the cumulative solar potential was plotted against each parameter. Thereafter, inflection points were identified where small changes in parameters resulted in a significant increase in potential. With these multiple inflection points, the entire data was then divided into brackets, such that each bracket had approximately equal potential. Subsequently, the cut-off values were identified for the parameters to indicate and quantify the extremities. A detailed discussion of the methodology is explained in Annexure X.

Similar to the case of onshore wind, land prices below INR 6 lakh per acre are assumed to fall into a low-value bracket. Climate exposure values lower than 0.2 (ranging from 0 to 1) are considered low exposure. These values for climate exposure are derived from an analysis by the authors, which estimated district-level exposure to hydro-meteorological disasters based on historical data (Mohanty and Wadhwan 2021). The normalised values of this measure range from 0 to 1, with values from 0 to 0.2 reflecting low exposure areas. Further details are provided in Annexure III.

Approximately 5,618 GW (22 per cent of the total potential) of solar potential is in areas with low land price and low climate risk exposure (green zone). Further, 4,759 GW (19 per cent of the total potential) of solar potential is located in areas with high land price and high climate risk exposure (Figure 16). The latter scenario illustrates the challenges in exploiting solar potential, which is clearly evident on the ground in states like Odisha. In Odisha, high solar potential is difficult to harness due to high land prices and climate risks. Our assessment estimates that about 38 per cent (508 GW) of the total solar capacity (1,347 GW) in Odisha is located in areas with high land prices and high climate risk exposure. This shows that climate risks and land prices will impede Odisha's ability to realise its solar potential.

Figure 16 Only 5,618 GW (22%) of solar potential is in areas with low land prices and low climate risk exposure



Source: Authors' analysis

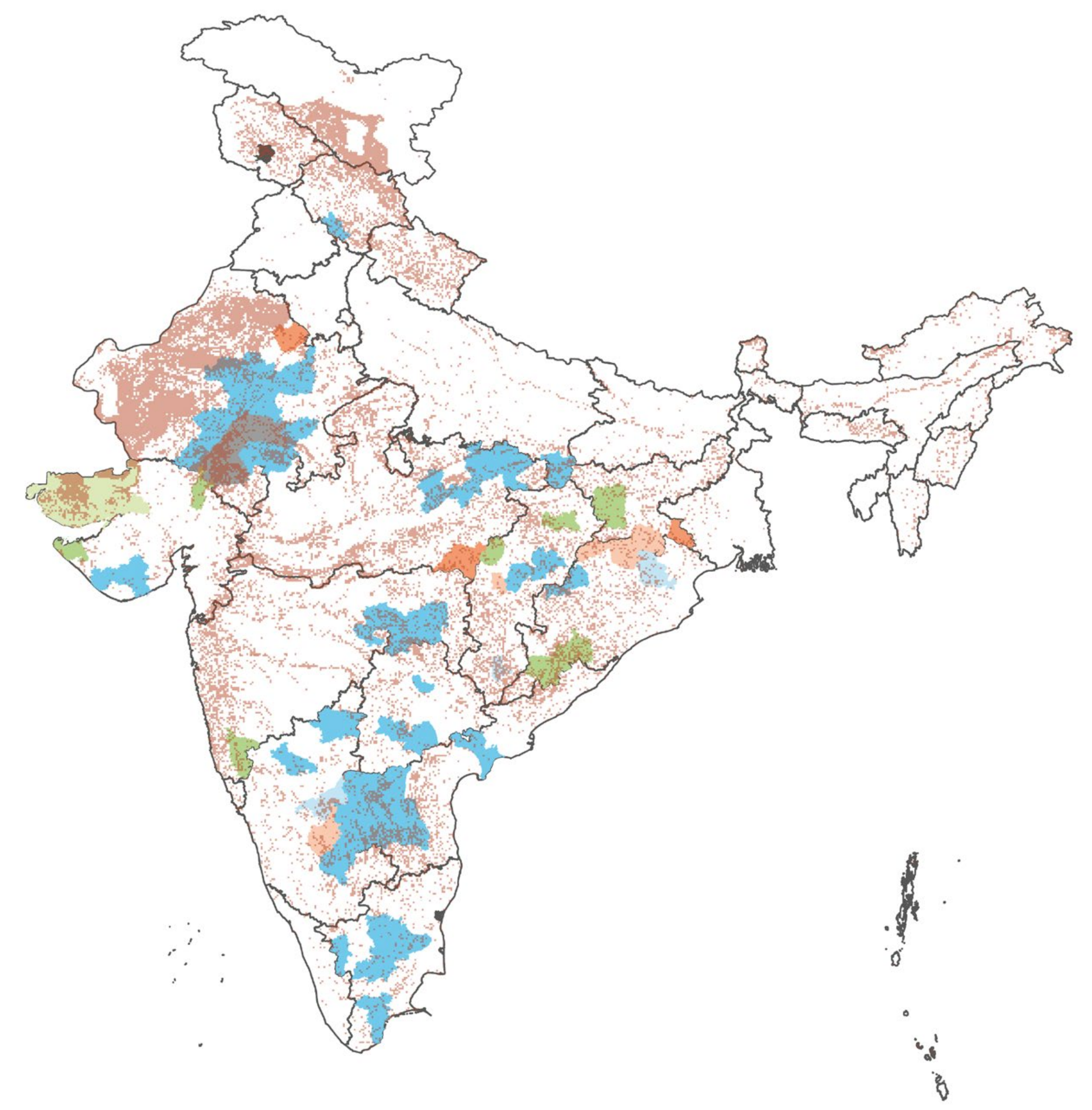
Note: This figure represents the total solar potential of 25,492 GW without considering any PLF cut-off criteria.

BOX 1 Land availability for setting up RE projects might be a challenge in India's mining districts

One of the challenges associated with scaling up RE, even in states and union territories with significant potential, pertains to the existence of competing land uses, especially in the case of mining for raw materials for use in heavy industries. In such cases, heavy industries may often be prioritised due to their higher returns on investment, and this land bank may not be available for installing RE projects. While mining areas constitute a small fraction of the total land available in a district, further analysis is needed to quantify the RE potential loss due to land being taken up for mining and heavy industries development. Nevertheless, this section identifies the solar and wind potential in India's mining districts without quantifying the potential loss due to the aforementioned factors.

Figures 17 and 18 show the districts with a high concentration of ores and active mines across various industries. Our analysis shows that around 30 per cent of the country's total estimated wind potential, i.e., 625 GW, is located in districts with limestone, bauxite, and iron ore mines (Figure 17). In these districts, alternative land uses such as steel, aluminium, and cement plants are likely to attract more investments because they are commercially more lucrative than establishing RE plants. Around 17 per cent of India's total solar potential, i.e., 4,390 GW, is in districts with limestone, bauxite, and iron ore mines (Figure 18). While it would be difficult to quantify the exact wind and solar potential lost due to mining activities, the study shows the potential barrier that it poses to unlocking India's RE potential.

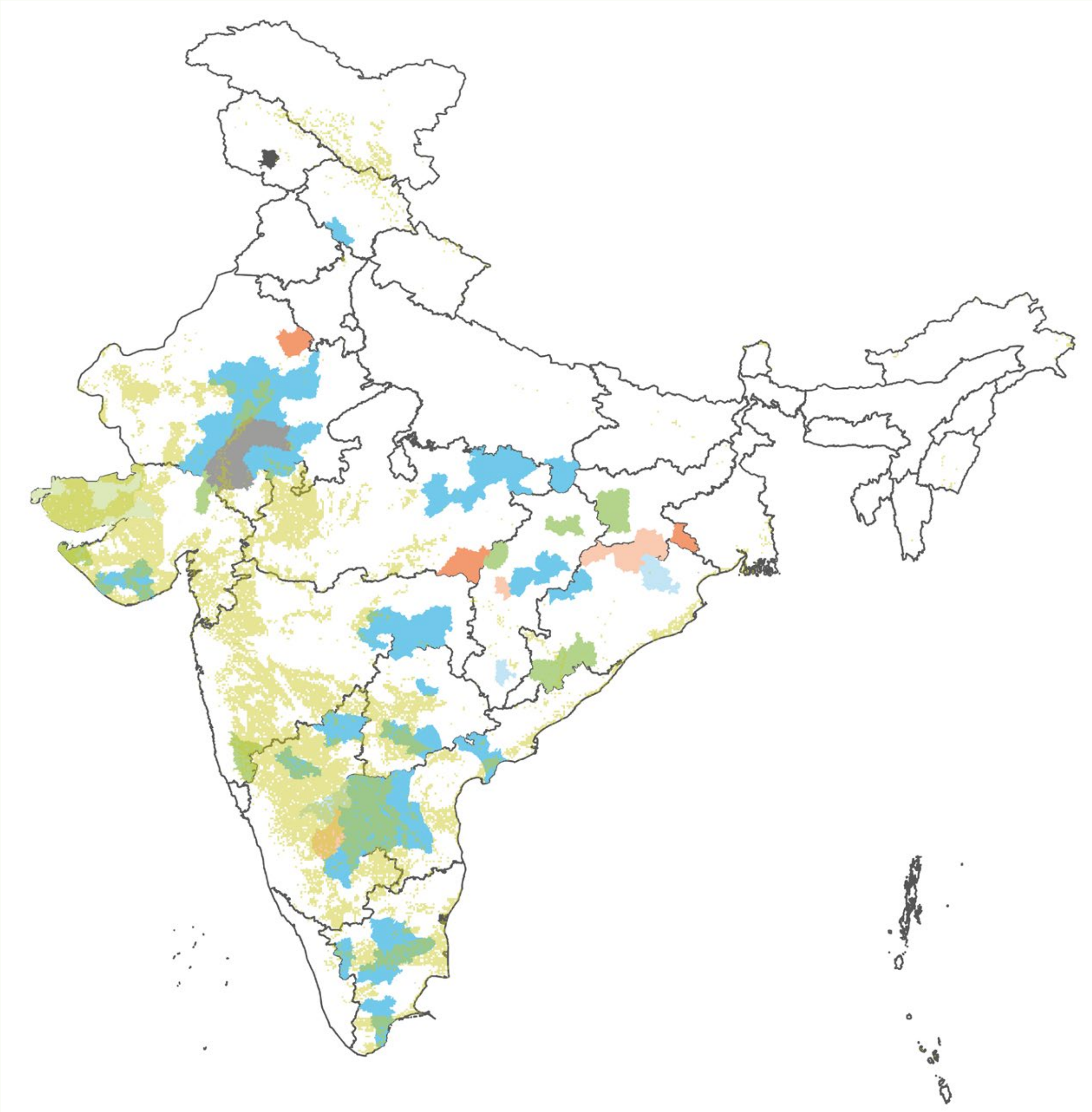
Figure 17 4,390 GW (17%) of solar potential is in districts that have mining activities



Limestone | Copper | Lithium | Bauxite | Zinc | Limestone and bauxite | Limestone and iron | Iron ore | Solar potential

Source: Authors' analysis

Figure 18 **625 GW (35%) of wind potential is located in districts with mining activities**



Limestone | Copper | Lithium | Bauxite | Zinc | Limestone and bauxite | Limestone and iron | Iron ore | Wind potential

Source: Authors' analysis

Source: Authors' compilation from IBM. 2020. Indian Mineral Yearbook. Nagpur: Indian Bureau of Mines.

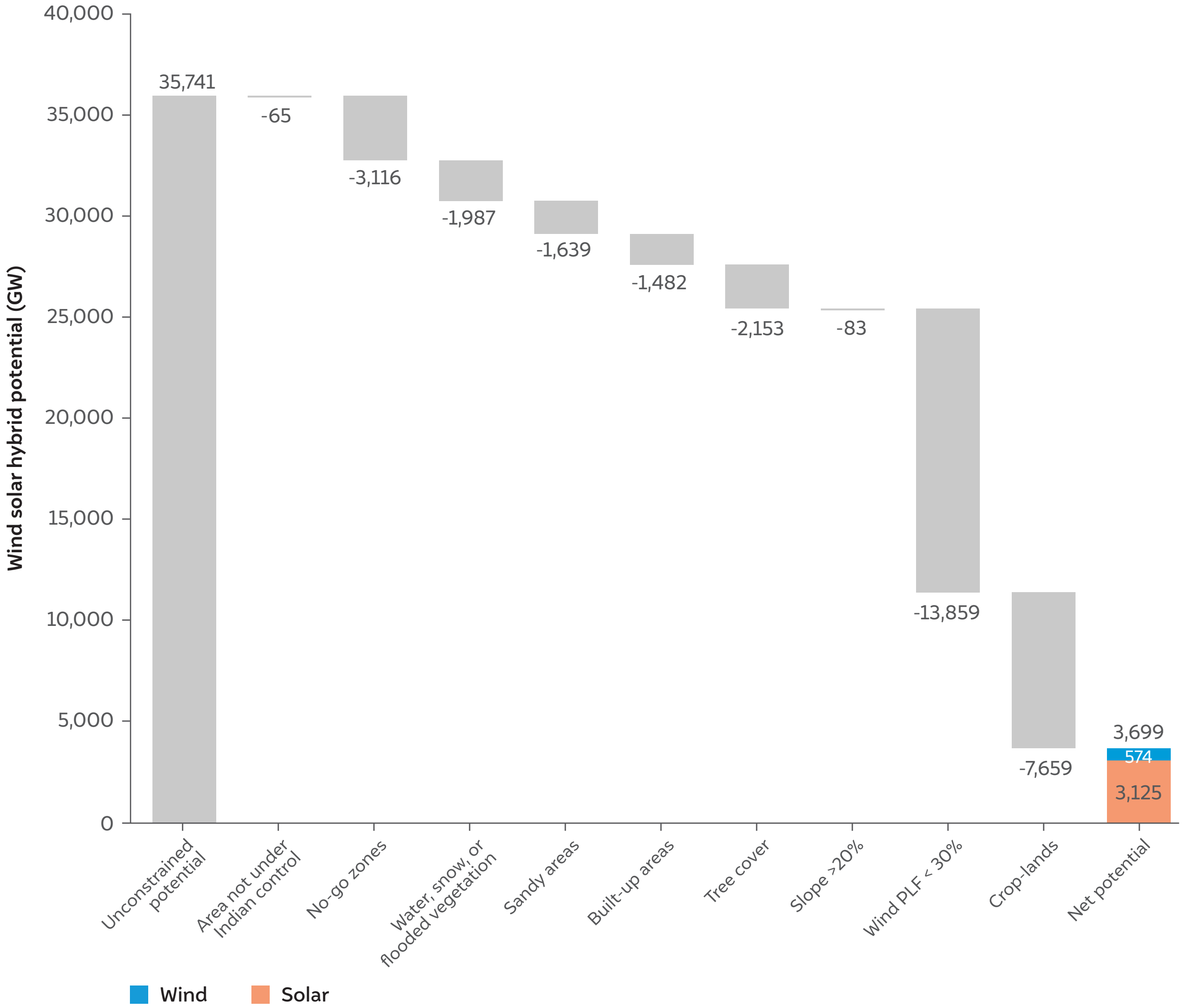
Locations with wind-solar hybrid potential are preferable for green hydrogen projects due to complementary nature of wind and solar availability.

