Assessing and Planning for Variability in India's Wind Resource

Jai Shekhar, Selna Saji, Disha Agarwal, Asim Ahmed, and Tarun Joseph

Report | August 2021

India's wind sector faces the risk of climate-induced uncertainty in resources, a glimpse of which was visible in the monsoon season of 2020.

Image: iStock

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

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The Council's major contributions include: The 584-page *National Water Resources Framework Study* for India's 12th Five Year Plan; the first independent evaluation of the *National Solar Mission*; India's first report on global governance, submitted to the National Security Adviser; irrigation reform for Bihar; the birth of the Clean Energy Access Network; work for the PMO on accelerated targets for renewables, power sector reforms, environmental clearances, *Swachh Bharat*; pathbreaking work for the Paris Agreement, the HFC deal, the aviation emissions agreement, and international climate technology cooperation; the concept and strategy for the International Solar Alliance (ISA); the Common Risk Mitigation Mechanism (CRMM); critical minerals for *Make in India*; modelling uncertainties across 200+ scenarios for India's low-carbon pathways; India's largest multidimensional energy access survey (ACCESS); climate geoengineering governance; circular economy of water and waste; and the flagship event, Energy Horizons. It recently published *Jobs, Growth and Sustainability: A New Social Contract for India's Recovery*.

The Council's current initiatives include: A go-to-market programme for decentralised renewable energy-powered livelihood appliances; examining country-wide residential energy consumption patterns; raising consumer engagement on power issues; piloting business models for solar rooftop adoption; developing a renewable energy project performance dashboard; green hydrogen for industry decarbonisation; state-level modelling for energy and climate policy; reallocating water for faster economic growth; creating a democratic demand for clean air; raising consumer awareness on sustainable cooling; and supporting India's electric vehicle and battery ambitions. It also analyses the energy transition in emerging economies, including Indonesia, South Africa, Sri Lanka and Vietnam.

The Council has a footprint in 22 Indian states, working extensively with state governments and grassroots NGOs. It is supporting power sector reforms in Uttar Pradesh and Tamil Nadu, scaling up solar-powered irrigation in Chhattisgarh, supporting climate action plans in Gujarat and Madhya Pradesh, evaluating community-based natural farming in Andhra Pradesh, examining crop residue burning in Punjab, promoting and deploying solar rooftops in Delhi, Bihar and Meghalaya.

This is an excellent topic for analysis

Comments from industry leaders and our partners

The research is an excellent topic for analysis and study. It is relevant for India considering our past adverse experiences in areas such as gas generation, coal-fired generation etc.

S. R. Narasimhan, Director of System Operation, POSOCO, New Delhi

As a professional and a system operator, I agree that the findings of the team in this paper are correct and need further deep-diving into the subject by all stakeholders. It is indeed a fact that in the peak season of 2020, there was a drastic reduction in wind energy generation. Hence there is a need for more efforts towards long-term wind forecasting, say three to four months in advance, so that the likely impact of resources variability be captured well in advance for an optimised system operation and market operation planning in the Indian Power System. The planned outages of thermal plants and other resources planning can be readjusted if such advance forecasting exercises are undertaken using advanced technology by all concerned stakeholders.

V. K. Shrivastava, former Executive Director, Western Regional Load Despatch Centre

With 38 GW of wind energy installed capacity in India, it is important to focus on improved forecasting of wind generation and variability. This report highlights a dip in the wind speeds during the peak wind season of 2020 and analyses the impact on wind power output in different regions. The report provides detailed comparative data for different regions and should be useful to anyone interested in wind power in India.

Prof Rangan Banerjee, Head of the Department of Energy Science and Engineering, IIT Bombay

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Lastly, we are grateful to the Outreach team for their the design and outreach of the report.

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Jai worked as a consultant with the Renewables team at The Council. He was an integral part of the wind energy programme. Driven by a keen interest in the climate and energy nexus, he studied energy markets, renewable energy development, and climate change. He is pursuing his bachelor's degree at the Manipal Institute of Technology and was one of the youngest researchers working at The Council.

"We must analyse the socio-economic feasibility of wind energy projects thoroughly in the coming decade. The financial sensitivity of the industry calls for exhaustive supply and demand-side analysis."

Selna Saji
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Selna is a former programme associate at The Council. She is an energy and environmental analyst who focuses on renewable energy technologies. At The Council, she worked towards developing business models and tools that will facilitate the sustainable growth of renewable power in India. Selna holds a dual postgraduate degree in Management and Engineering of Environment and Energy from Queen's University Belfast and Universidad Politécnica de Madrid.

"Wind power development is an essential component in India's drive to improve its renewable energy portfolio. The public and private sector must remain cognizant of potential risks that can harm the financial sustainably of the wind sector."

Disha Agarwal
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Disha co-leads The Council's Renewables team. She works on legislative, policy, and regulatory frameworks at the intersection of power and renewables. Disha has experience in strategy development, renewable energy policy, and market analyses; stakeholder management and collaborations; grant-making; and fund-raising. Before joining The Council, she worked at the Shakti Sustainable Energy Foundation, where she led programmes on renewables and climate policy.

"Wind power is and will continue to be a key contributor to building a cost-effective electricity system in India. We must, therefore, anticipate and mitigate any risks that can slow down the deployment of projects."

Asim Ahmed
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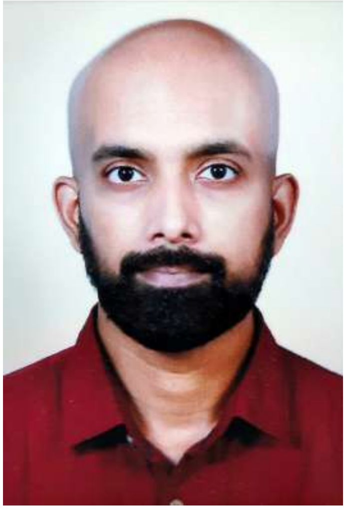
Asim has worked in artificial intelligence (AI) and weather technology development for energy utilities and renewable energy (RE) businesses over the last six years. He currently serves as Director of Engineering at REConnect Energy. He holds a bachelor's in Electrical Engineering and a master's in Power and Energy Systems from the University of Manchester.

"Weather uncertainties and unexpected weather events are having a growing impact on multiple sectors, and we saw in 2020 that the renewables sector is not alien to such events. It's time to make a concerted effort to incorporate climate change adaptation strategies into long- and short-term planning and operational processes in all sectors that have assets exposed to the atmosphere or hydrosphere."



Tarun Joseph
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Tarun has been active in the field of high-resolution numerical modelling of the atmosphere, satellite meteorology and its applications in renewable energy, with an aim to investigate weather events; and the development of forecasting platforms capable of quantifying their impacts. He currently serves as a Senior Meteorologist at REConnect Energy. He holds a master's in Earth System Science and Technology from the IIT, Kharagpur, and a post-graduate diploma in Remote Sensing and Geographic Information System from ISRO, Dehradun.

"Short-, medium-, and long-term weather forecasts, when blended seamlessly, can empower industries vulnerable to vacillating weather to proactively address scenarios that are likely to unfold instead of reacting to those that do occur."

Despite an increase in installed capacity, India witnessed a sharp 24% drop in wind power generation in the peak season of 2020, relative to 2019.

Image: iStock

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Acronyms

CEA	Central Electricity Authority
CEEW	Council on Energy, Environment and Water
CERC	Central Electricity Regulatory Commission
CUF	capacity utilisation factor
DSM	deviation settlement mechanism
ECMWF	European Centre for Medium-range Weather Forecasts
ENSO	El Niño–Southern Oscillation
GW	gigawatt
Hz	hertz
IMD	Indian Meteorological Department
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
IPP	independent power producers
IRR	internal rate of return
ISRO	Indian Space Research Organisation
JJAS	June July August September
kmph	kilometre per hour
ML	machine learning
MNRE	Ministry of New and Renewable Energy
MW	megawatt
MU	million units
NIWE	National Institute of Wind Energy
NLDC	National Load Despatch Centre
NWP	numerical weather prediction
POSOCO	Power System Operation Corporation Limited
PPA	power purchase agreement
R&D	research and development
RE	renewable energy
ROI	returns on investment
RLDC	Regional Load Despatch Centre
RMSE	root mean square error
FairRPSS	fair ranked probability skill score
SLDC	State Load Despatch Centre
VRE	variable renewable energy
WTG	wind turbine generators

2020 was marked by a flurry of anomalous weather events leading to lower than expected wind speeds during the monsoons.

Image: iStock

Executive summary

Wind energy has vast potential in India. There has been a steady growth in the Indian wind industry since 1985, primarily due to favourable policies. Given the growing importance of wind in India's energy mix, understanding the subcontinent's wind resource characteristics is essential to chart the sector's future.

In 2019, 56% of the total wind energy generation occurred during the peak monsoon months of June to September

Seven states in the southern and western parts of the country host about 95 per cent of all wind energy installations (MNRE 2021). This concentration is partly because of the geographic locations of these states, which offer a high number of 'healthy wind days' in a year. Additionally, 56 per cent of the total output of wind energy occurred during the peak monsoon season between June and September, reflecting the uneven distribution of wind power generation through the year 2019 (POSOCO 2019f–POSOCO 2019i).

In the peak season of 2020, India experienced a significant resource anomaly that led to a 24 per cent lower energy generation compared to 2019 (POSOCO 2019f–POSOCO 2019i; POSOCO 2020r–POSOCO 2020u). Industry stakeholders are concerned about the unanticipated variability during peak generation season. In this context, the aim of this report is to stimulate discussion on how the industry and the government can deal with the variability of wind resources in India.

The report examines the decline in wind energy generation, outlines the micro and macro impacts of the resource anomaly that occurred in 2020 and identifies potential solutions. It also discusses the causes of increasing wind unpredictability in India, as well as its likely consequences in the long term.

The unexpected resource variability in 2020 had multiple implications

The peak monsoon season of 2020, when wind power producers usually secure a large portion of their revenue, saw a dramatic drop in generation. The western and southern regions experienced a 29 per cent and 17 per cent decline in wind power generation, respectively, during this period. Although the overall decline in 2020 was only about 5.3 per cent relative to 2019, the unanticipated dip observed across regions and the resultant difficulties in generation forecasting is concerning. (POSOCO 2019a–POSOCO 2020u).

We undertook a case study to assess the plant-level impact of variability in wind speeds. For this, we analysed the daily average wind speeds between June–September for two wind farms located in Jamnagar, Gujarat and Tirunelveli, Tamil Nadu. Results of the investigation showed that Jamnagar experienced a decline in wind speeds relative to 2019 and 2018. Similarly, Tirunelveli indicated a decline in wind speeds compared to 2018 but no reduction when compared to 2019.

Jamnagar, Gujarat, experienced a decline in wind speeds relative to 2019 and 2018

This drop in generation led system operators to resort to other available balancing resources in real-time. Between June to August, the western region increased its hydro power by 12 per cent relative to same period in 2019. Similarly, share of coal power increased by 4 per cent in June and July 2020 relative to the previous two months of the year. In addition, our analysis of number of ramps in generation across two wind sites in Gujarat and Rajasthan highlight increased challenges in forecasting. This in turn translated into cost implications under the deviation settlement mechanism (DSM).

A decline or anomalous pattern in the availability of wind resources can have several implications for the wind industry and the overall power sector. For wind power producers, increased unpredictability in wind resources could lead to diminished revenues.

An analysis of the impact of changing wind resource patterns for a 100-MW (megawatt) plant showed that a 10 per cent reduction in the capacity utilisation factor (CUF) every five years would result in an internal equity rate of return (IRR) of 13.14 per cent, as against a base case IRR of 14.97 per cent. This drop in IRR, in turn, translates to an INR 122 crore reduction in the total revenue. Similarly, a 5 per cent reduction in the CUF every five years would result in an equity IRR of 14.10 per cent, which would translate to a reduction of INR 61 crore in the total revenue.

To quantify the impact of increasing variability on wind forecasting, we analysed the number and magnitudes of positive and negative ramps that occurred in July 2019 and July 2020 at two wind plant sites in Gujarat and Rajasthan. Both sites have capacities of more than 70 MW.

Unexpected changes in wind resource availability over the life of a plant may have an effect on long-term power sector planning and could lead to demand and supply imbalances, increasing the total cost of system balancing.

The various stakeholders and the impact that wind resource variability can have on them are listed in Table ES1.

Table ES1

Assessment of the impact of wind resource uncertainty on various stakeholders

Stakeholder	Impact
Wind power generators	Loss of revenue and additional DSM charges. Delays in revenue realisation.
Investors	Our analysis shows that a 10 per cent drop in CUF for five years during the plant life could lower the IRR by 1.83 percentage points. If such events become more frequent, profit margins can reduce, which may move the investors out to other more attractive technology options amidst stiff competition in the RE sector.
Forecasting agencies	Increase in error rates with increasing unpredictability.
Load despatch centres: SLDCs (State Load Despatch Centres), RLDCs (Regional Load Despatch Centres), and NLDC (National Load Despatch Centre)	Increasing variability and unpredictability would raise the cost of grid balancing. An overall increase in the per unit transmission charges borne by buyers with a decrease in wind power output.
Central and state power sector planners	With the addition of higher levels of wind capacity, power systems and their long-term planning would be more vulnerable to seasonal variations and changing weather patterns.

Source: Authors' analysis

Impact of changing climatic patterns on wind speeds

Changing climate has ramifications for almost every industry on the planet. Numerous reports have looked at the effect of extreme climate variability on India's wind speeds, given the increasing incidence of extreme weather events and changing climate around the world. More than 75 per cent of Indian districts are extreme event hotspots, making wind plants located in these areas highly vulnerable to climate risks (Mohanty 2020).

Typically, climate variables need to be tracked over a long time to understand changing patterns (Ogwang et al. 2015). An examination of annual average wind speeds at 100 metres in various wind-rich states of India over 1979-2020, except Tamil Nadu, showed an overall decline and, hence, a worrisome reality for the Indian wind energy sector (Figures ES3, ES4, and ES5).

