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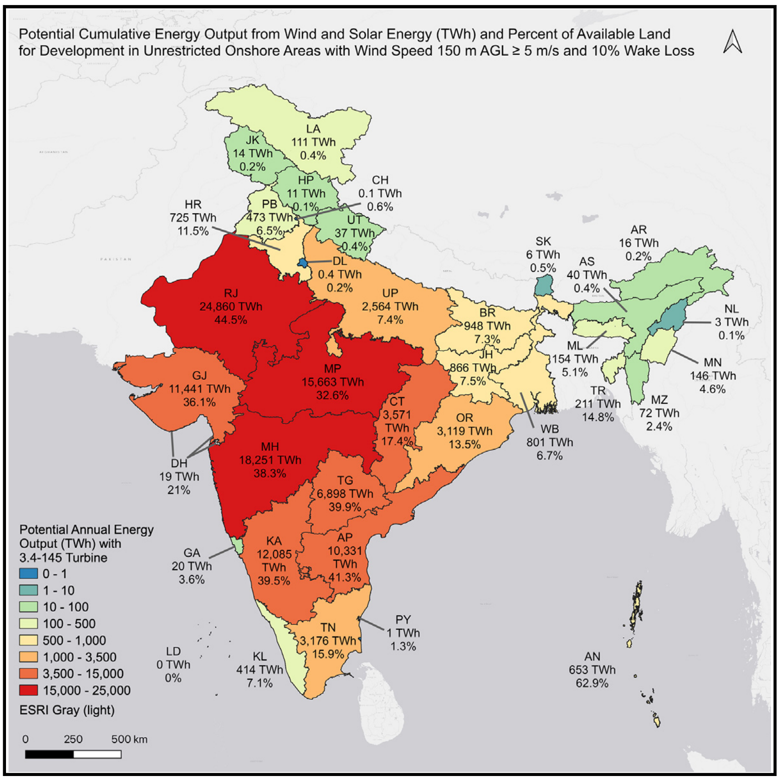
Article

India onshore wind energy atlas accounting for altitude and land use restrictions and co-located solar

Graphical abstract



Highlights

- Co-located wind and solar resources in India with multiple wind speed thresholds
- Site suitability information for hub heights up to 200 m at 10 m resolution
- Potential wind at 150 m exceeds India's 2050 all-purpose energy by a factor of 2
- 2019 electricity demand can be satisfied using 1.5% of India's total land area

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In brief

High-resolution maps that account for wind speeds at multiple heights and exclusions are used to quantify the land available for onshore wind and co-located utility-scale solar photovoltaic electricity generators. This atlas can facilitate India's renewable energy transition by lowering costs, reducing risk, and increasing access to key data.

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Article

India onshore wind energy atlas accounting for altitude and land use restrictions and co-located solar

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SCIENCE FOR SOCIETY Climate change, air pollution, and energy security are significant challenges in India. This study helps address these challenges by quantifying onshore wind resources at different relevant altitudes over India, a major global carbon emitter. A high-resolution wind energy atlas is developed that accounts for technical, climate, environmental, and social exclusions. Findings indicate that, with all but the highest wind speeds, more than sufficient area and potential are available to meet demand for all energy purposes in India by 2050 using wind energy alone. The maximum area and potential for repowering, as well as the co-locational opportunities for wind with solar photovoltaic (PV) resources, are also analyzed. The outcome is a series of maps that can increase certainty for resource planning, expedite the siting process, reduce investment risk, decrease future project costs, increase access to key data for energy planners, and drive India closer to a sustainable energy system.

SUMMARY

India faces the simultaneous challenges of meeting rising energy demand and reducing carbon emissions. To address these, India must transition to renewable energy sources. This study provides high-resolution maps that quantify available areas for wind farms, accounting for wind speeds at multiple altitudes between 100 and 200 m and excluding infrastructure, sensitive land use, and unsuitable terrain. Results indicate that, with wind speeds greater than 5 m/s at 150 m above ground level, 23% (~750,300 km^2) of India's land area is available. This equates to ~18,300 TWh/y produced using modern wind turbines, more than twice that needed to meet India's 2050 energy demand upon electrification of all energy. In addition, 117,700 TWh/y of solar photovoltaic (PV) and wind resources are available when the two are co-located. This atlas can facilitate strategic site selection, reducing time, cost, and uncertainty in the renewable energy development process in India.

INTRODUCTION

India faces the simultaneous challenges of meeting rising energy demand from a large and growing population, providing reliable and fully electrified energy, and eliminating its pollutant and carbon emissions. India has the opportunity to accelerate the use of renewable energy to provide an abundant, clean, and secure energy supply.[1] India's substantial energy demand could double by 2040, with electricity demand potentially tripling as a result of increased appliance ownership and cooling needs.[2] Most energy currently comes from coal and oil.[3,4] India's coal supply has increased rapidly since the early 2000s, and coal continues to be the largest domestic source of energy and electricity generation.[5] Meanwhile, wind, solar, and hydro energy accounted for only 3% of total supply in 2020.[5] It is crucial for India to implement energy sources that reduce vulnerability to fluctuating global energy prices and geopolitical risks without hindering economic growth or continuing to contribute to global emissions.[6]

Despite enormous progress in electrification, India's population lacks full access to electricity, with 2.4% of households unelectrified and much of the country facing daily blackouts.[7] Lack of electricity access is often linked to cooking with polluting fuels, such as wood or cow dung, which is a major global health issue.[8,9] Indoor air pollution claims more than 125 premature deaths per 100,000 people per year in India, which still has 840 million people reliant on traditional biomass for cooking.[3,10] By 2050, Indian air pollution mortalities are expected to increase to 1.66 million people per year under a business-as-usual scenario.[11]

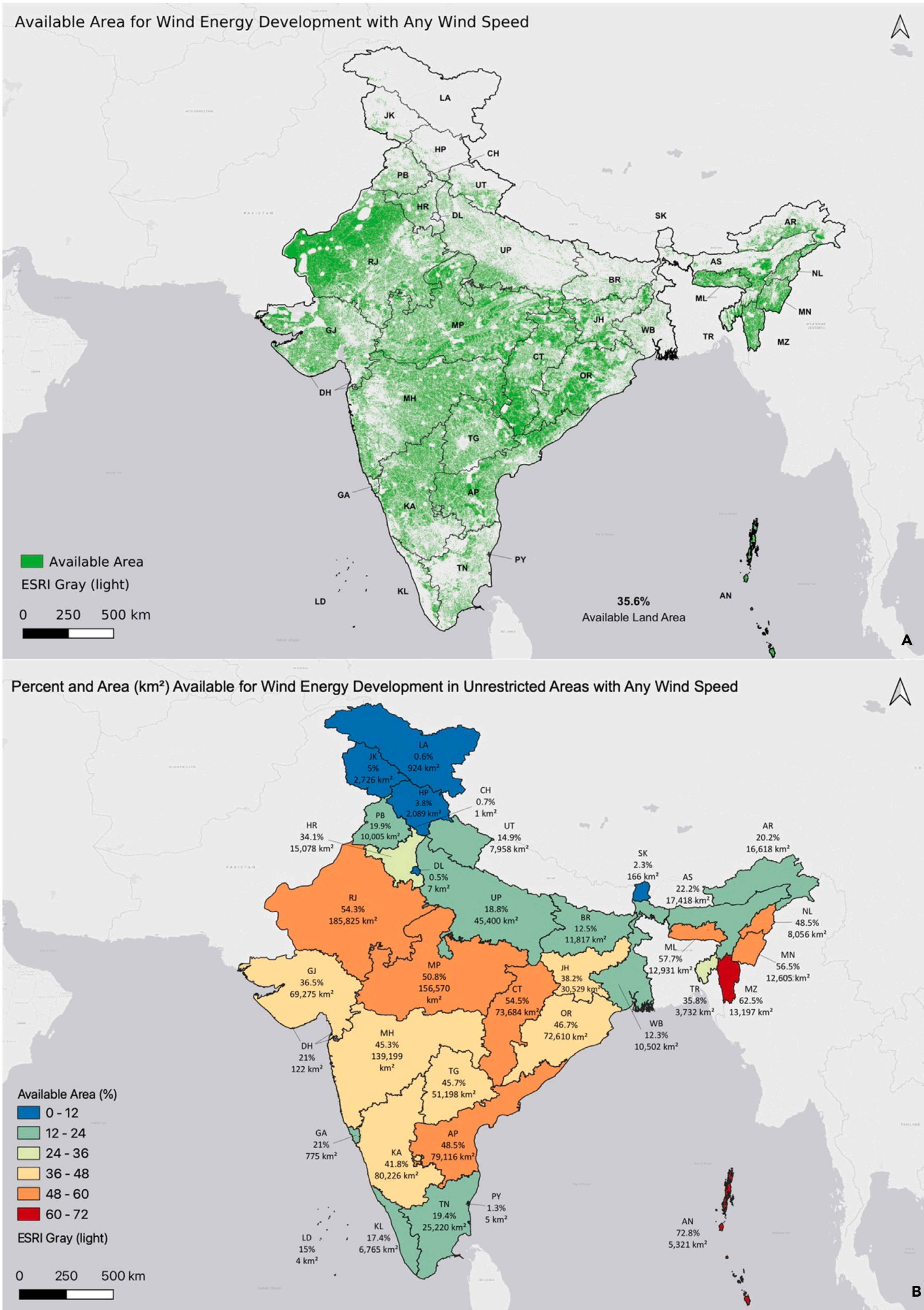
As part of the Paris Agreement, India pledged to reduce the emissions intensity of its gross domestic product (GDP) by 33%–35% (below 2005 levels), increase the share of non-fossil-based energy resources to 40% of installed electric power capacity, and create a carbon sink of 2.5–3 $GtCO_2e$ through additional forest and tree cover by 2030.[12] Despite uncertainties around India's long-term strategy for low carbon development (LTS), which calls for net zero by 2070, India's renewable power generation capacity is growing rapidly. India is targeting 500 GW of renewable nameplate capacity for 2030,[13,14] of which 110 GW would be onshore wind.[15] One potential method for India to reach 100% renewable energy by 2050 is to deploy a total of 630 GW of onshore wind energy capacity and 3,322 GW of combined rooftop and utility-scale photovoltaic (PV).[11] The government of India has acknowledged the necessity for renewable resources by supporting several initiatives, including net metering, the development of mini- and microgrids, the establishment of solar parks, the creation of the Ministry of New and Renewable Energy (MNRE), auctions for large-scale projects, and regulations at the national and sub-national levels that attempt to streamline private investments in small to medium-scale renewable energy rural electrification projects.[16,17] Other policies such as generation-based incentives (GBIs), state-level renewable energy preferential tariffs, renewable energy certificates (RECs), and renewable purchase obligations (RPOs) have also helped to hasten the transition.[18,19]

India's installed onshore wind capacity was 41 GW in 2022, the fourth largest in the world,[15,20] and India's installed solar capacity was 63 GW.[21] The prevailing estimate provided by the National Institute of Wind Energy (NIWE) for country-wide wind potential is 102 GW at 80 m height and 302 GW at 100 m,[22–24] with an update that estimates 695 GW of wind potential at 120 m, the highest altitude to date, with 500 m resolution.[25] The more recent studies performed by NIWE are among the most comprehensive to date, taking into account site suitability based on land use, slope, climate conditions, and other parameters. Another India-wide study to note is Saraswat et al., which analyzes land availability for wind and solar resources based on suitability categorizations, concluding that 213 GW and 3,653 GW of wind and solar potential, respectively, are located in "highly suitable" land area.[26] Phadke et al. provide an estimate up to 1,549 GW at 120 m when including all farmland and a minimum capacity factor of 20%, with 5 km resolution.[27] Mentis et al. approximate 487 GW potential at 80 m hub height using coarse resolution exclusion data.[28] Kiesecker et al. estimate a capacity of 1,789 GW of wind and solar energy based on the availability of converted lands.[29] The analysis performed by the Greening the Grid initiative explores the technical and economic feasibility of integrating 175 GW of wind and solar capacity into India's electricity grid by 2022 after screening for suitable sites.[30] Jain et al.[31] and Deshmukh et al.[32] similarly prioritize low-cost sites based on an economic analysis of available areas for wind and solar resources. Some studies focus on individual states or regions, but these estimate potential without considering infrastructure or other restrictions[20,33–36] or otherwise include India as part of a less granular resource potential estimation overview.[37,38] Others measure resource uncertainty and data reliability without quantifying potential.[39] Still others analyze performance, critique policies, or present pathways to achieve high levels of renewable energy penetration but do not develop potential estimates of their own or evaluate site suitability.[40–50]

Overall, insights from previous studies are limited in granularity due to the use of lower-resolution data and altitudes, which this study addresses. Studies before 2020 primarily measure wind speeds at 50, 80, or 100 m,[22–24,28,37,51,52] while more recent studies up to 2023 use hub heights no greater than 120 m.[25–27] By contrast, this study estimates potential at 150 and 200 m to represent contemporary and future turbines. Proper assessment and planning allow developers to select sites that will supply maximum power output while minimizing project costs and interference with other land uses. This atlas considers infrastructural and land use restrictions to reveal maximum available area, nameplate capacity (GW), energy output (TWh/y), output power density (MW/km^2), and output energy density ($TWh/y/km^2$) for all Indian states and territories. With four wind speed thresholds at three hub heights and with three wake loss scenarios, this study more accurately reflects modern siting conditions. Some of these metrics are compared with 2050 clean energy targets and 2019 national energy consumption data. Another key insight is derived from detailed land use data to help inform turbine repowering opportunities. Most of India's installed wind capacity is generated with older technology that does not maximize on available wind resources.[53] This can be addressed by identifying which sites to renew with modern turbines to increase production and power density. Past studies have examined regional or wind farm-specific repowering feasibility,[53–55] rather than quantifying total repowering potential, as is done here.