Image: iStock

5. Wind-solar hybrid potential

The WSH potential is calculated based on the availability of co-located solar and wind resources in India. After excluding the no-go zones, water/snow areas, trees, built-up areas, and crop-lands, the WSH potential stands at ~3,700 GW (Figure 19), assuming a wind PLF cut-off of 30 per cent. Solar energy accounts for 84 per cent of the total WSH potential, at around 3,125 GW, while wind energy accounts for the remaining 574 GW. The comparatively

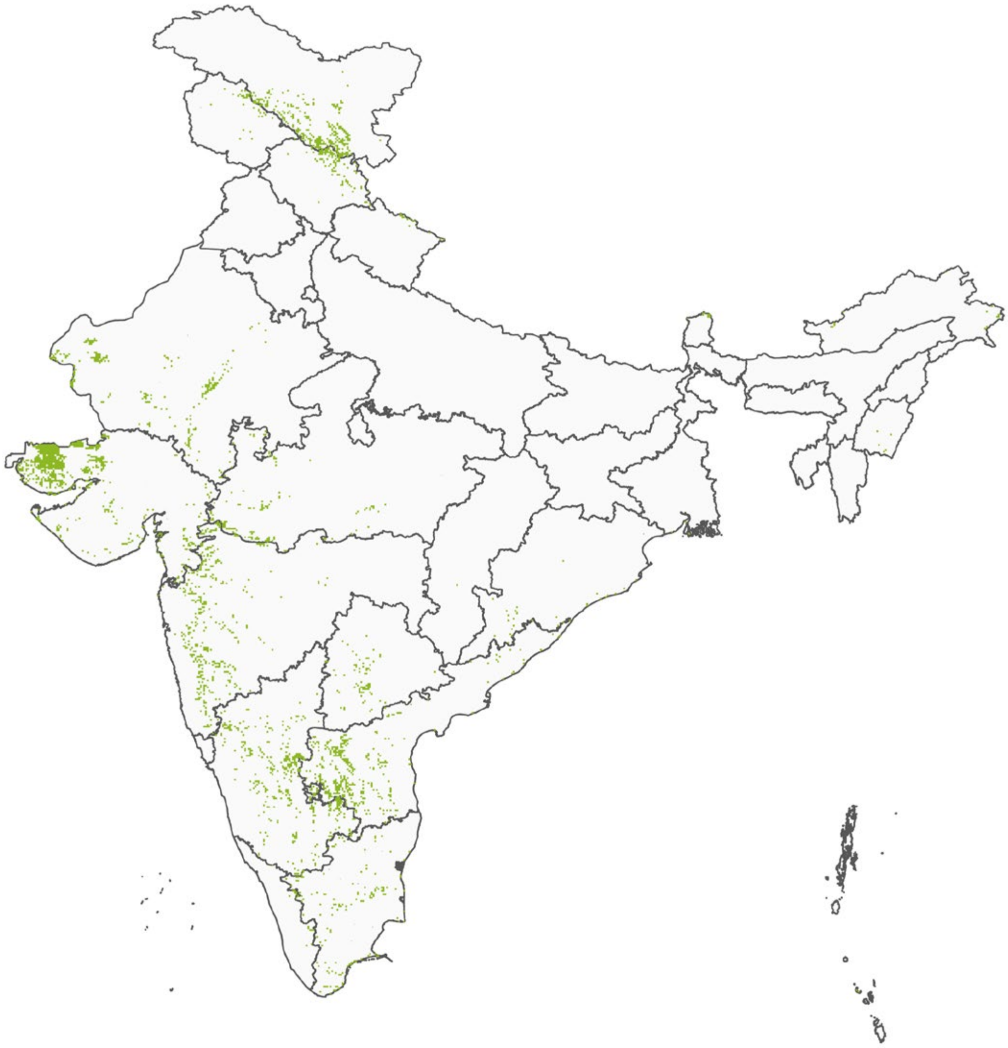
Figure 19 **The co-located wind–solar hybrid potential in India is 3,699 GW but dominated mostly by 3,125 GW of solar power**



Source: CEEW analysis

lower share of wind power in the WSH potential implies that access to round-the-clock RE will still require a significant amount of energy storage to balance daily (and seasonal) variations in solar power. Out of the total 3,699 GW potential, 411 GW is in seismic zone 5. An assessment of the distribution of the total WSH potential across various land types indicates that 7,659 GW of hybrid potential is lost in crop-lands. About 84 per cent of hybrid potential is in rangelands, while the rest is in bare ground. If the wind PLF cut-off is 25 per cent, then the total WSH potential is 7,295 GW, of which wind potential is 1,132 GW, and the remaining 6,163 GW is solar power. Figure 20 shows the WSH locations in India.

Figure 20 **Wind–solar hybrid sites are located in the western and southern part of India**



Co-located wind-solar hybrid potential

Source: Authors' analysis

6. Land policies for RE projects

Wastelands often have social uses such as for road access or cattle grazing that often conflict with project development.

This section provides key insights into the land-related provisions in the RE policies of selected states. The assessment was conducted across five broad dimensions: land use conversion, stamp duty fee exemption, land ceiling limits, land banks, and wasteland allocation provisions (Table 2). Before delving into the details of these land-specific aspects of RE policies, two broad observations about the structure of these policies need to be noted. First, there is no standard format for reporting land-related provisions. Second, some state policies, such as those in Tamil Nadu and Gujarat, do not include any provisions for land use conversion and land banks in their RE policies, creating an information gap in these important states for RE development. However, Gujarat has recently introduced a policy for leasing government fallow land for green hydrogen production using RE sources such as solar, wind, and WSH energy (Government of Gujarat 2023). According to the policy, an applicant shall not be given more land than required to produce 30 lakh TPA of green hydrogen. Nevertheless, in the absence of information from state-level RE policies and other existing sources, it is assumed that these states do not offer the specified provisions.

While most states include a provision for deemed land use conversion, the conversion still requires statutory approvals as well as a fee payment. States like Jharkhand, Madhya Pradesh, Odisha, and Rajasthan exempt developers from paying the land use conversion fee. The other six states – Andhra Pradesh, Haryana, Karnataka, Maharashtra, Telangana, and Uttar Pradesh – have deemed land use conversion provisions that require payment of applicable fees. Land use conversion charges as a percentage of land value is 3 per cent for Madhya Pradesh, Gujarat, and Andhra Pradesh, while it is 5 per cent for Odisha. Regarding land ceiling limits, states like Madhya Pradesh and Tamil Nadu have removed them under the ambit of their overall industrial policies, while some states like Andhra Pradesh have extended the land ceiling limits under their solar policies. Contrary to expectations, Karnataka has imposed a limit on the land that can be used for RE projects.

Concerning land transactions, most states have fully or partially exempted project developers from stamp duty payments for purchasing land. Madhya Pradesh offers a 50 per cent reimbursement on stamp duty charges. Other states, such as Maharashtra and Gujarat, do not offer any waivers on stamp duty charges. Since most states provide some degree of stamp duty exemption, this acts as a monetary incentive for developers. However, these exemptions are likely to have a limiting impact on states' finances. As land availability is becoming a concern for scaling up the RE capacity in the country, many states are likely to discontinue these exemptions.

Land banks that are critical from a land identification and availability perspective are given the least attention in the states' RE/solar policies. Among the states analysed, only Jharkhand, Karnataka, and Uttar Pradesh have provisions for land banks in their policies.

While wastelands are a go-to option for project developers, RE policies do not currently include specific provisions for them. Only Maharashtra, Gujarat, and Rajasthan – states with the highest RE potential – mention wasteland procurement, though not in detail. The allocation process for wastelands should not only outline administrative procedures but also include social impact assessments of these lands. This approach will reduce the likelihood of conflicts over these plots of wasteland.

Most state-level renewable energy policies do not include provisions for land banks

Table 2 Land-related provisions in the state-level RE policies

S. No.	State policy	Solar potential (GW)	Land use conversion policy	Land ceiling	Stamp duty exemption policy	Land bank	Measures to facilitate land allotment	References
1.	*Andhra Pradesh Solar Power Policy,* 2018	1,409	Partial waivers	NA	Waived	NA	Priority allocation of government land in solar parks on a long-term lease basis, which is for 10 years or longer	Government of Andhra Pradesh (2019)
2.	*Gujarat Solar Power Policy,* 2021	1,329	No mention	NA	No waivers	NA	Wasteland allocation policy for wind/solar	Government of Gujarat (2021)
3.	*Haryana Solar Power Policy,* 2021	48	Partial waivers	NA	Waived	NA	Panchayat land on lease	Government of Haryana (2016)
4.	*Jharkhand State Solar Policy,* 2022	652	Waived	NA	Waived	NA	Land allocation and identification of suitable sites	Government of Jharkhand (2022)
5.	*Karnataka draft Renewable Energy Policy,* 2021–2026	866	Partial waivers	NA	Waived	NA	Land allotment details provided	Government of Karnataka (2021)
6.	*Madhya Pradesh Renewable Energy Policy,* 2022	2,978	Waived	NA	50% re-imburse-ment on stamp duty on purchase of private land	NA	Facilitation of government land procurement	Government of Madhya Pradesh (2022)
7.	*Unconventional Energy Generation Policy,* 2020	2,410	Partial waivers	NA	No waivers	NA	Government wastelands for solar plants on a leasehold basis	Government of Maharashtra (2020)
8.	*Odisha Renewable Energy Policy,* 2022	1,348	Waived	NA	Waived	NA	—	Government of Odisha (2022)
9.	*Rajasthan Solar Energy Policy,* 2019	7,291	Waived	NA	RIPS 2022 offers up to 100% exemption	NA	Facilitating allotment of government land	Government of Rajasthan (2019)
10.	*Tamil Nadu Solar Energy Policy,* 2019	521	No mention	NA	50–100% exemption depending on investment and location	NA	—	Government of Tamil Nadu (2019)
11.	*Telangana Solar Policy,* 2015	711	Partial waivers	NA	Waived	NA	—	Government of Telangana (2015)
12.	*Uttar Pradesh Solar Energy Policy,* 2022	681	Partial waivers	NA	Waived	NA	Facilitation for government land/space	Government of Uttar Pradesh (2022)

Source: Authors' compilation

Note:

1. Green colour indicates that the provision/benefit has been extended to RE projects (though there can be variations in the extent of benefits across states); red indicates otherwise.

The solar potential represents the total potential of solar energy without considering any PLF cut-off criteria.

Wind turbines can be installed in croplands, but solar power plants face challenges unless using agrovoltaics.

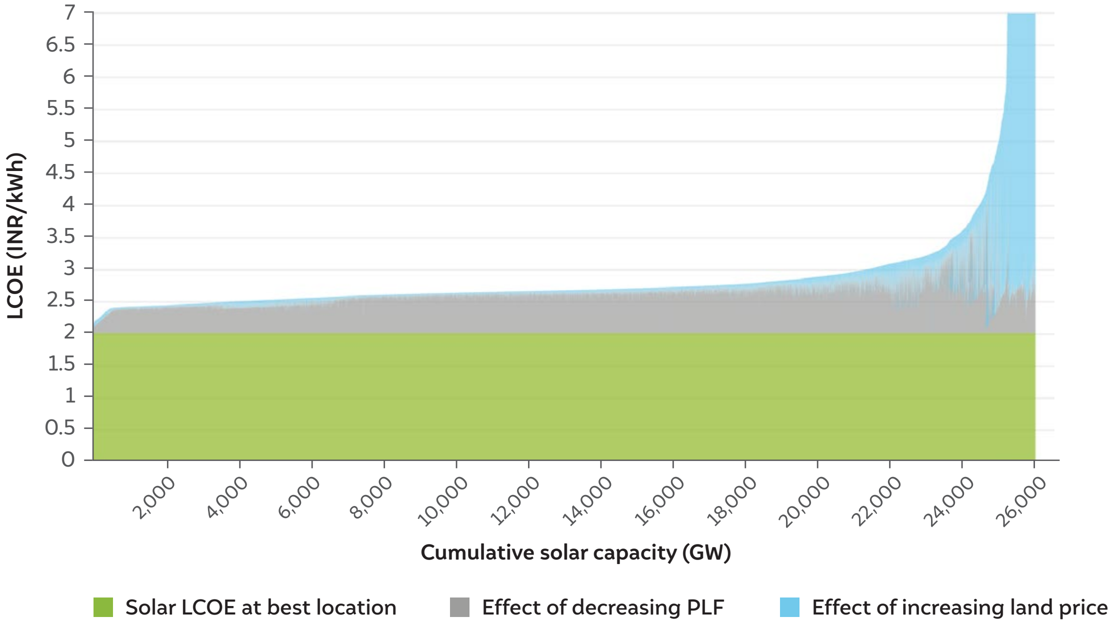
Image: Alamy

7. The levelised cost of electricity for RE across the country

The unavailability of land and high land prices are impediments to the rapid growth of RE in India. While our estimation of RE potential accounts for the unavailability of land due to various exclusion criteria and constraints, high prices are likely to impact the cost of generating RE and green hydrogen wherever land is available. Similarly, the PLF of wind and solar power varies significantly across the country depending on local weather conditions. These factors are expected to create significant variations in the LCOE and LCOH across the country. This section assesses spatial variations in the LCOE of RE power due to changes in solar and wind PLFs and land prices.

Figure 21 indicates the variations in the solar LCOE. As discussed earlier, the LCOE primarily depends on two factors: land cost and solar PLF. The curve has three components. The green component corresponds to a location (in Ladakh) with the lowest land cost and highest PLF, resulting in the lowest generation cost. The grey component reflects the effect of decreasing solar PLF on the solar LCOE. Data from the Global Solar Atlas indicates that there is no significant variation in solar PLF across the country (Global Solar Atlas n.d.). Consequently, variations in solar PLF do not have a significant impact on the cost of solar power generation. However, land prices also have a significant impact on the cost of solar power. In Figure 21,

Figure 21 India has a solar potential of ~24,000 GW with a generation cost of less than INR 3 per kWh

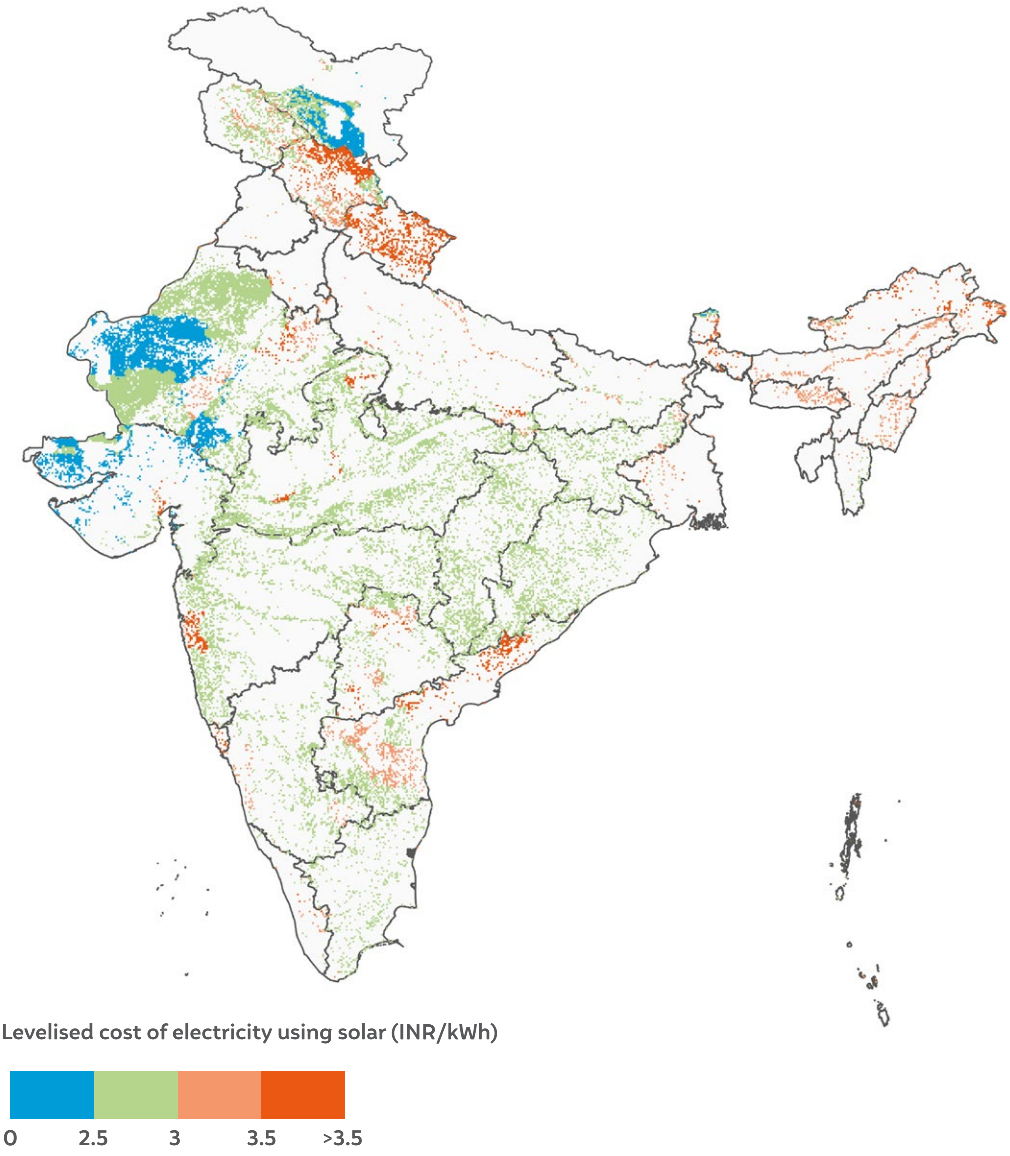


Source: CEEW analysis

the effect of land prices is indicated in blue. It is seen that the effect of land prices becomes non-trivial only after a solar capacity of 18,000 GW. However, anecdotal evidence suggests that land prices are prohibitively high for industrial use. Whether this is true can only be established through the validation of these estimates using ground-level information.

