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The role of repowering India's ageing wind farms in achieving net-zero ambitions

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Abstract

India's ambitious net-zero climate goals include plans for a four-fold increase in current levels of wind energy generation by 2030. Many existing wind farms in India occupy sites with the best wind resources nationally but use older, smaller turbines that achieve lower capacity factors compared to modern turbine designs. A strategy of replacing existing wind turbines with state-of-the-art models (termed repowering) could boost capacity factors and ensure maximal use of available wind resources. However, a nationwide assessment of the potential wind generation increases resulting from repowering is currently lacking for India. Here, we present the first validated synthetic wind generation dataset for India based on reanalysis data and show that full repowering of the existing fleet of wind turbines could boost capacity factors by 82% nationwide (from 0.19 to 0.35). Our assessment of attainable capacity factors under full repowering exceeds equivalent estimates within the National Electricity Plan of India and national decarbonisation pathways compiled by the Intergovernmental Panel on Climate Change (IPCC), suggesting less total installed capacity is required to achieve specific generation outcomes than previously estimated. Ongoing technological progress, leading to increased turbine dimensions, will drive capacity factors beyond the levels estimated here, which could further add to the generation benefits of repowering. Yet, despite the higher average output from a repowered fleet of wind generators, substantial variability in generation across timescales persists, highlighting the increasing need for power system flexibility within a decarbonised energy system.

1. Introduction

India became the world's most populous country in spring of 2023 [1] and is anticipated to become the third-largest economy by 2030 [2]. Such growth could double per capita energy use in India and drive the largest increase in energy needs of any country globally over the next decade [3]. Already the third-largest greenhouse gas emitter globally [4], the rate and scale at which India shifts to low-carbon energy supply will significantly affect the success of global climate change mitigation goals.

At COP26, India set targets of net-zero emissions by 2070 and a goal of sourcing 50% of total electrical generation capacity from renewables by 2030 [5]. These pledges were reiterated within an updated Nationally Determined Contribution submission at COP27 [6]. The Indian Government has since finalised a tendering schedule for renewable energy projects designed to realise a non-fossil fuel electricity generation capacity of 500 Gigawatts (GW) by 2030, and a recently updated National Electricity Plan of India (NEP) proposes 121 GW of wind and 365 GW of solar PV by 2032 (together ∼90% of the 500 GW target) [7, 8].

The NEP figures mark a three-fold increase in wind (40.8 GW) and six-fold increase in solar PV (57.7 GW) capacity compared to total installed capacity in 2022 [9]. While record levels of solar PV installations occurred in 2022 (13 GW), and a vast solar project pipeline indicates acceleration in the installation rate [10], the pace of wind installations is languishing. Since 2017 the average additions were just 1.8 GW yr^{-1}, well below the record annual installations of 4 GW achieved in 2016 [9]. Boosting the pace of wind installations is therefore critical to achieving India's national renewable energy goals [11].

The technical potential for wind power in India is significant in absolute terms (official government estimate of 695 GW[4]), though wind resources are modest compared with many other regions globally, with 98% of 100 m wind speeds over land rated below class III (<7.5 m s^{-1} annual mean)[5]. Averaged over the last five years, wind capacity factors across India rank lowest out of countries with more than 1 GW installed capacity[6]. Wind resources are regionally concentrated in the West of the country, with many of the best sites already host to existing wind farms [14]. Meeting wind capacity targets for 2032 will require expansion beyond these zones, however, the necessary pace of upscale required from the wind sector prompts the question of whether existing wind farm sites are being adequately exploited, particularly given that many accommodate technically obsolete turbine designs approaching the end of operational lifetimes [15].

Repowering wind farms, whereby turbines of design lifetime (typically 20 years) are decommissioned and replaced with contemporary turbine models, is an accepted strategy that capitalises on existing infrastructure (transmission connection, road access, etc) at a proven wind farm site [16, 17]. Repowering typically results in higher energy yields as modern turbines feature greater hub heights and rotor diameters [18]. Although only a small proportion of wind turbines in India have reached design lifetime (∼4% total capacity >20 years [19]), a comparatively high share of smaller, lower energy yielding turbines favours a strategy of early retirement and repowering (see supplementary material (SM) section 1 for breakdown of existing wind installations by turbine size). Indeed, a recently revised repowering policy for India incentivises upgrading turbines <2 MW rated output, corresponding to 25.4 GW or ∼60% of total wind capacity [20].

Previous analyses of wind repowering potential in India rely on simplified methods of capacity summation by vintage year and lack an assessment of resulting changes in energy yield [15, 21]. Detailed analyses of changes in energy yield are limited to case studies of individual wind farms [22–25]. Other studies have used detailed energy system model representations of the Indian electricity network to assess operational reliability consistent with the expanded use of wind technology [26–28], while others have focussed on quantifying technically achievable wind resource potential [29–31] and spatio-temporal generation patterns thereof [32–34]. However, these studies offer few insights into the relative performance of the existing versus repowered wind fleet, principally because they lack adequate characterisation of existing wind farms. Furthermore, few studies validate wind generation estimates against observed generation to correct for known biases in meteorological input data [35, 36].

Here, we address the knowledge gap surrounding nationwide repowering by constructing the first validated model synthesis of wind generation in India. The synthetic generation dataset uses wind fields from an atmospheric reanalysis and a detailed description of existing wind farms in terms of turbine model and commissioning date to replicate observed generation values for individual Indian states. Differences in energy yield between the existing fleet of turbines versus full replacement with state-of-the-art designs are quantified by comparing alternative versions of the generation synthesis. The work provides insights into the contribution of repowering to stated renewables targets and broader questions over the practicality of ambitious net-zero goals.

The remainder of the paper is laid out as follows: section 2 describes the input datasets and method used to create a wind generation dataset for India, section 3 presents the results of the repowering scenario and section 4 summarises the main findings and wider implications of the results.