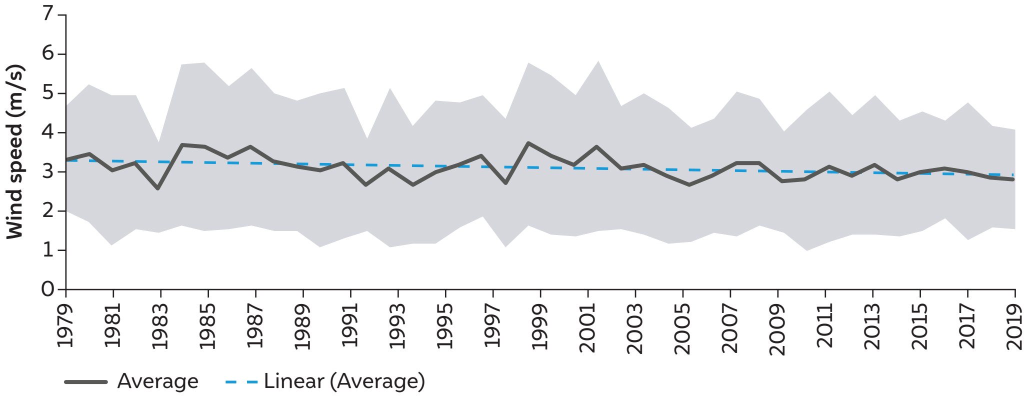


Figure ES1
There is a clear declining trend in wind speeds in Rajasthan between 1979-2020

Source: Authors' analysis of the ERA5 data set in the ECMWF database

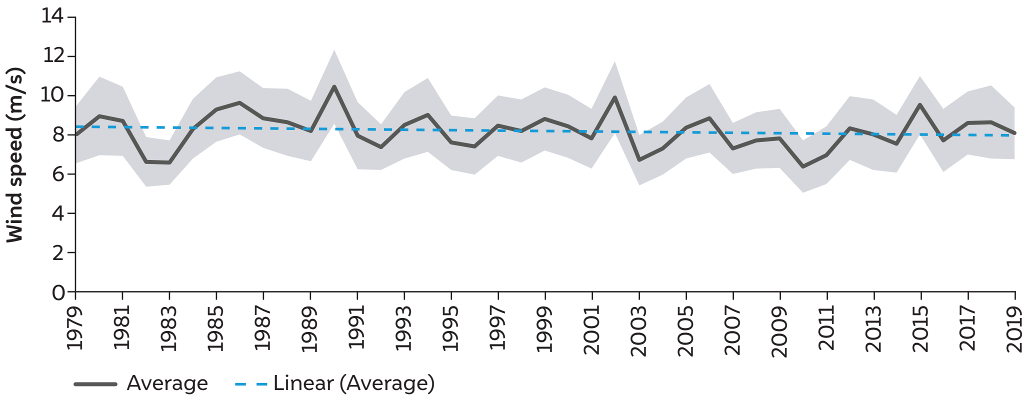


Figure ES2
There is a clear declining trend in wind speeds in Gujarat, India's second-most wind-rich state

Source: Authors' analysis of the ERA5 data set in the ECMWF database

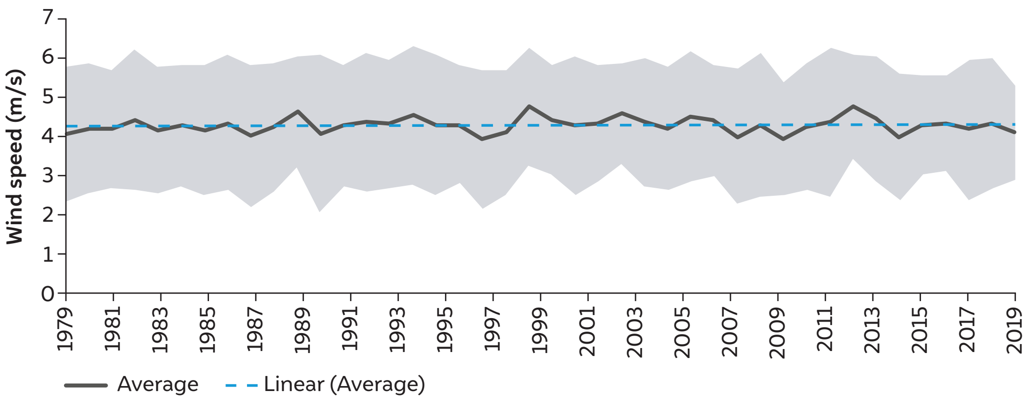


Figure ES3
Wind speeds in Tamil Nadu, India's top wind power producing state, are relatively stable

Source: Authors' analysis of the ERA5 data set in the ECMWF database

Explaining wind speed declines in 2020

The seasonal contrast between land–sea temperatures and pressure distribution across the Indian landmass and the adjacent Indian Ocean determines India's wind resource potential. As such, wind power in the country remains largely dependent upon the monsoons. However, a warmer-than-normal tropical ocean adjacent to Indian landmass in 2020 was the manifestation of what is most likely an anthropogenic or "man-made" effect on the climate system.

During the pre-monsoon period of 2020, India witnessed meteorological signatures that indicated a weak monsoon. They included the following deviations:

a) Cooler than normal northern plains in the Indian subcontinent

b) Warmer than normal neighbouring North Indian Ocean

c) Wetter than normal pre-monsoon season over India

The anomalies of the pre-monsoon and peak monsoon season fuelled the onset of sub-par wind fields from June to August over the Indian landmass that were responsible for reducing energy generation.

Anomalies in the Indian summer monsoon of 2020 paved the way for disrupted wind speed patterns during the peak season. Figure ES6 summarises various events that led to a decline in wind speeds over India from a climatological perspective.

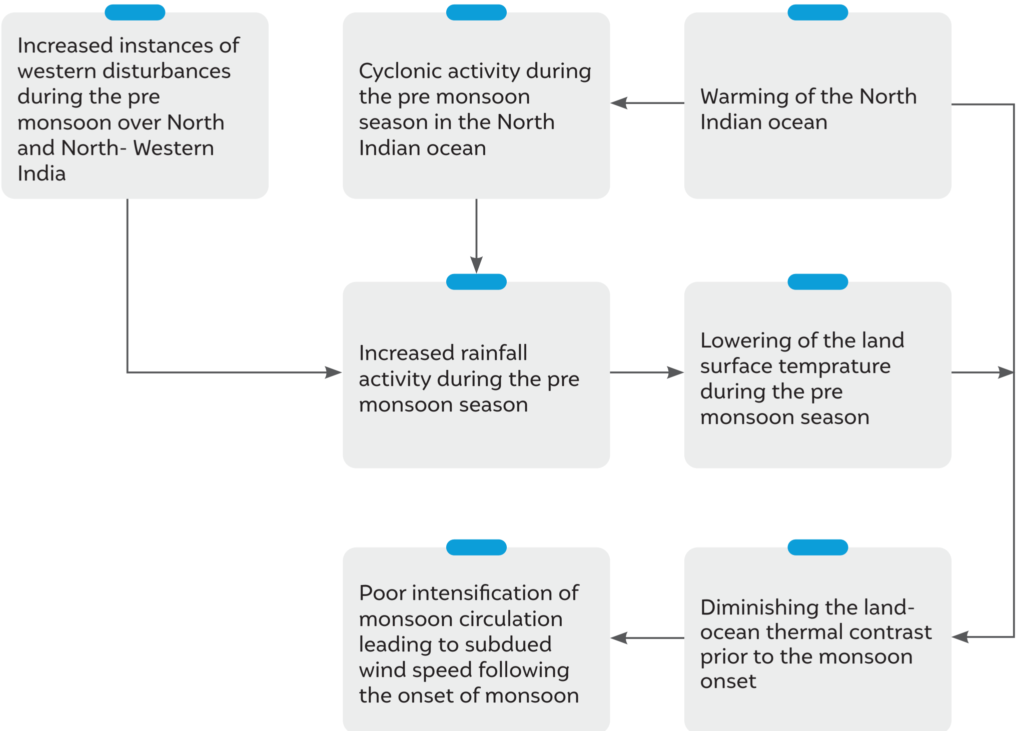


Figure ES4
Anomalies in the Indian summer monsoon of 2020 disrupted wind speed pattern during the peak season

Source: Authors' analysis

Recommendations

Several studies and scientific communities are pointing to the increased effects of climate change in the form of temperature and pressure changes and unusual and extreme weather events. Wind speeds are highly dependent on climatic variables. Therefore, the wind power sector could also be prone to these effects, a glimpse of which was visible in India in 2020. The wind power generation in the peak monsoon season of 2020 reduced sharply due to the interplay of weather anomalies. At the same time, we observed that towards the end of the year, wind speeds picked up and compensated for the dip in the monsoon months. An increase in instantaneous variability will impact system operations. Inter-annual variability, even though it may be lower, can affect system planning and investments. Both these types of variability need to be more rigorously and scientifically assessed. It is also essential that we proactively understand the likelihood and severity of situations similar to 2020 if they are to be a repeated phenomenon in the future.

To climate-proof the wind energy sector, governments, public sector organisations, and the industry must invest in deep climatological research, advanced weather and power forecasting techniques, and the development of cost-effective ancillary support technologies and services.

Figure ES5 Interventions needed to minimise the effects of wind resource variability

Source: Authors' analysis

Strengthening capacities and investments in research and development (R&D)

Investing in research on resource variations and climate modelling is imperative and needs to be done immediately.

Updating resource maps

Publishing resource maps more frequently can help mitigate the risk associated with new investments.

Improving data availability

Diaggregated generation data at plant-level is necessary to conduct long-term assessments of climate-induced impacts.

Adopting new and improved forecasting practices

Advanced forecasting tools help strengthen decision-making and the management of weather-induced variabilities that can widen the difference between energy supply and demand.

Investments in potent technologies, market mechanisms and services for grid integration

Adopting storage technologies is one proven way to effectively integrate variable renewable energy (VRE) into the grid.

Integrating uncertainty into planning

Long-term capacity expansion planning and demand-supply estimations should account for changing wind speeds and patterns across seasons.

Limitations of the investigation

The study identified **key factors** that were likely **responsible for the weak south-west monsoon winds** that led to the low generation of wind energy during the initial months of the 2020 monsoon. However, the analysis is not exhaustive in its coverage of a multitude of events like the ENSO, Atlantic Niño, and IOD, which **can influence monsoon wind fields** over the Indian subcontinent **through atmospheric teleconnection**.

The meteorological analysis focuses heavily upon two consecutive years **(2019 and 2020)**. It does not represent future or past trends in the wind field over the Indian subcontinent. We also do not explore the uncertainties surrounding the scenarios constructed for the IPCC report and their likely downstream impact on the evolution of the monsoon circulation over India in the years to come. A **more rigorous data analysis** with a climatological perspective is necessary to identify the causes of such varying trends.

The **offset observed in the wind speed** trend over Tamil Nadu is qualitatively attributed to the **seasonal influence** (e.g., north-east monsoon) and **regional forcings** (e.g., mountain passes) upon the wind field. Quantitative insights into this relationship **require further research and remain unaddressed** in the current investigation.

The ERA-5 datasets used for this investigation has not been subjected to bias correction, which largely restricts the insights derived from this study to remain qualitative in nature.

1. Introduction


Image: iStock

Wind energy has great potential in India. Since 1985, the nation's wind industry has steadily grown, largely due to favourable policy developments. With a total installed capacity of 38.6 GW (gigawatt) as of December 2020, India currently has the fourth-highest wind capacity in the world (MNRE 2021). It constitutes more than 42 per cent of the country's total grid-interactive renewable energy (RE) capacity (CEA 2021). The role of wind in the energy generation mix is expected to grow further, particularly with India's ambitious targets of 60 GW by 2022 and estimates of 140 GW by 2030 (GWEC 2020).

Given the growing importance of wind energy in India's power generation, it is critical to understand the characteristics of wind resources in the subcontinent and factor this information into the sector's planning and development. There are two crucial characteristics of wind availability in India that need to be considered. First, seven states in the southern and western parts of the country account for around 95 per cent of India's wind energy capacity (MNRE 2021). This concentration is primarily due to their geographical locations, due to which they experience a large number of 'healthy wind days' in a year. Tamil Nadu has the highest wind energy capacity, at 9.2 GW, followed by Gujarat, Maharashtra, and Karnataka, which have installed capacities of 7.2 GW, 4.8 GW, and 4.7 GW, respectively (MNRE 2021). Second, India's wind energy generation is distributed unevenly through the year, with 56 per cent of the total wind energy production occurring during the peak monsoon season between June to September 2019 (POSOCO 2019f–POSOCO 2019i). Additionally, wind energy is the primary source of clean energy during the monsoon as solar energy generation is relatively low at this time because of cloud cover (Matuszko 2012).[1]

These two characteristics of wind energy have played a critical role in the RE sector's development in India. This also affects the power sector, from short- and long-term power procurement planning by distribution companies to long-term capacity expansion plans at the national level.

1.1 The role of wind forecasting in integrating variable renewable energy

The geographical and temporal variations in wind resource availability impact how wind energy is integrated into the electricity grid. Electricity transmission and distribution networks require a real-time balancing of power injected into and drawn from the grid. Real-time balancing is mandatory to maintain the grid's stability at a predefined frequency of 50 hertz (Hz). Balancing the grid by matching supply and demand at all times can only be achieved with accurate predictions of demand and corresponding scheduling of supply.

To accommodate intermittent renewable sources of generation in the grid, forecasting is essential for the grid operator to balance the grid. Forecasting for this purpose involves multiple time frames. Short-term forecasts are of primary interest for grid operators. Day-ahead and intra-day forecasts bases are used for daily power planning and dispatch. Thus, accurate forecasting reduces the uncertainty associated with power generated by uncontrollable sources of energy.

Renewable energy forecasting

Wind and solar power generation patterns are entirely dependent on weather phenomena, namely, wind fields, solar insolation, and cloud movements. As such, forecasting wind and solar power generation require an understanding of weather variables. The second layer in forecasting wind and solar generation is based on mathematical modelling of the physical characteristics of generation plants to formulate a method of converting weather variables into power generation patterns, considering the relationships between the weather and power outputs. Further improvements in forecasting accuracy may be achieved through the use of data-driven statistical methods.

1 During the peak monsoon season, solar panels may harness less energy from solar irradiation than usual due to the constant interference of rain clouds throughout the Indian subcontinent.

1.2 Rationale and objective

India experienced a significant resource anomaly in 2020 that led to a 24 per cent reduction in wind energy generation in June, July, August, and September (JJAS) as compared to the same months in 2019 (POSOCO 2019f–POSOCO 2019i; POSOCO 2020r–POSOCO 2020u). Gujarat, for instance, had a monthly average wind speed of 18.8 kmph (kilometre per hour) in July — the slowest in 42 years. Meanwhile, the overall decline in 2020 compared to 2019 was only around 5.3 per cent. This means that the wind power generation in 2020 was only marginally lower than in 2019. However, it is essential to note that the decline during the peak season had disproportionate implications for wind power producers and system operators in wind-rich states. Additionally, there has been a historical decline in wind speeds in the Indian subcontinent since 1979 (Jaswal 2013). Annual average wind speeds have reduced at a rate of 0.88 kmph with every decade; the sharpest declines occurred in June (-1.33 kmph with every decade) and July (-1.27 kmph with every decade). Such resource anomalies can pose forecasting challenges, thus affecting the wind sector value chain.

There has been a historical decline in wind speeds in the Indian subcontinent since 1979

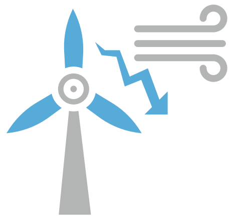
This report aims to catalyse discussions on tackling wind resource variability in India. It is an attempt to understand the factors leading to the resource anomaly in 2020, highlight the associated impacts across stakeholders, and identify risk-proofing strategies for the sector.

Slower wind speeds over wind-rich states in India led to fall in power generation. It is essential to assess the rate of decline in wind speeds and identify key underlying factors.

Image: ReNew Power

2. A sudden drop in wind power generation during the peak season of 2020

The peak monsoon season of 2020 — when wind power producers typically amass a large proportion of their revenue — experienced a steep decline in wind energy generation. The overall wind energy generated in the months between June and September was 24 per cent lower compared to the same period the previous year. The most significant decline occurred in July when the wind power output was only 6,967 million units (MU), 40 per cent lower than the 2019 output.[2,3]



July 2020 saw the steepest decline in wind power generation - 40 per cent lower than that in July 2019

The decline in wind power generation evidently concerned stakeholders, as the industry had not anticipated this sharp fall. This marks the first noticeable drop in wind speeds over India due to unforeseen circumstances in recent years. 2020 saw the greatest decline in wind energy generation during the peak season in three years despite increments in installed capacity (Sreeram 2019).