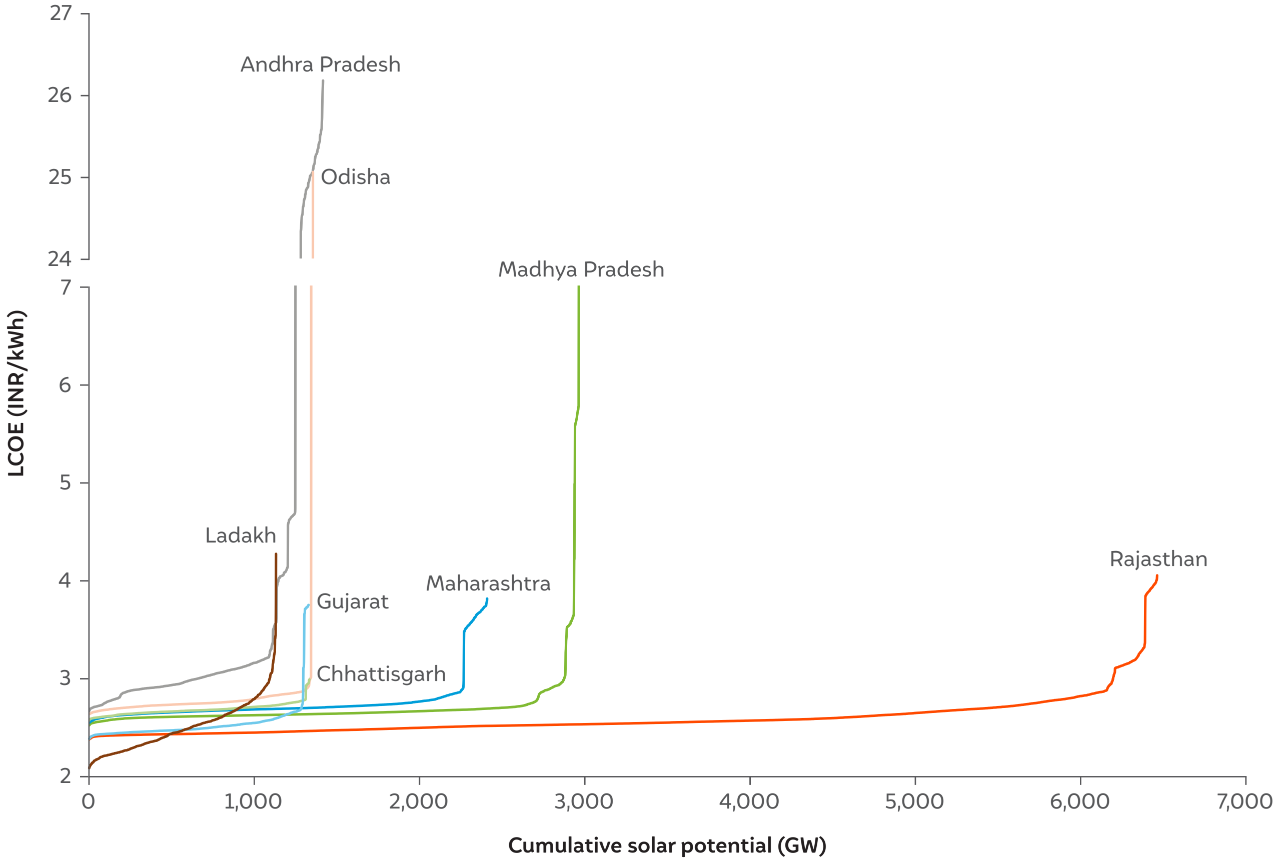
Figure 22 shows the spatial heat map of LCOE across India. Figure 23 plots solar generation costs as a function of RE capacity across states and union territories with large solar capacities. As expected, western Rajasthan has significant solar potential at lower costs. Madhya Pradesh, Maharashtra, and Andhra Pradesh also exhibit significant solar potential at competitive costs. The plot indicates that while Gujarat and Odisha have similar solar potential, there is a marked difference in their solar generation costs due to lower solar PLF and land costs in Gujarat (Annexure VII). This clearly shows the challenges for Odisha in realising its solar potential. Although Ladakh has a solar potential exceeding 1,000 GW at competitive prices, unlocking it would be a challenge due to difficult terrain and a lack of power evacuation infrastructure.

Figure 22 Western and central India have significantly lower LCOE compared to other parts of the country



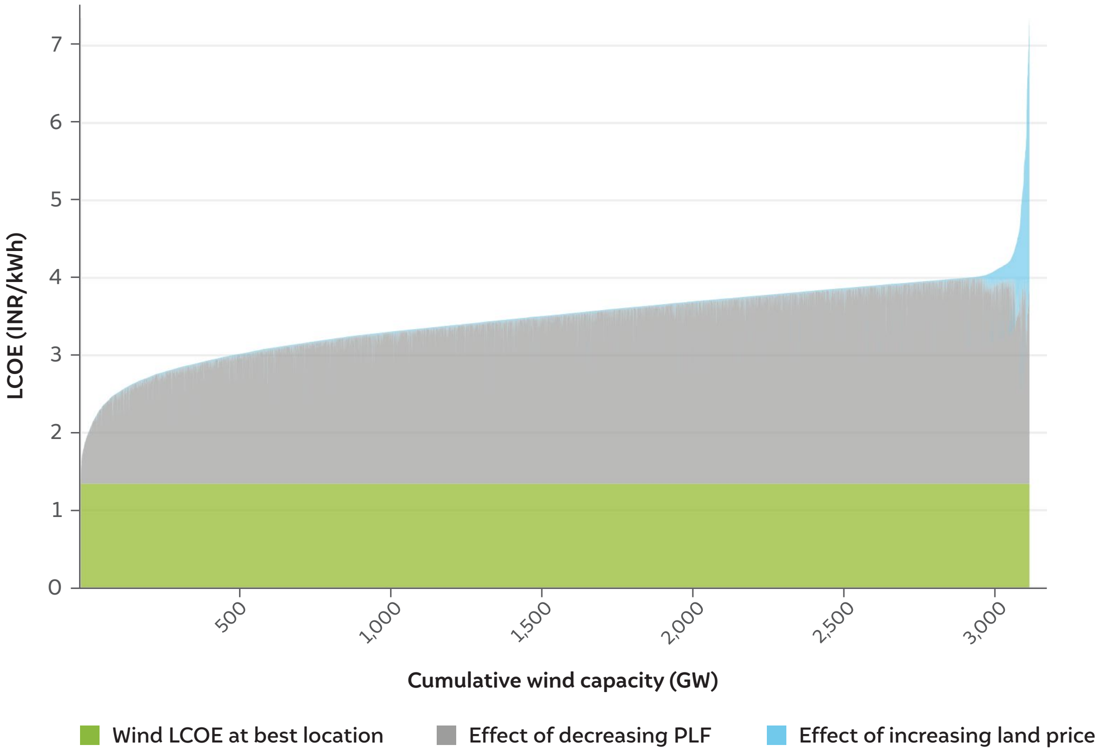
Source: Authors' compilation

Figure 23 **Rajasthan has the highest solar potential and the lowest generation cost**



Source: Authors' analysis

Figure 24 **India has over 1,500 GW of wind potential at a generation cost less than INR 3/kWh**

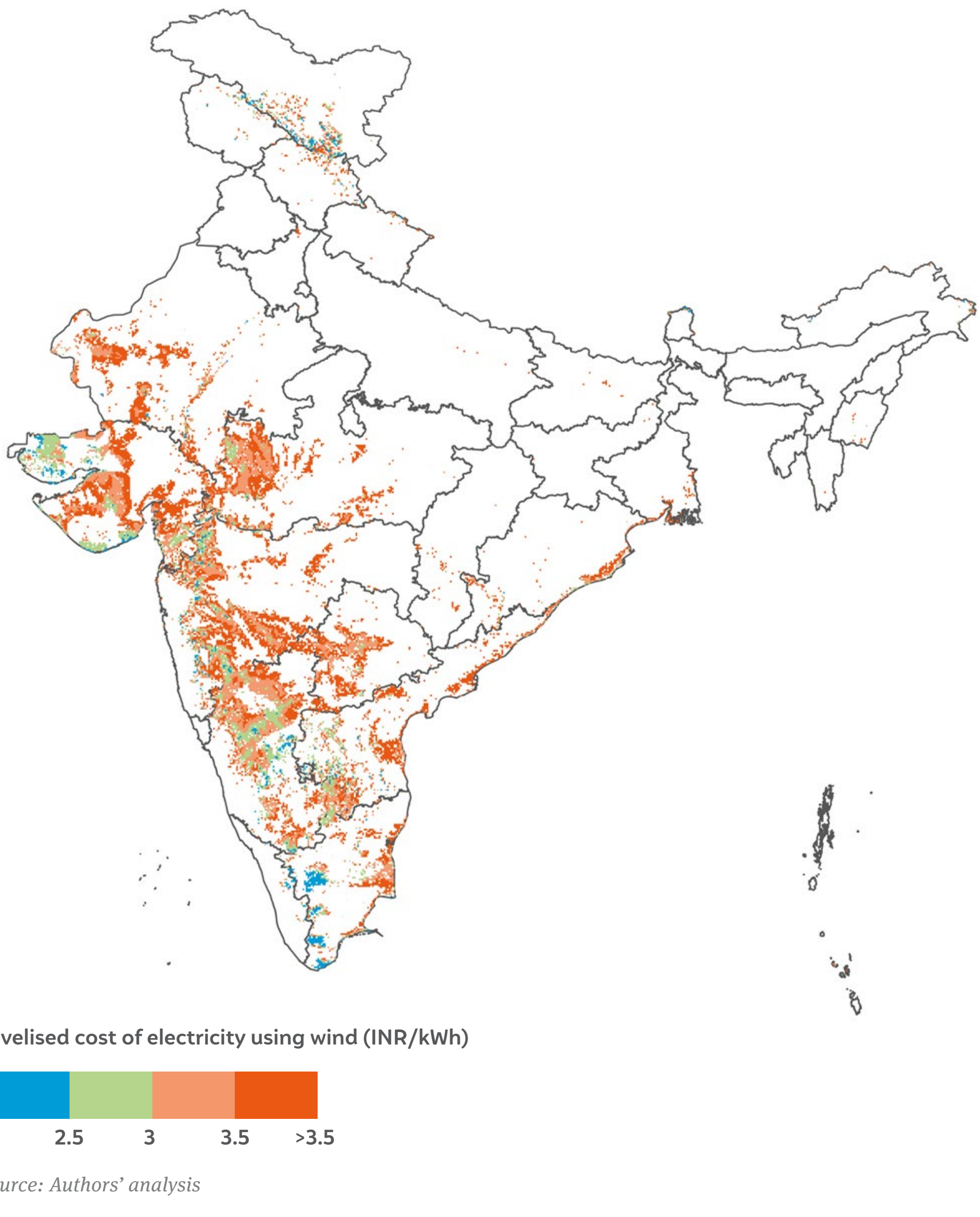


Source: Authors' analysis

Figure 24 shows the variations in the cost of wind power generation as a function of wind power capacity in the country. Unlike Section 3, where we estimate wind capacity for a cut-off PLF of 30 per cent, in this figure, we consider a wind cut-off PLF of 25 per cent to capture variations in LCOE across low PLF areas. Similar to solar power capacity, the curve has three components. The green component corresponds to the lowest land cost and highest PLF and hence has the lowest cost of generation (Kanyakumari in this case). The grey component reflects the effect of decreasing wind PLF on the LCOE. The data from the Global Wind Atlas indicates that, unlike solar power, wind potential is limited to a few geographies in India. Therefore, wind PLF plays a dominant role in influencing generation costs. The actual land footprint of wind power plants is significantly lower than that of solar power plants. Therefore, the land cost does not have a significant effect on the cost of generation.

Figure 25 shows the areas with onshore wind potential and the corresponding generation costs. It can be seen that the low LCOE wind potential is concentrated in western and southern India. The cost assumptions are listed in Annexure XII. Figure 26 plots the LCOE

Figure 25 **Only western and southern India have significant wind potential**

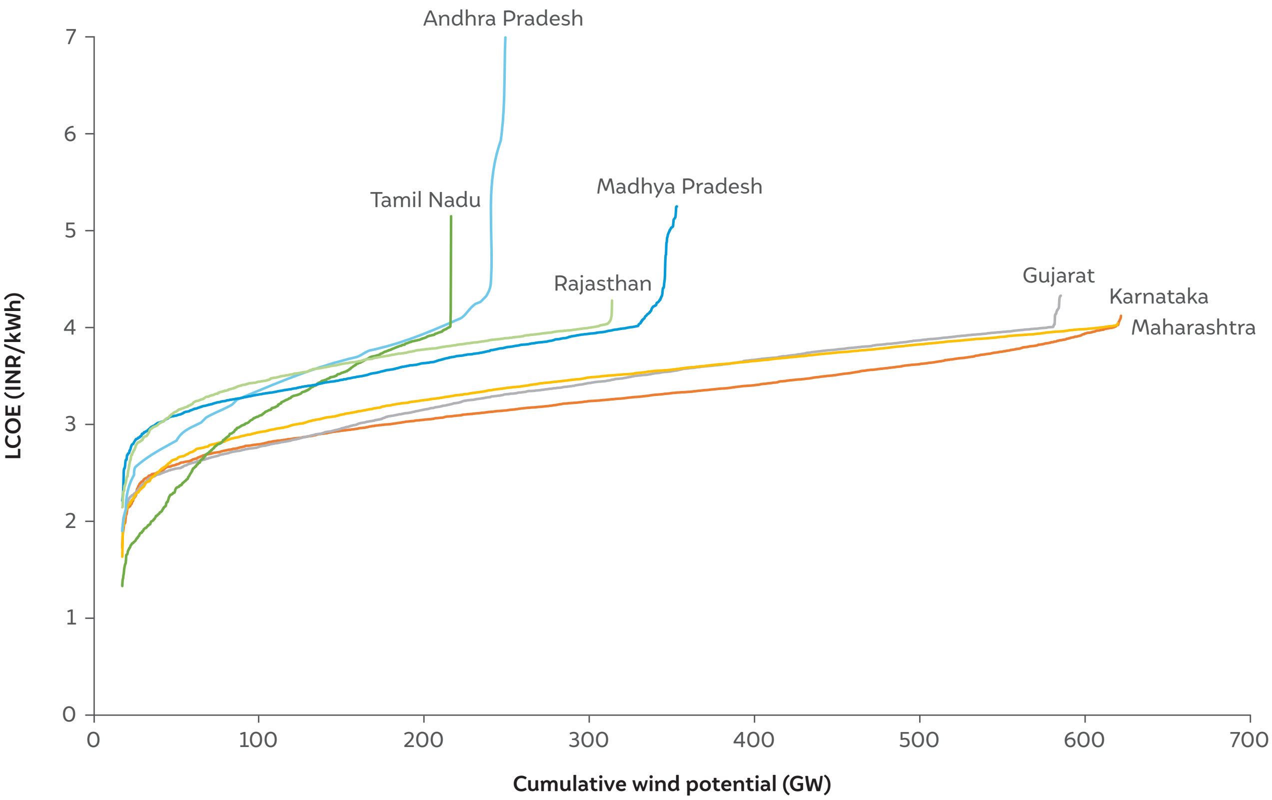


Source: Authors' analysis

of wind power against wind power capacity across various wind resource–rich states and union territories in India. Tamil Nadu, Karnataka, Gujarat, and Maharashtra have significant wind potential in India. While Karnataka and Gujarat have the lowest cost of wind power, Maharashtra has a slightly higher cost.