2. Data and methods

2.1. Dataset of wind farms in India

A comprehensive dataset of existing wind farms in India was compiled by reconciling unrelated national government and industry datasets. Digitised records from the Central Electricity Agency of India provided information on turbine rating and commissioning date per wind farm [37]. And the Geospatial Energy Map of India, produced by the National Institution for Transforming India (NITI Aayog), provided wind farm location data down to the nearest village settlement [38]. The turbine model used at each site was obtained from the Directory of Indian Windpower publication [19, 39]. The wind turbine technical specifications database produced by 'thewindpower.net' provided power curve data and hub height values per turbine model. The compiled dataset covers 978 wind farm locations, corresponding to ∼36 000 individual wind turbines (see

[4] Capacity potential estimate evaluated at 120 m hub height [12].
[5] Based on area of Indian mainland (excluding Himalayan range), data from www.globalwindatlas.info.
[6] Considering onshore wind capacity and generation data [13] for 36 countries with >1GW capacity.

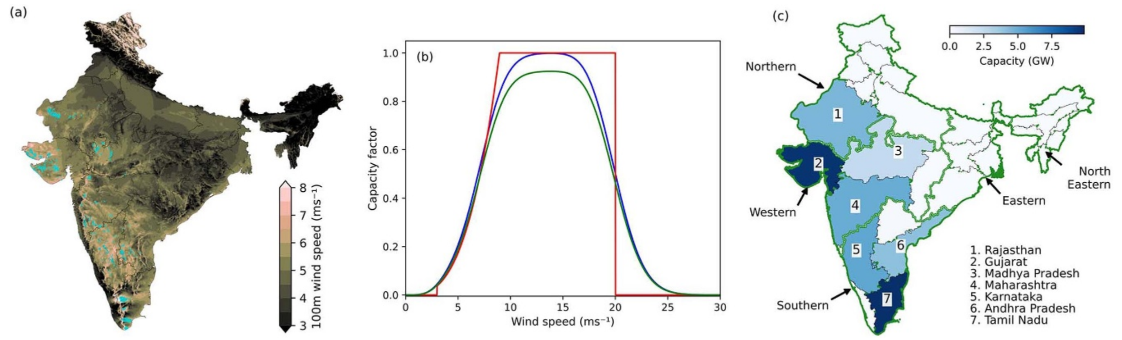


Figure 1. (a) Wind farm locations (blue points) in the compiled Indian wind farm dataset, with shading representing ERA5 100 m mean wind speeds for the period 1979–2021; (b) manufacturer power curve for Suzlon S144 3.15 MW turbine (red line), smoothed power curve (blue line); smoothed power curve +13% loss term (green line); (c) installed wind capacity per state in August 2022 [9]; green borders represent five mainland Regional Load Dispatch Centre (RLDC) zones (see SM4 for further description of RLDC data); and numbers denote individual states considered in the analysis.

figure 1(a)). SM2 provides further details of the compilation process, and the resulting dataset is openly available [40] (see Data Availability Statement).

2.2. Transformation of wind speeds

Wind energy generation is estimated using wind speeds from the ERA5 reanalysis dataset [41] (see SM3 for further details). The simplified Power-law model of vertical wind shear ($v_2 = v_1(h/100)\alpha$) is used to interpolate/extrapolate 100 m wind speed, v_1, to wind speed, v_2, at the hub height, h, of a given turbine [42]. The parameter α was defined empirically per grid cell using hourly 10 m and 100 m wind speed data, and then averaged over the hour-of-the-day ($n = 24$) and month-of-the-year ($n = 12$) to create 288 ($n = 12 \times 24$) unique α values per grid cell. Synthesis of hourly wind generation was conducted per wind farm, using the corresponding wind farm power curve and wind speed from the nearest reanalysis grid cell, with the appropriate vertical scaling applied. A smoothing operator is applied to all power curves within the dataset of wind farms to account for the diversity of wind speeds across a given wind farm (following [35, 43]) and an additional fixed loss term of 13% is applied to represent the estimated combined effects of inefficiencies in voltage transformation, turbine availability and ageing [44–46] (see figure 1(b) for representation of both the smoothing and loss term, and SM4 for additional methodological descriptions).

2.3. Verification and bias correction

To verify the synthetic wind generation dataset described in section 2.2, the resulting timeseries are aggregated to state and national level and compared to historical records of actual wind generation sourced from five Regional Load Dispatch Centres (RLDCs) (see figure 1(c)). These RLDCs maintain an archive of daily generation and installed capacity since the year 2017 for individual states of each RLDC zone (seven Indian states are considered here, representing 99.5% of total installed wind capacity). Daily capacity factor values (ratio of daily generation to maximum attainable generation for installed capacity over 24 h) for the period 2017 to 2021 were calculated and are hereafter referred to as 'observed' values.

Using reanalysis data to synthesise wind generation can result in biases, attributable to: the meteorological input variables(e.g. uncaptured orographic effects on winds at the scale of individual wind farms), the energy transformation model (e.g. incorrect specification of power curve), the validation data (e.g. uncertainty over the coverage of centrally collected data from a grid operator—i.e. net of system losses, inclusive of embedded generation, etc), or any combination of these factors [47]. Here, it is assumed that available observations of generation are accurate and representative of generation net of losses from transmission connected wind generation. With limited information on farm-level technical characteristics, few options exist for further refinement of the wind farm parameterisation. Therefore, the bias correction procedure used here applies alterations to wind speed only and takes the form of a constant multiplicative adjustment factor (AF), which is applied to wind speeds at all wind farms within respective states. The particular AF value that minimises mean bias in the synthetic capacity factors compared to the verification data over the period 2017–2021 is found iteratively. This adjustment method is favoured over a fixed bias adjustment with additional climatological wind speed data, as a trial correction using the Global Wind Atlas [48] still resulted in mean generation bias (see SM5 for further details). All results presented in the following sections make use of this AF approach to bias correction. The resulting synthetic generation timeseries are openly available (see Data Availability Statement).