We undertake regional and plant-level analysis to assess the extent and impact of reduced wind generation.

2.1 A decline in generation across regions

The western region of India has the highest concentration of wind installed capacity at 15,062 MW as of 31 March 2020 (MNRE 2021). Figure 1 shows the daily capacity utilisation factor (CUF) during the peak season of 2020 in a year-over-year (y-o-y) analysis of the western region. There was a 29 per cent decline in power generation in the western region in 2020 compared to 2019 (POSOCO 2019f–POSOCO 2019l; POSOCO 2020r–POSOCO 2020u).

Methodology

We first extracted the daily generation data from the POSOCO data portal to identify the daily CUF of the wind turbine generators (WTGs) in the western region during the specified months. These data were then divided by the total installed capacity in the western region and further divided by 24 to give us the daily CUF.

2 Authors' analysis of Earthmetry data.
3 Adjusted for 1.3 GW of capacity addition between the years.

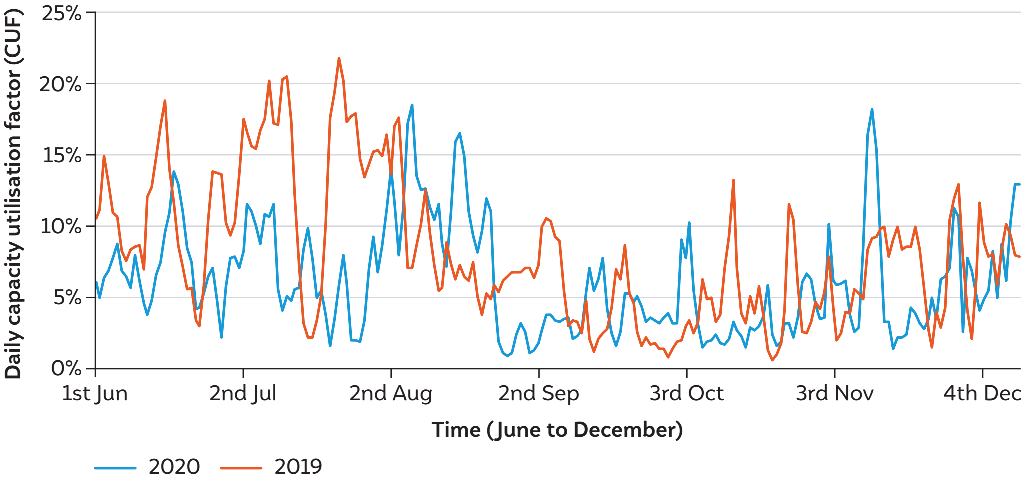


Figure 1
Wind generation in 2020 was lower than that in 2019 in western India

Source: Authors' analysis of POSOCO data (POSOCO 2019f–POSOCO 2019l; POSOCO 2020r–POSOCO 2020u).

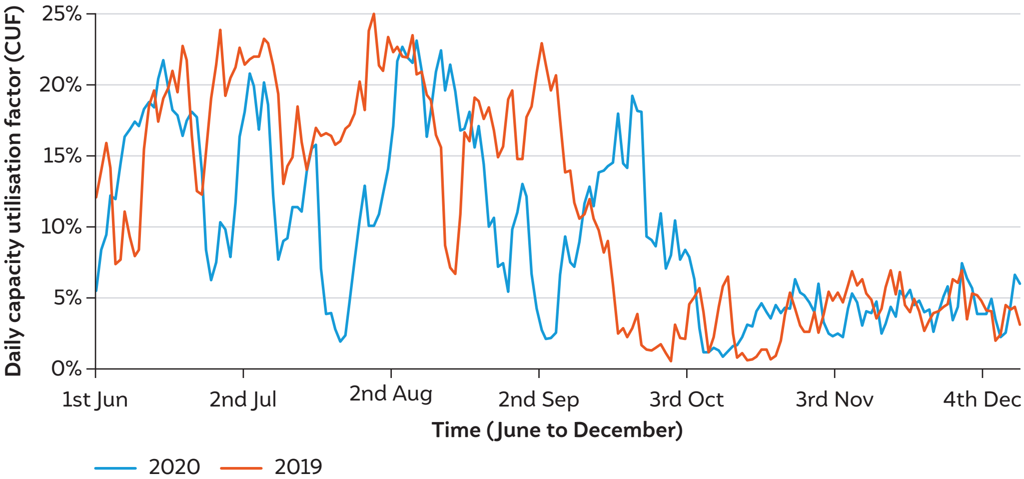


Figure 2
Decreased wind power production in 2020 in the southern region of India

Source: Authors' analysis of POSOCO data (POSOCO 2019f–POSOCO 2019l; POSOCO 2020r–POSOCO 2020u).

The southern region, which includes Tamil Nadu, the most prominent wind power producing state in India, experienced a 7 per cent decline in wind power generation during the peak season in 2020 compared to 2019.

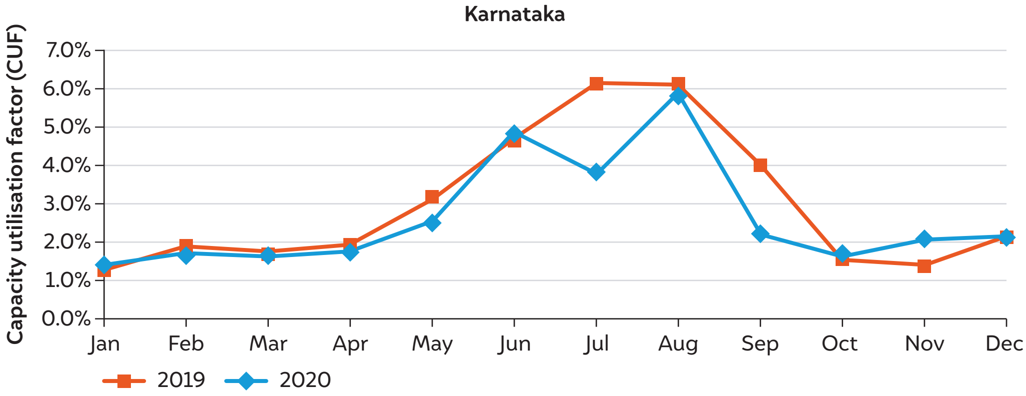
Figure 3 shows CUFs[4] for a sample set of wind power plants in 2020 as compared to 2019. As the plots show, monthly generation at all sample sites varied similarly in 2019 and 2020 up until the monsoon months, where there is a clear decline in generation for the latter year. The site in Rajasthan recorded marginally increased generation in the months leading up to the monsoons; this may be explained by increased wind flow in the region during the pre-monsoon months, owing to cyclonic activity. This case in Rajasthan also highlights the variability in impacts across sites — a few regions in the country were not affected much or at all.

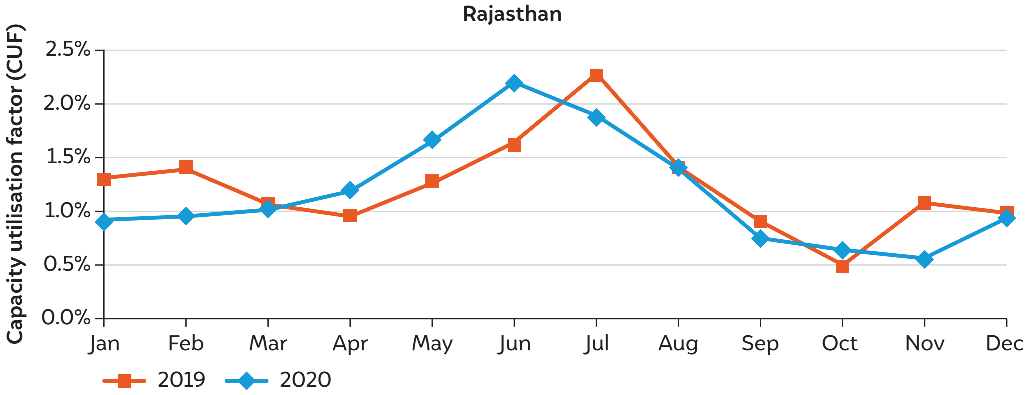
4 Calculated as the total wind energy generation in the given month divided by the maximum possible annual energy generation. This is done to highlight the differences between 2019 and 2020 as well as those between months.

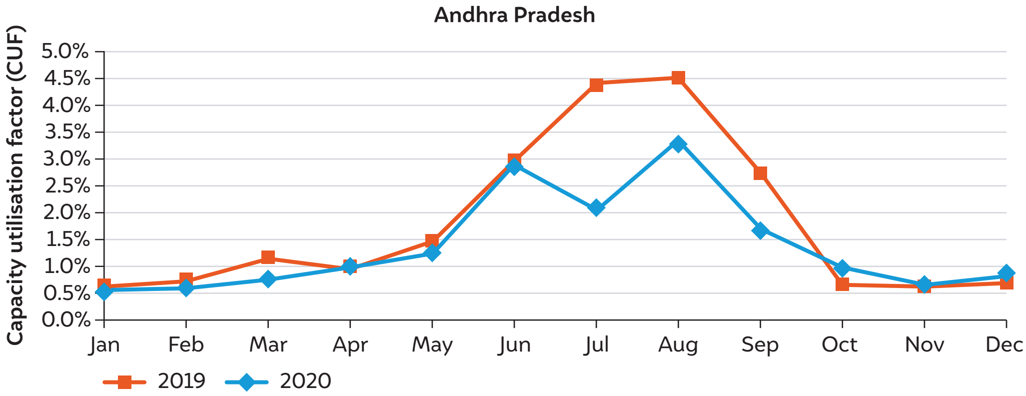
Figure 3
Relative to 2019, wind power generation from January to December 2020 was lower across plants in various states[6]

Source: Authors' analysis

5 The generation plants range in capacity from 30 to 250 MW







As the peak monsoon months from June to September usually produce high wind power output due to the many 'healthy wind days', power producers tend to rely on the season for a good power yield and a significant proportion of their annual revenue recovery. Installed wind power capacity is projected to increase 5-fold by 2035. Such abrupt declines during the peak monsoon season could have even greater implications for the sector if their occurrence becomes more frequent.

2.2 Wind resource decline: the primary cause of reduced generation in 2020

To understand the short-term decline in power generation, we undertook a case study focused on Gujarat and Tamil Nadu. We chose the two states based on their contribution to the total installed capacity of wind in India and geographical locations.

In Gujarat, we looked at daily average wind speeds at 100 metres in the Jamnagar district.[6] Jamnagar currently houses 10 per cent of Gujarat's installed wind power capacity. Similarly, we chose the Tirunelveli district in Tamil Nadu as it accounts for 16.5 per cent of the existing installed wind energy capacity in the state.

The wind speed analysis for Jamnagar and Tirunelveli between June and September for 2018, 2019, and 2020 shows a decline in wind speeds in 2020 compared to previous years.[7,8] Figures 4 and 5 illustrate the wind speed–duration curves from June to September for Jamnagar and Tirunelveli. In 2020, Jamnagar experienced a decline in wind speeds compared to 2019 and 2018. Similarly, Tirunelveli indicated decline in wind speeds compared to 2018 but no reduction when compared to 2019. Thus, there is a declining pattern in wind speeds for both cases in 2020 compared to the previous three years.

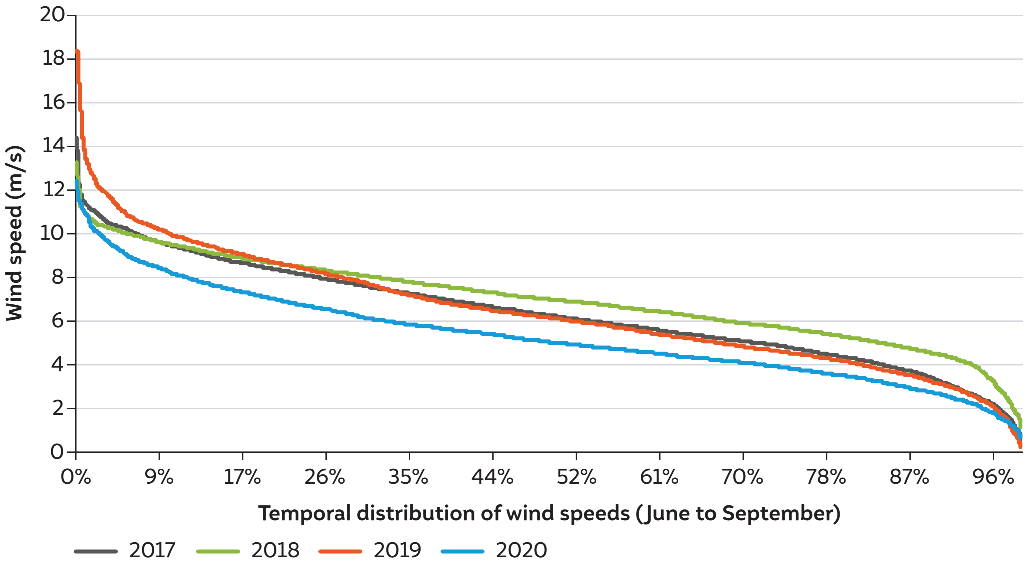


Figure 4
Jamnagar in Gujarat saw a steep decline in wind speeds during the peak season of 2020

Source: Authors' analysis of ERA5 data set in the ECMWF database

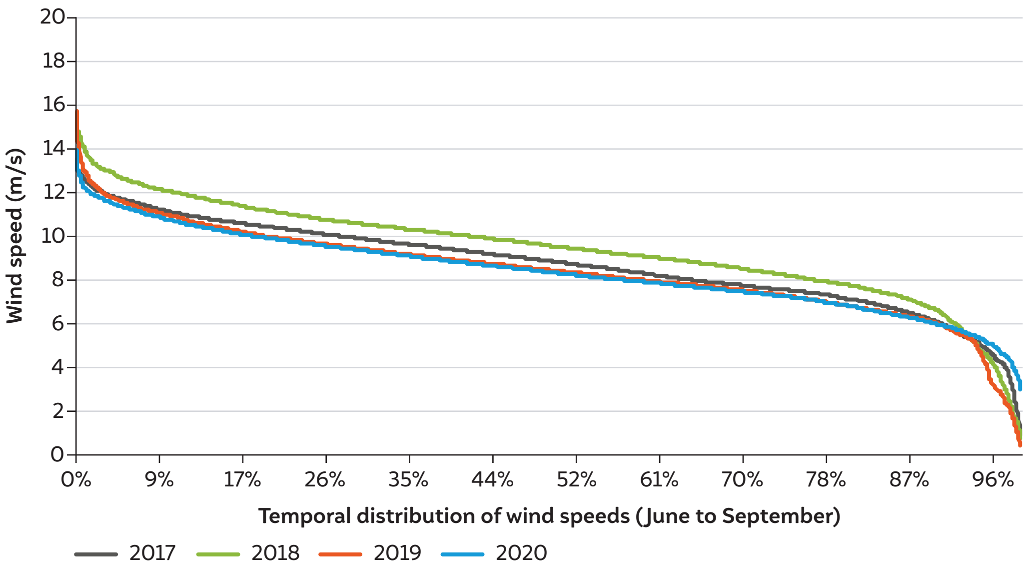


Figure 5
Tirunelveli in Tamil Nadu has seen a gradual decline in wind speeds during the peak season since 2018

Source: Authors' analysis of the ERA5 data set in the ECMWF database

Estimations of wind speeds across India (Figure 6) also show reductions in average wind speeds over large parts of the country spanning RE-rich regions. Depressed wind flow over water bodies surrounding the country's peninsular region also indicates an overall decline in wind fields in 2020.