Further, few studies quantify wind and solar PV co-locational potential.[56] Most studies consider only wind energy or address wind and solar resources independently, whereas this study measures their complementarity. There are multiple benefits to siting wind and solar systems together, such as minimizing variability and optimizing land and transmission infrastructure use.[24] Policies have been developed to incentivize hybrid systems,[57] which this study seeks to help identify opportunities for. A significant contribution of this study is the use of solar output data to determine the potential for co-located wind and solar farms. From this analysis, conclusions can be drawn about the spatial distribution of resource potential, which has important implications for policy and financial support. Contrary to trends toward new investments in coal and despite doubts about the regulatory, financial, and operational viability of renewable energy in some Indian states,[58–60] this study asserts that most every Indian state has sufficient potential from wind and solar energy to fulfill end-use demand and provide reliable energy.

This atlas provides guidance and increased certainty for resource planning by elucidating the optimal sites for onshore wind and utility-scale solar energy development[58–60] based on exclusions and power potential. Overall, approximately 18,300 TWh/y can be produced using modern wind turbines, more than twice that needed to meet India's 2050 energy demand upon electrification of all energy. When considering wind and solar energy together, 117,700 TWh/y is available when the two are co-located. This study helps to facilitate strategic site selection and drive India closer to a sustainable, reliable, and affordable energy system.



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RESULTS

Overview

A series of maps has been created to quantify and illustrate the available area for development, the subsequent wind and solar energy potential, and associated characteristics that inform siting decisions and elucidate development opportunities.

The available areas (Figures 1, 2, and 3; Tables S2 and S3) and the average wind speed in all regions for each height and wind speed threshold are shown (Figures 4 and S1–S3; Table S7). These results enabled the computation of the maximum possible nameplate capacity (GW) (Figure 5; Tables S5 and S6), output power density (MW/km^2) (Figure 5; Table S9), output energy and energy density under different wake loss scenarios (TWh/y/km^2) (0%, 5%, 10%, and 20%) (Figure 6; Tables S10 and S11),[61] and other useful metrics for wind farm site selection.

Furthermore, the repowering potential is calculated by examining brownfield sites that can potentially be developed with fewer obstacles and costs (Figure 7; Table S15). Finally, the co-locational opportunities for wind and solar energy and the average annual solar energy output throughout different regions of India are estimated (Figure 8; Table S14).

Available area is dependent on wind speed threshold and hub height

Figure 1 shows both a visual representation of available land throughout India and quantifies the amount of area unrestricted by infrastructure, protected and sensitive land uses, and challenging energy development conditions. Overall, 1,167,670 km^2, or 35.7%, of land is available before applying any wind speed restrictions. Most of India's 36 states and union territories have a fair amount of available land. All but Ladakh, Jammu and Kashmir, Himachal Pradesh, Delhi, Puducherry, and Sikkim have greater than 12% land availability, while states and union territories such as Mizoram and the Andaman and Nicobar Islands have land availability up to 72.8%.

As wind speed thresholds are applied in addition to all other restrictions, the amount of available land area sharply declines with higher wind speeds. As seen in Figure 2, at 150 m above ground level (AGL), 22.9% of land is available with a 5 m/s wind speed threshold, 9.4% with a 6 m/s threshold, 2% with a 7 m/s threshold, and finally 0.2% with an 8 m/s wind threshold. Mean wind speeds across India are relatively low, severely limiting energy output if restricted to higher thresholds. Consequently, turbines deployed in India are designed to capture low to medium wind speeds with long blades that have a large swept area and corresponding ability to produce more energy.

Another method to increase energy production is to build taller turbine towers to capture wind speeds that are typically greater at higher altitudes AGL. The effect of increasing hub height on land availability is explored in Figure 3. It is apparent that available area is consistently greatest when the turbine hub height is 200 m. The states and union territories with the highest percentage of available area are the Andaman and Nicobar Islands, Rajasthan, Andhra Pradesh, Telangana, Madhya Pradesh, and Maharashtra, which each have over 40% available area with 200 m hub height turbines.

The rate at which available area declines with lower altitudes is not uniform, as this is determined by the mean wind speed across the state at each altitude AGL, which varies across the country. Figures S1–S3 show the mean wind speed at each hub height without exclusions. From comparing these maps, it is clear that wind speeds become substantially higher with each 50 m increase in altitude. In fact, the mean wind speed across India with a 5 m/s wind speed threshold at 100 m is 5.87 m/s, the mean wind speed at 150 m is 6.07 m/s, and that at 200 m is 6.28 m/s. However, some regions show more change in wind speed than others. In general, there is a 0.24 m/s wind speed increase per 50 m altitude increment. The trends between different regions can be compared in Figure 4.

As seen in Figure 4, the change in mean wind speed with increasing hub height varies greatly between regions across India. Notably, wind speeds are most stable in the northeastern states, which is also evident when comparing Figures S1–S3. In this region, wind speeds remain predominantly between 5.8 and 6 m/s from 100–200 m with a 5 m/s wind speed threshold. By contrast, states in the southern region experience the greatest increase in mean wind speed with increasing hub height. Here, wind speed varies from just under 6 to 7 m/s over the same altitude increase.

The rate of increase does not necessarily correlate with the actual mean wind speed values. For instance, both the eastern and island regions have moderately increasing trends but have the lowest mean wind speeds with a 5 m/s wind speed threshold, ranging from 5.2 to 5.6 m/s. The effect of low wind speeds is evidenced in the sharp decline of available area with increasing wind speed thresholds in most regions.

Without any wind speed restrictions, mean wind speeds are as low as 2.8 m/s in states such as Uttarakhand, severely limiting available area when any wind speed threshold is applied. On the other hand, India has excellent wind energy resources in the western and southern portions of the country, up to 7.5 m/s at 200 m AGL. Consequently, these areas tend to have the highest wind potential, as explored in Figures 5 and 6.

Turbine output translates to substantial potential

Rajasthan, Maharashtra, Madhya Pradesh, and Karnataka each have over 650 GW of potential nameplate capacity when a 5 m/s wind speed threshold is applied at 150 m AGL. Each of these states individually has more potential capacity than is needed to meet the 630 GW of onshore wind capacity recommended in 2050.[11] When considering potential cumulative capacity of

Figure 1. Available area for wind energy development with any wind speed

(A) Available area for wind energy development. This map shows the available area (green) throughout all 36 Indian states and union territories with all restrictions in Table S1 and no wind speed threshold. Overall, 35.6% of India's land area is available for wind energy development.

(B) Percentage and area (km^2) available for wind energy development. Land available for wind development is shown as area (km^2) and a percentage of total area for each state or union territory. All restrictions from Table S1 are considered except wind speed.

See Tables S2 and S3 for all wind speed and height combinations.

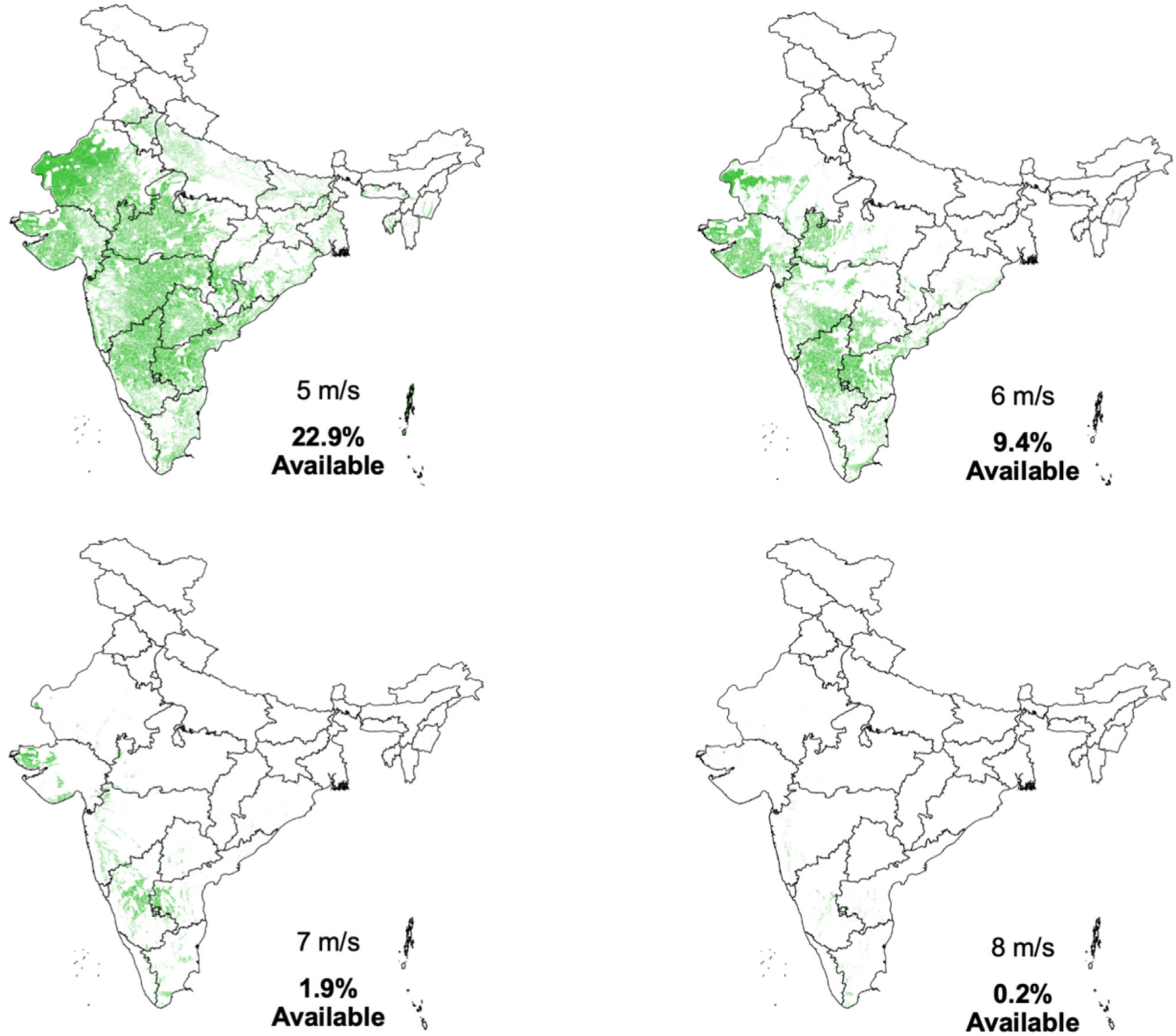

Figure 2. Progression of available area with increasing wind speed threshold at 150 m AGL
Shown here is the rapid decrease in available area (green) as a progressively higher wind speed threshold is imposed beyond all other restrictions in Table S1 (5 m/s: 22.9%; 6 m/s: 9.4%; 7 m/s: 1.9%; 8 m/s: 0.2% available land area).

6,460 GW across all states, India's onshore resources can fulfill the wind portion of this target by more than a factor of 10. Compared with the 41 GW of onshore capacity installed as of 2022, much progress can be made.

States and union territories in Figure 5 with the largest output power densities include Ladakh, Sikkim, and Himachal Pradesh, which can each produce over 4 MW/km^2. Relative to their remaining areas, these smaller states and union territories have more wind energy potential. What distinguishes these areas is the very high mean wind speeds of the north and northeastern regions (see Figures S1–S3). However, given the highly restrictive Himalayan mountains, the remaining area is very low, resulting in exceptionally high output power densities. More feasible states for wind energy deployment include Kerala, Karnataka, and Gujarat, which have high power densities (over 3.5 MW/km^2), more abundant land area, and high overall energy output (TWh/y), as seen in Figure 6A. The range of average output power densities across all states from 100–200 m hub height is 2.99–3.28 MW/km^2. When considering all wind speed thresholds and hub heights, the average output power density is 3.49 MW/km^2.