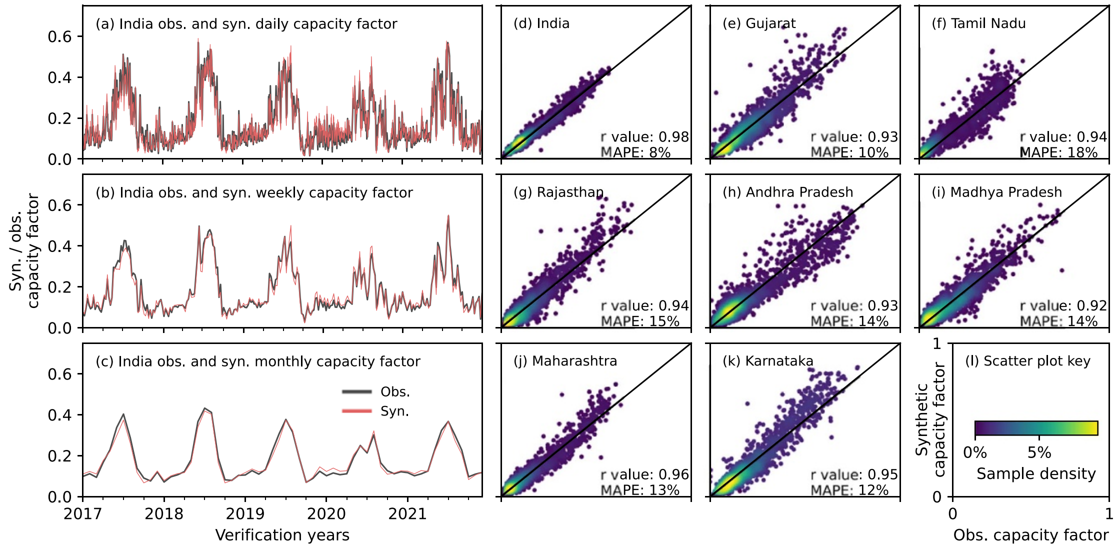


Figure 2. (Left-most column) time series of all-India generation synthesis (red) and observations (black) at (a) daily, (b) weekly, and (c) monthly timescales (underlying synthesis at hourly timescale, with temporal aggregation for visual clarity). Scatter plots for daily generation synthesis against observations for all-India (d) and states (e)–(k).

3. Results

3.1. Wind generation synthesis performance

The wind generation synthesis performs well for both the all-India aggregate case (figures 2(a)–(c)) and constituent states (figures 2(d)–(k)), showing high correlation with observed daily generation values (lowest r value 0.92; all-India *r* value 0.98) and low daily mean absolute percentage error (MAPE) (highest value 18%; all-India value 8%) (figures 2(d)–(k)). This confirms that the relatively simple constant AF bias correction procedure is suitable at an aggregate regional scale. The effect of the AF bias correction is mainly to reduce mean bias, which is greatest in Southern India, where the effect of orography on windspeed in the mountain passes of the Western Ghats are likely misrepresented in ERA5 (see SM5 for comparison with non-bias corrected generation synthesis).

Wind generation shows strong seasonality, with peak generation in the summer monsoon season figures 2(a)–(c). The rise in generation ahead of monsoon onset (which averages 1 June), likely reflects the formation of the summer monsoon circulation and enhanced westerly flow, while the smaller generation peak during boreal winter coincides with the northeast monsoon [49]. Higher frequency variability in generation is observed for individual states compared to the all-India case; a consequence of a greater number of random uncorrelated variations being cancelled out at the larger spatial aggregation [50]. The poor generation year in 2020 (11% lower than 2017–2021 annual average), evident in figures 2(a)–(c) highlights the importance of considering interannual variability (IAV) in both resource assessment and power production.

3.2. Modern turbine designs increase capacity factors

To assess the effect of differing turbine specifications on energy generation, the generation synthesis method is repeated with alternative turbine models assigned to all wind farms. In total, 805 alternative turbine models are considered (the total number available in the wind turbine technical specifications database), with the resulting generation syntheses reflecting the different turbine power curve and hub height in each case. In real-world settings, the choice of turbine model is specific to the wind climate of a candidate site, with energy yield and financial performance the decisive optimisation variables, subject to additional planning and logistical constraints [51]. Here, the aim is to demonstrate the relative energy performance between turbines rather than perform any such optimisation.

A wide range of plausible capacity factors result from the different turbines assignments (figure 3), with the greatest capacity factors attained by taller turbines with fewer KW of rated power per unit swept area (this ratio is referred to as specific power herein). The lower specific power turbines enhance energy capture, while taller turbines exploit higher wind speeds [52].

The higher capacity factors are predominately attained by newer turbines (see figure S5 SM6),