6 To reduce the chances of inaccurate assessment of changes in average wind speeds, we picked one district each in Gujarat and Tamil Nadu instead of examining data sets for the entirety of either state.

7 The analysis compares wind speeds during the peak monsoon season from 2017 to 2020, but does not attempt to define a 'trend'.

8 The wind speed curves have been created using daily average data for visualisation. The same may also be created using wind speed data with higher granularity.

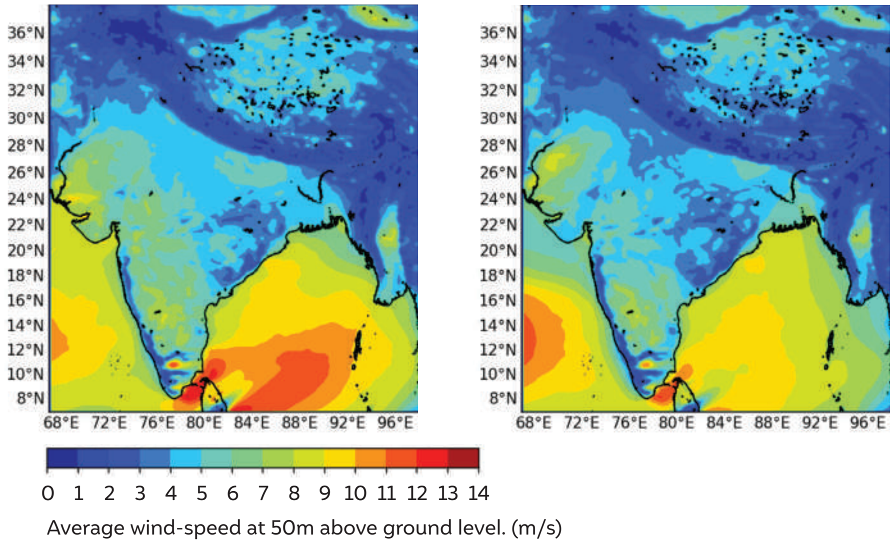


Figure 6A
Reduced wind speed over the Indian peninsula in 2020 compared to 2019

Source: Authors' analysis

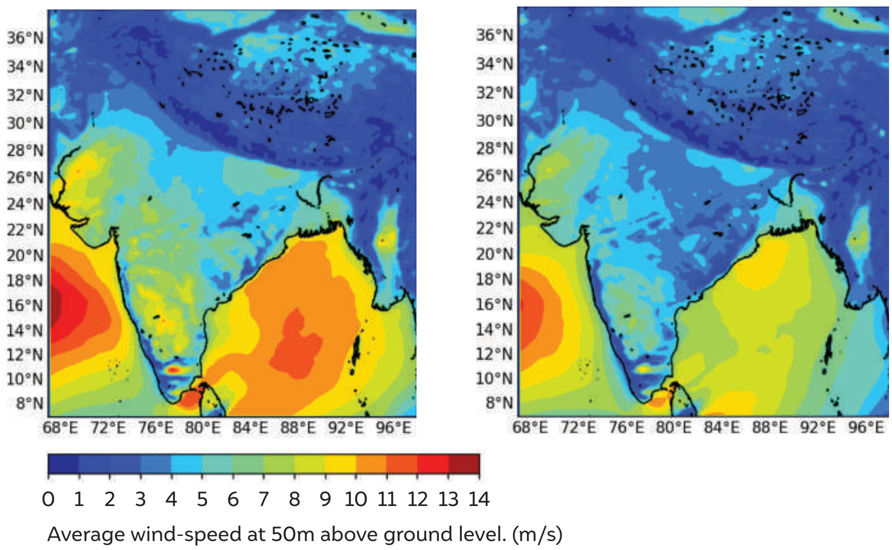


Figure 6B
Wind movement intensity declined in the neighbouring water bodies of India in July 2020 compared to 2019

Source: Authors' analysis

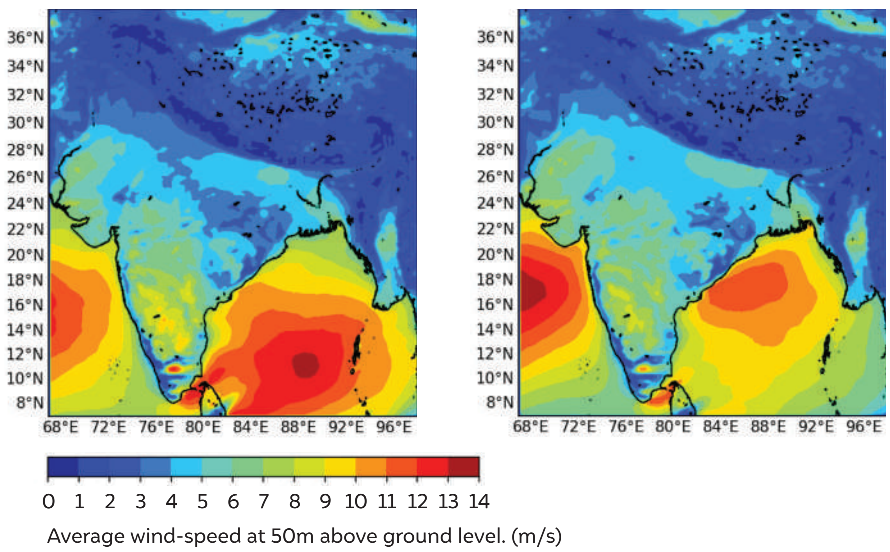


Figure 6C
Poor development of monsoon circulation reduced wind speeds in July 2020 compared to 2019

Source: Authors' analysis

The observed wind speed decline clarifies that the primary reason for the reduced wind energy output in 2020 was a decrease in wind resource.

Explaining the wind speed decline in 2020

Image: iStock

The seasonal contrast between land–sea temperatures and pressure distribution across water bodies surrounding the Indian peninsula determines India's wind resource potential. Thus, the wind energy generation in the country remains largely dependent upon monsoon winds (Saha et al. 1979).

The difference between the land and sea temperatures that develop during the pre-monsoon season (March, April, and May) drives moisture-carrying winds from the neighbouring oceans to the Indian subcontinent. This temperature contrast leads to the intensification of the pressure differential that extends across the Indian mainland and the adjacent ocean. This strengthens the monsoon circulation that brings rain-bearing clouds on the south-west winds (Ratnam et al. 2009).

Strong winds, originating from the Mascarene High (a high-pressure area located between 20°S–40°S and 45°E–100°E) in the South Indian Ocean, turn north-easterly as they cross the equator to reach the Indian subcontinent as summer monsoon winds around late May or early June. Warming of the Indian Ocean implies a decrease in the temperature contrast that drives the monsoon winds across the land, which in turn dampens the wind speed over the subcontinent (Roxy et al. 2015; Gao et al. 2018; Vidya et al. 2020).

According to our review of the scientific literature, the pressure gradient between the land and sea was strongly correlated with wind-based electricity generation potential during spring and summer in 2020. This timeline aligns with the occurrence of the Indian summer monsoon under normal conditions (Vidya et al. 2020).

3.1 Understanding what happened: The anomalous monsoon in 2020

In 2020, what was probably an artificial influence on the climate system manifested as a warmer than normal tropical ocean surrounding the Indian subcontinent. The meteorological signatures of the pre-monsoon season in 2020 indicated a weak monsoon.

a) Cooler than usual northern plains of the Indian subcontinent

Most of the northern Indian mainland was marginally cooler (by ~1^{o} C) in 2020 compared to both the 1971–2000 monthly climatology and 2019 (Figure 7). The 2020 pre-monsoon season was at its coolest since 1997. This also co-existed with a warmer than normal neighbouring ocean surface temperature (by ~1^{o} C). This, in turn, compounded into a minimising effect on the land-sea thermal contrast, which is a critical ingredient for roping moisture-carrying winds towards the Indian mainland.

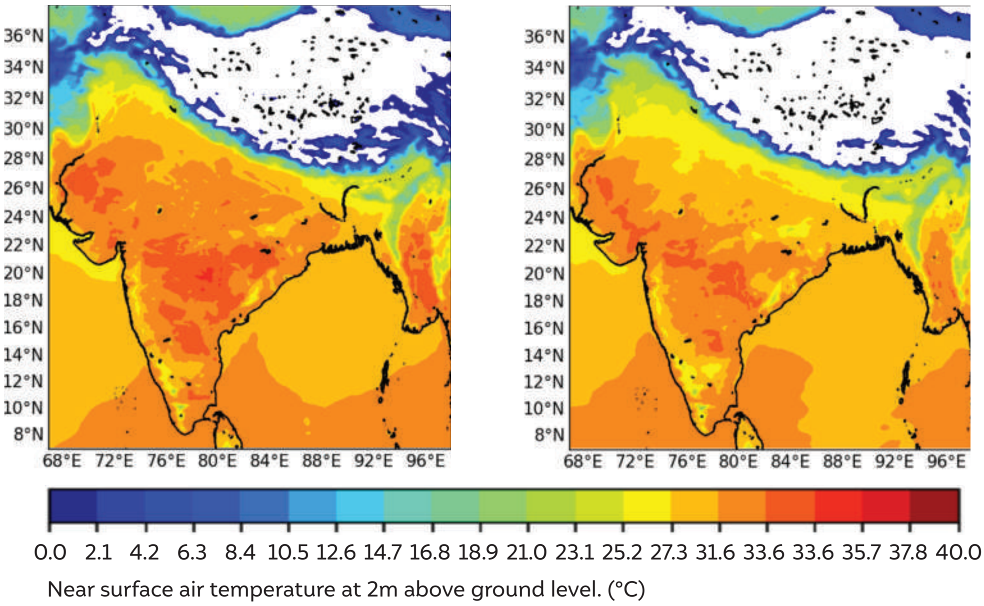


Figure 7
Near-surface temperature during April 2020 was lower than in 2019

Source: Authors' analysis

b) Warmer than normal neighbouring North Indian Ocean

The presence of a warmer than normal ocean surface (i.e., the North Indian Ocean comprising the Arabian Sea and Bay of Bengal) next to India facilitated the formation of cyclones towards the tail end of the pre-monsoon season in 2020. In the Bay of Bengal, Cyclone Amphan (which made landfall in mid-May 2020) had wind speeds of close to 175 kmph and inundated the coastal regions of West Bengal. In the Arabian Sea, the formation and sustenance of Cyclone Nisarga were likely responsible for pulling the monsoon into the Indian subcontinent. This, in turn, facilitated a timely onset (i.e., on 1 June 2020) despite weak monsoon winds (which formed due to a reduced land-sea temperature gradient as per Figure 8). Except for the timely onset, the 2020 south-west monsoon circulation was unable to sustain its traction post the dissipation of Cyclone Nisarga.

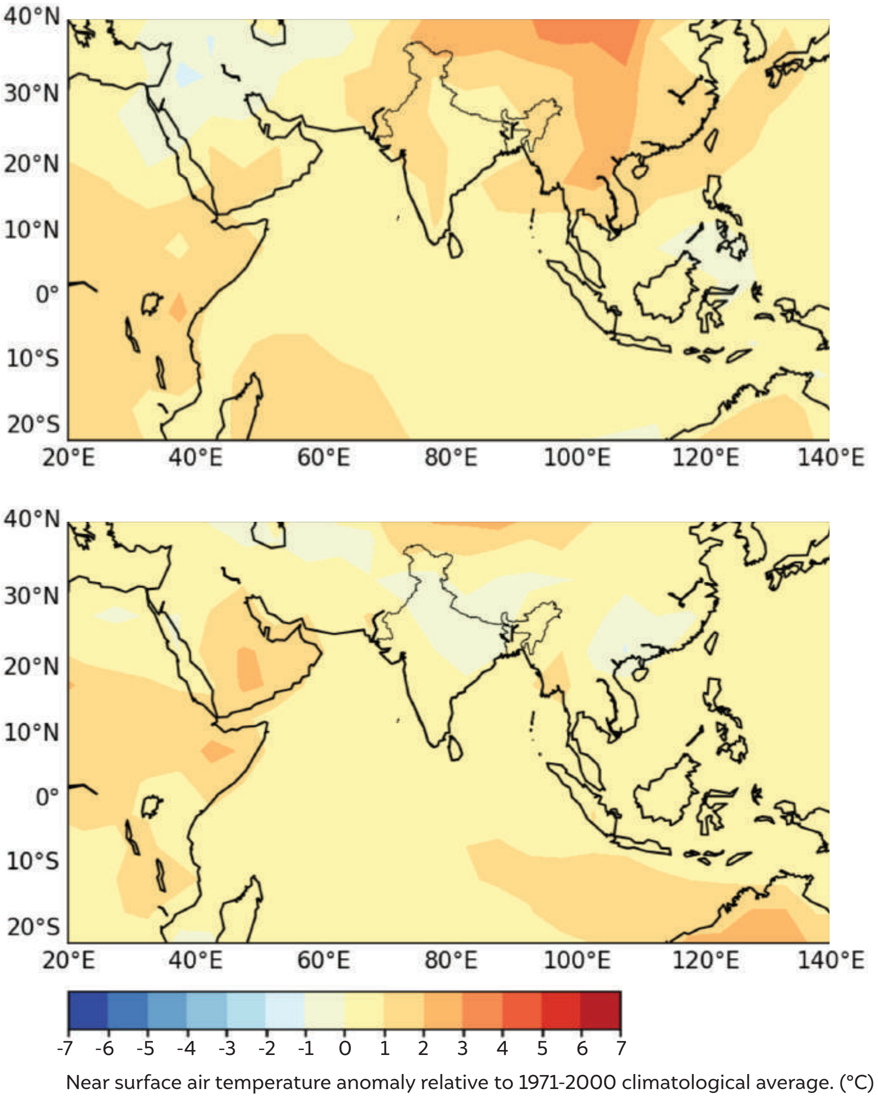


Figure 8
Land sea thermal contrast in April 2020 was lower than the normal average during the same period between 1971-2000

Source: Authors' analysis

The frequent western disturbances during the pre-monsoon season and the cyclonic activity towards its tail end likely contributed to the excessive rainfall of March to May 2020 across India. These occurrences may have led to the lowering of land surface temperatures across the Indian mainland and, in turn, a weaker monsoon circulation and subdued wind speeds at the wind turbine height (Kumar, Naidu, and Prasanna 2020).

c) Wetter than normal pre-monsoon season in India

The pre-monsoon season also included excessive rainfall between March and May 2020; 354 heavy rainfall events had above 64.5 mm of rainfall in March and April alone (Sangomla 2020). There were similar heavy rainfall episodes reported in 2019 across Iran, Pakistan, and Afghanistan (Agarwal 2020). The jump in rainfall received during the pre-monsoon season may be attributed to the increase in incidences of western disturbances over northern India.[9]

9 Western disturbances are extra-tropical storms that originate in the Mediterranean region and are usually harbingers of dust storms as they travel to India on subtropical jet streams.