The total potential annual energy output from onshore wind throughout India is 18,290 TWh/y with a 5 m/s wind speed threshold at 150 m AGL and 10% wake loss. According to Figure 6A, the states that could produce the most energy are Rajasthan, Maharashtra, and Madhya Pradesh, which are also the three largest states by total land area. Compared with the 1,207 TWh/y of electricity demand in 2019, onshore wind energy alone

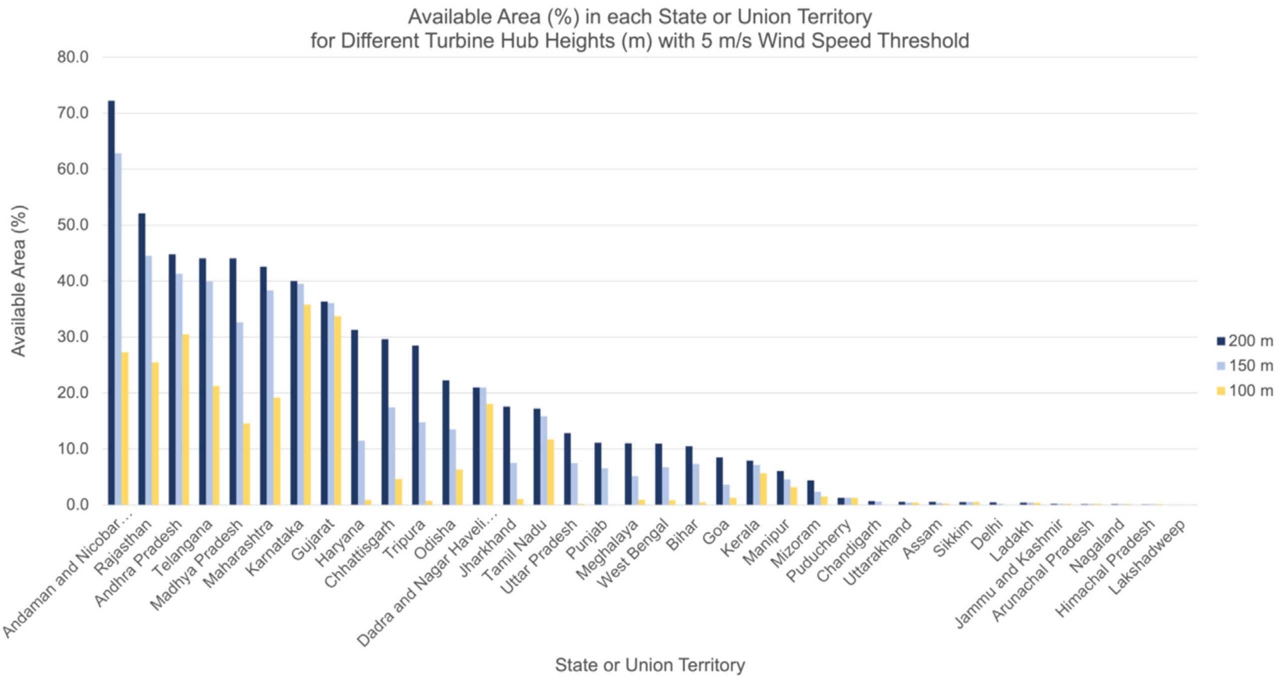

Figure 3. Available area (%) in each state or union territory for different turbine hub heights (m)

Graph shows the impact of increasing turbine hub height on available area due to higher mean wind speeds at progressively higher altitudes. Values after accounting for all restrictions in Table S1 with 5 m/s wind speed threshold. The trend of decreasing area with increasing altitude remains consistent across all states, with 200 m (dark blue) being the greatest, followed by 150 m (light blue), and finally 100 m (yellow).

can fulfill this using only 6.6% of available land area for development,[62] or 1.5% of India's total land area (49,521 km^2). In reality, not all energy will be captured, as India is unlikely to use all available land for wind turbines. Even so, as electricity demand continues to rise in the coming years, onshore wind energy offers an abundant source of clean energy that India can take advantage of. Especially when combined with other renewable sources, such as solar energy, India has sufficient potential to meet its net zero goal using current technology.

The output power density is a measure of how much energy can be produced within the available area in each state, accounting for unique capacity factors. With a 5 m/s wind speed threshold at 150 m AGL, this value varies between 0.017 TWh/y/km^2 in Chandigarh to 0.04 TWh/y/km^2 in Ladakh, with a mean of 0.025 TWh/y/km^2. In general, states and union territories with high wind speeds relative to their available area have the highest power densities. This does not necessarily translate to better overall siting opportunities, as this metric does not reveal other important decision-making factors, such as total land availability. Output power density remains quite consistent between wind speed thresholds. With an 8 m/s wind speed threshold at 150 m AGL, the output power density ranges from 0.037 to 0.044 TWh/y/km^2.

In comparison with the potential energy output found by summing the annual energy output across all states with a 5 m/s wind speed threshold in Figure 6A with a medium wake loss scenario of 10%, when the low wake loss scenario of 5% is used, the annual energy output is 19,305 TWh/y, whereas when a high wake loss of 20% is used, 16,257 TWh/y can be produced. In Figure 6B, one can see the change in energy output with increasing wind speed thresholds and progressively higher wake loss scenarios. The aggregated energy output is highest when wake loss is lowest (5%) and decreases with higher losses for each respective wind speed threshold. However, as the wind speed threshold increases, the estimated energy output values steadily converge around 250 TWh/y with an 8 m/s wind speed threshold. This shows that energy output is influenced by land availability more than by incremental wake losses.

Repowering brownfield sites contributes additional capacity

Figure 7 shows the area occupied by existing turbines of all ages and capacities, which might otherwise be viable for modern wind energy development. The installed nameplate capacity has risen rapidly throughout India in the past several years, quadrupling from 2009 to 2022 to nearly 42 GW.[63] The maximum possible nameplate capacity in Figure 7 is that which could be installed if all land currently used for wind turbines is repowered with modern Siemens Gamesa (SG) 3.4–145 turbines. Using a spacing density of 4.375 times the rotor diameter,[64] an additional capacity of up to 31.2 GW could be gained by repowering. However, if the same number of turbines were repowered as accounted for here, the capacity addition would amount to 109.8 GW. Because the 3.4–145 turbine is larger than most currently installed turbines, particularly models from previous decades, more land would be required.

Older wind farms occupy highly suitable land with excellent wind potential but do not maximize power output due to

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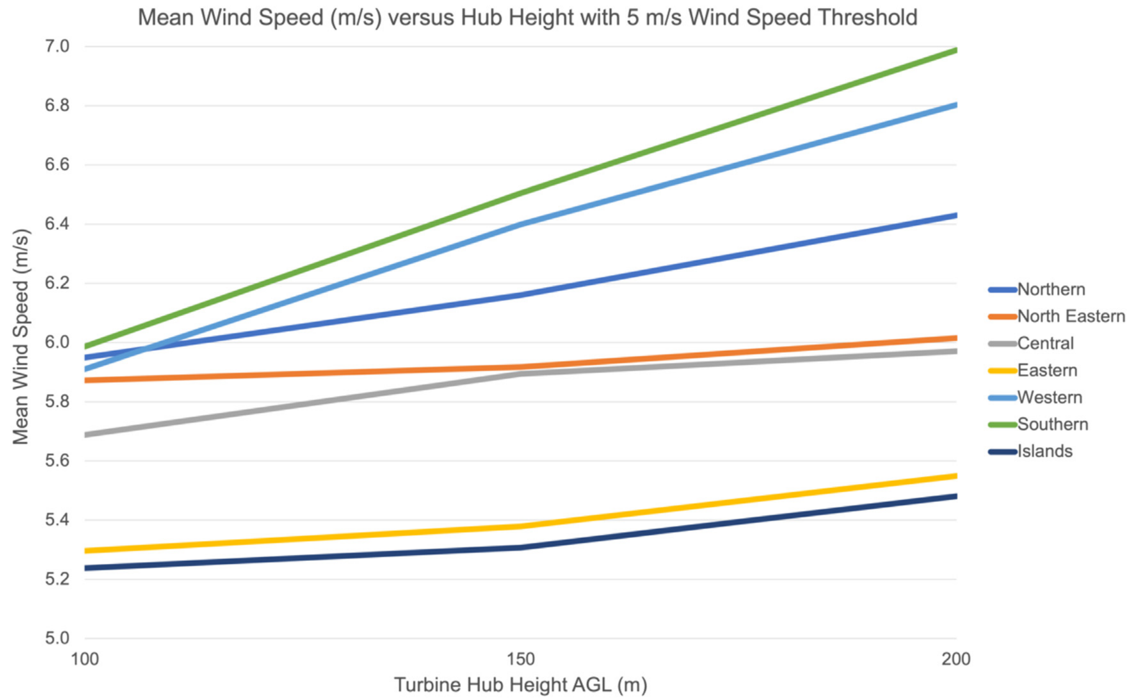

Figure 4. Mean wind speed (m/s) versus hub height

The increase in mean wind speed with each hub height with a 5 m/s wind speed threshold is shown for all regions of India (Northern: Chandigarh, Delhi, Haryana, Himachal Pradesh, Jammu and Kashmir, Ladakh, Punjab, and Rajasthan; North Eastern: Assam, Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Tripura, and Sikkim; Central: Chhattisgarh, Madhya Pradesh, Uttarakhand, and Uttar Pradesh; Eastern: Bihar, Jharkhand, Odisha, and West Bengal; Western: Dadra and Nagar Haveli and Daman and Diu, Goa, Gujarat, and Maharashtra; Southern: Andhra Pradesh, Karnataka, Kerala, Puducherry, Tamil Nadu, and Telangana; Island: Andaman and Nicobar Islands and Lakshadweep).
See Table S7 for all hub height and wind speed threshold combinations.

outdated technology. It is estimated that over 2 GW capacity from before the year 2000 can be repowered with up to three times the capacity using the same land area.[65] Because brownfield sites typically have a smaller environmental impact, social opposition, and permitting requirements, it is often more feasible for a developer to repower existing turbine sites rather than seek new areas for wind development.[65] However, the benefits of repowering are sometimes confounded by India's complex land ownership system, which can make it difficult to negotiate new contracts. Due to these uncertainties and lack of data availability about land ownership, future studies can focus on refining this information to streamline the repowering process and capture India's full generating capacity.

Co-located wind and solar development opportunities are present across India

Figure 8A shows the result of summing solar potential and wind energy output at 150 m AGL with any wind speed threshold and 10% wake loss in all available areas. The colored areas indicate the summed energy potential in each 10 × 10 m grid cell. When added across all state and union territories, this reveals the total annual energy output across India to be 174,741 TWh/y for solar and wind combined. In particular, it is apparent where the most energy could be captured if these resources are co-located on land that contains no restrictions for wind energy development. For example, large portions of Rajasthan, Gujarat, Madhya Pradesh, Maharashtra, Karnataka, Andhra Pradesh, and other western, central, and southern states have excellent resources. These are many of the same areas that were previously determined to have high wind speeds. Solar resources in India tend to be fairly uniformly distributed, with slightly higher potential in the western region. Indeed, Rajasthan, Karnataka, and Gujarat are the top three states for large-scale solar capacity installations, accounting for 54% of installations as of 2022.[21] However, solar output is high throughout India, with an average (range) annual solar energy output of 12,402 kWh/y (9,732–13,908 kWh/y) across all states. The spread is quite small, with a coefficient of variation, or relative standard deviation, of only 6.85%. This distribution is apparent in Figure 8B, which shows the average annual output (kWh/y) in available areas for each state, colored by region.

From Figure 8B, one can observe that (1) the average annual output (kWh/y) values for each state are relatively homogenous, and (2) with the exception of northeastern states, which tend to have slightly lower energy output, the average energy output for states from each region span most of the range. This has important implications, as some suggest that only western and southern regions are suitable for renewable energy development,[66,67] which is clearly not the case. In particular, India's primary coal burning and mining states, Chhattisgarh, Jharkhand, and

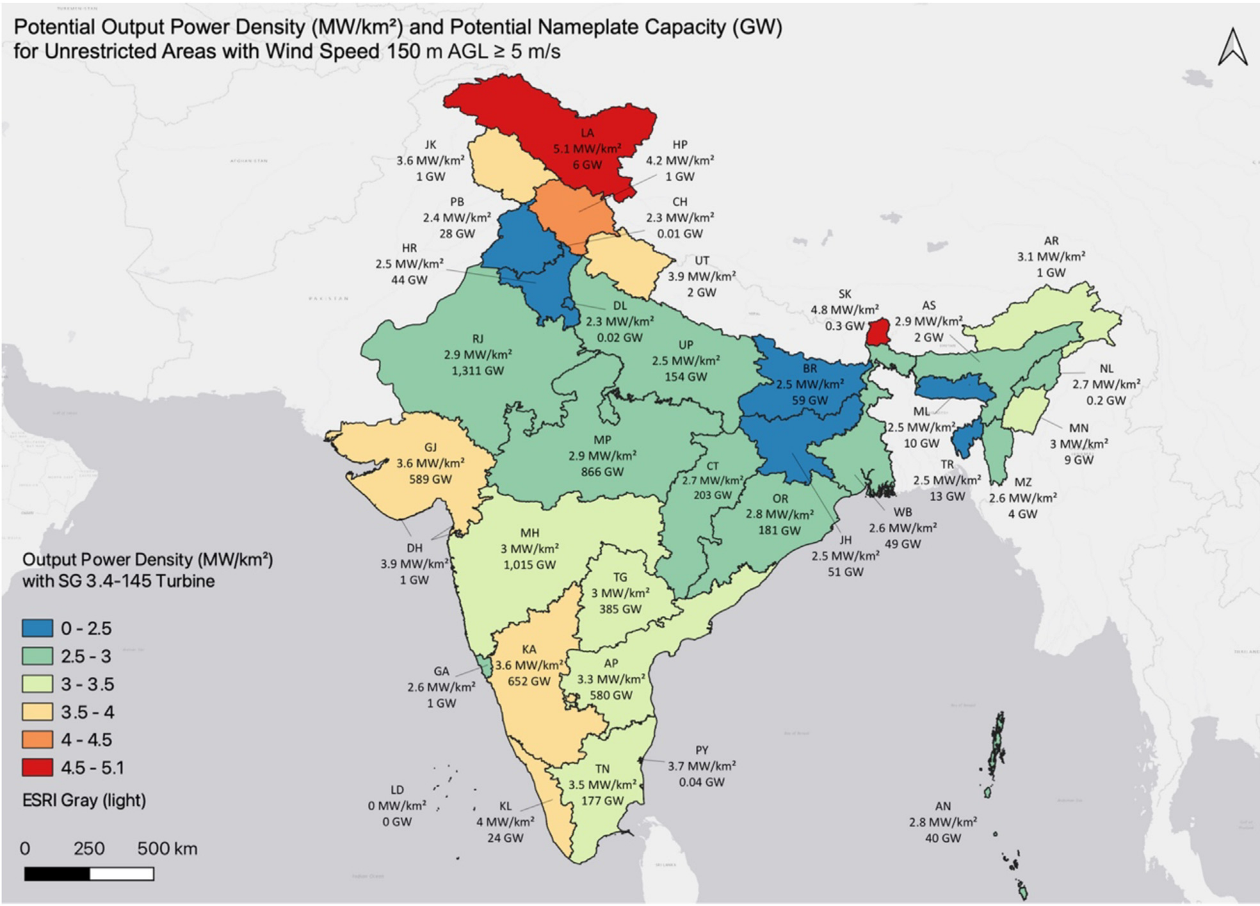

Figure 5. Potential output power density (MW/km^2) and potential nameplate capacity (GW)

The color scale represents the output power density (MW/km^2) in each state or union territory in available areas with wind speed at 150 m AGL $\geq$ 5 m/s after accounting for restrictions in Table S1. Output power density was calculated by multiplying nameplate capacity by the capacity factor in each corresponding state (Table S8), divided by the remaining area after accounting for each wind speed threshold, as seen in Equation S4. Also shown is the maximum possible nameplate capacity (GW) that can be installed in these areas when using SG 3.4–145 turbines.
See Tables S4, S5, S6, and S9 for all combinations of hub height and wind speed thresholds.