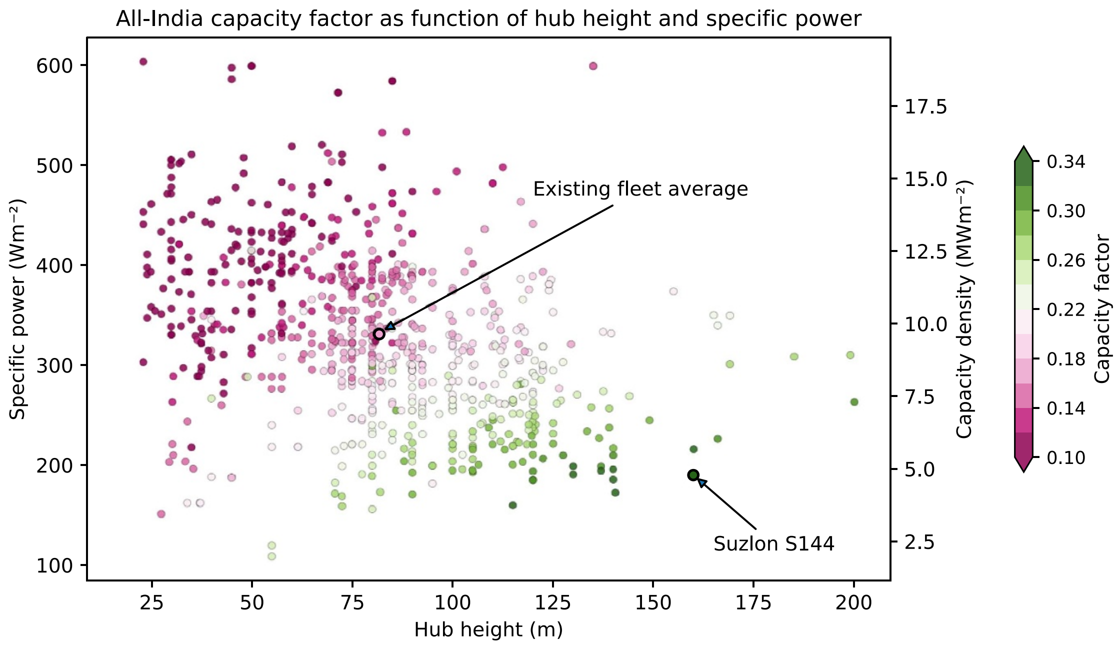


Figure 3. All-India capacity factor as a function of hub height and specific power, for alternative turbine model assignments ($n = 805$, with each scatter point representing a different turbine model assigned to all wind farms in India). Theoretical capacity density as secondary y-axis, assuming regular 8Dx4D turbine spacing. Arrow labels show existing Indian wind farm fleet average capacity factor and the turbine assignment with the highest capacity factor (Suzlon S144 3.15 MW).

reflecting well-documented technological developments within the wind industry towards taller, lower specific power designs [53].

Compared to a version of the generation syntheses that represents the true locations and turbine models of Indian wind farms at the end of 2021, assigning the best performing turbine (Suzlon S144 3.15 MW, 160 m hub height) to all wind farms (hereafter referred to as 'full repowering') achieves an 82% increase in capacity factors for all-India (table 1). The greatest regional increase in capacity factors is in Maharashtra (+94%) and Tamil Nadu (+96%). These states have the oldest average age wind turbines, with ~50% of total wind capacity installed before the year 2010. Although this full-repowering scenario is purely hypothetical and subject to multiple challenges (discussed herein), in pure performance terms, the capacity factors attained under full-repowering are comparable in magnitude to those found in farm-level repowering studies in India (e.g. [22, 25]) and international repowering experience (e.g. [17, 53, 54]), and so likely reflect realistic performance values rather than artifacts of the synthesis methodology.

Table 1. Annual mean wind capacity factor by region for true wind farm locations and turbine models at the end of 2021 (reference) and highest capacity factor turbine assigned to all farms (full repowering).

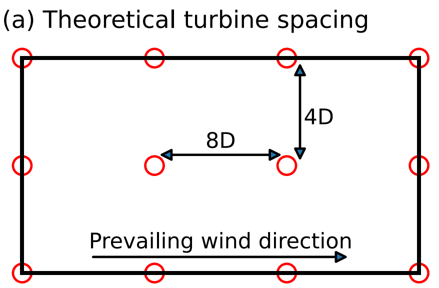
	Annual mean capacity factor		
Region	Reference	Full repowering	% change
India	0.19	0.35	82%
Northern region	0.18	0.35	82%
Western region	0.21	0.37	76%
Southern region	0.17	0.31	83%
Gujarat	0.26	0.43	67%
Madhya Pradesh	0.18	0.33	86%
Maharashtra	0.15	0.29	93%
Andhra Pradesh	0.21	0.35	66%
Tamil Nadu	0.14	0.27	96%
Karnataka	0.20	0.37	84%

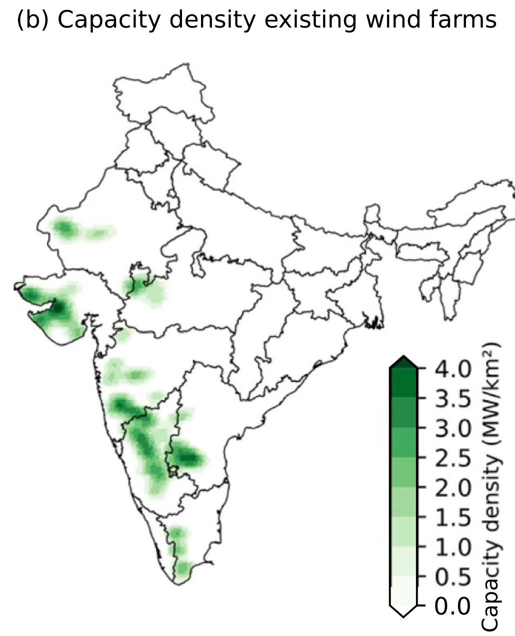
Table 2. National wind capacity, generation and fleetwide capacity factors in 2032 as envisaged in Indian NEP [8], for all wind capacity and additional wind capacity installed since 2021 (assuming present day installations remain operational).

	Capacity (GW)	Generation (TWh)	Capacity factor
2021	40	63	0.18
2032	121	258	0.24
Additional	82	195	0.27

3.3. Implications of performance improvement for 2030 targets

The previous section has shown capacity factors under full repowering of up to 0.35 for all-India (table 1). These capacity factors exceed those implicit within India's NEP targets for the year 2032 (0.24 fleetwide and 0.27 for additional capacity, assuming present day installations remain operational—see table 2). Realising greater levels of wind generation with repowering depends not only on the use of state-of-the-art technologies (i.e. turbines that achieve the





(c) Capacity density per region

Region	Mean	Min.	Max.
India	2.5	1.6	4.2
Andhra Pradesh	3.1	2.4	4.2
Karnataka	2.9	2.2	3.9
Maharashtra	2.6	1.7	3.2
Gujarat	2.4	1.6	3.3
Madhya Pradesh	2.2	1.9	2.8
Tamil Nadu	2.2	1.8	2.7
Rajasthan	2.0	1.6	2.3

Figure 4. (a) Highest density theoretical turbine layout, with spacing defined by 8×4 rotor diameters (D) and major axis aligned with the direction of the prevailing wind; (b) capacity density of existing wind farms based on bounding polygons of wind turbines geolocated within OpenStreetMap data (smoothed with Gaussian kernel filter for visual clarity, as shaded bounding polygons for individual farms are illegible in whole country visualisation); and (c) summary of capacity density values of existing wind farms per state.

greatest capacity factor) but also the density at which new wind turbines can be installed.