Since setting up wind power plants does not require significant land resources compared to solar parks, it is noted that unlike with solar power plants, there is no sudden increase in wind power tariffs after reaching a peak capacity due to land costs. According to the Global Wind Atlas, a few areas in Tamil Nadu have very good wind PLFs, exceeding 60 or 70 per cent, which significantly reduce the cost of generation. Therefore, Tamil Nadu has the lowest generation costs compared to other states and union territories for wind potential up to 50 GW. States like Madhya Pradesh and Rajasthan have smaller wind capacities and higher generation costs compared to key states like Karnataka, Gujarat, and Maharashtra.

Figure 26 **Karnataka, Gujarat, and Tamil Nadu have significant low-cost wind potential**



Source: Authors' analysis

India can produce ~80 MTPA of green hydrogen in wind-solar hybrid areas.

Image: Alamy

8. Potential for green hydrogen production in India

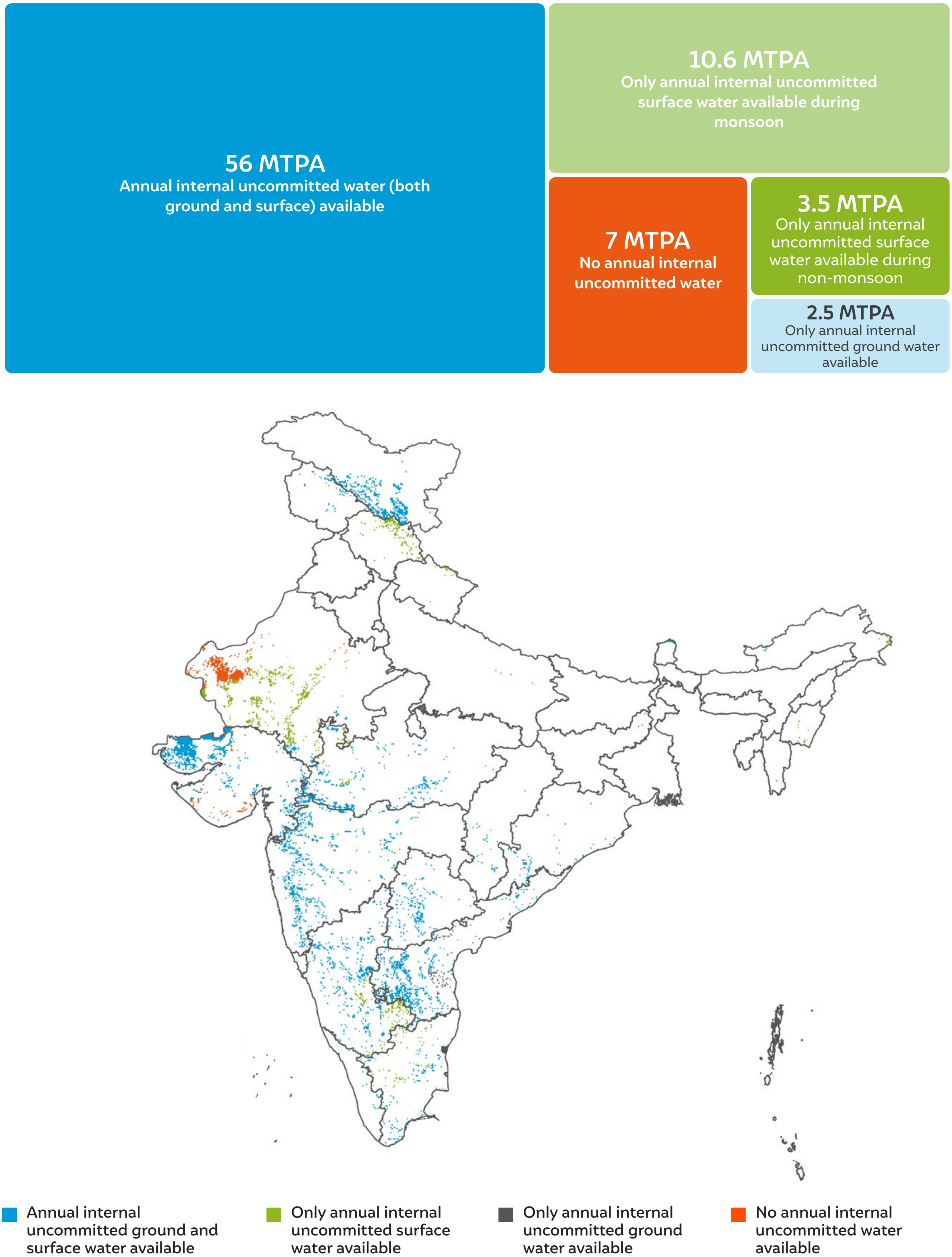
The NGHM and several state-level policies have made significant commitments to green hydrogen production and use. This section highlights the challenges related to resource availability for producing green hydrogen. based on the potential RE capacity discussed in Sections 3, 4, and 5, we estimate that 983 MTPA, 154 MTPA, and 79 MTPA of green hydrogen can be produced using solar, wind, and WSH capacities, respectively. While this green hydrogen potential is large, only a fraction of this potential is practically required, as the bulk of renewable power will be transmitted to the grid and used for electricity-based applications. Additionally, factors such as water availability, RE costs, and electrolyser costs pose challenges in realising this potential. Section 8.1 discusses the nexus between water and green hydrogen. Subsequently, Section 8.2 evaluates the cost of producing green hydrogen based on the costs of RE, water, and electrolysers. Section 8.3 explores the nexus of green hydrogen, water, and transportation infrastructure.

Approximately 56 MTPA of green hydrogen can be produced in WSH areas without encountering any water availability challenges

8.1 Green hydrogen and water nexus

Water availability is a key prerequisite for green hydrogen production. This section discusses the interplay between green hydrogen production and water availability. For green hydrogen to be cost-competitive, the electrolyser needs to have a high utilisation factor. Currently, the cost of hydrogen storage is prohibitive, and green hydrogen will be cost-effective only when a WSH is utilised for producing it. Therefore, in this study, we consider only WSH for analysing the green hydrogen and water nexus. Figure 27 indicates that about 30 per cent of the area in India with WSH potential faces challenges related to water availability. About 7 MTPA of green hydrogen potential, mostly in western Rajasthan, is in areas with no internal uncommitted water availability. Therefore, green hydrogen production in these areas can only be achieved by transporting water from other regions. About 14.1 MTPA of green hydrogen production potential is located in areas with no groundwater availability. Out of this, about 10.6 MTPA of green hydrogen potential is in areas with only surface water availability during the monsoon months, while the remaining 3.5 MTPA has surface water available during the non-monsoon months due to water storage facilities. Additionally, 2.5 MTPA of green hydrogen potential is in areas that do not have any surface water. About 56 MTPA of hydrogen production capacity, mostly in western and southern India, can be developed in areas that do not face any water-related issues. However, storage is available for only 25 per cent of the internal uncommitted surface water (Annexure XVI), indicating potential additional costs for storing monsoon water from the storm-water stream to ensure consistent year-round production.

Figure 27~56 MTPA of green hydrogen can be produced at wind–solar hybrid locations without any water availability challenges

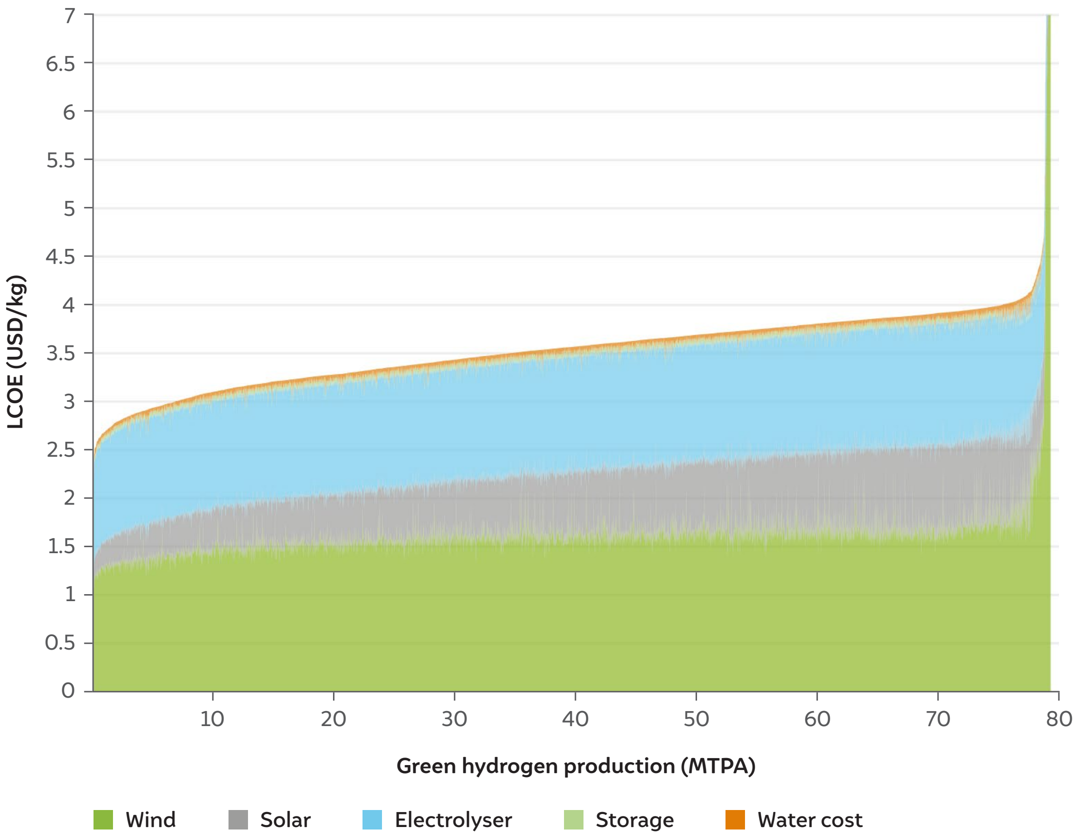


Source: Authors' analysis

8.2 How does the cost of green hydrogen production vary in India?

While the wind potential is estimated for a cut-off PLF of 30 per cent, the hydrogen cost and production potential are estimated for a wind cut-off PLF of 25 per cent, as wind power is available during night-time, which increases the electrolyser PLF and consequently reduces the cost of green hydrogen. As discussed in Section 5, the total WSH potential in the country with a wind PLF exceeding 25 per cent is 7,295 GW, out of which 6,163 GW is solar, and the remaining 1,132 GW is wind energy. Figure 28 shows the variations in hydrogen production costs at different levels of production capacity across all WSH areas in the country. It is observed that India can produce approximately 40 MTPA of green hydrogen at a cost lower than USD 3.5 per kilogram (with less than 85 per cent annual availability of hydrogen). The cost of RE (wind and solar power) significantly affects the green hydrogen production cost, while the effects of hydrogen storage and water costs are minimal. The share of wind power cost in the overall cost of green hydrogen is higher than the share of solar power. This is primarily due to the higher PLF and continuous availability of electricity from the wind power system. For an optimised WSH configuration, about 70–75 per cent of the annual power requirement for electrolysers should be met through wind power; the final share depends on the relative cost of electricity. A detailed discussion on solar and wind capacity requirements for setting up WSH projects for green hydrogen can be found in Annexure XIII. Therefore, while the entire wind potential is used for green hydrogen production, about 5,601 GW of solar potential remains unutilised in an optimal WSH combination.

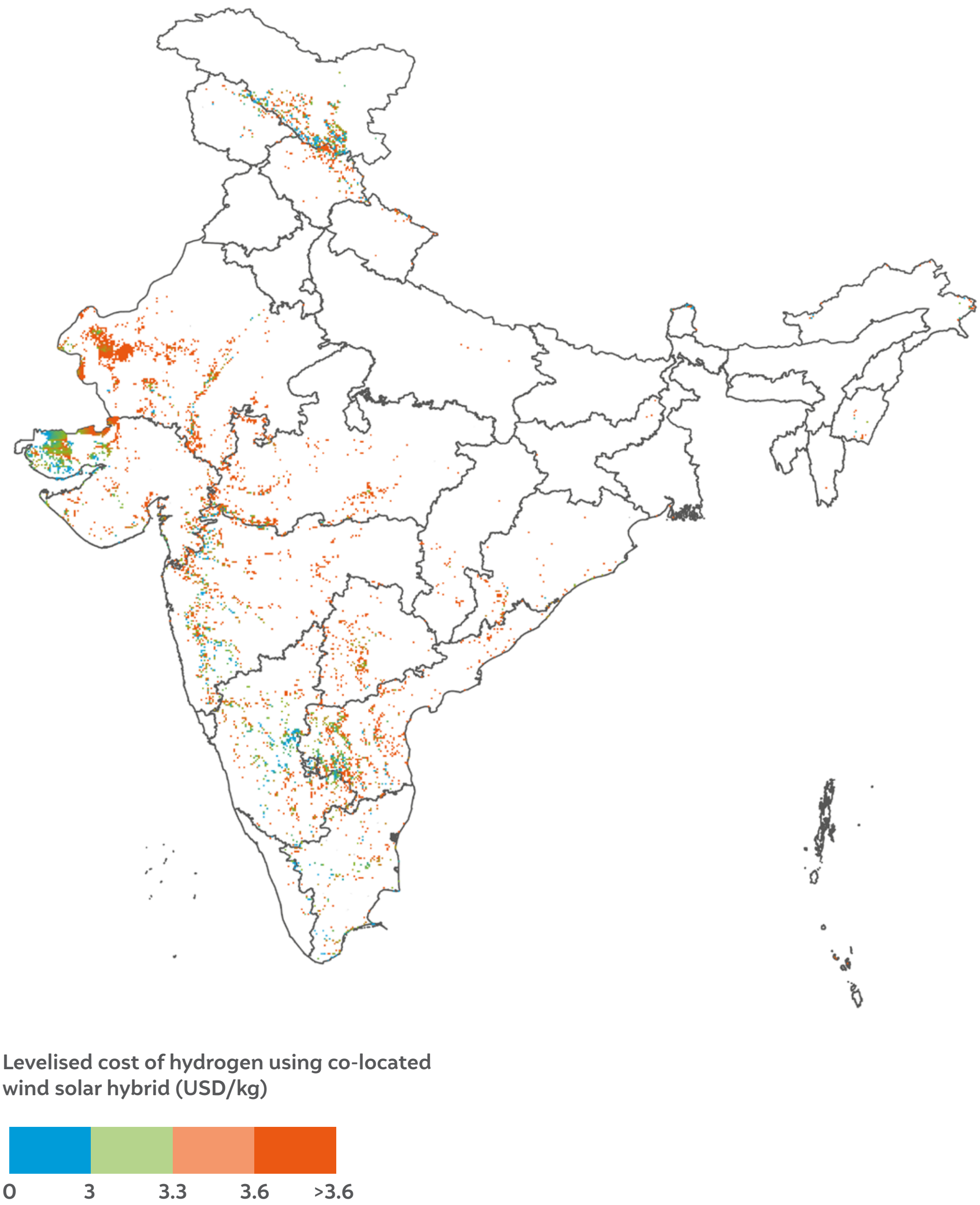
Figure 28 India can produce 40 MTPA of green hydrogen at costs lower than USD 3.5 per kilogram



Source: Authors' analysis

Figure 29 shows the heat map of green hydrogen production costs in India for WSH locations. For WSH, we consider a wind PLF cut-off of 25 per cent; hence, the green hydrogen production costs are very high in areas with low wind PLF. Pockets in Western Rajasthan and Gujarat have the potential to produce large volumes of green hydrogen. Similarly, pockets along the Karnataka and Andhra Pradesh border have good potential to produce green hydrogen at scale.