Odisha,[68] have annual energy outputs of 13,022, 12,665, and 12,603 kWh/y, respectively, all of which are above the India-wide mean. Contrary to the belief that these states are reliant on fossil fuels for energy production, these results indicate that solar energy resources are abundant. Together with wind energy, Chhattisgarh and Jharkhand alone can produce 15,038 TWh/y, enough to exceed the entire country's electricity demand in 2019 by a factor of 12.5, produce ample jobs,[69] and ameliorate the disproportionate health impacts these regions suffer.[70] Individually, each region except the islands can produce more than the 1,207 TWh/y of electricity demand in 2019, with the central region able to produce as much as 10,511 TWh/y.

Solar output in Figure 8A ranges between 7,440–16,000 kWh/y, with most areas falling within the range of 12,000–14,000 kWh/y. This means that solar potential outweighs wind potential in most locations. When summed across each state, solar energy output accounts for between 79%–99% of total possible output. This is due to the significantly higher solar output energy density, which is on average 0.124 TWh/y/km^2 versus 0.016 TWh/y/km^2 for wind. A spacing density of 81.75 MW/km^2 is used here to represent the configuration of modern solar arrays.[11] This is higher than some estimates[71,72] but accurately reflects the improvement in utility scale PV energy density.[73,74] This is also consistent with the finding that hybrid solar-wind power systems in tropical climates should be dominated by solar PV to minimize variability of daily energy production and curtailments.[75]

It is important to note that the output indicated here is a hypothetical maximum and not necessarily representative of a real wind or solar farm. There is likely to be more space between wind turbines and solar arrays, and possibly between groups of solar arrays. The values here assume all available land is used exclusively for energy production, which itself is not realistic. Instead, these quantities should be analyzed for their relative values to determine co-locational opportunities. From there, a micro-siting assessment must still be completed to site resources such that specific economic, environmental, and social parameters are also satisfied.

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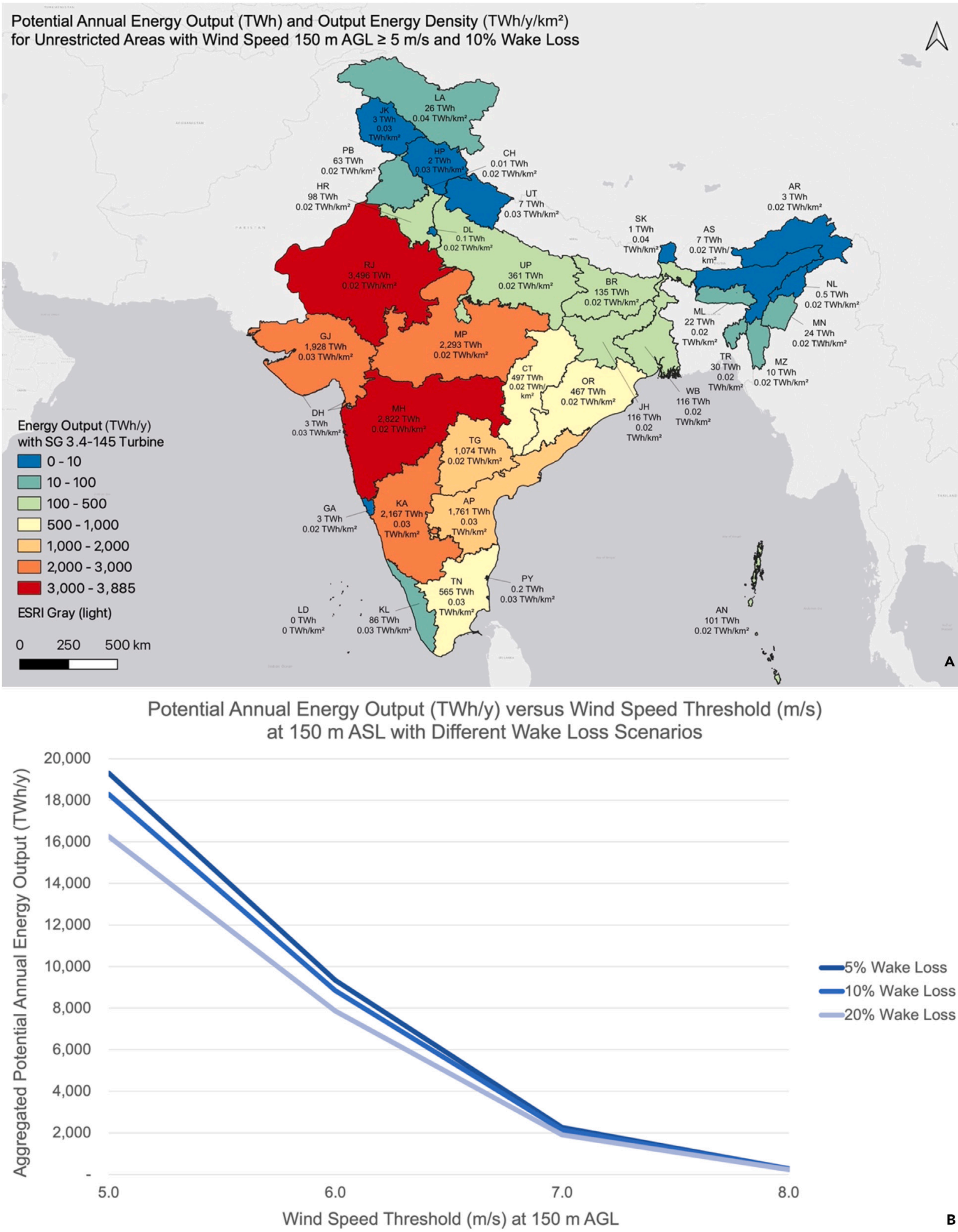

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DISCUSSION

Siting complexities

Development of domestic renewable resources is critical to ensure that India can meet both economic and environmental objectives. Despite the existence of supportive policy structures,[76] in practice, project development is often complex and costly. Firstly, land procurement can be complicated by overlapping permits, contested ownership, and incongruities of land records with ground realities, which has led to the delay and cancellation of projects.[60] It can take over 6–9 months to procure land for wind or solar projects. As significant as this step is in the siting process, there is currently a lack of available digitized data that comprehensively indexes this information, or regulation to streamline this process.[65] The lack of a cohesive land utilization policy paired with outdated requirements that do not reflect current energy generation capabilities also hinders growth. Policies are not uniform across states, which impedes progress, particularly for international developers or corporations looking to build and acquire new renewable energy capacity across different parts of India.[41]

It is important that there are attractive options for renewable energy procurement. Limitations in electricity metering disempower consumers from accessing better prices, leading to suboptimal arrangements and less participation.[77] Other policy structures, such as green tariffs or direct procurement, are either unpopular or becoming disincentivized, respectively.[78–80] For renewable energy siting to happen as quickly and favorably as possible, appealing long-term support structures must exist.[81] One such example is behind-the-meter energy storage paired with distributed PV, which has been critical to the deployment of rooftop solar.[82]

The proximity to substations is also an important factor in determining the economic viability of wind energy sites. Developers prefer areas near load centers to minimize transmission costs, but this presents a degree of conflict with the use of fertile land for nonagricultural uses.[65] The agriculture sector supports over 60% of the Indian population, but farmers are facing increasing pressures, such as from floods and droughts. The decrease in fertile land for food production can impact food security.[65] On the other hand, the additional revenue stream from co-locating wind farms on cropland may boost farmers' livelihoods. An additional complication is the quality of the infrastructure itself, as electricity systems in India can face high transmission and distribution losses of greater than 30%, making the grid inefficient.[4] Rather than limiting available areas by proximity to transmission infrastructure, as is sometimes done,[28] this study assumes that new transmission capacity can be built to connect these areas to the grid, which might be economically feasible depending on the project. These decisions are highly site specific and require further study.

Mapping challenges and opportunities

From a mapping perspective, data availability and quality are obstacles that must be addressed before more realistic energy atlases can be developed. This atlas relies on the use of multiple datasets to compensate for gaps and uncertainties. For instance, buildings are restricted using both vector footprint data from OpenStreetMap,[83] which is more accurate but incomplete, and 10 m resolution satellite data from ESRI,[84] which is exhaustive but imprecise in its catch-all "built area" classification. Similarly, certain land use restrictions contain redundancies to be conservative (these do not impact overall remaining area, as available land is quantified from a binary raster indicating the presence of any restriction in a given pixel). Data scarcity is a challenge for layers such as military zones, which could contain classified or secure information, and hazard-prone areas, which affect large parts of India and can endanger wind farms.[85,86] Excluding land that has a high probability of landslides, drought, floods, or earthquakes would improve future siting feasibility studies and provide valuable information to developers about additional risks and potential costs.

Changing wind conditions due to climate change may present a new challenge to predicting large-scale wind patterns in India. Winds in India are influenced by strong seasonal monsoons. However, in recent years, climate change has been disturbing these patterns, introducing phases of flood and drought.[87–89] During the dry spells, the demand for power from agriculture and cooling equipment increases, whereas during the wet periods, such demand decreases, although simultaneously, the power supply increases because the strong westerly winds contribute to elevated production.[90] Furthermore, the magnified effect of air pollution in mega-cities is a challenge that the Indian power system contends with. Aerosol particles and aerosol-enhanced clouds reduce wind speeds below them by reducing the vertical transport of horizonal momentum.[91] Reduced wind speeds limit wind turbine electricity potential, so it is important to take this into account through more precise datasets that reflect daily and seasonal variations, particularly in developing countries that still suffer from much worse air pollution in metropolitan areas. However, these phenomena also lack adequate resources for detailed mapping in relation to prospective wind energy sites.

Rapid urbanization presents another challenge, as the growing footprint of cities will reduce the area available for energy development while simultaneously likely contributing to further pollution and increasing energy demand. For example, Delhi experienced an 80% expansion in urban extent from

Figure 6. Potential annual energy output at 150 m AGL

(A) Potential annual energy output (TWh/y) and output energy density (TWh/y/km^2). The color scale represents the output energy (TWh/y) in each state or union territory in available areas with wind speed at 150 m AGL $\geq$ 5 m/s after accounting for restrictions in Table S1. Values are computed using SG 3.4–145 turbine and 10% (medium) wake loss. Also shown is the output energy density (TWh/y/km^2) (annual energy output divided by available area). See Tables S10 and S11 for all combinations of hub height and wind speed thresholds.

(B) Potential annual energy output (TWh/y) versus wind speed threshold (m/s). Graph shows how cumulative India-wide energy output at 150 m AGL varies with wind speed thresholds for different wake loss scenarios (dark blue: 5%, medium blue: 10%, light blue: 20%). Not shown is no wake loss scenario. See Table S10 for all hub height and wake loss combinations.