Capacity density describes the installed capacity of a wind farm per unit area (MW km^{-2}) and is theoretically defined by specified multiples the turbine rotor diameter (D), which entails a maximum capacity density if all turbines within a farm conform to a regular layout (figure 4(a)). However, obstacles and constraints at the farm-level often prevent regular turbine siting, resulting in lower capacity density values then theoretically achievable values [55]. Figure 4(b) shows the range of capacity density values achieved across wind farms in India, determined by calculating the area of bounding polygons around wind farms and dividing by the total capacity of the wind farm (see SM7 for details).

The median capacity density value for all-India of 2.5 MW km^{-2} is lower than theoretical values used in other studies of technical potential (e.g. [56]), and indeed lower than the theoretical densities shown in figure 3 but is in-line with empirically derived values in other regions [57–59]). Capacity density values are highest at hilltop and coastal wind farms (Andhra Pradesh and Gujarat, respectively), while lower at clustered wind farms (mountain passes in Tamil Nadu the Thar desert region centred on Jaisalmer in Rajasthan). Assuming that existing values of capacity density are realised under repowering, changes to resulting generation by vintage year and turbine rating can be calculated (figures 5(a)–(d), respectively). By the year 2032, 43% of the entire fleet would be of retirement age (>20 years), entailing a 45% increase in generation from repowering of this outmoded segment of total capacity (figure 5(b)). Early retirement and repowering of existing farms is an option to gain further generation increases; ∼65% for all-India (figure 5(d)) when replacing turbines under 2 WM (i.e. the threshold considered in India's current repowering policy).

3.4. Net zero implications of modern turbine designs

The wind capacity and generation volumes consistent with net-zero outcomes have been extensively studied, most recently within national-scale decarbonisation pathways considered by Working Group III (WGIII) of the IPCC Sixth Assessment Report (AR6) [60]. All 388 of the IPCC decarbonisation pathways for India that are consistent with end of 21st-cenurty warming outcomes of less than 2 °C envisage a massive roll-out of wind technologies, with 334 of those pathways exceeding the generation levels considered within the Indian NEP by 2030 (figure 6). However, 90% of capacity factors implicit within these IPCC pathways[7] are below those achieved in a fully repowered Indian wind fleet (colour shading in figure 6).

If capacity factor values close to the level achieved with full repowering (∼0.35) can be sustained in an expanded Indian wind fleet, net-zero compliant levels

[7] In 2030, implicit wind capacity factors are 0.227 for pathways consistent with end of 21st-cenurty warming outcomes of less than 2 °C ($n = 334$) and 0.233 for all pathways ($n = 823$).

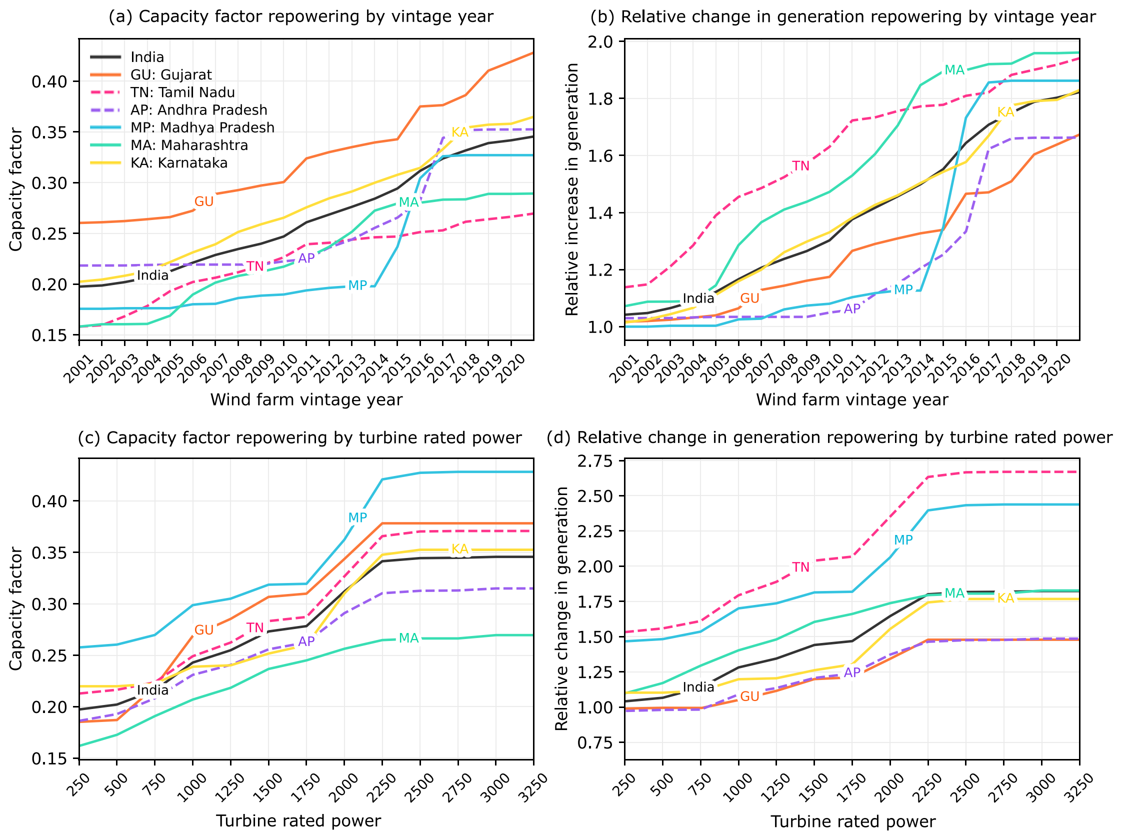


Figure 5. Capacity factor (a), (c) and relative change in generation (b), (d) per region considering repowering by wind farm vintage year (a), (b) and turbine rated power (c), (d) (i.e. repowering all wind farms that comprise turbines of a given vintage year / turbine rated capacity). Relative change in generation refers to the ratio of repowered generation and generation resulting from existing wind farm distribution in the year 2021.

of generation could be achieved with less installed capacity. For example, NEP 2032 generation targets of 258 TW h/year (see 'NEP' guideline in figure 6(b)) could be achieved with ∼33% less capacity at a capacity factor of 0.35 compared to the capacity required at the median AR6 pathways capacity factor value in 2030 of 0.233[8]. Prospects for the performance of a significantly expanded Indian wind fleet warrant further detailed study, though 30 GW of planned offshore wind expansion by 2030 could achieve capacity factors in the region 0.3–0.6 [61–63]. Thus, a fully repowered existing wind fleet and 30 GW offshore wind capacity could conceivably attain ∼96% of the NEP 2032 generation targets (e.g. 71 GW total at a fleetwide capacity factor of 0.4).