The increase in western disturbance incidences likely channelled moisture from its origin to western and northern India. Its subsequent interaction with the warm air over the Indian subcontinent probably led to the formation of thunderstorms and increased rainfall responsible for making the 2020 pre-monsoon season wetter than normal.

Table 1
Identifying anomalies in the physical conditions of the 2020 Indian summer monsoon

Source: Authors' analysis of the ECMWF database

Deviations/anomalies	Normal conditions	2020
Cooler than normal northern plains of the Indian subcontinent	28–31º C	26–31º C (cooler by 1.5–2º C)
Warmer than normal neighbouring North Indian Ocean	29–30º C	30–31º C (warmer by 0.5–1º C)
Wetter than normal pre-monsoon season over India	<5 mm; less widespread; localised to the coasts, Himalayas, and the Western Ghats	1–8 mm; more widespread, with North India receiving additional precipitation of approximately 3 mm (relative to a typical April month)

Note: The 1979–2019 April climatology serves as the benchmark for normal conditions.

The complex interplay between the land and sea is summarised in Figure 9. The warm Indian Ocean (responsible for spawning cyclones) coupled with the cold northern Indian landmass (owing to rainfall associated with western disturbances) contributed to the decrease in the land-ocean thermal contrast, which eventually resulted in the depletion of the monsoon circulation strength. This, in turn, fuelled the onset of sub-par wind fields over the Indian landmass, which were responsible for the reduction in energy generation from June to September.

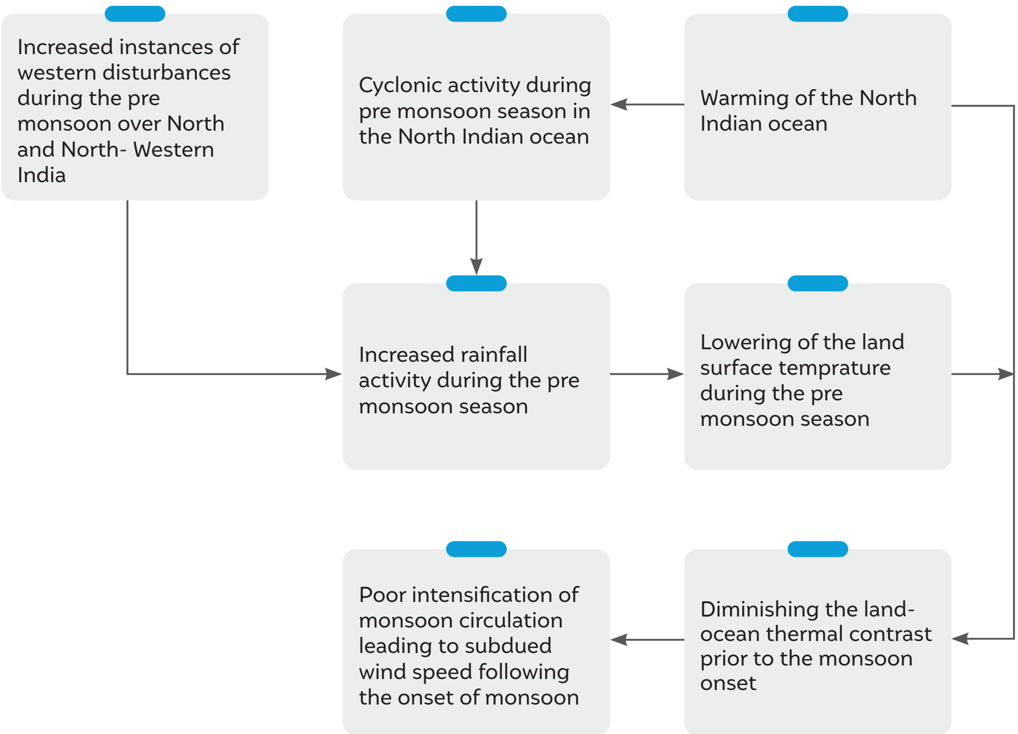


Figure 9
Anomalies in the Indian summer monsoon of 2020 disrupted wind speed pattern during the peak season

Source: Authors' analysis

4. The impact of changing climatic patterns on wind speeds: a long-term assessment

Image: iStock

Climate change has various implications for the functioning of almost every industry in the world. Given the rising rate of extreme weather events and changing climate worldwide, various studies have attempted to explore the impact of climate change on wind speeds in India. (Gao et al. 2018) simulated complex climatic models to analyse wind speed variations over the Indian subcontinent during a period of 37 years. The results indicated a gradual decline in wind speeds, especially over the western states of India. Further, the changes in wind speed patterns were mainly attributed to anomalies in the Indian summer monsoon due to modulating trends in the sea surface temperatures of the sea surrounding the Indian subcontinent. The current research, which analyses wind speed data over 40 years, similarly indicates a decline in wind speeds.

4.1 Assessment of historical wind speeds

Typically, climatic variables are studied over a long time to observe changing climatic patterns (Ogwang et al. 2015).

Average wind speed data for Gujarat, Rajasthan, and Tamil Nadu were analysed monthly from 1979 till 2019. Figures 10 and 11 display a declining trend in wind speeds over Gujarat and Rajasthan. Contrarily, Tamil Nadu demonstrated a rising trend in the wind for the same period (see Figure 12). The results of the long-term analysis agreed with those of a recent study conducted by the Ministry of Earth Sciences, which forecasted an increase in wind speeds over the southern peninsula as an indirect impact of climate change in India (Krishnan et al. 2020).

Methodology

We extracted wind speeds at 100 metres for 40 years (1979–2019) from the ECMWF database. This was part of the ERA5 fifth-generation ECMWF reanalysis of global climate and weather for the past seven decades. The data were extracted at a resolution of 0.25 degrees x 0.25 degrees and were readily available at monthly averages. Hence, the authors conducted the analysis using the average monthly wind speeds in the specified geographical locations.

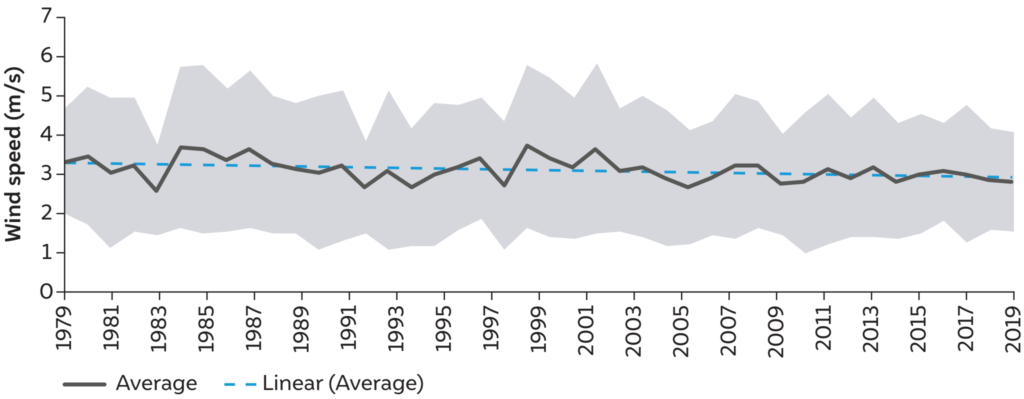


Figure 10
There is a clear declining trend in wind speeds in Rajasthan

Source: Authors' analysis of the ERA5 data set in the ECMWF database

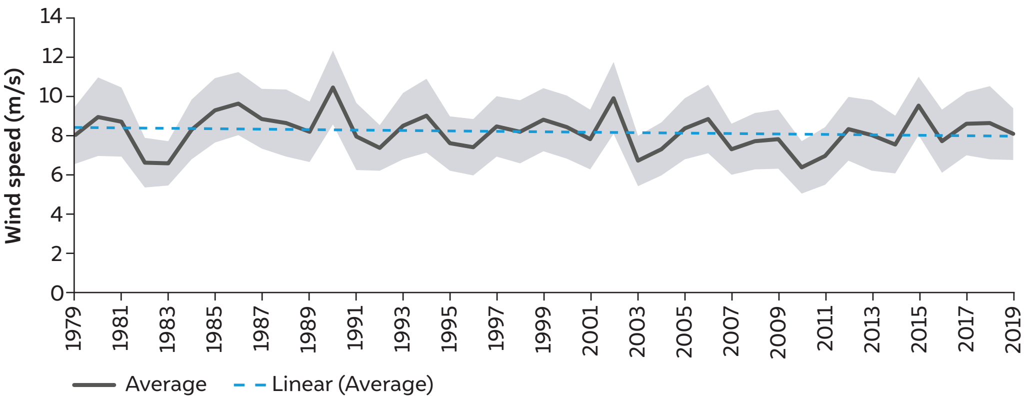


Figure 11
There is a clear declining trend in wind speeds in Gujarat, India's second-most wind-rich state

Source: Authors' analysis of the ERA5 data set in the ECMWF database

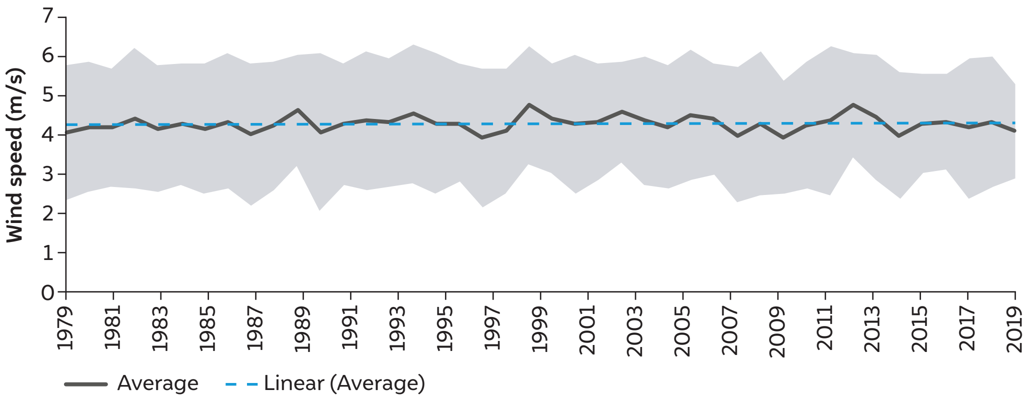


Figure 12
Wind speeds in Tamil Nadu, India's top wind power producing state, are relatively stable

Authors' analysis of the ERA5 data set in the ECMWF database

In our analysis, trends in Tamil Nadu consistently stood in stark contrast to the dips in wind speed observed in the rest of the country's wind-rich states. This could be attributed to the following factors:

1. **The seasonal predominance of the north-east monsoons in the state**: Tamil Nadu is one of the few states in the country that benefits from the north-east monsoon wind field that typically spans October to December. This factor likely mitigates the dip in the wind speeds in places such as Muppandal, Kayathar and Poolavadi (where there is at least 8.2 GW installed capacity for wind as of 21 June 2019), which are usually rich in wind resource.[10]

2. **Presence of mountain passes**: Tamil Nadu has multiple mountain passes, which include the Aralvaimozhi pass, Sengottai pass, Cumbam pass, and Palghat pass. The presence of mountain passes channels and accentuates the flow of wind to downstream districts (Coimbatore, Tirupur, and Dindigul). Likewise, Muppandal near the Aralvaimozhi pass has the largest installed wind capacity in Tamil Nadu to capitalise on this natural funnelling of the wind field (Department of Environment, Government of Tamil Nadu 2020).

We observed mean annual wind speeds of over 15 kmph only in Gujarat and southern Tamil Nadu. Although state-level trends show that wind-rich states have better wind speeds than other states in India, average wind speeds have been dropping every decade in these states since 1979. Average annual wind speeds all over the country are currently falling at a rate of 9.2 per cent per decade. Average annual wind speeds declined by 49 per cent from 1961 to 2008, indicating the effects of a changing climate on the wind power sector (Jaswal 2013). The highest decrease in monthly wind speeds occurred in June and July, both of which are part of the peak monsoon season in India.

4.2 The difference in land-sea temperatures and their impact on wind speeds

Warm oceans serve as incubators for cyclonic systems. Increases in sea surface temperatures are likely driven by anthropogenic influences on the climate system. These effects can exacerbate the formation, severity, and frequency of cyclones. The increase in sea surface temperature in 2019 in the Indian Ocean was approximately 1°C higher than what it was in 1951 (Pörtner et al. 2019). This surpasses the global rise in temperature of 0.7°C in 1951–2015; during this period, there was also a decline in rainfall during the monsoon season (Krishnan et al. 2020).

A chapter within the recent Intergovernmental Panel on Climate Change (IPCC) report titled "IPCC Special Report on the Ocean and Cryosphere in a Changing Climate" highlights that an increase in the frequency and intensity of extreme events such as marine heat waves is 'very likely' in the coming decades (Pörtner et al. 2019).

10 Based on an analysis of the Genesis Ray database.

As warmer oceans with high specific heat capacity are likely to become common, the land-sea thermal gradient will primarily be dictated by the land surface temperature of the Indian mainland. As such, the signature features of the Indian monsoons, such as their onset and spatio-temporal distribution, are expected to remain volatile and respond to a confluence of myriad factors. These factors include the surface temperature of the Indian subcontinent during the pre-monsoon season, the incidence of western disturbances in northern India and cyclonic activity in the North Indian Ocean, especially during the pre-monsoon season.

The lower specific heat capacity of the landmass makes the evolution of the monsoon more unpredictable

The lower specific heat capacity of the landmass makes the evolution of the monsoon more unpredictable as the land surface temperature responds with minimal latency to rainfall associated with events like western disturbances over northern India. Therefore, a cooler and wetter pre-monsoon season is capable of weakening the monsoon winds. In contrast, a warmer, drier pre-monsoon period is more likely to encourage the south-west monsoon winds to mature and attain their full climatological strength.

The inter-annual comparison of 2020 with 2019 offers insights into the complex interplay of land and ocean and a repository of critical weather parameters (e.g., the land-sea thermal contrast, incidence of western disturbances and associated rainfall in northern India, and cyclonic activity in the North Indian Ocean) that ought to be monitored closely both prior to and during the onset of the summer monsoon in India. If the present trend of warming oceans continues, the dampening of the cross-equatorial wind field is likely to lead to the weakening of the monsoon current over the Arabian Sea (owing to the incapacitation of the Mascarene High in the South Indian Ocean). Therefore, a critical understanding of the interplay (and realistic replication via mathematical models) between land and ocean (along with quantifying their capability to modify atmospheric circulation) remains indispensable to the development and refinement of predictive capabilities that can provide insights into similar incidences and their impacts with sufficient lead time.

5. Implications of variability in wind resource

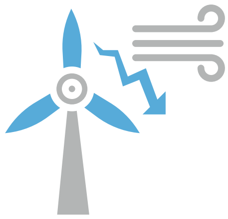
Image: iStock

Due to an increased possibility of a higher wind resource variability, we analyse the multi-fold impact the phenomenon can have on the wind energy sector and the power sector.