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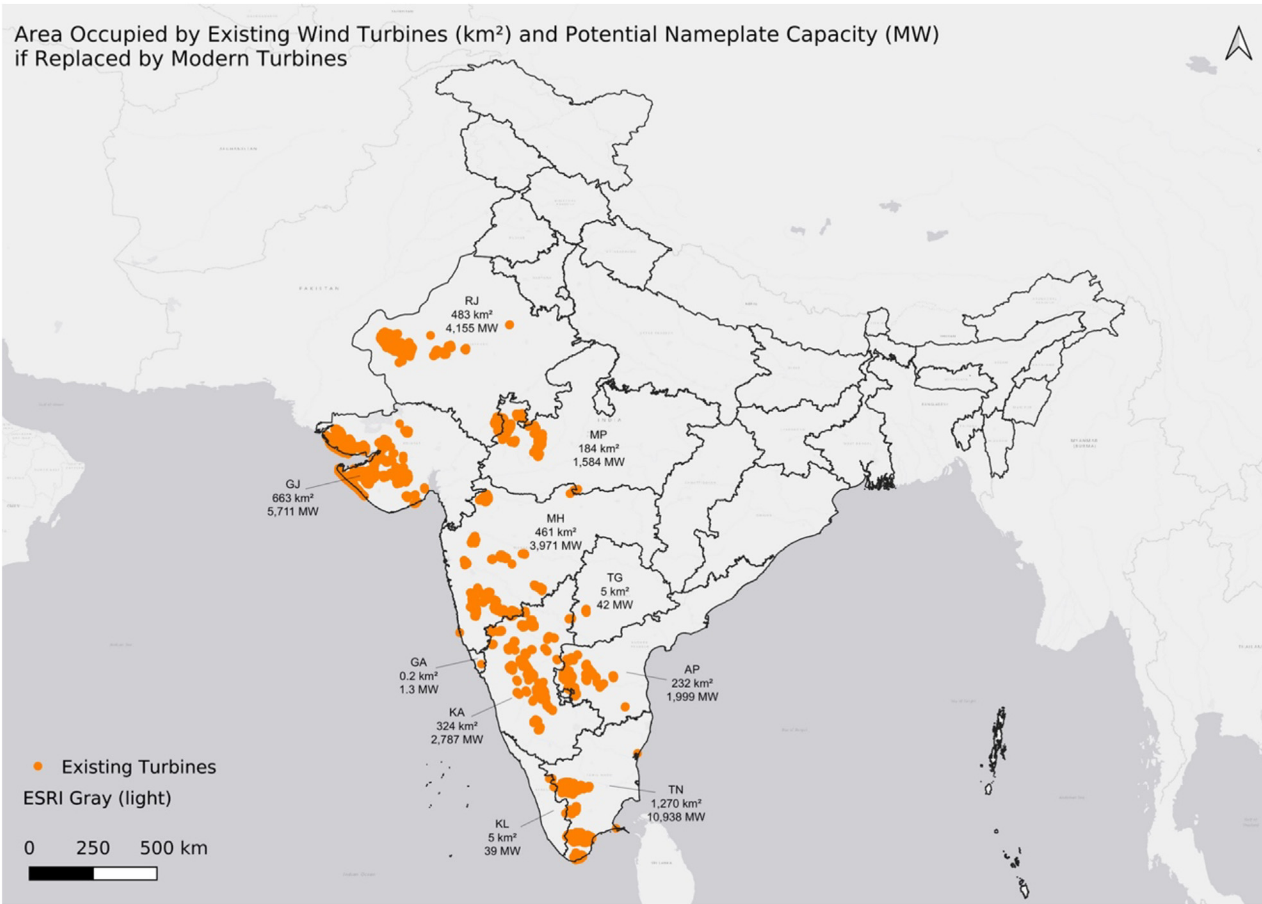


Figure 7. Area occupied by existing wind turbines (km^2) and potential nameplate capacity (MW) if replaced by modern turbines
Map shows total area occupied by 31,702 existing wind turbines (orange) buffered with 220 m setback distance and nameplate capacity that can be installed in this area, without considering any other restrictions. 10 states have existing turbines: Andhra Pradesh, Goa, Gujarat, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Rajasthan, Tamil Nadu, and Telangana. Area not to scale.
See Table S15.

2000 to 2009 alone.[92] Urban area encroachment will make some wind locations less available in the future, as well as alter resource characteristics such as near-surface radiation flux and wind speed. Resource assessment studies must use recent data that reflect the rapid rate of land use change, while energy planners must account for transforming energy needs.

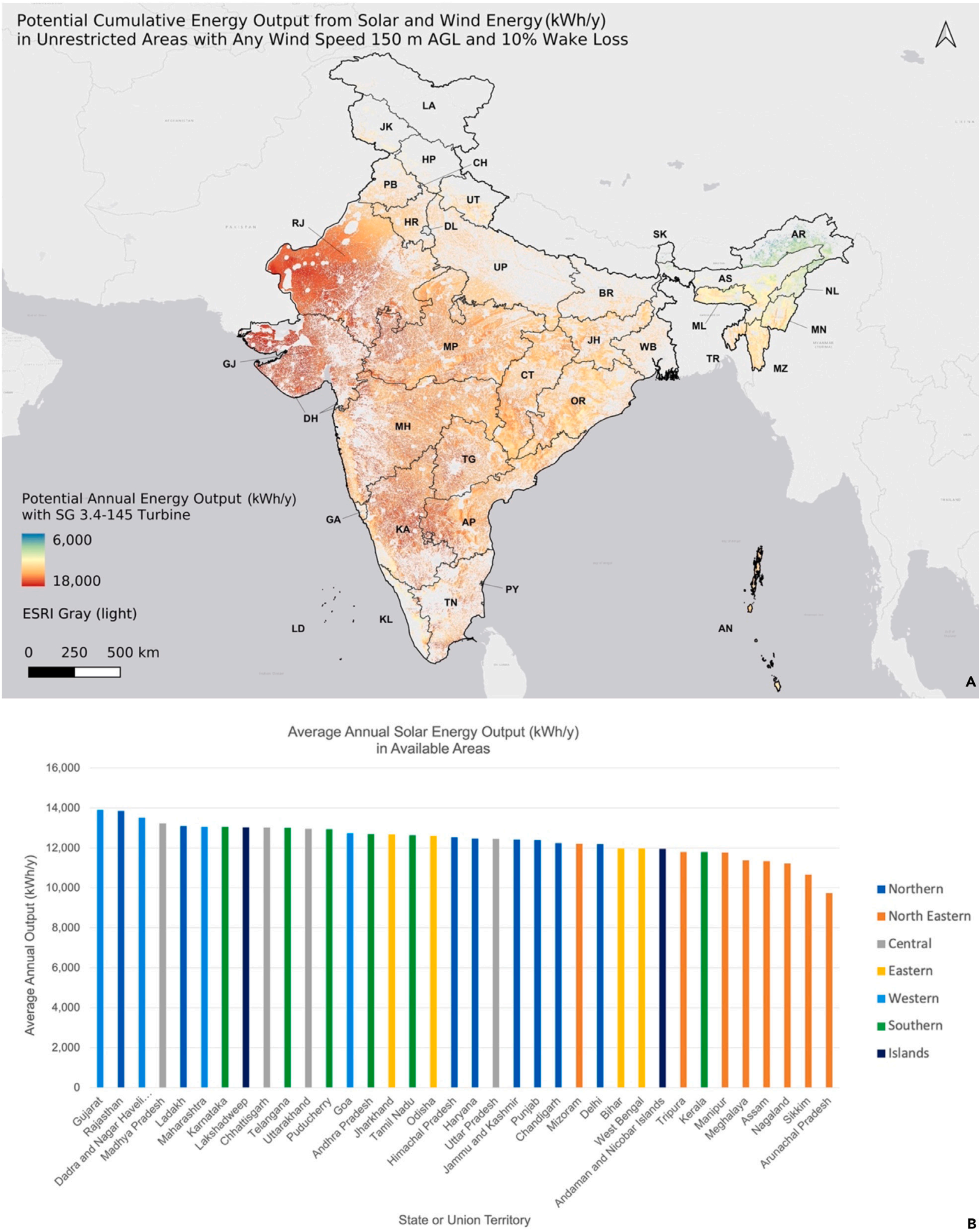
In future studies, the optimal locations for pairing storage systems with renewable energy can be investigated, as battery storage can help offset grid reliability challenges and provide additional load flexibility.[93,94] Similarly, the potential of Indian offshore wind energy is a promising resource that should be further investigated for accelerated site identification.[95,96] Continued exploration of solar siting availability would be worthwhile, especially given supportive policies such as the National Wind-Solar Hybrid Policy.[57] The solar potential in this study is only quantified within areas available for wind farm siting, meaning rooftop solar is not considered, as buildings are excluded from available wind development area. Further analysis must be done to update India's solar potential with considerations specifically for rooftop and utility-scale solar arrays. With additional solar site selection criteria, it would be useful to measure and map solar and wind complementarity, particularly if there are areas where these resources peak at different times of the day, as this would be very beneficial for balancing the local grid.

Results validation

Most resource review studies conclude that India has an abundant source of wind and solar energy that exceeds energy demand, yet the degree of available area and resulting potential varies between studies. The difference can be accounted for primarily in the use of lower hub heights, lower spacing densities, lower spatial resolutions, and more conservative setback distances and exclusion criteria compared with this atlas.

Most existing studies focus on wind speeds at altitudes below 120 m.[22–28,37,51,52] This study instead uses heights of 150 and 200 m to represent contemporary and future turbines. At these altitudes, mean wind speeds tend to be higher, contributing to greater average potential.

The spacing density is another factor that contributes to diverging potential capacity estimates. Compared with the



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5 × 7 D micro-siting configuration used by NIWE,[25] which results in a 6 MW/km^2 power density, this study uses an updated density of 4.375 × 4.375 D,[97] which leads to an installed power density of 8.61 MW/km^2. Other studies used even lower power densities of 5,[27,28] or 2.25, and 7.5 MW/km^2, for wind and solar, respectively.[30]

Perhaps most importantly, more conservative setback distances are typically applied to lower-resolution datasets. In comparison with the 10 m resolution used in this study, the NIWE and Greening the Grid studies both have a resolution of 500 m,[25,30] Saraswat et al. use a spatial resolution of 1,000 m,[26] and Phadke et al. use 5 km.[27] The granularity in this study allows for more nuanced findings. Further, the restrictions used in most studies are not derived from policy, as is done here to determine setback requirements. Instead, certain infrastructural and land use restrictions, such as buildings, water bodies, roads, railways, and protected areas, are buffered with larger distances than mandated by law. This could lead to uncertainties in the outcome, either over- or underestimating available land in different places. For example, railways and highways must be buffered with a distance equivalent to the turbine hub height plus half the rotor diameter plus 5 m (approximately 205 m with an SG 3.4–145 turbine), yet a 500 m buffer is applied to these restrictions in the study performed by NIWE. Buildings must be buffered with a maximum distance of 500 m, yet NIWE uses a buffer distance up to 10,000 m. Phadke et al.,[27] Mentis et al.,[28] and Greening the Grid[30] each exclude a combination of either forests, grasslands, or agriculture, when in reality, these can each be used for energy development.[98] Although this approach may better account for obstacles faced by possible social opposition, it severely underestimates available potential for development. Finally, both NIWE and Saraswat et al. explicitly limit their study area to greenfield sites, overlooking the large potential that could be captured from brownfield sites.

Impact

Wind and solar energy together accounted for 93% of capacity additions in 2022.[21] Renewable energy will continue to grow at a rapid pace as the mounting pressures of greenhouse gas emissions, energy insecurity, and air pollution motivate policymakers and energy planners. India's policy conditions recognize the need for improved energy reliability, environmental quality, industry competitiveness, and cost-effective electricity. This atlas aims to further accelerate the transition to renewable energy to help address these challenges.

By providing information about wind and solar potential, sensitive and protected areas, and other relevant restrictions, developers will be able to limit the initial site selection process dramatically through a more strategic review and verification of high-potential areas. This is especially true of developers who plan to build in a new area and are not necessarily familiar with the landscape, local policies, and limitations.[99] Providing more certainty at an early stage will also allow for earlier turbine selection and customer engagement, reducing the number of abandoned projects, improving investment decisions, and lowering project costs and the levelized cost of energy (LCOE) of wind and solar.

Ultimately, transitioning to 100% renewable energy will reduce the number of premature mortalities caused by air pollution, eliminate a substantial portion of emissions, and decrease energy costs, while creating economic opportunities and millions of new jobs, enhancing energy security, improving grid reliability, and providing access to clean electricity for all Indian towns and cities.[11]

Conclusions

This study develops a wind energy atlas for India, where enormous energy demand, ample energy resources, and government incentives present renewable energy development opportunities. Using geographic information system (GIS) maps, available areas are quantified after accounting for restrictions, including airports, buildings, protected land use, military zones, railways, roads, water bodies, waterways, wildlife and nature, high elevation and slope, and existing solar farms, to which policy-informed setback distances are applied. This study finds the wind and solar potential within available areas considering three altitudes (100, 150, and 200 m), four wind speed thresholds (5–8 m/s), three wake loss scenarios (5%, 10%, and 20%), unique capacity factors in each 10 m grid cell, and modern wind turbine and solar array dimensions, resulting in the most detailed and highest resolution atlas to date (see Figure S5).

Results for each Indian state and union territory are presented. Overall, ~1,167,600 km^2, or 35.7% of India's land area, is available before applying any wind speed restrictions. With an installed power density of 8.61 MW/km^2, this translates to 10,050 GW of nameplate capacity. Based on the method of calculating capacity factor spatially as described here and assuming a 10% wake loss, that translates to 23,100 TWh/y in output. For wind speeds greater than 5 m/s at 150 m AGL, the available area is ~750,300 km^2, or 23% of India's land area; the nameplate capacity that can be installed is 6,460 GW and the potential power output (with 10% wake loss) is 18,300 TWh/y. The resulting output exceeds that needed for India to provide 100% of its energy from wind alone upon electrification of all energy sectors by over a factor of 2. When combined with other renewables to meet total electrified load, India's wind needs are exceeded by a factor of 10.

With the 18,300 TWh/year that can be produced with 10% wake loss, 100% of India's 2019 electricity demand could be satisfied with wind using only 1.5% of India's total land area. The states with the largest available areas include Rajasthan

Figure 8. Summed annual energy output from solar and wind and average output from solar

(A) Potential cumulative energy output from solar and wind (kWh/y). Combined solar and wind energy potential is shown in available land areas across all Indian states and union territories. Color scale shows cumulative energy output (kWh/y) within each 10 × 10 m pixel. All restrictions from Table S1 are accounted for, and wind speed is measured at 150 m with no threshold and 10% wake loss. See Table S14 for all wind speed and height combinations.

(B) Average annual solar energy output (kWh/y) in available areas. For each state and union territory, the average annual solar output (kWh/y) is shown in areas available for energy development for any wind speed. The colors correspond to each state's region within India.