3.5. Changes in temporal patterns of generation

The results presented so far are for annual averages, however, patterns of generation on other timescales, and how these change under repowering, are important considerations for electricity system operations and planning. Here, changes in the patterns of generation across timescales are quantified for the all-India case with a generation synthesis using the full 43 year timespan of the reanalysis dataset (1979–2021). Full repowering increases the absolute magnitude of variability in generation across a range of timescales. The changes to temporal variation reflect the steeper ramping segment of lower specific power turbines [18] and the increased magnitude of wind speeds at greater hub height. The maximum magnitude and relative frequency of rapid positive or negative changes in capacity factor (termed ramps) are greater for the repowered case (figure 7(a)). For example, capacity factor ramp events of ∼ ±10% within a 6 h period occur four times more frequently in the repowered case (∼20% of hours each year precede such events in the repowered case versus ∼5% for current installations).

Regarding the average generation profile across a single day, a strong diurnal cycle is apparent for both the existing and repowered cases (figure 7(b)), consistent with insolation-driven sensible heating over land that creates gradients in surface pressure with adjacent oceans and enhanced downward turbulent mixing of momentum [64]. However, the absolute magnitude of the diurnal cycle in generation increases by 270% in the repowered case (absolute range of 0.188 and 0.289 for existing and

[8] Or at 30% less capacity than envisaged in the NEP itself (84.1 GW vs. 121 GW).

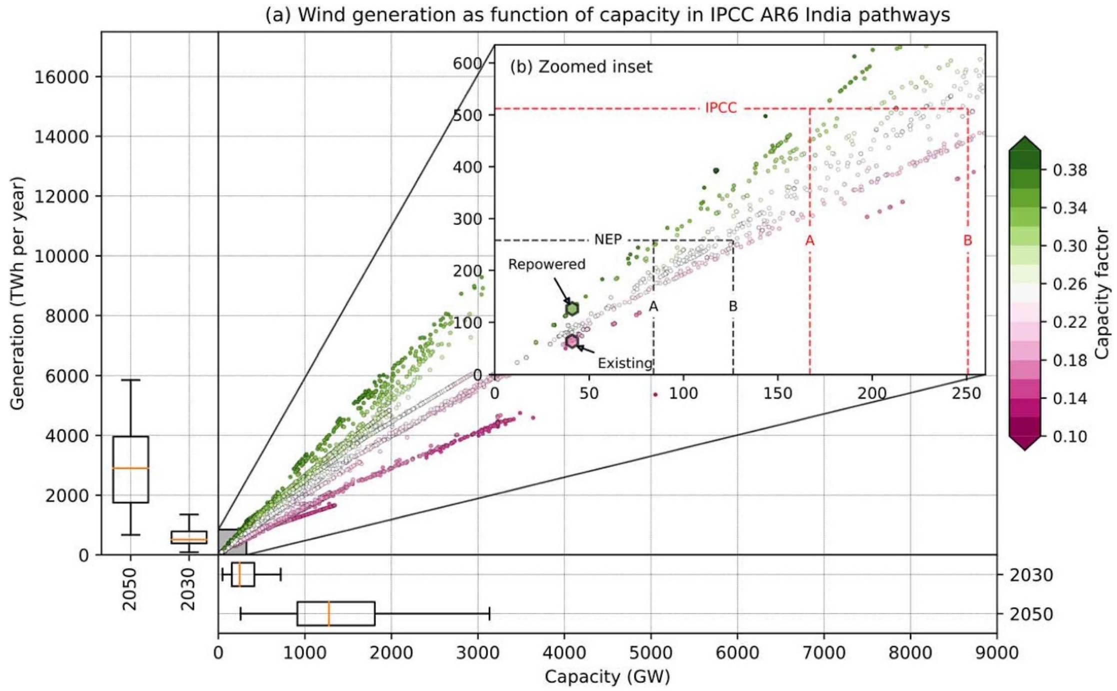


Figure 6. Generation versus capacity for India decarbonisation pathways from IPCC AR6 ($n = 823$) in the 2030 to 2100 timeframe, with shading denoting implied capacity factor (ratio of secondary wind energy per year and wind capacity $\times$ 365.25 $\times$ 24). Box-and-whisker plots denote 10/25/50/75/90th percentiles of capacity and generation in 2030 and 2050 for India decarbonisation pathways that achieve an end of 21st-cenurty warming outcome of less than 2 °C with >67% likelihood ($n = 388$). (b) inset axes show lower range of capacity/generation values. Guidelines in (b) depict generation/capacity requirements for NEP2032 targets (258 TW h yr^{-1}; 84.1 GW 'NEP-A' and 126.3 GW 'NEP-B') and median wind generation value for IPCC AR6 India decarbonisation pathways in 2030 that achieve less than a 2 °C end-of-century global warming outcome (512 TW h/year – 167 GW 'IPPC-A' and 251 GW 'IPCC-B'). Guidelines A and B denote capacity requirements resulting from capacity factor values for full repowering and the mean of capacity factors implicit within IPCC AR6 India decarbonisation pathways, respectively.

repowered, respectively). The modest negative trends in the annual mean values of the generation syntheses (figure 7(c)) possibly reflect a 'stilling' phenomenon, which has been documented elsewhere across the globe [65] and is noted in other studies of lower-level winds in India [66, 67]. Accounting for these trends, the range in annual mean generation increases by 25.3% and the standard deviation by 33.2% for all-India in the repowered case. The relative changes in IAV remain virtually the same under repowering, with max/min years amounting to +/−9% of the mean for all-India and ∼+/−15% for individual states. This state-level IAV is smaller than typical IAV in onshore wind generation seen in some midlatitude regions, e.g. Europe [68]. This is likely due to different prevailing meteorological environments within the tropics and extratropics and warrants further investigation.