5.1 Impact of resource variability on wind power producers

The renewable energy market in India is becoming more competitive — power producers bid to offer the lowest price possible for electricity. To achieve low wind tariffs, power producers rely on maximising generation during the peak season, when most revenue recovery happens.

High inter-annual variability of wind could ultimately impact expected revenues for power generators in the industry. As IPPs (independent power producers) within the sector compete to produce the lowest power tariffs during power auctions, anomalies in generation output could impact profitability. A decline in monthly power generation can further result in a lower internal rate of return (IRR) for investors. With pre-existing challenges like curtailment, a reduction in wind resources could create turmoil within the industry.



High inter-annual variability of wind could ultimately impact expected revenues for power generators

Additionally, with rising variability, the deviation settlement mechanism (DSM) charges that IPPs have to pay for inaccurate forecasts will increase. This could impact cash flows and diminish revenues from wind projects.

To understand the impact of declining resources across two key geographies, we conducted two case studies. We used real-time conditions and provisions and a scenario-based approach to acknowledge a range of possible outcomes.

The first case study highlights the impact an anomalous wind pattern can have on the equity IRR of a wind project located in Gujarat. Wind power production in Gujarat declined by almost 12 per cent in 2020 compared to 2019.[11] To forecast variations in the equity IRR, we considered three scenarios depicting varying declines in the CUF and frequency of occurrence over the 25-year life of the plant. We assumed no variations in the working capital of the plant during its lifetime.

Case study: Impact on equity IRR

Methodology

To assess the impact of the decline in wind resources in India, we chose a site in Gujarat with a discovered tariff of INR 2.8 per kWh as per the power purchase agreement (PPA) (Prasad 2020). We assumed a plant size of 100 MW. We varied the CUF of the plant to analyse the change in equity IRR[12] and the decline in net revenue over 25 years, which is concurrent to the average life of a wind project.

To assess the decline in the CUF by a certain percentage for a single year during the plant's life, we assumed that the decrease in the CUF would occur during the thirteenth year of operation.

We built three scenarios to conduct a sensitivity analysis:

1 Scenario

A decrease in CUF for a single year during the entire life of the plant.

2 Scenario

A decrease in CUF every five years in the life of the plant.

3 Scenario

A decrease in CUF for all 25 years of the life of the plant.

11 Authors' analysis of Earthmetry data. The data analysed were extracted on a daily basis between 1 January to 30 September for both 2019 and 2020.

12 The post-tax equity IRR has been analysed in the entire case study.

In the financial model developed for the IRR analysis, we considered inputs and assumptions as defined by CERC's (Central Electricity Regulatory Commission) tariff determination order for 2019–20 (CERC 2019). We determined a base case scenario considering 'normal' wind power generation equivalent to that in 2019.[13,14] To arrive at a levelised cost of INR 2.8 per unit (same as the PPA tariff), we used a CUF of 37.4 per cent as the base case CUF. The base case IRR thus calculated was 14.97 per cent over 25 years.

The equity IRR for a 12 per cent reduction in CUF for a single year was 14.62 per cent, a decrease from 14.97 per cent, the base case IRR value. This represents a revenue loss of INR 29 crore for a 100 MW plant in 2020.

Figure 13 presents the decline in equity IRR with varying degrees of decline in the CUF from the base case CUF. Figure 14 illustrates the corresponding reduction in revenue realisation for a 100 MW plant with the same parameters as assumed for the equity IRR analysis.

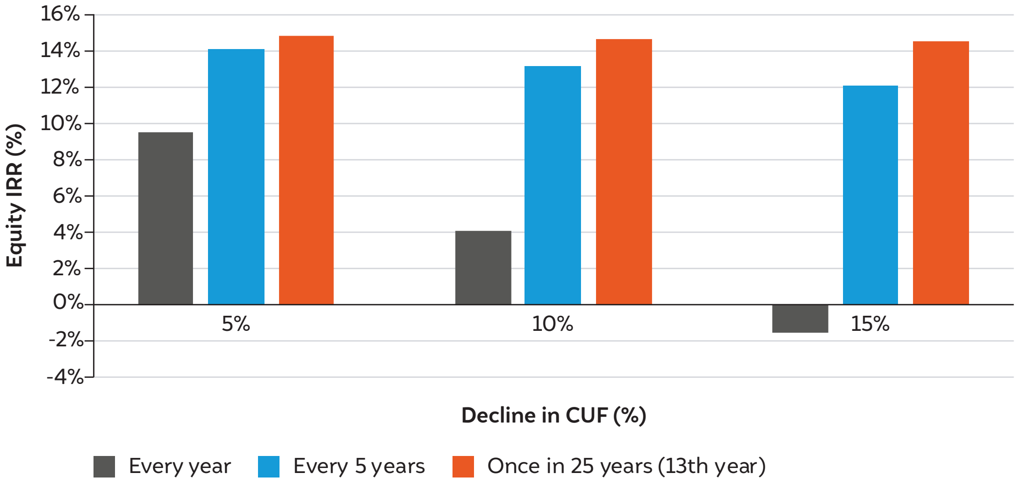


Figure 13
Wind resource variability can impact equity returns

Source: Authors' analysis

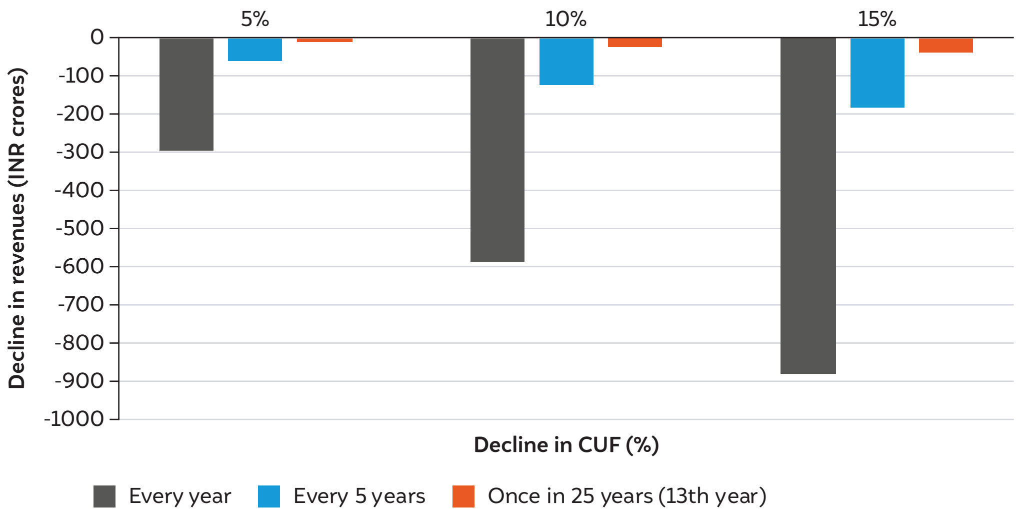


Figure 14
Resource variability could lead to revenue loss for a wind project

Source: Authors' analysis

The five-year scenario can be considered a more realistic depiction of the impact of wind resource variability. Our analysis shows that a 10 per cent reduction in the CUF every five years would result in an equity IRR of 13.14 per cent against the base case equity IRR of 14.97 per cent. This, in turn, translates into a decline of INR 122 crore in the total revenue. Similarly, a 5 per cent reduction in the CUF every five years would result in an equity IRR of 14.10 per cent, which would imply a fall of INR 61 crore in the total revenue. Likewise, a 15 per cent

13 We used a debt equity ratio of 80:20 along with a realistic interest rate of 8.5 per cent
14 Useful life is 25 years; the power plant costs 6 crores per MW; system size considered is 100 MW.

drop in the CUF every five years would result in an equity IRR of 12.06 per cent, which would mean a decrease in the total revenue of INR 184 crore. In all these cases, we considered a 100-MW plant and applied an identical drop in equity IRR to calculate the total revenue loss.[15]

This analysis highlights the financial impact of a decline in wind generation on the industry. Though we do see a decline in the IRR and total revenues, the IRR remains positive in almost all scenarios. Additional DSM charges on account of inaccurate forecasts could further add to losses. Additional cost implications could arise due to increased system balancing requirements.

Additional DSM charges on account of inaccurate forecasts could further add to losses.

In addition, the wind sector is already dealing with other risks such as curtailments, PPA renegotiations, and delayed payments by distribution companies. All these factors and associated implications can have compounded effect.

Case study: Impact on power forecasting

Methodology

We selected **two wind generation sites** in **Gujarat and Rajasthan** to assess the impact of the **decline in the generation** on **wind power forecasting**. With July as the reference month, we compared corresponding patterns **in 2019 and 2020**.

The **ease of predicting wind patterns** is influenced by the number and magnitude of **positive and negative ramps** that occur in a given period. Hence, we employed the number of ramps as an indicator of predictability for the sites during the two periods and collated forecast accuracies using the **root mean squared error (RMSE) metric**. This metric is widely accepted as a **global standard**; it has strong correlations with DSM charges as per the forecasting and scheduling regulations adopted in India.

The power forecasting models that agencies use to predict future generation values rely on a base of numerical weather predictions (NWP), which are projections of weather parameters generated by atmospheric simulation models. These NWP values are used to estimate generation by converting wind into power values by considering the physical characteristics of WTGs. The accuracy of weather to power conversions is, in many instances, enhanced by machine learning (ML) techniques that utilise historical data sets to learn error patterns and site-specific characteristics, such as wake effects and WTG performance deterioration. Most power forecasting models deployed in the industry use a combination of NWP data, weather to power conversions, and associated ML-based error corrections. Different models may be deployed for various forecast 'horizons' (i.e., time frames). Shorter horizons such as 1 hour ahead are generally more accurate than longer ones, such as 24 hours in advance due to the availability of more recent data in the former case, which allows for better estimates.

As the decline in generation in 2020 was most pronounced in the northern and western states, we selected two sites in Gujarat and Rajasthan for study. Both sites have capacities of more than 70 MW. As the following charts (Figures 15 and 16) indicate, both sites show a decline in total generation in July 2020 as against July 2019.

15 The base case CUF considered in this case study represents one of the best wind sites in the country. Most project sites across wind-rich states may typically yield an annual average CUF in the range of 20-32 per cent as per CERC's generic tariff orders. Therefore, a similar impact analysis can be done for other sites considering lower base case CUFs. It is possible that projects on these sites operate on thin margins, and therefore may be relatively more impacted if anomalous weather events become more frequent in the future.

The plots for the two sites also illustrate an increased number of ramps (both positive and negative) in generation in 2020 as compared with 2019. Such ramps pose a challenge to forecasting as they are driven by highly localised weather phenomena. As the regulatory framework in India requires forecasts to be applicable about 45–60 minutes from the time of issuance, the challenge is exacerbated since many ramps are short-lived and, consequently, cannot be captured in projections.

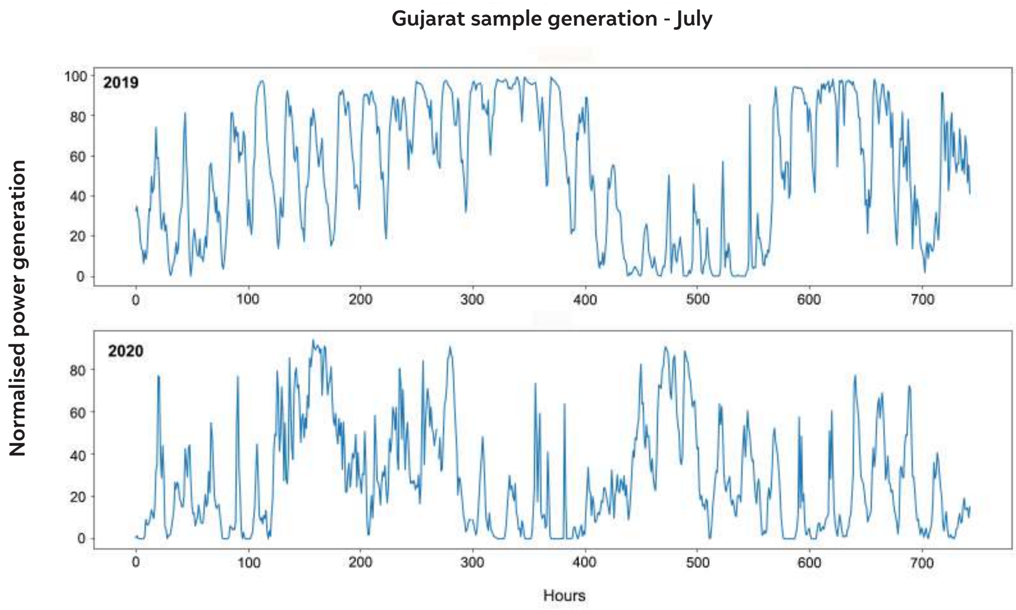


Figure 15
Wind generation in Gujarat declined significantly in July 2020

Source: Authors' analysis

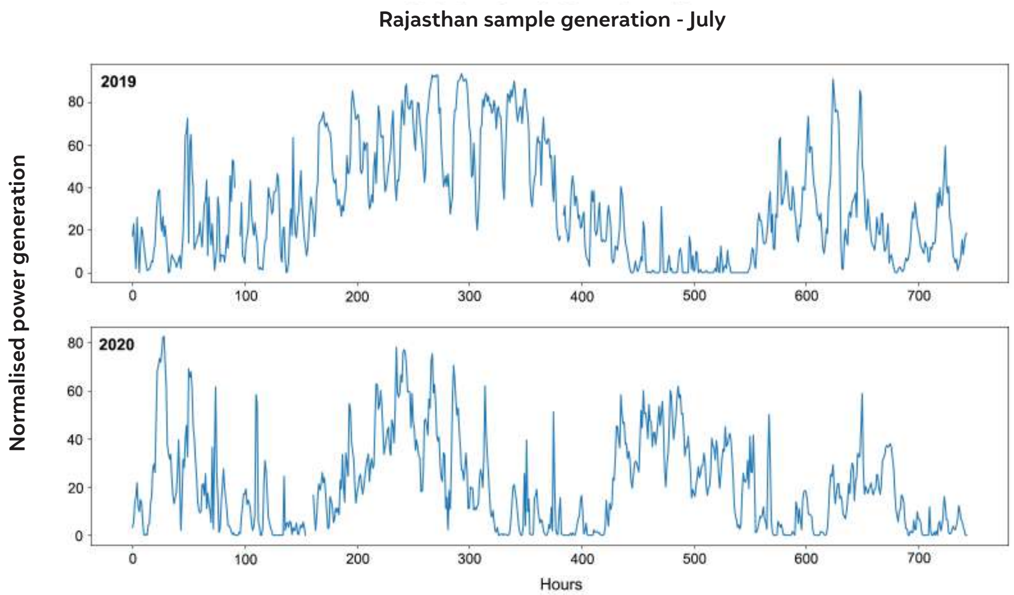


Figure 16
Rajasthan's wind power generation in July 2020 was lesser than that in July 2019

Source: Authors' analysis

Note: Graphs in figures 15 and 16 must not be recreated without prior consent from REConnect Energy Solutions

To quantify the impact on power forecasting, the ramps (both positive and negative) are listed in Table 2 according to incremental generation percentage brackets. These ramps in generation are observed in 15-minute blocks, i.e., a ramp instance indicates a change in generation by a certain percentage of total capacity in a 15-minute period. In Gujarat, there were 23 instances of a 20 per cent increase in generation within 15 minutes in 2019, whereas, in 2020, there were 42 such occurrences. Similarly, in Gujarat and Rajasthan, the number of ramps increased significantly in July 2020, leading to a greater unpredictability for these sites and hence larger DSM impacts.