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(~152,300 km^2), Maharashtra (~117,800 km^2), and Madhya Pradesh (~100,600 km^2). In relation to total land area, the Andaman and Nicobar Islands (62.9%), Rajasthan (44.5%), and Andhra Pradesh (41.3%) have the most availability. When also including solar energy potential within available land areas, a cumulative maximum of 117,700 TWh/y can be produced under the same conditions. Results for combined wind and solar energy output indicate optimal areas for resource co-location, contributing to grid flexibility. In general, solar potential is higher than wind due to higher energy density of closely packed solar arrays. For wind energy, it is apparent that wind potential increases with increasing hub heights due to faster mean wind speeds at higher altitudes. As modern wind turbines have taller hub heights and larger rotor diameters to capture more wind energy, the higher altitudes and turbine dimensions used in this study are most representative of current and future siting conditions. Land availability from existing turbines is also determined to quantify the maximum possible capacity additions from repowering old turbine technology in high wind resource areas. This study finds that an additional capacity of up to 31–110 GW could be gained by repowering.

In addition to finding the maximum available land area and potential (GW and TWh/y) for wind energy development at different wind speed thresholds, altitudes, and wake loss scenarios, the maximum possible number of wind turbines, mean wind speeds, output power densities (MW/km^2), and output energy densities (TWh/y/km^2) are estimated for each combination. This highly detailed, India-wide atlas can help wind developers with streamlined site selection, policymakers with setting realistic targets and providing appropriate incentives, and scientists with further feasibility assessments, expediting India's transition to a renewable energy grid.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed and will be fulfilled by the lead contact, Anna-Katharina von Krauland (krauland@stanford.edu).

Materials availability

This study did not generate new, unique materials.

Data and code availability

- Raster data files developed by this study indicate available areas after aggregating restrictions for different combinations of altitude and wind speed threshold. These have been deposited at Zenodo under the DOI https://zenodo.org/records/10846269 and are publicly available as of the date of publication. Input datasets can be found by accessing the corresponding references, except for SG power curves, which can be provided by Siemens Gamesa Renewable Energy upon request. This paper does not report original code.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

Siting parameters

When siting an onshore wind project, the most suitable places generally have strong and consistent wind resources, large and unobstructed space, such as agricultural land, minimal risk to wildlife, and high levels of community acceptance.[100,101] Similarly, solar PV plants require a high degree of consistent solar radiation, which depends on location, weather patterns, plant layout, and shading, as well as adequate land area and minimal environmental and social impact.[102,103] The first step in the analysis was to identify relevant constraints that would impede or preclude renewable energy development (e.g., existing infrastructure, sensitive land used for nature conservation or human activity, and dangerous or unsuitable conditions) through extensive review of regulatory requirements, official reports, peer-reviewed studies, and interviews with industry and policy experts (see Table S1). These restriction layers included airports and helipads, buildings, world heritage sites, military areas, roads, railways, water, waterways, wildlife and nature, high elevation and slope, protected and incompatible land use types (flooded vegetation zones, allotments, cemeteries, quarries, and recreation grounds), and existing solar farms.

Individual restrictions can have a major influence on viable land for energy development. One of the most limiting layers is buffered buildings, particularly in high concentrations within and around urban areas. Similarly, buffered roads occupy a substantial amount of land and fragment available areas. Of course, turbines are usually built away from densely populated areas, but proximity to transmission infrastructure is crucial to curb project costs and energy losses.[104] Another layer with a major influence on available area is restricted land use, which consists primarily of nature reserves and wildlife zones that protect land parcels from development. The exclusion of lakes and buffered rivers and canals is also highly restrictive, as there are thousands of such water bodies scattered across India. Similarly, flooded vegetation poses a substantial constraint. Turbines must be constructed on sufficiently solid ground and maintain a distance from major waterways, as not to obstruct commerce or cause safety issues.[101] Finally, the elevation and slope restrictions preclude development in a large portion of states and union territories containing the Himalayas.

Geoprocessing

GIS mapping was used to analyze and buffer this data according to policy-informed setback values that account for safety, environmental, and aesthetic concerns in the proximity of infrastructure and sensitive areas (see Table S1). Policies and regulations published by Indian government agencies such as MNRE and Indian R&D institutions such as NIWE informed the setback distances implemented in this atlas. Siting guidelines established by MNRE were particularly influential in the choice of setback distance, as they stipulate that developers must maintain a distance equivalent to the turbine hub height plus half the rotor diameter plus 5 m (approximately 205 m with a SG 3.4–145 turbine) from public roads and highways ("major roads" in Table S1), railway tracks, buildings, and public institutions.[105] Accordingly, these layers were buffered to adhere to official guidelines. In the case of dwellings, 500 m must be maintained for the mitigation of noise.[105] This restriction was applied uniformly to all buildings to be conservative, as building use data were not available. Where no explicit guidelines were available, a reasonable setback distance was applied. For instance, a 10 m buffer distance was applied to solar energy installations to allow for operation and maintenance of panels.

After buffering each layer as outlined in Table S1, each vector layer was converted to a 10 × 10 m resolution raster to facilitate the subsequent remaining area calculation, following a similar methodology as in Enevoldsen et al.,[106] which was later refined in von Krauland et al.[107,108] The use of a 10 m pixel resolution enables developers to make highly detailed, site-specific decisions about land constraints, resource availability, and turbine placement throughout India. This represents a major advancement over previous maps that used far coarser resolution with which it was only possible to draw insights over an entire region.

Wind speed data were then included as an additional restriction from the Global Wind Atlas, which uses downscaled ERA5 multi-year average wind data from 2008–2017 to model local climates using WAsP software on a 250 m grid.[109] Data with three different altitudes AGL (100, 150, and 200 m) were used to encompass current and future turbine scenarios, as turbine height and blade length continue to increase.[110] The SG 3.4–145 turbine, with a 71 m blade, 127.5 m hub height, and 200 m tip height, is used here as a representative example of turbines currently being deployed in the Indian market.[111] To analyze the wind power distribution and visualize the results, the data were first overlaid with the 10 m resolution restriction layers. Four binary wind speed threshold layers were then generated in a range relevant for industry use (5–8 m/s, with 1 m/s intervals). These layers are combined with all other restrictions and indicate whether the wind speed at each pixel exceeds the corresponding threshold. As seen in Figure 2, the implementation of increasing wind speed thresholds has a significant impact on the number of unrestricted pixels. These thresholds can be used to estimate economic viability of a wind farm site.

The remaining area was calculated by subtracting each restriction layer and wind speed scenario from the border layer. These findings, combined with the average wind speeds and Equations S1–S4, enabled the computation of the maximum possible nameplate capacity (GW), annual energy output (TWh/y), and output energy density (TWh/y/km^2) for each combination of height AGL and wind speed threshold.

Rather than including existing turbines as a restriction layer, land area currently occupied by turbines was calculated separately and used to compute the maximum possible nameplate capacity (MW) that could be installed with modern turbines if these areas are fully repowered. Two different versions of this potential are reported: that of buffered existing turbines considered in isolation from other restrictions (km^2 and MW) (Figure 7), and the difference when comparing the remaining land area accounting for all restrictions (except wind speed) with and without existing turbines (km^2 and MW) (Table S15). The 220 m buffer is derived by multiplying 1.1 times the 3.4–145 turbine tip height of 200 m to prevent safety hazards in case the turbine collapses or sheds debris.

India has excellent wind and solar energy resources that can be combined to meet rising demand, electrify villages, and decarbonize the power grid. To find wind energy potential, the capacity factor in each available grid cell was first computed using data from the wind turbine power curve (Figure S4). The energy potential was then calculated, accounting for turbine spacing, nameplate capacity, and wake loss. A 10% wake loss value was used in these calculations to comply with MNRE's wind farm siting guidance.[105] The resulting wind energy potential was summed with corresponding solar potential values to find the maximum solar and wind energy output in each pixel (kWh/y), which helps determine co-locational opportunities for wind and solar energy. Multi-year, sub-hourly time series solar PV power production data (kWh/y/kWp) from the Global Solar Atlas were used to compute the energy output (kWh/y) in available grid cells for each wind energy threshold and altitude scenario (Tables S12 and S13), assuming that PV modules occupy the same available land area as wind turbines, and accounting for spacing requirements. Wind and solar energy output values were aggregated to quantify the total maximum potential annual energy output (TWh/y) across each state and union territory (Table S14). Lastly, the average annual solar energy output was compared to provide insights about renewable energy suitability across regions.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.crsus.2024.100083.

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AUTHOR CONTRIBUTIONS

A.-K.v.K.: conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing – original draft, writing – review & editing, visualization, project administration, and funding acquisition. M.Z.J.: conceptualization, writing – review & editing, and supervision.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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CRSUS, Volume *1*

Supplemental information

India onshore wind energy atlas accounting for altitude and land use restrictions and co-located solar

Anna-Katharina von Krauland and Mark Z. Jacobson

Overview

This study presents an onshore India wind energy atlas at multiple hub heights above 100 m that accounts for technical, environmental, and social exclusions based on Geographic Information System (GIS) mapping. This document provides information about the methods applied to determine the availability and potential for wind and solar project development for all states and union territories in India. It also supplies figures for visualizing mean wind speed (m/s) versus hub height (m) and capacity factor. Finally, a series of tables is provided detailing important results for all combinations of wind speed thresholds (no wind restriction and 5-8 m/s) and altitude scenarios (100 m, 150 m, and 200 m AGL). These results include area available for energy development (km^2 and %), the number of turbines that can be installed in available areas, maximum possible nameplate capacity (GW), mean wind speed (m/s), capacity factors used for calculations, potential output power density (MW/km^2), wind and solar potential energy output (TWh/y), wind and solar potential output energy density ($TWh/y/km^2$), cumulative wind and solar potential energy output (TWh/y), and turbine repowering area (km^2) and capacity (MW).

Supplemental Experimental Procedures

Data and Setback Distance Selection

Table S1. Summary of Restrictions, Setback/Threshold Values, and Data Sources

Layer Name	Description	Setback/Threshold Value	Sources
Airports and Helipads		**Airports:** 10,000 m **Helipads:** Excluded	**Data:** HDX [1] **Setback:** NIWE [2]
Buildings and World Heritage Sites	ESRI “built area” classification	500 m	**Data:** ESRI [3]; OSM [4]; Unesco [5] **Setback**: MNRE [6]
Land use	Allotments, cemetery, quarry, recreation ground; ESRI “flooded vegetation” classification	Excluded	**Data:** OSM [4]; ESRI [3]
Military		10 km	**Data:** OSM [4] **Setback:** NIWE [2]
Railways		Hub Height + ½ * Rotor Diameter + 5 m (~205 m), using SG 3.4-145 turbine	**Data:** OSM [4]; WFP [7] **Setback:** MNRE [6]
Roads	**Major roads:** living streets, motorway, motorway link, residential, secondary, secondary link, tertiary, tertiary link, trunk, trunk link **Minor roads:** all others	**Major roads:** Hub Height + ½ * Rotor Diameter + 5 m (~205 m), using SG 3.4-145 **Minor roads:** Excluded	**Data:** OSM [4] **Setback:** MNRE [6]
Water	ESRI “water” classification	Excluded	**Data:** HDX [1]; OSM [4]; ESRI [3] **Setback:** NREL [8]
Waterways		**Rivers:** 500 m **Canals:** 205 m **All others:** Excluded	**Data:** HDX [1]; OSM [4] **Setback:** NIWE [2]

Wildlife and Nature	Protected areas, nature reserves, national parks	Excluded	**Data:** Overpass turbo [9]; OSM [4] **Setback:** MNRE [10]
Elevation		> 2,000 m	**Data:** RE Data Explorer [11] **Setback:** Saraswat et al. [12]
Slope		> 20 degrees	**Data**: RE Data Explorer [11] **Setback:** NIWE [2]
Solar Farms	Footprint of existing solar installations	10 m	**Data:** Kruitwagen et al. [13]
Wind Turbines	Used for repowering analysis	220 m	**Data:** QuickOSM (GIS plugin)
Wind Speed		Measured at three altitudes: 100 m, 150 m, and 200 m; Thresholds from 5–8 m/s	**Data:** Global Wind Atlas [14]
Solar Potential			**Data:** Global Solar Atlas [15]
Borders			**Data:** Planning Academy Data Hub [16]

Restriction layers in this atlas were selected to exclude sensitive environmental and cultural areas (e.g., wildlife and nature areas, recreation grounds, world heritage sites), protect public safety (e.g., airports, buildings, roads, railways, waterways, water), account for siting feasibility (e.g., high slope and elevation areas, military land, existing solar energy infrastructure), and identify opportunities for high-potential renewable energy sites (e.g., wind speed and solar potential). A diversity of data sources was selected, although some, such as the OpenStreetMap (OSM) dataset [4] and The Humanitarian Data Exchange (HDX) [1] are used extensively. For all layers, the most comprehensive, accurate, high-resolution data was chosen. Each dataset was validated against other datasets containing similar data. In cases where one dataset could not capture the variety, detail, or geographic extent, two or more complementary datasets were combined. For example, for both buildings and land use, OSM [4] and ESRI ESA Sentinel-2 10 m land use/land cover (LULC) [3] data were leveraged to take advantage of the detailed footprint data that OSM offers while ensuring that full coverage is provided with the highest resolution satellite imagery available. The model uses AI and billions of human-labeled image pixels to produce LULC predictions for nine classes, including “built area” and “flooded vegetation,” which are incorporated in the buildings and land use restrictions, respectively.