The daily climatology of generation (figures 7(d) and (e)) remains qualitatively similar in both cases, with 54% and 48% of total annual generation falling within the period June to September for existing and repowered cases, respectively. However, the absolute range of daily capacity factors increases in the repowered case, with the greatest increases observed outside of the summer monsoon season. This is likely due to steep linear response of the power curve in the ∼0.25–0.75 interval, which conveys the effect of the diurnal cycle in wind speeds in the repowered case but not for the existing deployment (for which average capacity factors are below 0.25 outside of the summer monsoon period).

Despite increases in the absolute magnitude of variability across timescales, the shift in the distribution of generation values upwards under repowering implies less frequent low-generation and more frequent high-generation events (figures 7(f) and (g)), a consequence of the increased responsiveness of the power curve at lower wind speeds and the greater magnitude of wind speeds at taller hub heights. For example, incidences of capacity factors falling below the 10th percentile for at least 10 continuous hours average five cases per year for the existing wind farm fleet, but disappear almost entirely in the repowered case (just one such event in the entire 43 year repowered generation synthesis).

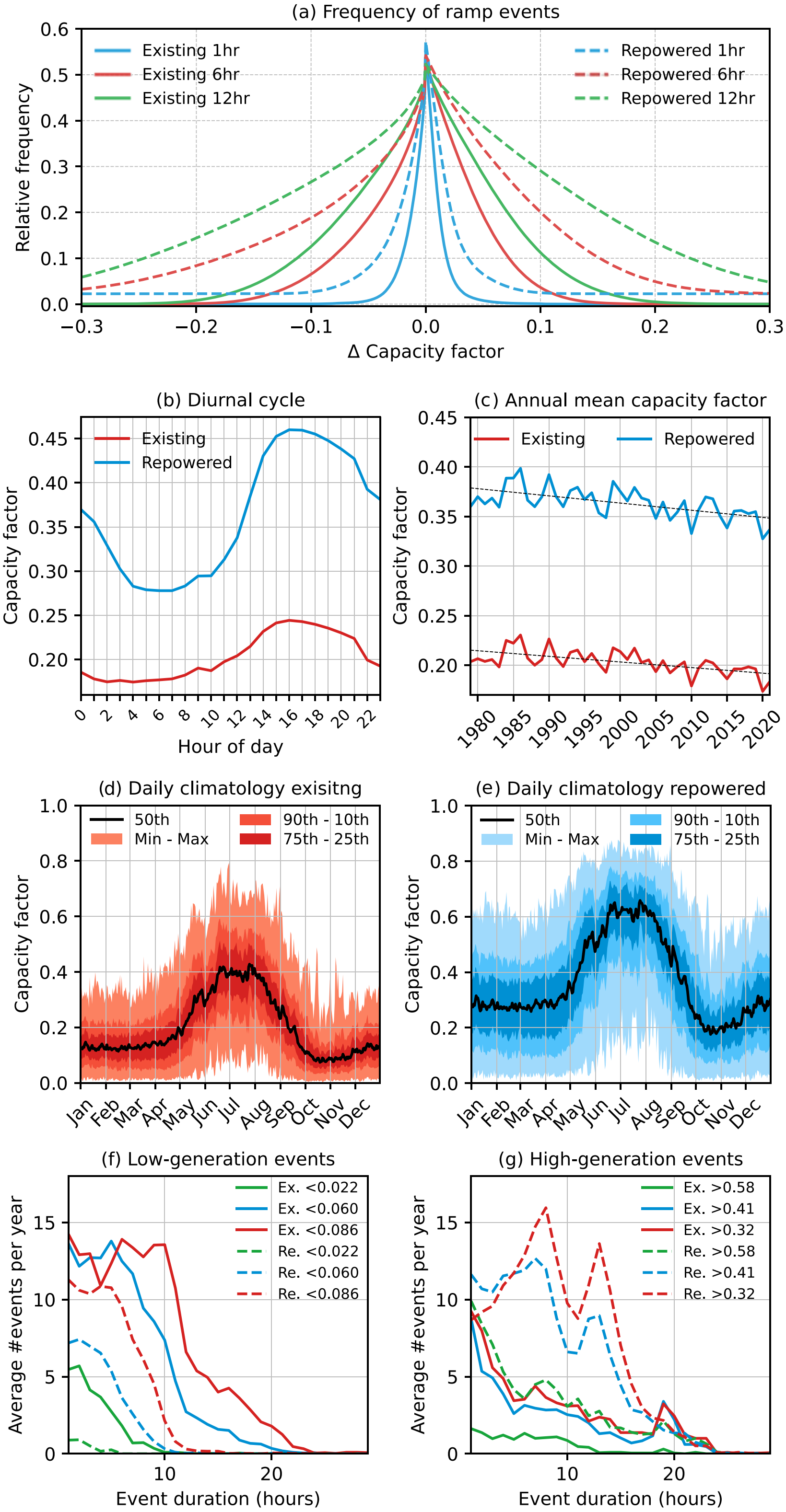


Figure 7. Temporal analysis of generation synthesis for existing and repower wind fleets for the period 1979–2021, showing (a) average proportion of hours per year preceding ramps in all-India capacity factor within 1 h, 6 h and 12 h periods; (b) annual average diurnal cycle of all-India capacity factor; (c) annual mean capacity factor for all-India, with linear trends overlaid, which are significant at the 99% level using a Mann–Kendal test; (d) and (e) daily climatology for existing and repowered wind farms, respectively, with shading signifying percentiles of generation climatology; (f) and (g) frequency of low/high generation events, respectively, by duration for three absolute thresholds of capacity factor (corresponding to the 1st, 10th and 20th / 99th, 90th and 80th percentiles of capacity factors under the existing wind fleet).