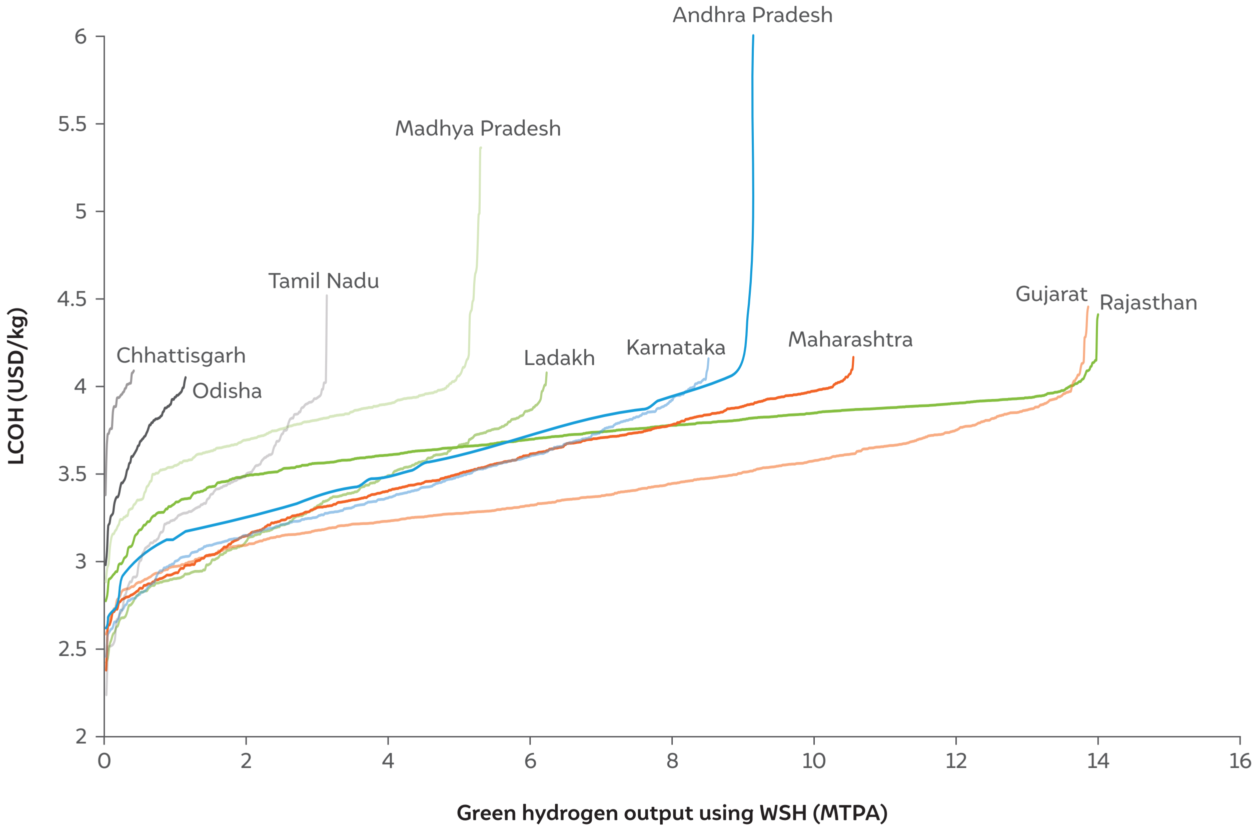
Figure 29 **Low-cost green hydrogen can be produced in western and southern India**



Source: Authors' analysis

Figure 30 shows that Gujarat, Karnataka, and Maharashtra have a large capacity to produce green hydrogen at low cost. Although Rajasthan has significant potential for producing green hydrogen, there are very few areas within the state that can produce hydrogen at competitive prices, primarily due to low capacity and PLF of wind power. The cost of producing hydrogen is significantly higher in southeastern and central India due to low wind potential and high land costs. It should be noted that the hydrogen production potential also considers areas that might already have existing solar and wind power plants in India. It is expected that these plants would have been installed in areas with low LCOEs; therefore, the low LCOH areas indicated in Figures 28 and 29 might not be available for hydrogen production.

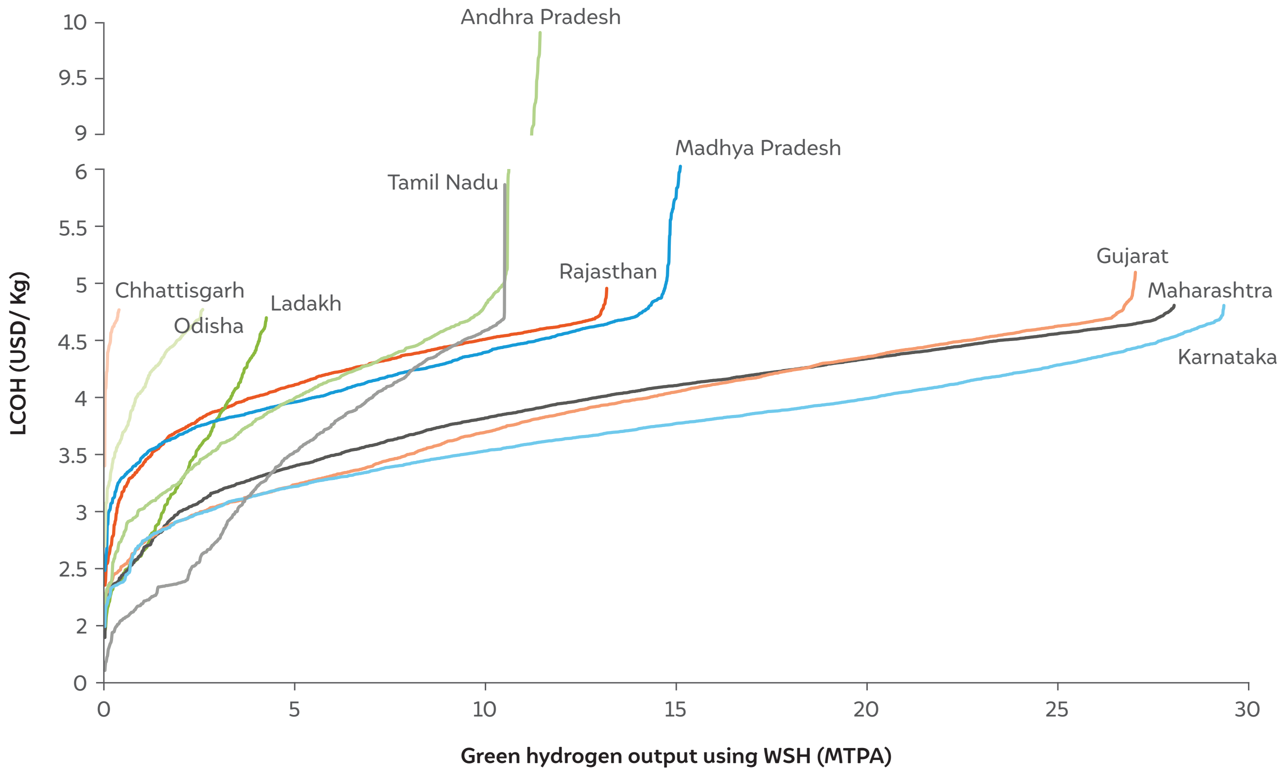
Figure 30 **Gujarat, Karnataka, and Maharashtra have low-cost green hydrogen production potential**



Source: Authors' analysis

Figure 31 shows the cost of producing green hydrogen using only wind power across several wind resource–rich regions in India. Similar to the case of WSH, we consider a wind PLF cut-off of 25 per cent; hence, the green hydrogen production costs are very high in areas with low wind PLF (Annexure XV). Gujarat, Karnataka, and Maharashtra have the potential to produce large volumes of green hydrogen at a low cost. While Tamil Nadu has comparatively lower potential, the cost of production is the lowest due to its high wind PLF. For example, Tamil Nadu can produce 2.5 MT of green hydrogen at a cost lower than USD 3 per kilogram, while Gujarat, Karnataka, and Maharashtra can produce only 1, 1, and 1.2 MT, respectively. Although Madhya Pradesh has significant wind potential, its production cost is higher compared to Gujarat, Karnataka, and Maharashtra. The results indicate that India can produce 22 MTPA of green hydrogen at a cost lower than USD 3.5 per kilogram across all wind resource–rich areas (Annexure XV).

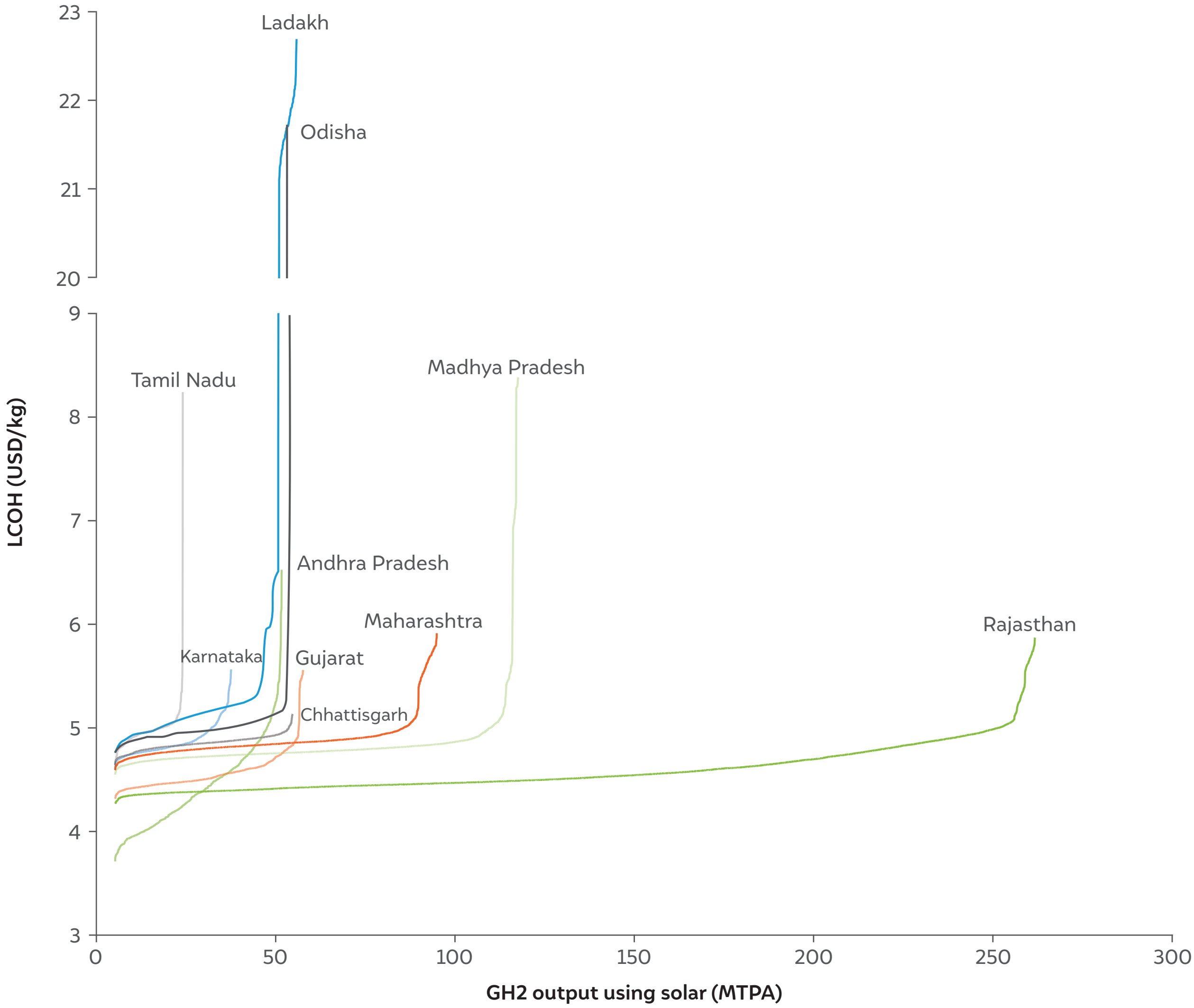
Figure 31 **Tamil Nadu has the most favourable wind resources for producing low-cost green hydrogen**



Source: Authors' analysis

Figure 32 shows the plot of green hydrogen production costs with a solar-only configuration across various solar resource–rich states and union territories in India. Unlike the wind-only configuration shown in Figure 31, the cost of producing green hydrogen does not vary significantly across states and union territories in India. Rajasthan has the highest green hydrogen production potential, followed by Ladakh, Madhya Pradesh, and Maharashtra. As evident from Annexure VII, only a fraction of solar potential has a good solar PLF. Therefore, while 175.7 MTPA of green hydrogen can be produced at less than USD 4.5 per kilogram, a significant portion has production costs exceeding USD 5 per kilogram. Nevertheless, the cost of producing green hydrogen using only solar power is prohibitively high, and a significant reduction in solar power and electrolyser costs is needed for this option to become cost-competitive. Annexure XV shows that Rajasthan and Gujarat have the best solar hydrogen production potential in the country. However, green hydrogen production through the solar-only configuration is not viable due to the low PLF of the electrolyser and, hence, high production costs. This may, however, be mitigated in the future with lower storage costs. Nonetheless, it is expected that the cost of producing hydrogen will be lower in WSH areas, which will likely be the preferred locations for setting up green hydrogen projects. Therefore, solar-only green hydrogen production may not become commercially viable unless the cost of solar power decreases significantly.