Wherever possible, official policy guidance from the Ministry of New and Renewable Energy (MNRE) was used to determine setback distances that wind turbines must maintain from different kinds of infrastructure. A common distance is the turbine hub height plus half the length of the rotor diameter plus 5 m. Using the SG 3.4-145 turbine, which is a representative contemporary turbine with a hub height of 127.5 m and rotor diameter of 145 m, the buffer distance implemented for major streets and railways was 205 m. In the case of buildings, 500 m was used, as the policy stipulates the use of the maximum of the above turbine-dependent distance, or 500 m. For other layers, setback distances were ascertained through published reports and expert interviews with Indian think tanks such as the National Institute of Wind Energy (NIWE) and the Council on Energy, Environment and Water (CEEW), and companies such as ReNew Power, Siemens Gamesa Renewable Energy, and Vestas. Insights about major technical and regulatory challenges were also collected to ensure that the atlas is addressing pertinent obstacles to wind farm siting. For each layer, a distance that was reasonably conservative yet not overly restrictive for new development was chosen. In cases where minimal distance must be maintained from wind turbines, restrictions are either excluded (e.g., water, elevation, slope) or buffered with 10 m (e.g., solar farms). Conversely, some restrictions require large 10 km setback distances (e.g., airports and military areas). Finally, existing turbines are buffered with a distance of 1.1 times the representative contemporary turbine tip height (220 m), to avoid debris from potential collapse, as well as blade or ice throw. This layer is not treated as a restriction, but instead is used to quantify land available for repowering existing turbines.

It is advantageous to pair wind and solar resources, as their output is often complementary in nature. [17] To estimate solar and wind resource potential, data was sourced from the Global Solar Atlas [15] and Global Wind Atlas, [14] respectively. The Global Solar Atlas provides photovoltaic power production from multi-year, sub-hourly time series data of solar radiation and air temperature data from Solargis. It uses data inputs from geostationary satellites and meteorological models to find electrical energy produced by a photovoltaic (PV) system based on both local climatic conditions and temperature, accounting for global irradiation, optimal tilt angle, 2% shading loss, and DC to AC conversion loss at every location. The Global Wind Atlas has a 250 m horizontal resolution and is derived by downscaling large scale atmospheric data to ultimately produce predicted wind climates accounting for high resolution topography. Wind speed data at 100 m, 150 m, and 200 m was used to encompass an array of existing, contemporary, and future turbine hub heights. Because this study covers all of India, which has a broad variety of wind conditions, it is appropriate to use the multi-year averaged wind speed as an initial constraint in the macro-siting stage of analysis, as is regularly done in industry.

Geoprocessing

In total, 12 restriction layer categories were considered in the analysis. Layers were buffered according to the setback values indicated in Table S1. The Asia South Albers Equal Area Conic reference system was selected, as this projection minimizes distortion across the large study area, while maintaining area dimensions, which will be important when calculating available area after taking into account all restrictions.

The restriction vector layers were then either rasterized with a fixed burn-in value, or in the case of the land use, water, and buildings layers, which were sourced at least in part from the ESA Sentinel-2 dataset, restrictions were reclassified using Reclassify Values to identify pixels to be excluded. These restrictions were polygonized, buffered, and rasterized again before being converted to binary using a conditional statement in the Raster Calculator. Upon conversion to raster, each layer was resampled to a 10 m resolution to match the resolution of ESRI land use data (the conversion from vector to raster does not result in significant data loss). To combine all 12 restriction layer categories, these restriction layers were subtracted from the Indian border raster (for which all pixels have values of 1). These output layers were converted to a binary format by changing values smaller than 1 to 0 to denote “unavailable” areas, which facilitated the computation.

In some cases where the data did not fully encompass disputed areas in the Indian territories of Jammu and Kashmir and Ladakh, it was necessary to include portions of corresponding China and Pakistan datasets. These datasets were clipped with the Indian border and merged with other datasets for full coverage. This was particularly necessary for the OSM and Global Wind Atlas datasets.

Wind speed layers at all three heights were sorted using a conditional statement in the Raster Calculator to identify pixels with wind speeds larger than each of the 5-8 m/s thresholds. They were simultaneously resampled to 10 m resolution and converted to a binary format, and finally combined with other restriction raster layers.

Each raster layer was subtracted from the India border raster then converted to binary using Raster Calculator expressions to compute the available area in each state and union territory. The resulting remaining area and wind speed rasters were multiplied to create layers that reveal wind speeds only in available grid cells. The Zonal Statistics tool was then used to sum the number of available cells for each of the different hub height and wind speed scenarios, and the mean wind speed within each of these.

Similarly, the solar potential (kWh/kWp) raster was clipped to the India border, then multiplied by each of the remaining area layers, the installed power density (kWp/km^2), and a conversion factor of 10,000 to account for the 10 m pixel size relative to km, in order to produce a set of rasters with energy output (kWh/y) in available grid cells. These were also processed using Zonal Statistics for each Indian state, resulting in cumulative energy output (TWh/y) in available areas. An installed power density value of 81,750 kWp/km^2 was used, derived by dividing an assumed average rated panel power of 327 W by 4 m^2, which accounts for the area of the panel (1.63 m^2) and space around each panel. [18] The total quantity of potential energy output does not account for inverter area or other infrastructure requirements, but instead indicates a theoretical maximum using modern technological capabilities. [19,20]

Corresponding wind energy output (TWh/y) rasters were produced for each wind threshold and height combination. This was done by first using the Raster Calculator to find the capacity factor in each grid cell based on a third-order polynomial equation that was computed using the SG 3.4-145 turbine power curve. The 150 m and 200 m capacity factor values were scaled based on changing air density with height. Next, Raster Calculator was employed to multiply the raster with remaining area values, turbine spacing density, turbine nameplate capacity, the number of hours per year, unique capacity factor values, and wake loss to find the energy output (kWh/y) in each pixel. Finally, matching solar and wind rasters were summed to find the cumulative energy output in each grid cell. Zonal Statistics was again used to report the total wind and solar energy potential for each height and wind speed threshold for all states and union territories.

To calculate the area occupied by existing turbines that have the potential to be repowered with modern turbines that can produce more energy, an additional raster layer was generated for uniformly buffered existing turbines. This raster was subtracted from all other restrictions to create a separate binary remaining area layer. The sum of available pixels in each state was determined using Zonal Statistics, and the difference between this result and that with all other restrictions was computed. This area is different from that reported in Figure 7, which presents the total area and maximum possible nameplate capacities for modern turbines in currently occupied areas without considering any restrictions or wind conditions. However, given that turbines are currently located on this land, it is unlikely that restrictions would pose a challenge, and in fact, these brownfield sites are typically easier to develop.

Data Analysis

Once the available area in each state or union territory is determined by summing and converting the number of available grid cells, wind potential is calculated based on different wind speed thresholds and hub height scenarios, starting with the number of turbines that can be installed. The SG 3.4-145 turbine was used as the reference turbine throughout the analysis, representing the state-of-the-art technology that developers have indicated will be used for upcoming projects due to its exceptionally low LCOE. [21] As it is optimized for low and medium wind conditions, this turbine is a good fit for the Indian onshore market. [22] The theoretical maximum number of wind turbines (N_{turb}) is based on the area required per wind turbine generator, as seen in the following calculation:

$$Nturb = \frac{Available\ Area\ (m^2)}{Turbine\ Spacing\ Density\ (m^2)}$$ (Equation S1)

where *Turbine Spacing Density* = $(F * D)^2$.

The turbine spacing density is a function of the turbine rotor diameter (m), D, and a spacing factor, F, based on a study that analyzed the spacing density of global onshore multi-megawatt wind turbines (mean spacing factor of 4.375 times the rotor diameter between onshore rural and forested wind farms). [23] This number is then multiplied by the turbine nameplate capacity (rated power, P_r) in order to estimate the maximum possible nameplate wind capacity over an entire state.

$$Potential\ Installed\ Nameplate\ Capacity = N_{turb} * P_r$$ (Equation S2)

From here, it is necessary to account for the capacity factor to have a more realistic assessment of energy output, rather than an idealized scenario. The capacity factor measures energy production relative to the maximum rated output. Instead of multiplying by a uniform capacity factor, the capacity factor for each state and union territory was calculated using the power curve for the SG 3.4-145 turbine. With this, the annual energy production (AEP) for a range of wind speeds can be computed from the probability of each wind speed occurring throughout the year, the hours per year at each wind speed, and the turbine power output at each wind speed. [24] The shape parameter, k, which informs the probability distribution, was assumed to be 2 because wind speed distributions are often Rayleigh in nature. [24] The power output at the hub height and air density of 1.21 kg/m^3 was obtained from the power curve and specifications from the Siemens Gamesa turbine identified above. [21] The capacity factor can then be calculated at different mean wind speeds by dividing the summed AEP by the product of the rated power and the number of hours in a year, or the maximum possible energy produced. A chart was plotted of capacity factor versus mean wind speed in order to fit a third order polynomial that describes the capacity factor for a range of values relevant to this study. The equation used was as follows:

$$CF = -0.0007x^3 + 0.0077x^2 + 0.0815x - 0.2506$$ (Equation S3)

where x is wind speed in m/s.

The resulting capacity factors at 150 m were then multiplied by a constant ratio of 0.995203086, while those at 200 m were multiplied by 0.990414414 to account for the change in air density with height. [25]

Once again, Zonal Statistics was employed to calculate the mean wind speed in available areas for each wind speed threshold and height across each state (Figures S1-3). With the mean wind speed as the input to the third order polynomial equation, it was possible to calculate the capacity factor for each combination within every grid cell (Figure S4).

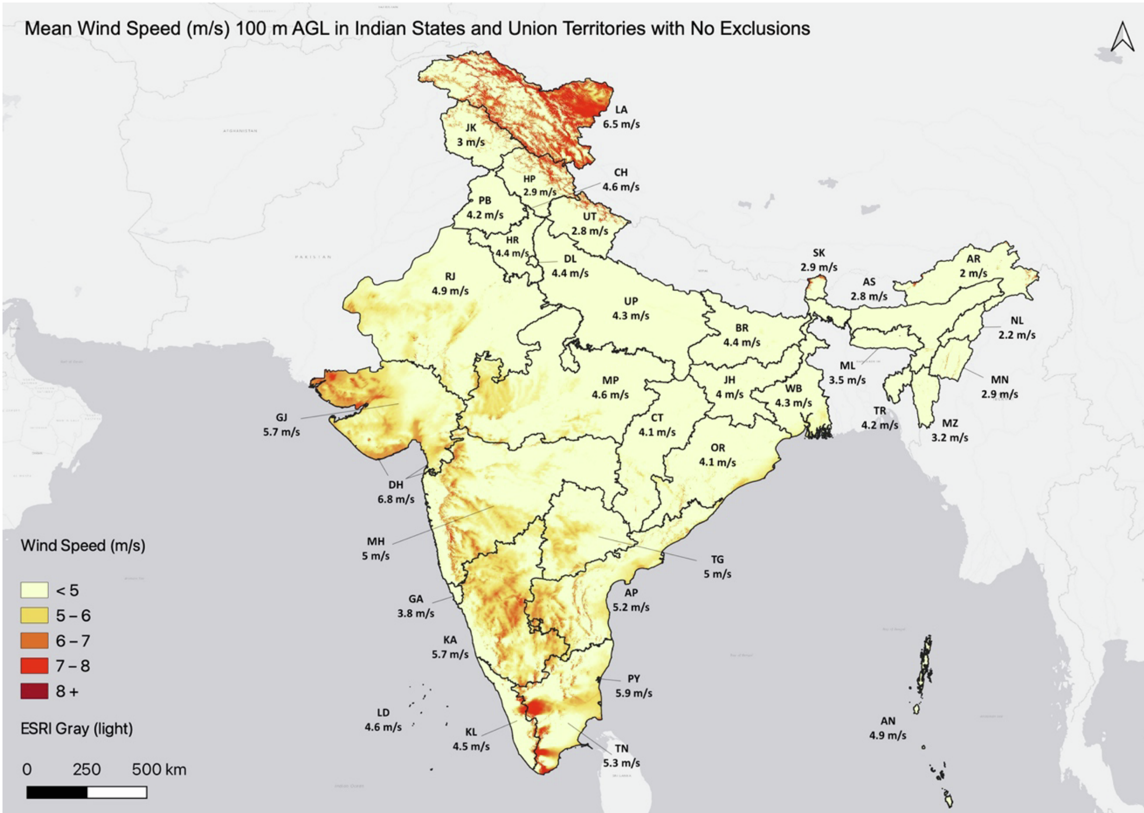

Figure S1. Mean Wind Speed (m/s) 100 m AGL. Mean wind speed for each state or union territory with no exclusions or wind speed restrictions. The color scale represents wind speed values up to 24.5 m/s, with a focus on the threshold values in this study (5-8 m/s).