4. Discussion and conclusion

Repowering will become an increasingly common activity within the unfolding energy transition, as a greater proportion of existing wind capacity reaches its design lifetime [69]. Despite the recognised importance of repowering for India's energy transition [6, 20], existing studies lack country-wide assessment of changes in wind energy generation resulting from turbine technology upgrades. This paper addresses this gap by presenting a model synthesis of wind generation in India for which turbine characteristics can be selectively altered to gauge consequent effects on energy yield. The generation synthesis uses wind fields from an atmospheric reanalysis and a detailed description of existing wind farms in terms of turbine model and commissioning date to replicate observed generation values for individual states with appreciable accuracy (all-India r value 0.98 and MAPE value 8% at the daily timescale). Although numerous studies have produced generation syntheses using reanalysis data inputs for other countries (see SM3 for examples), this work presents the first validated version for all wind farms in India.

The analysis presented here demonstrates that fully repowering India's fleet using modern turbine designs with taller towers and lower specific power could boost capacity factors from the existing wind fleet by 82% nationwide, with the greatest regional increase in Tamil Nadu state (+96% - see table 1). Repowering wind turbines under 2 MW rated capacity (the threshold considered in India's national repowering policy) could increase fleetwide capacity factors to ∼0.3[9] (see figure 5), some 25% greater than the capacity factors implicit within the current NEP [8]. Whether these increased capacity factors could translate into higher energy generation depends on the relative capacity density at which new turbines are installed. Though, the capacity densities of existing wind farms across India are approximately half the value resulting from modern turbines spaced at regular multiples of rotor diameter (∼2.5 MW km^{-2} versus ∼5 MW km^{-2}, see figures 3 and 4), suggesting generation gains from repowering are at least proportionate to capacity factor increases.

Most nations[10] have announced or are deliberating net-zero emissions targets and use decarbonisation pathway studies to guide strategic decisions on technology choices and inform energy policy. The full repowering results presented here show capacity factors at the top-end (>90th percentile) of values found across decarbonisation pathways for India compiled by WGIII of the IPCC in AR6 [60], suggesting less installed capacity is required to achieve a certain generation outcome. Although decarbonisation pathways are not necessarily calibrated to observed performances, accurate characterisation of the energy yield from an expanded wind fleet is necessary to inform the strategic design of renewably powered energy systems. Ground-truthing the performance of specific technologies within decarbonisation pathways or complimenting such information with calibrated generation syntheses is, therefore, an important exercise to gauge implications for policymaking.

Predicted increases in turbine dimensions will drive capacity factors beyond the levels estimated here, which could further add to the generation benefits of repowering[11] [73, 74]. Taller, longer-bladed turbines imply higher capacity factors but also potentially lower capacity densities, with the balance between the two factors directly scaling the 'generation-density' and land-use footprint of wind power. This is an important consideration for land-scarce countries like India, where land rights are contested and the procurement of land for renewable projects is challenging [75]. Further detailed study of relevant technical, social, and commercial factors is required to appraise wind expansion and land requirements at a scale consistent with the order-of-magnitude capacity scale-up envisaged in net-zero pathways (e.g. trade-offs between capacity density and wake losses [76, 77]; visual and physical disturbance to local residents [69, 78]; and the multi-owner structure of existing wind farms [15].

The results presented here show how modern wind turbine designs modify the variability characteristics of generation, namely, increasing the absolute scale of changes across timescales. This result underlines the increasing need for power system flexibility within a decarbonised energy system [79], implying greater levels of energy storage, responsive demand, grid reinforcement/interconnection, and complementary forms of generation [80, 81]. Without such flexibility, electricity network constraints would heighten the risk of curtailment of the increased generation from repowering. Improved characterisation of generation variability across timescales can help appraise design elements of power system flexibility, particularly the likelihood of extreme low generation events (e.g. [82]), which although less frequent under full repowering, are not eliminated. The

[9] For comparison, turbines installed onshore in 2022 in Europe achieved capacity factors in the range 0.30–0.45, while the European onshore fleet average capacity factor is 0.24 [70].

[10] 131 countries, equivalent to 78% of total global emissions annually, with net-zero polices in-law, announced or in deliberation [71].

[11] The theoretical ultra-low specific power turbine presented in [72] achieves 0.44 capacity factor when implemented with the repowering methodology.

co-variability of generation with demand for electrical energy is another dynamic factor not considered here, and other work has noted how the anti-phasing between wind generation and air temperatures in India contributes to enhanced variability in electricity demand net of wind generation on intra-seasonal timescales [83]. However, other studies have suggested possible compensatory generation from solar PV on diurnal [84] and seasonal timescales [33], with the phasing of the annual cycle of wind and solar PV generation particularly advantageous in the South of India [85]. Further investigation of potential balancing between these two sources is warranted, given the importance of wind and solar PV technologies within India's national renewable targets.

Repowering offers several economic and logistical advantages over developing greenfield sites for wind farms, including the potential re-use of existing feasibility studies and planning appraisals, existing road access, and transmission connections. These factors offer a possible route to expediting the delivery of ambitious renewables targets and boosting the currently underutilised domestic turbine manufacturing industry [86]. A growing wind energy sector may also generate employment that can compensate for job losses in a constrained fossil-power sector. However, the exact distributional effects require further study. Additionally, the development of a generation synthesis provides a basis for future investigations into the economic case for early-retirement of ageing wind farms and subsequent repowering. Furthermore, anticipating variations in generation is an important component of electricity network operations [87, 88] and generation syntheses can provide a basis for the statistical downscaling of meteorological forecasts. Finally, generation syntheses provide a statistical description of the impacts of specific meteorological phenomena on weather-dependent generation, potentially aiding in the targeted improvement of generation forecasts over a range of timescales [89–92].

Data availability statement

Supporting data for the study (the dataset of Indian wind farms and synthetic generation timeseries per state) are openly available at the following URL/DOI: https://doi.org/10.5518/1418.

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