Figure 32 **Rajasthan has the best solar resources for producing green hydrogen**



Source: Authors' analysis

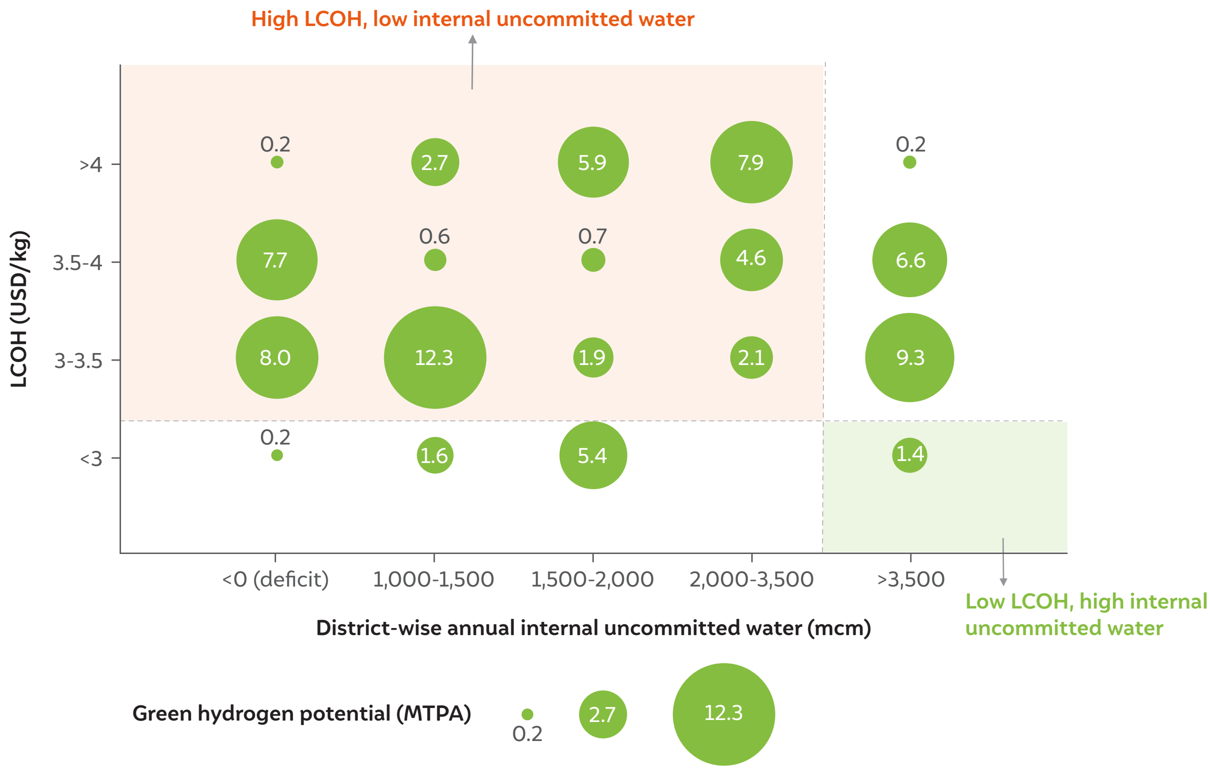
8.3 Green hydrogen production, LCOH, and internal uncommitted water

Section 8.2 shows that water costs have a minimal impact on the green hydrogen production cost. However, water availability will pose challenges in some regions due to competing domestic, commercial, and industrial applications. The expanding economy and burgeoning population are likely to exacerbate conflicts in water-stressed areas and might impede the development of green hydrogen projects in the future. This section captures the trade-off between the economic viability of green hydrogen production and the availability of internal uncommitted water. As discussed in Section 8.2, WSH areas have lower green hydrogen production costs compared to wind-only and solar-only areas. Therefore, the green hydrogen, LCOH, and water cost nexus considers only WSH areas.

For this assessment, the two constraint parameters – LCOH and internal uncommitted water – were divided into their respective brackets based on the inflection point approach explained in Annexure X. These brackets for both parameters were then divided into their low- and high-range values. In Figure 33, the internal uncommitted water in the 80th percentile was considered to be surplus internal uncommitted water availability, and LCOH values lower than 3 USD per kilogram were considered to be in the low-value bracket.

The analysis shows that only 1.4 MTPA of the total green hydrogen production potential from WSH (indicated in green) is in areas with a water surplus and favourable LCOH, while 16.1 MTPA lies in water-deficit areas. Further, 54.6 MTPA of green hydrogen potential is located in areas with low water-availability regions or in areas with high LCOH (indicated in orange). This implies that areas with a favourable LCOH and water availability are insufficient to meet India's green hydrogen target of 5 MTPA, and developers need to move to areas with constraints relating to either water availability, the total cost of green hydrogen production, or both. The severity of the problem will increase as we scale up production. This implies additional costs for ensuring water availability and management for green hydrogen projects that will also impact the cost of green hydrogen.

Figure 33 **Only 1.4 MTPA green hydrogen potential exists in areas with low LCOH and high uncommitted water availability**



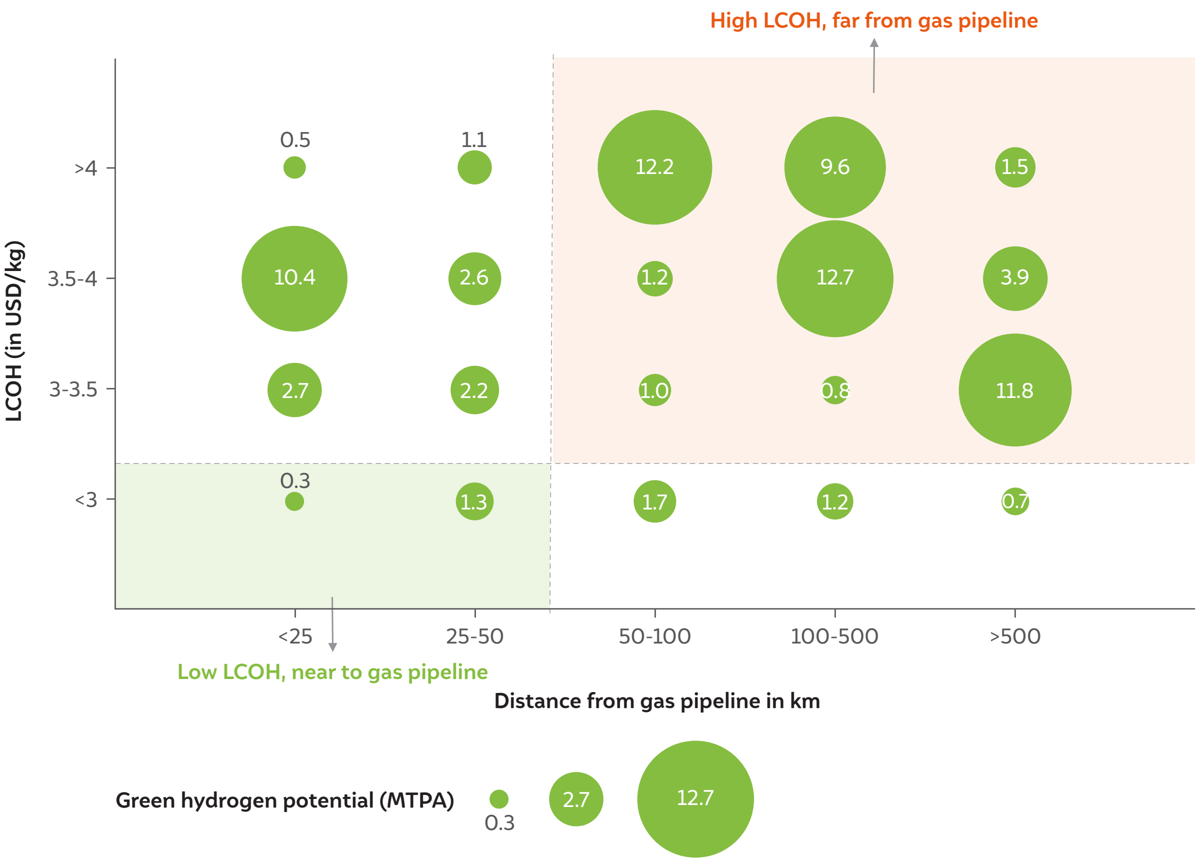
Source: Authors' analysis

8.4 Green hydrogen production, LCOH, and distance from gas pipelines

One of the key factors that would determine the utilisation of green hydrogen production is the readiness of hydrogen transportation infrastructure. Hydrogen can potentially be transported through either the existing natural gas pipeline network or through new pipelines along the RoW of the existing network. Green hydrogen can also be blended into existing natural gas pipelines, provided there are no challenges regarding the integrity of gas pipelines and end-use applications. Therefore, it is important to assess the potential of green hydrogen in relation to India's existing gas pipeline network.

Figure 34 plots the cumulative green hydrogen production against the distance from gas pipelines. About 13.9 MTPA of green hydrogen potential is located in areas that are less than 25 kilometres from gas pipelines. It should be noted that this potential will decrease if other parameters such as water availability and production costs are considered. The remaining hydrogen production potential is located further from existing gas pipelines. For example, there is 21.1 MTPA of green hydrogen potential within 50 kilometres from gas pipelines while the remaining 58.1 MTPA potential is beyond 50 kilometres of gas pipelines. This potential can be realised by either transporting green hydrogen to these pipelines or laying additional pipelines. Both options come with challenges. While transporting hydrogen can be quite cost-intensive, planning for dedicated green hydrogen pipelines may encounter obstacles in land acquisition for RoW. These challenges need to be addressed if India wants to develop a long-distance hydrogen transportation network.

Figure 34 **Only 1.6 MTPA of low-cost green hydrogen production potential is located within 50 kilometres of gas pipelines**



Source: Authors' analysis

Unlocking the potential for green hydrogen and renewable energy in India will require overcoming numerous challenges and constraints.

Image: iStock

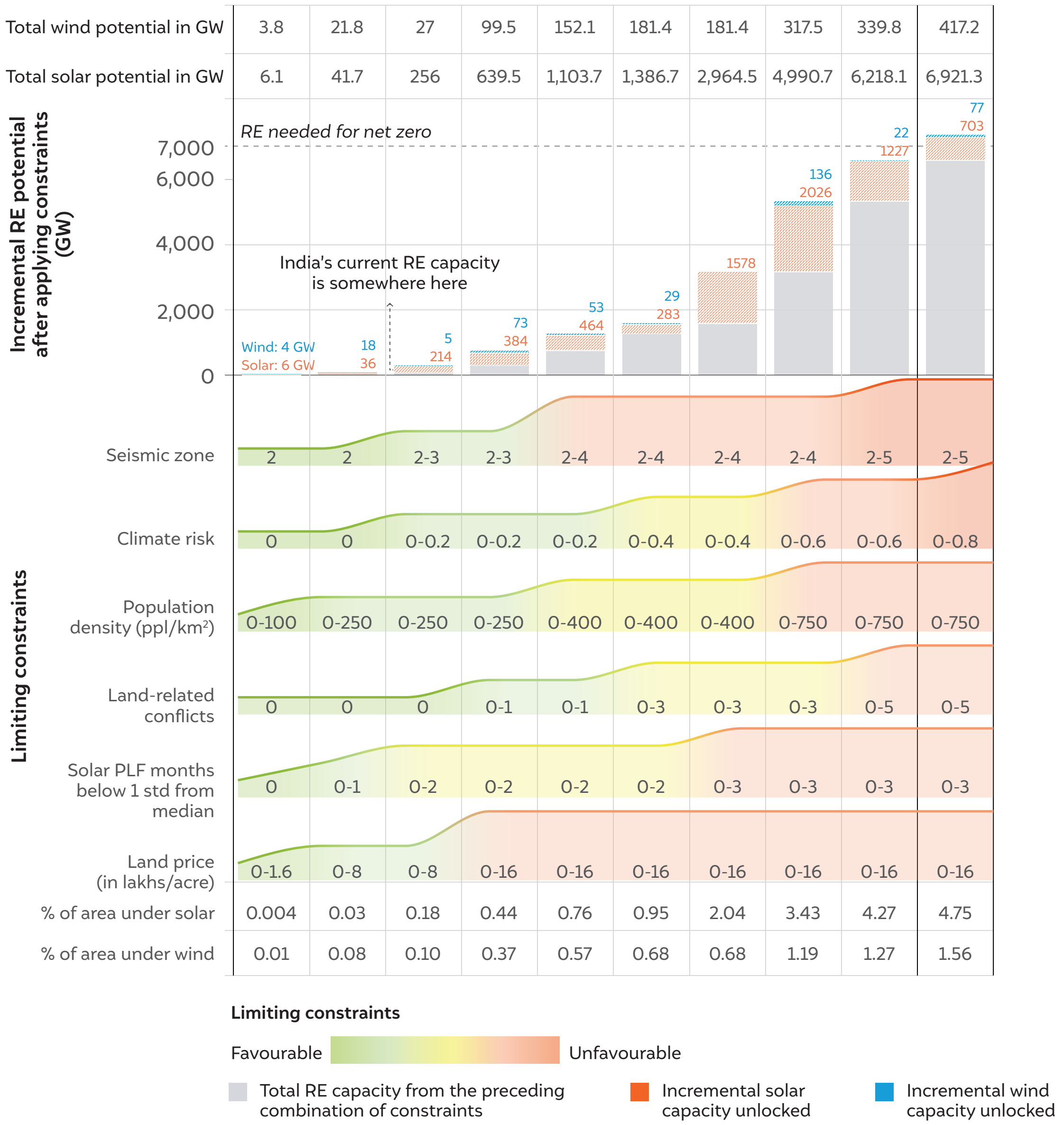
9. Achieving RE and green hydrogen targets and addressing associated nexus challenges

India has significant potential for RE and green hydrogen production. The government has set a target of deploying 500 MW of non-fossil power and producing 5 MTPA of green hydrogen by 2030. It is estimated that India would need up to 7,000 GW of non-fossil fuel capacity to achieve net-zero emissions by 2070 (Chaturvedi and Malyan 2022). Additionally, there are plans to increase green hydrogen production and establish India as a global hub for green hydrogen. However, with the incremental deployment of capacity, new constraints will emerge that will increase the challenges associated with setting up RE and green hydrogen projects in India. To evaluate these challenges, we incrementally selected rasters countrywide that have the optimal combination of constraints to cumulatively achieve the target of deploying 7,000 GW of RE capacity to meet India's net-zero targets.

Seismic zones, climate risks, population density, seasonality, land conflict and land price are the major constraints for RE and green hydrogen projects

There are multiple combinations of constraints that can be evaluated to understand the nexus and the corresponding RE potential. We have presented two sets of combinations in Figures 35 and 36. The constraints considered for the evaluation are listed on the left side of the table in Figure 35 and include earthquake risks, climate risks, population density, land conflicts, seasonality (months below one standard deviation from the median PLF), and land price. These constraints are colour-coded – green indicates the best conditions for setting up RE projects, whereas red indicates the most challenging conditions. The total wind and solar potential is shown in the first row, and a bifurcation is provided in the subsequent rows. In the chart, the cumulative RE capacity from the previous block is indicated in grey, whereas the additional capacity unlocked for a given set of constraints is indicated in blue.