The penalties for generators under the forecasting and scheduling regulations follow a formulaic approach — deviations are calculated as percentage differences between forecasted or scheduled generation values and actual metered generation values against a base of the available. The higher generation deviations incur larger financial penalties. The curve of financial penalties as a function of deviation forms a rough approximation of the root mean square error (RMSE) metric.

	Gujarat site		Rajasthan site	
Ramp (percentage)[16]	2019	2020	2019	2020
10	132	185	29	117
20	23	42	4	29
30	8	20	0	6
40	5	9	0	2
50	1	6	0	0
60	0	1	0	0

Table 2
2020 saw a significant increase in the number of ramps in Gujarat and Rajasthan

Source: Authors' analysis

We created simulations of forecasts for July 2019 and July 2020 to quantify the change inaccuracies (Table 3).

	Gujarat site		Rajasthan site	
	2019	2020	2019	2020
NRMSE (percentage)	13.7	14.6	10.3	11.7

Table 3
Increased change inaccuracies in forecasts for July 2020 at Gujarat and Rajasthan sites

Source: Authors' analysis

In Gujarat, the change in forecast accuracy reflects a 15 per cent rise in DSM charges as per the simulations, and in Rajasthan, an increase of 63 per cent.[17]

We carried out simulations using common sources of data and methods to maintain consistency across assessment periods. The numbers indicate possible impacts on DSM but do not represent actual implications for generators, which may vary depending on a multitude of factors.

5.2 Impact of resource variability on the power sector

Integrating VRE resources like wind power into the grid has long been a challenge across the world. Given India's high RE deployment ambitions, increased variability in wind resource can further aggravate grid integration challenges.

Anomalous wind patterns could increase forecasting errors and lead to real-time complexities in grid balancing

In the short term, anomalous wind patterns may impact grid balancing. DSM regulations applicable in states aim to restrict deviations between the forecasted and actual generation of variable RE. Accurate wind forecasting could mitigate grid integration challenges to some extent. However, unexpected variations in resource availability, like what happened in 2020, can increase forecasting errors, thus contributing to real-time complexities in grid balancing. For example, relative to 2019, the western region countered the unanticipated drop in wind power by increasing the hydropower generation by 12 per cent between June to August 2020. Also, the share of coal power in the region increased by 4 per cent in June and July 2020 in comparison to the previous two months of the year (Agarwal 2021).

16 Both positive and negative ramps have an adverse impact on short-term forecasting accuracy. In the analysis, both cases have been considered in conjunction.
17 We estimated DSM numbers based on hindcast simulations for the given periods and using state-specific forecasting and scheduling regulations to calculate financial impacts.

In the long term, increased variability can impact power system planning. Future capacity and infrastructure expansion plans rely on demand and supply projections. These projections account for certain levels and patterns of wind resource availability based on existing data measurements. However, instantaneous and inter-annual variations could impact long-term power sector planning and lead to demand and supply imbalances, thus increasing the overall cost of generating and supplying electricity.

Evidently, changing wind patterns and variations in the availability and intensity of wind over a long period of time can have cascading impacts. Wind resource uncertainty is likely to impact various stakeholders in the sector (Table 4).

Table 4
Assessment of the impact of wind resource uncertainty on various stakeholders

Stakeholder	Impact
Wind power generators	Loss of revenue and additional DSM charges. Negative impact on cash flow with delays in revenue realisation.
Investors	Our scenario analysis shows that IRR could be lower by 1.83 percentage points with a 10 per cent drop in CUF every 5 years in the 25-year life of the plant. Greater risk perception and higher return on investment expectations can lead to higher tariffs for wind power.
Forecasting agencies	Rise in error rates with increasing unpredictability.
Load despatch centres: SLDCs (State Load Despatch Centres), RLDCs (Regional Load Despatch Centres), and NLDC (National Load Despatch Centre)	More variability and unpredictability would increase grid balancing. An overall increase in per unit transmission charges borne by the buyers with a decrease in wind power output.
Central and state power sector planners	With the addition of higher levels of wind capacity, the power systems and their long-term planning would be more vulnerable to seasonal variations and changing weather patterns.

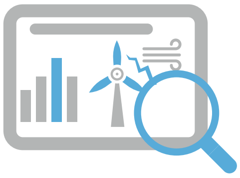
Source: Authors' analysis

Climate-induced variability in wind resources is an emerging risk that we do not know enough about. Deep climatological research using granular data can equip us to plan ahead in time.

Image: iStock

6. Recommendations

Due to the interplay of weather anomalies, wind power production in the peak monsoon season of 2020 decreased dramatically. In the 2019 monsoons, wind power in India's western and southern regions fell by 23 per cent and 7 per cent, respectively. As the monsoons receded, wind speeds picked up and compensated for the dip in generation during the peak season. A net decline of 5.3 per cent was witnessed in 2020 compared to 2019. However, similar instances in the future and declining wind speed patterns can complicate power system operations and increase investor risks within the wind energy sector. To mitigate such effects, stakeholders must invest in extensive research in the field of climate risks, weather predictions and power forecasting.



Understanding the likely frequencies and intensities of anomalous weather events needs an in-depth historical assessment of climatological variables and their correlation with wind speeds

Our study of weather anomalies in 2020 and historical assessment of wind speeds and weather patterns indicate that uncertainty and variability associated with wind in the Indian subcontinent are likely to increase in the coming decades. However, understanding the likely frequencies and intensities of such anomalous events would require an in-depth historical assessment of climatological variables and their correlation with wind speeds.

Timely strategies can mitigate resource variability risks and help the industry adapt better. Some strategies that can help address the resource variability issue are as follows:

Strengthening capacities and investments in R&D: Investing in research on resource variations and climate modelling is imperative and needs to be done immediately. The National Institute of Wind Energy (NIWE) may consider adopting innovative methodologies that allow for the measurement of long-term wind speeds and direction using reference stations deployed in major wind pockets across the country. Additionally, it is essential to invest in forecasting capabilities to predict extreme climate shocks that could damage infrastructure.

Updating resource maps: Publishing resource maps more frequently can help mitigate the risk associated with new investments. We recommend setting up a national wind resource monitoring centre, which the NIWE can lead in collaboration with the Indian Meteorological Department (IMD) and the Indian Space Research Organisation (ISRO).

Improving data availability: Non-availability of disintegrated plant-level data limits the scope of rigorous and long-term historical assessments of the likely interplay between climatic variables and wind speed distributions. Evolving a professionally-managed architecture for data collection, management and sharing can equip energy and climate science researchers to assess local impacts and project the likelihood of occurance of such phenemena in the future.

Adopting new and improved forecasting practices: Attempts to investigate the reliability of sub-seasonal to seasonal forecasts, particularly of anomalous wind speeds (e.g., dips in generation owing to lower than usual wind speeds), showed that they exhibited fair skill (with FairRPSS[18] skill score greater than or equal to 0.35) at capturing the incoming wind drought (in January–March 2015 in the USA) at multiple lead times (one, two, and three months ahead) (Soret et al. 2019; Ferro 2013). Despite the deficiency in capturing the actual values of wind speeds during the first quarter of 2015, the ensemble forecasts did point to lower than normal wind speeds, thereby enabling more accurate projections. Therefore, such forecasting tools can anticipate anomalous wind events; they help strengthen decision-making and the management of weather-induced variabilities that can widen the gap between energy supply and demand.

Advanced forecasting tools can help strengthen decision making and the management of weather-induced variabilities

Better grid balancing and integration: In the long term, better grid balancing and integration practices are necessary to manage weather anomalies effectively. Adopting storage technologies is one proven way to integrate VRE into the grid effectively. Detailed assessments of the costs and benefits of integrating storage at various levels can help identify optimum mechanisms for storage deployment. Furthermore, a transition to market-based platforms for the procurement of power and balancing resources could further reduce the impact of resource variability on system operations.

Integrating uncertainty into planning: Power sector planning and regulations should factor in the increasing uncertainty in resource availability. Long-term capacity expansion planning and demand-supply estimations should account for changing wind speeds and patterns across seasons. Advanced techniques and tools are necessary for the Indian power sector to achieve high levels of VRE integration and to accommodate multiple demand and supply scenarios.

18 FairRPSS (fair ranked probability skill score) is an index that quantifies the forecast skill of ensemble predictions within the context of categorical events. Negative scores indicate poor predictive skill for the ensemble whereas positive scores point towards an improvement against climatology. Sampling uncertainty was accounted for in the study.

Annexure

Section 1: Cooler northern plains of India in April 2020

The pre-monsoon season was observed to be cooler than normal. Temperature drops were seen in various regions of the nation. Our analysis resulted in thermal images that show an anomaly in temperatures in the northern plains.

The spatial plots depict near-surface temperatures for April 2020, the average near-surface temperature in April from 1971-2000 and a plot that describes the difference between the two aforementioned data plots. We concluded that a significant difference in land temperatures was witnessed in April 2020 where land temperatures were much cooler than expected.

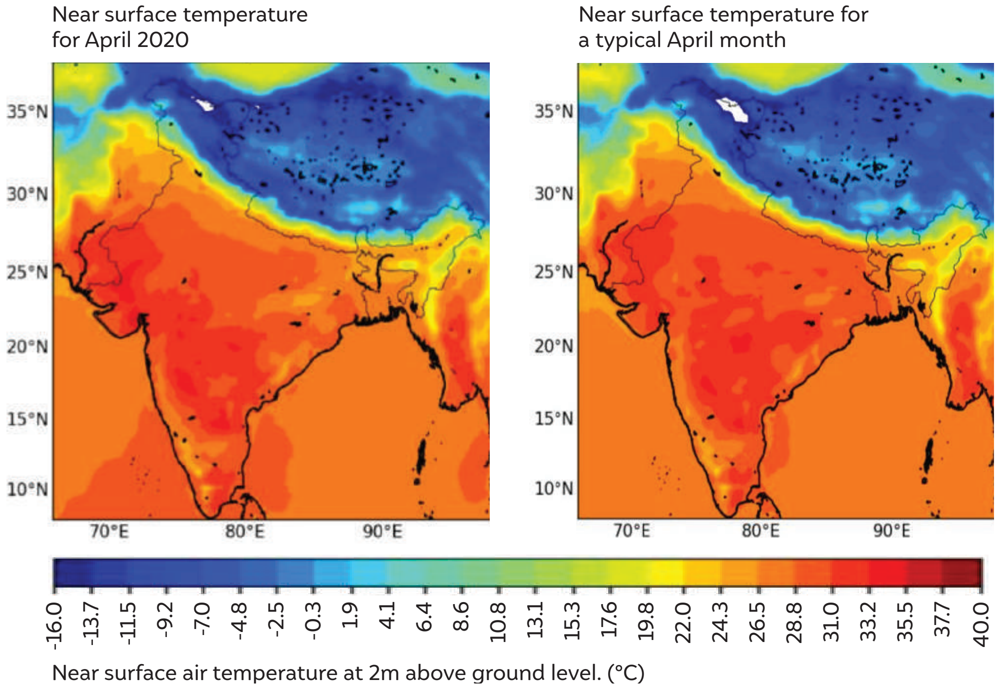


Figure A1
Near-surface temperature in April 2020 was lower than the average value

Source: Hersbach et al. 2019.

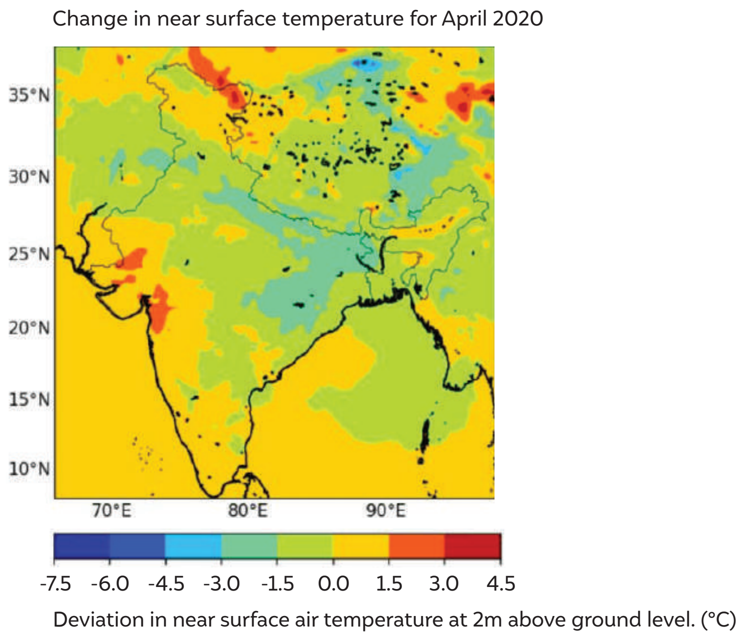


Figure A2
Deviation of near-surface temperatures in April 2020 show a cooler than average landmass

Source: Hersbach et al. 2019

Section 2: Warmer North Indian Ocean in April 2020

Sea surface temperatures are the primary drivers of monsoons in India. We see how sea surface temperatures in April 2020 were above the average value in 2020.

The spatial plots depict sea-surface temperatures for April 2020, average sea surface temperature in April from 1971-2000 and a plot that describes the difference between the two aforementioned data plots. We concluded that a significant difference in sea surface temperatures was witnessed in April 2020 where sea temperatures were much warmer than expected.

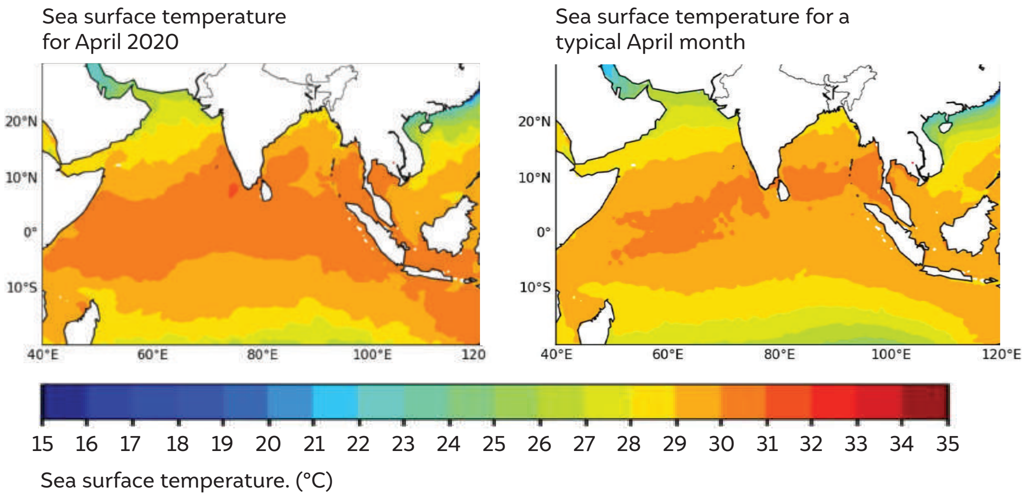


Figure A3
Sea surface temperatures in April 2020 were much warmer than the historical average temperatures

Source: Hersbach et al. 2019.