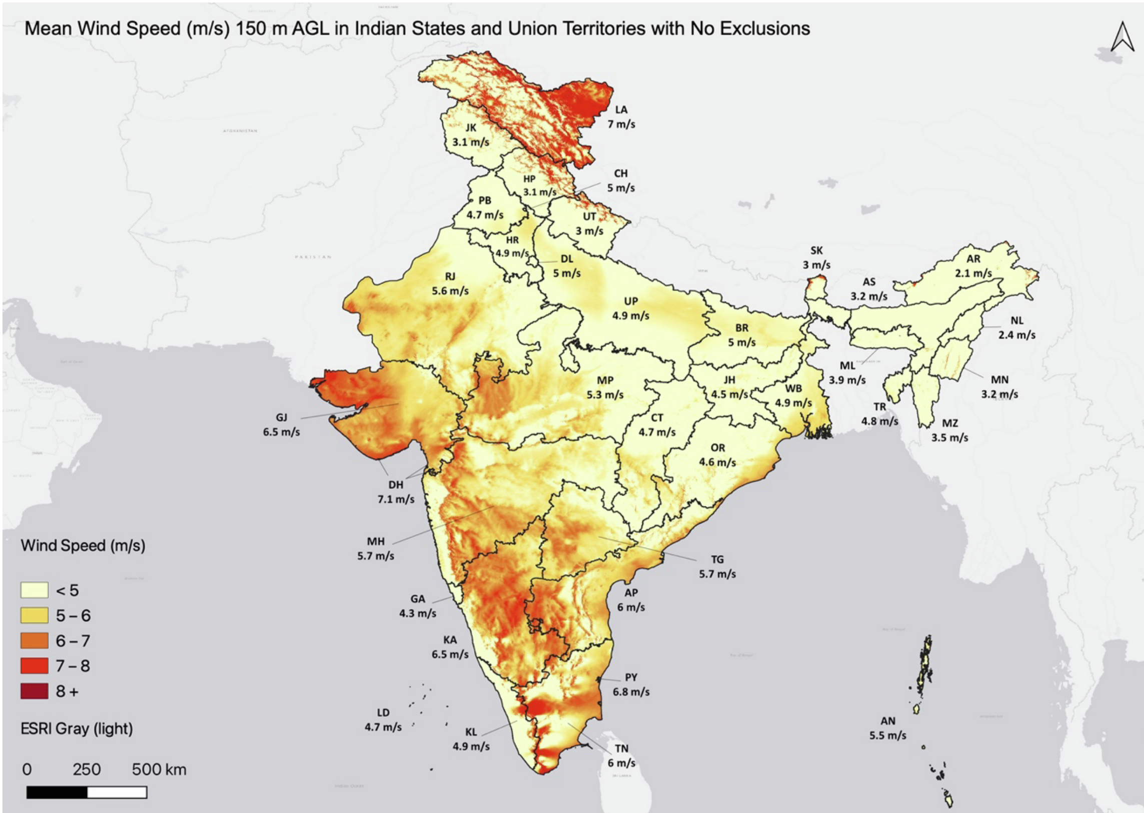

Figure S2. Mean Wind Speed (m/s) 150 m AGL. Mean wind speed for each state or union territory with no exclusions or wind speed restrictions. The color scale represents wind speed values up to 24.5 m/s, with a focus on the threshold values in this study (5-8 m/s).

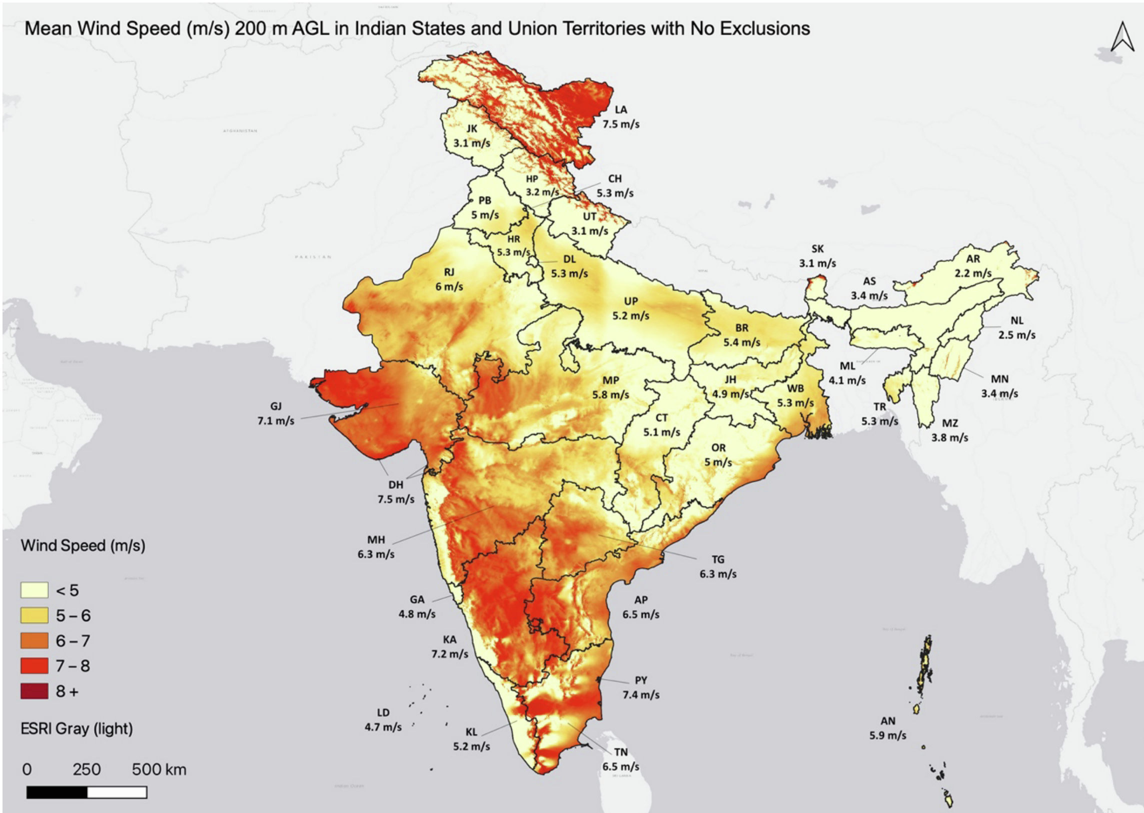

Figure S3. Mean Wind Speed (m/s) 200 m AGL. Mean wind speed for each state or union territory with no exclusions or wind speed restrictions. The color scale represents wind speed values up to 24.5 m/s, with a focus on the threshold values in this study (5-8 m/s).

The outcome is a table containing a unique capacity factor for every state and union territory with each wind speed threshold (no wind restriction, 5, 6, 7, and 8 m/s) and height (100 m, 150 m, and 200 m above ground level (AGL)). These values have been validated using an equation which gives the capacity factor as a function of three parameters: the mean Rayleigh-distributed wind speed (V_m) in m/s, the rated power of a turbine (P_r) in kW, and the turbine blade rotor diameter (D) in m, which works for nearly every geared wind turbine worldwide, and shows a very close agreement to these calculated values. [24]

Furthermore, the capacity factors tend to fall within the range of 30-50%, with an average of 40.5% with any wind speed. This is in close agreement with a study conducted by the U.S. Department of Energy, which concluded that the average capacity factor of a modern onshore wind turbine exceeds 40%. [26] The National Renewable Energy Laboratory found an average capacity factor of 36% for wind plants in India from modeled data, post-curtailment. [8]

The resulting capacity factors in each pixel across India are visualized in Figure S4 below.

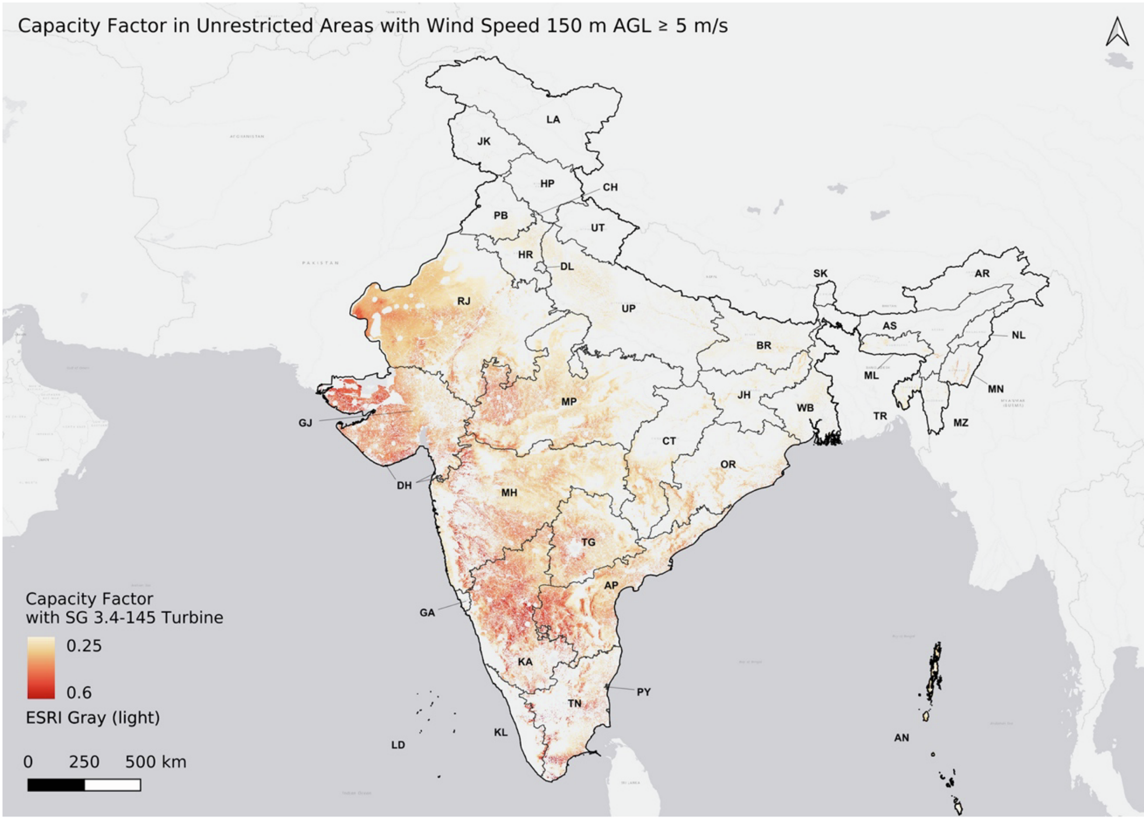

Figure S4. Capacity Factor in Unrestricted Onshore Areas with Wind Speed 100 m AGL ≥ 5 m/s. Capacity factor in available areas for wind energy development, calculated for each 10 m x 10 m pixel across India using Equation S3 for SG 3.4-145 turbine. All restrictions in Table S1 are accounted for, including wind speed threshold of 5 m/s at 100 m above ground level (see Table S8 for complete set of values).

With calculated capacity factors, many other useful metrics for decision-making, such as the energy output (TWh/y), both with and without array losses, or wake effects from other nearby turbines, can be computed. Since the study does not model a particular wind farm configuration, but rather the overall energy output over an entire state, it assumes that array losses are uniform. Three different wake loss scenarios–5%, 10%, and 20%–were analyzed to encompass a range of possibilities. The low (5%) value was derived from a global model which shows the loss in wind power extracted when accounting for competition among wind turbines for available kinetic energy. At higher levels of installed power, wake loss values up to 20% were found due to competition. [27] Other sources indicate average power losses due to wind turbine wakes on the order of 10-20% of power output of downstream wind turbines. [28]

Additional results such as output power density (MW/km^2) and output energy density (TWh/y/km^2) can be estimated. The output power density is the wind farm power output per unit area, or in other words, the installed power density multiplied by the capacity factor. The installed power density is the nameplate capacity divided by the spacing area of the wind turbine:

$$Output\ Power\ Density = \frac{Nameplate\ Capacity}{(F*D)^2} * CF \qquad \text{(Equation S4)}$$

where F = 4.375, D = Rotor Diameter (m).

These metrics have important implications for land use and therefore cost, along with the quantification of the tradeoff between the cost of transmission between turbines in a wind farm and wake effects. These will vary based on the specific location but are presented here as state averages.

Data and Setback Selection	• Extensive review of literature and best practices • Interviews with several industry and policy experts • Combine complementary datasets for unique level of detail and high-resolution
Buffer Restrictions	• Apply policy-informed setbacks to represent realistic siting parameters (more detail in Table S1)
Reproject Layers	• Asia South Albers Equal Area Conic reference system minimizes distortions over large study regions, equal area preserves area dimensions
Rasterize Restrictions and Resample	• Create uniform 10 m high-resolution files for all layers with matching extent • Assign value of 1 to all restricted pixels to facilitate subsequent calculation with multiple restriction layers
Sort Wind Speed Data Convert to Binary Format	• Compute wind speed thresholds from 5–8 m/s for 100 m, 150 m, and 200 m above ground level (highest of any study to date) to determine technical and economic viability of potential sites • Convert to binary format to expedite calculation
Subtract from Border Layer	• Merge restriction and wind speed raster layers for all combinations into one layer by subtracting from study boundary raster
Convert to Binary Calculate Available Areas	• Convert to binary format to distinguish available from unavailable cells • Quantify available cells from single layer and mean wind speeds in each region
Calculate Key Metrics	• Within available areas, compute key metrics with representative modern onshore wind turbine (SG 3.4-145), realistic spacing density, different wake loss scenarios (0%, 5%, 10%, 20%), and unique capacity factor in every pixel for each altitude and wind threshold
Determine Turbine Repowering Potential	• Compute area occupied by existing wind turbines and remaining area after considering restrictions without wind speed threshold to quantify maximum repowering potential with modern wind turbines (MW)
Calculate Cumulative Solar and Wind Potential	• Calculate solar potential (TWh/y) in unrestricted areas and sum with wind potential (TWh/y) to determine optimal sites for co-locating wind and solar energy resources

Figure S5. Summary of Experimental Procedure Components and Impact. Each step of the experimental procedure is described and the relevance is explained.

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