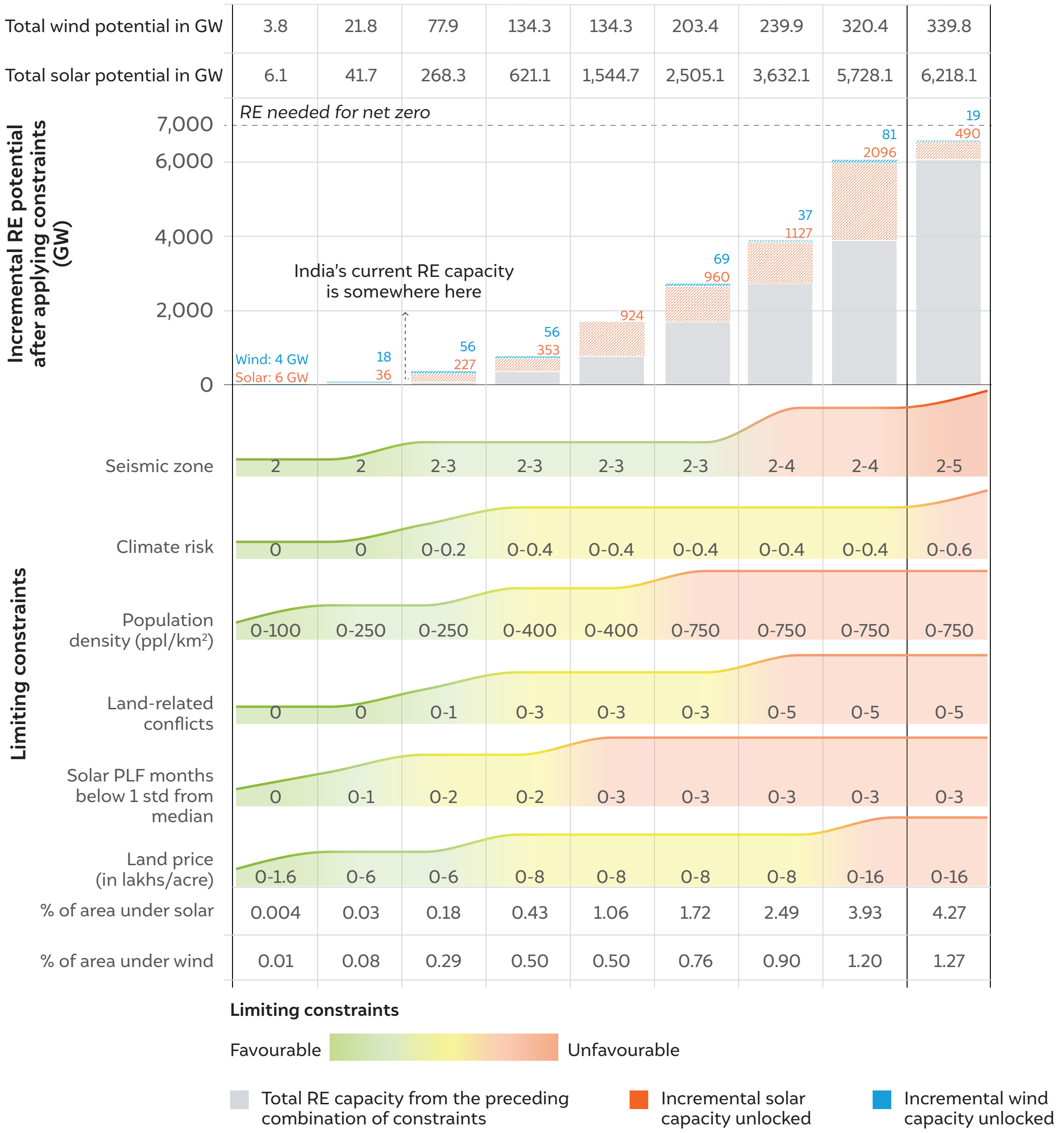
Figure 35 Case 1 for scaling up RE projects in India



Source: Authors' analysis

Each combination trajectory provides different insights, but based on the two cases evaluated in Figures 35 and 36, we observe some common patterns. There is no significant constraint for deploying the first 60 GW of RE capacity. However, between the addition of 60 and 300 GW of RE capacity, the intermittency of RE increases slightly, as these plants will be installed in locations with two months of generation lower than one standard deviation from the median generation. Additionally, we start entering locations that have existing land-related conflicts. In unlocking 300-750 GW of RE potential, there is a trade-off between significantly higher land prices (between INR 8 and 16 lakhs per acre) and higher population density (between 250 and 400 people per square kilometre). While there is a correlation between high land prices and high population density, areas with higher population density are also likely to face more land-related conflicts. Unlocking 300–750 GW of RE capacity will also require deployment in areas with climate risk levels ranging from 0 to 0.4. Beyond 750 to 1,500 GW, RE will need to be deployed in seismic zone 4 or in areas with higher seasonality, where generation is lower than one standard deviation from the median generation.

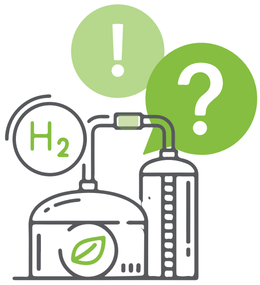
Figure 36 Case 2 for scaling up RE projects in India



Source: Authors' analysis

Deployment in seismic zone 4 will result in higher insurance costs, while high seasonality implies lower solar PLF and higher storage costs. This will also lead to an increase in the LCOEs for RE deployment between 750 and 1,500 GW. Deploying 1,500 to 3,000 GW of RE can only happen by accessing high population density areas with 400 to 750 people per square kilometre and exploring land resources in high-conflict zones. Beyond 3,000 GW, challenges increase across all constraints, from land price to population density and conflicts. At levels exceeding 5,000 GW, we have to deploy RE in highly earthquake-prone zone 5. Additionally, climate risks are quite high in some of the areas when we reach higher capacity requirements. India's population is expected to grow over the next few decades. Therefore, these factors will present significant challenges for India in achieving net-zero emissions.

Similar to RE, we also evaluated the challenges to scaling green hydrogen. For green hydrogen, we assume that the 5 MTPA target will only substitute the existing demand from fertiliser, refinery, and methanol plants. A significant amount of demand is expected to emerge from new applications such as steel, mobility, natural gas pipeline blending, and the making of products from carbon capture and utilisation pathways, such as sustainable aviation fuel. In addition to the domestic demand, there will be a large international market for green fuels. Hence, we evaluate the land and water nexus for the production of up to 50 MTPA of green hydrogen.



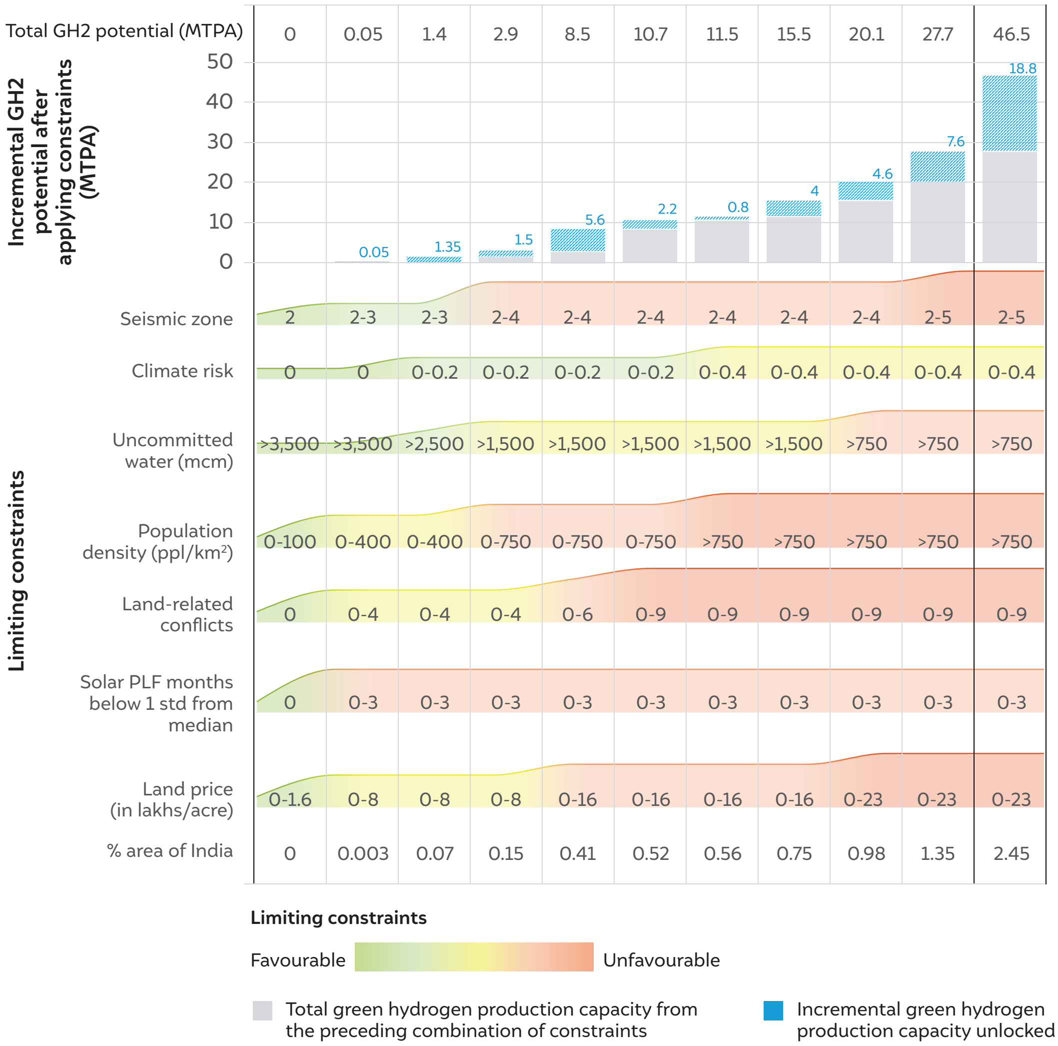
Population density and land conflicts will be major constraints for developing large-scale green hydrogen projects

We assume the use of a WSH system for green hydrogen production, as this results in a significantly lower levelised cost of production compared to using wind or solar power alone with storage. We also assume that the green hydrogen production is captive; that is, production occurs close to the RE generation site. In theory, RE power can be transmitted to the site of end use. However, given the high cost of power transmission, open access charges, and challenges related to grid capacity and integration to transmit power solely for the purpose of green hydrogen production, it is assumed that captive green hydrogen production will be dominant. In any case, it is not feasible to evaluate distributed green hydrogen production green hydrogen due to the large number of combinations that would need to be assessed.

Figure 37 provides a summary of the incremental challenges associated with green hydrogen production. It shows that land price is a challenge for most optimal WSH locations and will influence the hydrogen production costs. Most of these WSH locations are situated in the western part of the country, where there is high variation in solar PLF, with at least three months of solar generation being lower than one standard deviation from the median value in a given year. However, these same locations generally have wind PLF higher than 30 per cent, which will likely compensate for the variation in solar generation.

Achieving the first 1.5 MTPA of green hydrogen production will require projects to be installed in seismic zones 2–3 and in areas with a population density of up to 400 people per square kilometre. However, there will be no major challenges regarding water availability, climate risks, or land-related conflicts at this level of production. For production capacities between 1.5 and 8.5 MTPA, green hydrogen projects need to be installed in areas with a population density up to 750 people per square kilometre and in seismic zones 2–4. Additionally, the amount of internal uncommitted water decreases from 2,500 to 3,500 mcm to 1,500 mcm. At higher volumes beyond 3 MTPA, the number of land conflicts increases to between four and six, and the RE must be deployed in high land price areas. In the 8.5 and 15.5 MTPA production capacity ranges, the number of land-related conflicts increase to nine. This is expected to pose a significant challenge for green hydrogen projects in India. Beyond a production capacity of 15.5 MTPA, land prices increase significantly to the INR 23 lakh per acre range. Closer to 30 MTPA, green hydrogen projects must be developed in high-risk earthquake zones. The availability of internal uncommitted water decreases to 750 mcm, but it is still not a major concern.

Figure 37 Scaling up of green hydrogen projects in India will need overcoming multiple challenges



Source: Authors' analysis

The discussion given earlier indicates that new business and finance models are needed to access land at reasonable rates. This may include models where the land is utilised in addition to the deployment of RE. The infrastructure for large-scale RE might need to be enhanced for climate and seismic activity resilience that might have affected the LCOH. Additionally, stakeholders dependent on the land must be taken into confidence and their concerns addressed to avoid conflicts and prevent public resistance to such projects. Finally, the seasonality of RE will increase with higher cumulative targets, necessitating significant storage capacity.

Water availability might not be a challenge, but water management will be critical for producing green hydrogen.

Image: iStock

10. Green hydrogen and water policies

While water is an important component in the production of green hydrogen, national and state water policies do not specifically prioritise water allocation for this use (Table 3). Given that green hydrogen will be the fuel of the future, water policies need to be revised to include a water allocation priority for its production.

Table 3 None of the state policies prioritise water allocation for green hydrogen production

Water use sub-sectors	Priority for water allocation in states with water policy														
	AP	GA	HP	JH	KA	KL	MP	MH	ML	NL	OD	RJ	TN	UP	WB
Drinking water	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sanitation			1	1		1		1	1	1	1	3			
Other domestic uses				1		1		1	1	1	1	3			
Commercial						5				5		3			
Municipal										5		3			
Livestock				1							1	2			
Irrigation	2	2	2	3	2	2	2	2	3	2	3	4		2	3
Power generation		3				3	3					5			
Hydro-power	3		4	4	3			6	4	5	4			2	3
Thermal power								5		5				3	
Ecology	4		3	2				4	2	3	2	6			
Afforestation			3				2								
Biodiversity			3												
Agro-industries	5	4	4	5	5	4		3	5	4	5	7	3	4	2
Other industries	5	4	5	6	5	5	3	3	5	5	5	7	3	4	2
Navigation	6	6	6		6			9		5	6			5	
Flood control		5													
Aquaculture					4			7	5		3		4		
Tourism			3				4	8		5	6	8			

Ranks for water policies of various states

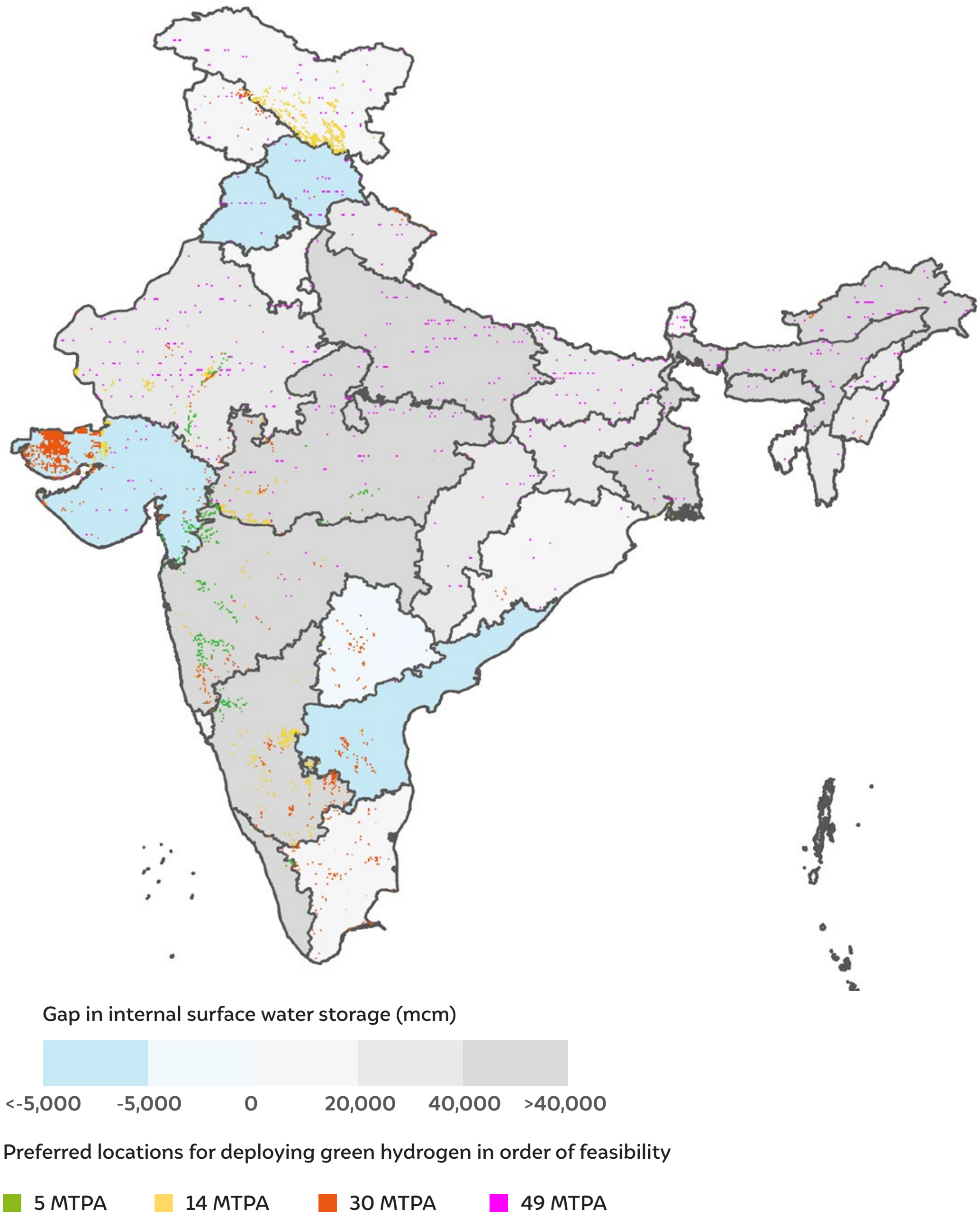
1	2	3	4	5	6	7	8	9

Source: Authors' analysis is based on a review of the water policies of various states in India.