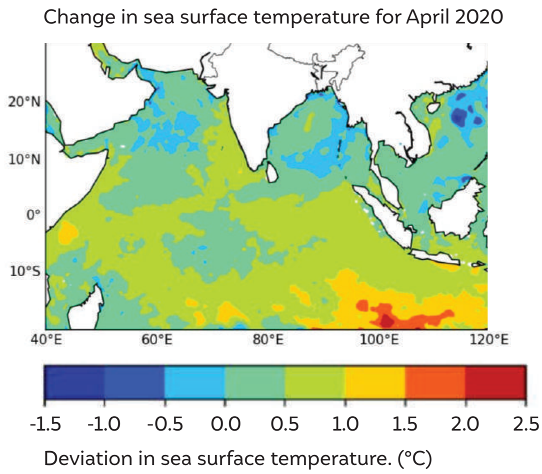


Figure A4
The deviation in sea surface temperatures of April 2020 discloses a high differential value

Source: Hersbach et al. 2019.

Section 3: Pre-monsoon season with widespread precipitation in April 2020

India saw a cooler than average pre-monsoon season due to a rise in rainfall from March-June 2020.

The spatial plots depict pan India precipitation values for April 2020, average precipitation values in April from 1971-2000 and a plot that describes the difference between the two aforementioned data plots. We concluded that rise in precipitation during April 2020 drove land temperatures to drop over Northern Indian landmass. This has further been proven in Section 1 of the annexure.

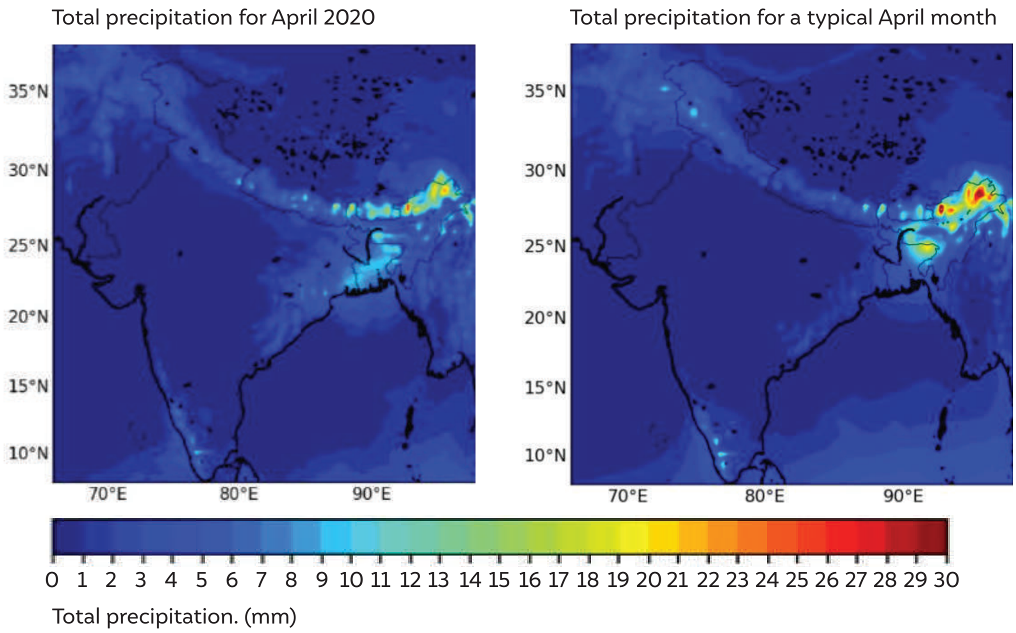


Figure A5
Precipitation in April 2020 all across India was much higher than expected

Source: Hersbach et al. 2019.

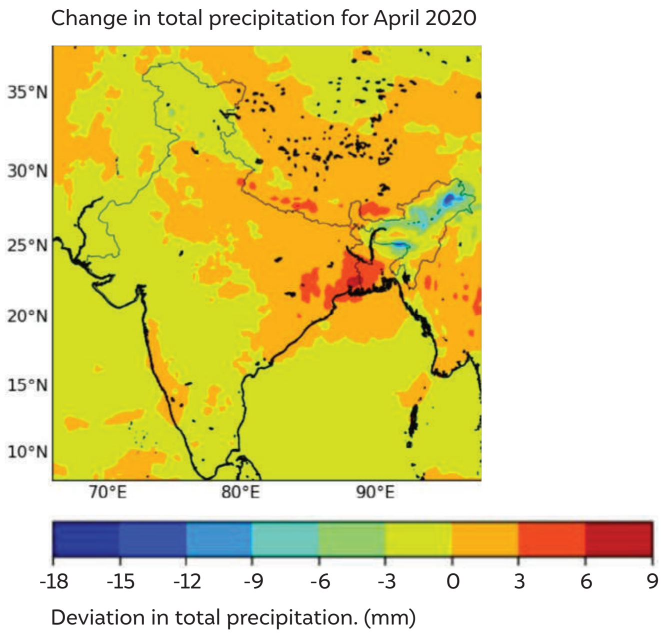


Figure A6
Differences between average precipitation values and observed values in 2020 are significant

Source: Hersbach et al. 2019.

References

Agarwal, Disha, Gagan Sidhu. 2021. "How did India's Renewable Energy Sector Perform During the Year of COVID-19 Lockdown?" *Connecting Dots - The CEEW Blog*, 7 April. Accessed May 07, 2021. https://www.ceew.in/blogs/how-did-india%E2%80%99s-renewable-energy-sector-perform-during-year-covid-19-lockdown.

Agarwal, Kabir. 2020. "Climate Change Brings the Worst Locust Attack in Decades to India: The Wire Science." *The Wire*, May 27, 2020. https://science.thewire.in/environment/locust-attack-india-jaipur-climate-change/.

CEA. 2021. "Executive Summary Month on Power Sector: January 2021." New Delhi: Central Electricity Authority. https://cea.nic.in/wpcontent/uploads/executive/2021/01/exe_summary.pdf.

CERC. 2019. "Renewable Energy Tariff Order 2019–20." New Delhi: Central Electricity Regulatory Commission. http://www.cercind.gov.in/2019/orders/1-SM-2019Suo-Motu.pdf.

Department of Environment, Government of Tamil Nadu. 2020. "Database on Energy Resources in Tamil Nadu." Chennai: Department of Environment, Government of Tamil Nadu. https://www.environment.tn.gov.in/template/ngc-reports/Database on Energy Resources in Tamil Nadu.pdf.

Dunning, C. M., A. G. Turner, and D. J. Brayshaw. 2015. "The Impact of Monsoon Intraseasonal Variability on Renewable Power Generation in India." *Environmental Research Letters* 10 (6). https://doi.org/10.1088/1748-9326/10/6/064002.

Ferro, C. A. T. 2013. "Fair Scores for Ensemble Forecasts." *Quarterly Journal of the Royal Meteorological Society* 140 (683): 1917–1923. https://doi.org/10.1002/qj.2270.

Gao, Meng, Yihui Ding, Shaojie Song, Xiao Lu, Xinyu Chen, and Michael B. McElroy. 2018. "Secular Decrease of Wind Power Potential in India Associated with Warming in the Indian Ocean." *Science Advances* 4 (12). https://doi.org/10.1126/sciadv.aat5256.

GWEC. 2020. "India Wind Outlook Towards 2022: Looking Beyond Headwinds." Brussels: Global Wind Energy Council and MEC Intelligence. https://gwec.net/india-wind-outlook-towards-2022-looking-beyond-headwinds/.

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J.,

Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N.2019. ERA5 monthly averaged data on single levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on 30-Nov-2020).

Jaswal, Ashok. 2013. "Climatology and Trends in Near-surface Wind Speed over India During 1961–2008." *Mausam* 64 (3): 417–436.

Krishnan, R., J. Sanjay, Chellappan Gnanaseelan, Milind Mujumdar, Ashwini Kulkarni, and Supriyo Chakraborty. 2020. *Assessment of Climate Change over the Indian Region: A Report of the Ministry of Earth Sciences (MOES), Government of India*. Singapore: Springer. https://doi.org/10.1007/978-981-15-4327-2.

Kumar, P. Vinay, C. V. Naidu, and K. Prasanna. 2020. "Recent Unprecedented Weakening of Indian Summer Monsoon in Warming Environment." *Theoretical and Applied Climatology* 140 (1–2): 467–486. https://doi.org/10.1007/s00704-019-03087-1.

Matuszko, Dorota. 2012. "Influence of the Extent and Genera of Cloud Cover on Solar Radiation Intensity." *International Journal of Climatology* 32 (15): 2403–2414. https://doi.org/10.1002/joc.2432.

Mohanty, Abinash. 2020. "Preparing India for Extreme Climate Events: Mapping Hotspots and Response Mechanisms." New Delhi: Council on Energy, Environment and Water.

MNRE. 2021. "Wind Energy Overview." Accessed February 18, 2021. https://mnre.gov.in/wind/current-status/.

Ogwang, Bob Alex, Victor Ongoma, Li Xing, and Faustin Katchele Ogou. 2015. "Influence of Mascarene High and Indian Ocean Dipole on East African Extreme Weather Events." *Geographica Pannonica* 19 (2): 64–72. https://doi.org/10.5937/geopan15020640.

P. J., Vidya, M. Ravichandran, M. P. Subeesh, Sourav Chatterjee, and M. Nuncio. 2020. "Global Warming Hiatus Contributed Weakening of the Mascarene High in the Southern Indian Ocean." *Scientific Reports* 10 (1): 1–9. https://doi.org/10.1038/s41598-020-59964-7.

POSOCO 2019a. "Operational Performance Report for the Month of January 2019." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly-report-january-2019/?wpdmdl=22031.

POSOCO 2019b. "Operational Performance Report for the Month of February 2019." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_february_2019/?wpdmdl=22125.

POSOCO 2019c. "Operational Performance Report for the Month of March 2019." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_march_2019/?wpdmdl=22786.

POSOCO 2019d. "Operational Performance Report for the Month of April 2019." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_april_2019/?wpdmdl=23145.

POSOCO 2019e. "Operational Performance Report for the Month of May 2019." New Delhi: Power System Operation Corporation Limited.

https://posoco.in/download/monthly_report_may_2019/?wpdmdl=23659

POSOCO 2019f. "Operational Performance Report for the Month of June 2019." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_jun_2019/?wpdmdl=24072.

POSOCO 2019g. "Operational Performance Report for the Month of July 2019." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_jul_2019/?wpdmdl=24464.

POSOCO 2019h. "Operational Performance Report for the Month of August 2019." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_aug_2019/?wpdmdl=24853.

POSOCO 2019i. "Operational Performance Report for the Month of September 2019." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_sep_2019/?wpdmdl=25303.

POSOCO 2019j. "Operational Performance Report for the Month of October 2019." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_oct_2019/?wpdmdl=25649.

POSOCO 2019k. "Operational Performance Report for the Month of November 2019." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_nov_2019/?wpdmdl=26240.

POSOCO 2019l. "Operational Performance Report for the Month of December 2019." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_dec_2019/?wpdmdl=26770.

POSOCO 2020m. "Operational Performance Report for the Month of January 2020." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_jan_2020/?wpdmdl=27331.

POSOCO 2020n. "Operational Performance Report for the Month of February 2020." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_feb_2020/?wpdmdl=27871.

POSOCO 2020o. "Operational Performance Report for the Month of March 2020." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_mar_2020/?wpdmdl=28541.

POSOCO 2020p. "Operational Performance Report for the Month of April 2020." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_apr_2020/?wpdmdl=29155.

POSOCO 2020q. "Operational Performance Report for the Month of May 2020." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_may_2020/?wpdmdl=29792.

POSOCO 2020r. "Operational Performance Report for the Month of June 2020." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_jun_2020/?wpdmdl=30332.

POSOCO 2020s. "Operational Performance Report for the Month of July 2020." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_july_2020/?wpdmdl=31265.

POSOCO 2020t. "Operational Performance Report for the Month of August 2020." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_august_2020/?wpdmdl=31937.

POSOCO 2020u. "Operational Performance Report for the Month of September 2020." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_september_2020/?wpdmdl=32593.

POSOCO 2020v. "Operational Performance Report for the Month of October 2020." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_october_2020/?wpdmdl=33302.

POSOCO 2020w. "Operational Performance Report for the Month of November 2020." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_november_2020/?wpdmdl=33840.

POSOCO 2020x. "Operational Performance Report for the Month of December 2020." New Delhi: Power System Operation Corporation Limited. https://posoco.in/download/monthly_report_december_2020/?wpdmdl=34420.

Pörtner, Hans-Otto, Debra C. Roberts, Valérie Masson-Delmotte, Panmao Zhai, Melinda Tignor, Elvira Poloczanska, Katja Mintenbeck, Andrés Alegría, Maike Nicolai, Andrew Okern, et al. (eds). 2019. "The Ocean and Cryosphere in a Changing Climate: A Special Report of the Intergovernmental Panel on Climate Change." Geneva: IPCC.

Prasad, Nithin. 2020. "Gujarat Commission Approves Tariff of ₹2.80/kWh for over 202 MW of Wind Projects." *Mercom India*, January 14, 2020. https://mercomindia.com/gujarat-commission-approves-tariff-wind-projects/.

Ratnam, J. Venkata, Filippo Giorgi, Akshara Kaginalkar, and Stefano Cozzini. 2009. "Simulation of the Indian Monsoon Using the RegCM3–ROMS Regional Coupled Model." *Climate Dynamics* 33 (1): 119–139. https://doi.org/10.1007/s00382-008-0433-3.

Roxy, Mathew Koll, Kapoor Ritika, Pascal Terray, Raghu Murtugudde, Karumuri Ashok, and B. N. Goswami. 2015. "Drying of Indian Subcontinent by Rapid Indian Ocean Warming and a Weakening Land–Sea Thermal Gradient." *Nature Communications* 6 (1): 1–10. https://doi.org/10.1038/ncomms8423.

Saha, K. R., D. A. Mooley, and S. Saha. 1979. "The Indian Monsoon and its Economic Impact." *GeoJournal* 3 (2): 171–78. https://doi.org/10.1007/BF00257706.

Sangomla, Akshit. 2020. "It's Mid-May and it Isn't as Hot as it Normally is: Here's Why." *DownToEarth*, May 13, 2020. https://www.downtoearth.org.in/news/environment/it-s-mid-may-and-it-isn-t-as-hot-as-it-normally-is-here-s-why-71083.

Soret, A., V. Torralba, N. Cortesi, I. Christel, Ll Palma, A. Manrique-Suñén, Ll Lledó, N. González-Reviriego, and F. J. Doblas-Reyes. 2019. "Sub-Seasonal to Seasonal Climate Predictions for Wind Energy Forecasting." *Journal of Physics: Conference Series* 1222. https://doi.org/10.1088/1742-6596/1222/1/012009.

Sreeram R. 2019. "What is Behind the Curious Decline in Generation of Renewable Energy." *Livemint*, October 1, 2019. https://www.livemint.com/market/mark-to-market/what-is-behind-the-curious-decline-in-generation-of-renewable-energy-11569864546939.html.

Declining wind speeds can complicate wind energy integration in the future. Development in every segment of the wind energy value chain must account for unforeseen climate risks.

Image: ReNew Power

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