Ranking 1 indicates the highest priority for water allocation while ranking 9 indicates the lowest priority.

Figure 38 shows the state- and union territory-level spatial distribution of green hydrogen potential at different production levels, as discussed in Section 9, compared to the gap in internal surface water storage capacity. The latter refers to the difference between the annual renewable surface water availability and the gross storage capacity of reservoirs at the state- and union territory-level. In most of these states and union territories, this is positive, and the gap in internal surface water storage is almost equal to the annual internal uncommitted surface water. This indicates that to utilise the latter, surface storage needs to be strengthened. Such states and union territories include Arunachal Pradesh, Assam, Bihar, Chhattisgarh, Ladakh, Manipur, Meghalaya, Mizoram, Nagaland, Rajasthan, Sikkim, Tamil Nadu, Tripura, Uttar Pradesh, Uttarakhand, and West Bengal.

Figure 38 **Most states and union territories in India lack adequate surface water storage infrastructure**



Source: Authors' analysis

Further, although there is a gap in the internal surface water storage in Odisha and Maharashtra, they have sufficient available surface water storage capacity to provide water for green hydrogen production during normal and wet rainfall years. In contrast, the promising states for utilising the annual internal uncommitted surface water for green hydrogen production include Andhra Pradesh, Gujarat, Himachal Pradesh, and Telangana. Here, the gap is negative, indicating higher storage capacity than the annual renewable surface water availability. However, there are areas within these states where creating additional surface water storage is not possible due to topographic constraints. One such area is the Kutch region in Gujarat, where the annual internal uncommitted surface water during the monsoon months in a normal or wet rainfall year is substantial, but the feasibility of harnessing this water by building large storage facilities is low.

Punjab is a unique case, as it does not have substantial annual renewable surface water resources internally. It depends on local groundwater stocks and imported water from outside the state, mainly from one of the largest surface water reservoirs in India, the Gobind Sagar formed by the Bhakra Dam, to meet various demands. As a result, the storage gap is negative, and the state does not have any annual internal uncommitted water available for green hydrogen production.

Due to its unique hydrology, Punjab does not have internal uncommitted water for green hydrogen production

The offshore wind potential in India should be evaluated for green hydrogen/ammonia exports.

Image: iStock

11. Limitations of the study

While this study aimed to comprehensively capture all the important factors for estimating RE potential and green hydrogen production and to quantify the corresponding costs, several challenges arose in implementing the planned strategy for the analysis. These challenges are listed as follows:

a. RE potential has several constraining variables in addition to land that could not be captured in this study. Land often has cultural significance or social status and identity, which may make access difficult. Legal and administrative limitations on changing land tenure might also restrict access. These are hyperlocal issues that are difficult to capture at a macro level and, hence, were not considered in this study.

b. For factors such as land prices, even though state and union territory departments maintain information on circle rates, there is no uniformity in the data management of these web portals, which makes the process time-consuming and resource-intensive. These portals face distinct issues, such as captcha security features and server problems. Some websites also have additional access barriers, such as requiring granular details like plot or street numbers without providing dropdown options for possible choices. While it will not be a barrier for a potential buyer or seller of the plot, such a detailed requirement makes access difficult for research-related tasks. We addressed this issue by using code-based web scraping to fetch all possible data from the website's backend. Due to the complexity associated with collecting circle rate data, we focused on key RE states like Gujarat, Odisha, Tamil Nadu, Andhra Pradesh, Chhattisgarh, Madhya Pradesh, and Rajasthan to comprehensively extract data for all tehsils in all districts within each state. For the remaining states and union territories, we limited the data to one random tehsil in each district of a state and union territory. We also had to rely on scaling factors to convert the circle rates to market rates. The random sampling and conversion to market rates can results in significant differences with actual market rates.

c. The availability of land is a challenge for RE and green hydrogen developers. An important distinction need to be made between public and private land. The government controls the allocation of land for project development. However, acquiring private land significantly increases the risks and costs associated with project development. No data is available in the public domain regarding the characterisation of land ownership. When this factor is considered, a significant amount of RE and green hydrogen potential might be constrained from a land acquisition perspective.

No data is available regarding the characteristic of land ownership causing uncertainty in realising the RE and green hydrogen potential

While spatial information on existing power grids is desirable for assessing RE potential, we had to proceed without this information because of data unavailability. In an ideal case, the nexus study grid should consider the power evacuation infrastructure as a constraint parameter. However, since we do not have access to the information, it can be assumed that areas with good RE potential will need deployment of power evacuation infrastructure or increasing the evacuation capacity where it already exists.

d. To capture the social perspective, the analysis relied on certain proxies, such as land conflicts and population density, due to a lack of information on this dimension. The main takeaway from this effort is the need for a data inventory that highlights social challenges at a localised level within a state and union territory.

e. We used a 3 per cent value of the land price as the lease cost. However, this varies widely across state and union territory and even within districts in the same state and union territory. The relationship between circle rates, land prices, and lease costs is not linear and can significantly impact localised RE generation costs.

f. The green hydrogen production cost reported in the study is for annual availability of less than 85 per cent. The costs are derived from the results of our previous publications and use regression models to link the cost of hydrogen with solar and wind PLFs. The cost of hydrogen can be further refined by using annual RE availability across all locations as inputs to the optimisation model. However, this approach is computationally intensive and was not pursued in this research.

There is a need to develop a data inventory that highlights social challenges at the local level within the state and union territory

12. Recommendations

On-ground validation is essential to accurately establish the realisable RE potential.

India has significant potential for renewable energy and green hydrogen production to meet the climate goals. Our recommendations are aimed at unlocking this potential while addressing the associated challenges. The recommendations are as follows:

a. Validation of RE and green hydrogen potential using higher quality data and on-ground assessments

We estimated RE and green hydrogen potential based on data already in the public domain. However, some of these datasets are outdated (such as circle rates for certain states and union territories) or lack sufficient granularity (such as water availability). Therefore, not all of the potential may be fully realisable. Further refinement should be undertaken, preferably at the state and union territory level, using more granular data available with the state and union territory. For example, land use is a critical factor that heavily influences RE and green hydrogen potential within the states and union territories. Additionally, on-ground surveys should be undertaken to validate the findings from this study so that the states and union territories can develop robust estimates. States and union territories should also consider hyperlocal factors such as social dependency, cultural identity, and land tenure to establish this potential.

States and union territories should create graded land banks for accelerating the deployment of RE and green hydrogen projects

b. Create graded land banks for RE and green hydrogen projects

After on-ground validations, states and union territories should create land banks that can be utilised for project development. Processes associated with accessing land and obtaining clearances can cause significant delays in projects. Given our national target to deploy 500 GW of non-fossil power and 5 MTPA of green hydrogen capacity, the creation of land banks will be critical in achieving these targets. Land banks can also be categorised based on RE and water availability attributes and the data that can be collected during on-ground assessments. For example, land banks can be divided into those with good RE but limited or no water availability, separate from land banks with both good RE and water availability for green hydrogen production. Additionally, specific land parcels can be identified that have good connectivity to the grid and the potential for evacuation of hydrogen or its derivatives via road, rail, or pipeline RoW to develop green hydrogen valleys or hubs.

c. Encourage the utilisation of existing landholdings for RE development

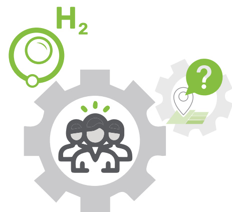
Several institutions, such as Indian Railways, public-sector undertakings, port trusts, defence establishments, special economic zones, state and union territory industrial departments, private industries, educational institutions, and private trusts hold significant land in the country. This land can potentially be utilised for RE development. Policies can be developed to incentivise or encourage the development of RE on these lands. The owners of these lands can be encouraged to generate RE and utilise it for their own purposes.

d. Evaluate the grid infra where there is promising RE

As we scale up RE in the country for power and green hydrogen needs, the existing grid will face capacity challenges, and new lines will need to be added to evacuate power. An on-ground assessment and land bank approach will provide reliable inputs for evaluating future grid infrastructure requirements. A detailed assessment is needed to determine how the grid can be prepared to address the challenges of large-scale RE deployment. This study was not able to conduct this assessment because the grid network is not available in the public domain.

e. Evaluate offshore potential, especially for green hydrogen exports

India has a significant offshore wind potential of 2,107 GW. A major challenge in exploiting this potential is the cost of transmitting power from offshore wind farms to the shore. However, this challenge can be addressed by utilising the offshore power to produce green hydrogen, which can then be converted into ammonia. Water can be sourced from the sea, and ammonia can be transported by ships.



Mechanisms for addressing social impacts can mitigate land conflicts arising from RE deployment

f. Evaluate grid resilience and storage requirements to address seasonality

India is currently deploying RE power projects in areas with the best RE potential, that is, high PLF and low variation in RE throughout the year. However, as we scale up RE deployment, we will need to develop RE locations with higher seasonality, especially for solar energy. Currently, storage solutions are being evaluated mainly from a diurnal variation perspective. With increased solar capacity, we will need to address seasonal variations. Therefore, there will be a need for greater grid resilience and storage requirements. This seasonal impact needs to be evaluated.

g. Evaluate the potential for agro-voltaics, especially in horticultural

Over 46 per cent of land in India is dedicated to agriculture. Therefore, accessing land for RE deployment is becoming increasingly challenging. One option to address this challenge is to explore installing RE capacity in lands where specific crops are cultivated that will be minimally impacted. Horticultural crops that grow in the shade or diffuse sunlight, or those that require only partial sunlight, should be considered. In 2021, India had over 28 million hectares of land under horticulture, with a solar potential of 13875 GW.

h. Prevent desertification that will limit access to RE

A significant area of land with the best RE potential in Rajasthan is in the deserts. For example, over 16,980 square kilometres of land in Rajasthan, with an RE potential of 832 GW, is located in the deserts. The natural desertification of other contiguous areas threatens to reduce additional RE capacity, which must be prevented. Desertification also leads to frequent dust and sandstorms travelling long distances that can reduce the efficiency of solar panels. Therefore, measures are needed to arrest the spread of desertification, and options such as green walls and the remediation of wastelands adjoining deserts should be considered.

i. Mechanism for addressing social impact

A major challenge in large-scale RE deployment is the need for land. To meet our net-zero objectives, this analysis suggests that up to 6.79 per cent of India's landmass may be required to deploy 7,693 GW of RE. Even with just over 100 GW of wind and solar deployment as of 2024, we are already seeing social conflicts. These are expected to increase with a larger scale of RE deployment. Social conflicts can lead to negative perceptions of RE projects, potentially delaying deployment and directly impacting the country's net-zero objectives. Therefore, a formal mechanism is needed to involve all stakeholders in the early stages of project conceptualisation and development to avoid conflicts.

j. Develop water management policies specifically for energy production

The production of green hydrogen is closely linked to water availability. In this study, we have provided an estimate of the internal uncommitted fresh surface water and groundwater that can theoretically be utilised for green hydrogen production. However, certain policy-related decisions need to be incorporated to realise this potential, which are as follows:
Ensure that additional groundwater extraction remains within its overall sustainable yield: In districts with available groundwater for supplying green hydrogen production plants, any additional extraction should stay within the overall safe or sustainable yield. This yield is defined as the percentage of annual recharge that can be pumped without adversely impacting the quantity and quality of water in aquifers. To achieve this, effective implementation of groundwater regulations and judicious pricing of energy for groundwater extraction to encourage its efficient use are desirable.

Assess the need for developing surface water storage: In districts where internal uncommitted surface water is available for transfer to green hydrogen plants, an assessment needs to be made to determine if water can be allocated from the existing surface water storage, such as reservoirs. This will require information on water inflow and diversion from the reservoirs in each district and whether there is any positive change in water stored in reservoir at the end of the hydrological year. This surplus water in the reservoir will be available for transfer. This should consider at least 30 years of data to estimate the average amount of water that can be made available per annum. If the change in storage is zero or negative, there would be a need to build additional storage for the diversion of internal uncommitted surface water (if any), as it is most likely flowing out of the districts. However, the additional water diversion should not adversely impact the downstream water commitments.

Acronyms

DEM	digital elevation model
ESRI	Environmental Systems Research Institute
GDP	gross domestic product
GIS	Geographic Information System
GoI	Government of India
LCOE	levelised cost of electricity
LCOH	levelised cost of hydrogen
LULC	land use land cover
MTPA	million tonnes per annum
NDCs	Nationally Determined Contributions
NGHM	*National Green Hydrogen Mission*
PLF	plant load factor
PNGRB	Petroleum and Natural Gas Regulatory Board
RE	renewable energy
WSH	wind-solar hybrid

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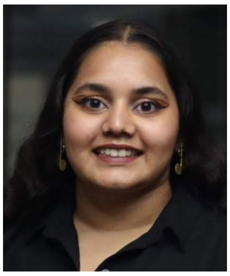
The authors

Hemant Mallya
hemant.mallya@ceew.in I @HemantMallya

Hemant is a Fellow at CEEW and leads the industrial sustainability team. He leads the team in four broad areas – energy transition and industrial decarbonisation, carbon management, circular economy and innovation, and R&D. He has nearly 20 years of experience in energy, environment, and climate change–related issues. Hemant holds a dual MS in industrial engineering and operations research from Pennsylvania State University, USA, and a BE from Mumbai University.

Deepak Yadav
deepak.yadav@ceew.in I @deepakyadav_25

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



Anushka Maheshwari
anushka.maheshwari@ceew.in

Anushka is a Consultant at The Council. Her work focuses on building the climate resilience of cities and its systems through data-driven quantitative and spatial analysis and using creative mediums to sensitise people and policymakers. Prior to joining CEEW, she interned at the Housing and Urban Development Corporation (HUDCO) in developing a GIS-based Integrated master plan for Rajgir and World Heritage Site Nalanda Mahavihara.

Nitin Bassi
nitin.bassi@ceew.in I @NitinBassiN

Nitin is a Senior Programme Lead for the Sustainable Water Team at The Council. He has nearly 18 years of experience in research, consultancy, and training in water resources. His work areas include river basin water accounting, agricultural water management, institutional and policy analysis in irrigation and water supply management, water quality analysis, climate-induced water risk assessment, and wetland management. He is a Natural Resource Management Specialist (MPhil, MSc) with more than 100 publications to his credit.

Prerna Prabhakar
prernaprabhakar12@gmail.com

Prerna Prabhakar was a Programme Associate at The Council's industrial sustainability team. Her work focused on understanding the key linkages between international trade and the environment. She holds a PhD in economics from the University of Delhi.

There is high wind energy potential near the coastline; however, infrastructure development in this region should be climate-resilient due to its exposure to multiple hazards.

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COUNCIL ON ENERGY, ENVIRONMENT AND WATER (CEEW)

ISID Campus, 4 Vasant Kunj Institutional Area
New Delhi - 110070, India
T: +91 (0) 11 4073 3300

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

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