Assessing the Value of Offshore Wind for India's Power System in 2030

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Foreword

Dinesh Dayanand Jagdale
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India has continuously showcased its leadership in accelerating the pace of the global energy transition in the pursuit of a net-zero future. It is racing towards 500 GW of clean power capacity by 2030, and counting on wind energy as one of its two most dependable players. From just about 9 GW in 2008 to more than 44 GW today, India ranks fourth globally in total wind installations. By 2030, the target is to reach 100 GW of onshore wind and introduce offshore wind in the clean energy mix. Offshore wind is fast emerging as a mainstream technology that can contribute to trebling global renewable energy capacity by 2030, as agreed under the recently concluded Leaders' Summit of India's G20 presidency.

With strong intent from all key institutions and stakeholders, India has progressed with its plans for kick-starting the deployment of offshore wind. The Ministry of New and Renewable Energy has benefitted from multitude of deep discussions that resulted in introduction of an auction trajectory of 37 GW capacity by 2030, development of business models, tender documents, and strategies to strengthen ports, evacuation infrastructure and implementation capacities, as well as advancements in shaping of financial support mechanisms. With these developments, the journey of offshore wind has now started unfolding.

I am pleased to introduce this study conducted by the Council on Energy, Environment and Water (CEEW) that demonstrates the case for building a supportive policy and regulatory ecosystem for offshore wind technology. It does so by assessing the value that offshore wind holds for power system operations considering Gujarat as a case study. It finds that adding offshore wind in the energy basket will aid system adequacy and reliability and lower the requirement of operational reserves, amongst other benefits pertaining to system balancing needs. As a result, offshore wind generation can help meet the rising peak demand and save on future power procurement costs, which is desirable to achieve energy security and affordability for consumers.

I congratulate CEEW for this first-of-its kind assessment that will inform efforts to design a robust offshore wind strategy for the country, and seek participation of all stakeholders in maximising the technical, social, economic and environmental benefits of this promising technology.

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About the study

WHY

First-of-its-kind techno-commercial case study of offshore wind in India to identify the system operation benefits it may offer when pooled with onshore wind and solar photovoltaic (PV)

FOR WHOM

The report provides insights to the Ministry of New and Renewable Energy (MNRE), Ministry of Power (MoP), system operators, state discoms, renewable energy developers, investors, and sector experts

This study covers the following aspects

1. Implications for system reliability and adequacy, reserves, ramping capability, and load following capability
2. Potential savings in terms of avoided cost of procurement from power exchanges
3. Impact on likely renewable energy (RE) curtailment in the system

Key highlights (1/2)

We compared two RE pools, Pool A and Pool B, to assess the impact of offshore wind on system operations in Gujarat and India

- **Pool A:** onshore wind and solar PV constitute a 31% share (by energy) in 2030*
- **Pool B:** 4% offshore wind, 8% onshore wind, and 19% solar PV, keeping the share of variable renewable energy (VRE) at 31% in 2030

We find that offshore wind has the following benefits

Higher adequacy and reliability

- **Gujarat:** Improved adequacy and reliability during the peak load hours of the monsoon months; but it has no significant impact in the non-monsoon months
- **India:** Improved adequacy and reliability during the peak load hours in the monsoon as well as non-monsoon months (Pool B)

Lower operational reserves

- Reduced uncertainty, thereby reducing operational reserve requirements
- Uncertainty reduced more during ‘non-solar generation hours’ than solar generation hours

No significant impact on ramping capabilities

- No significant impact on the variability of the net load; existing ramping capabilities may be sufficient to meet system requirements

*National estimates for 2029–30 indicate a 31% VRE generation share from wind and solar PV as per Central Electricity Authority, CEA (2020). Refer to slides (13 to 15) for the rationale behind these parameters.

Key highlights (2/2)

Negligible impact on balancing reserves

- No significant impact on the load following capabilities of the system for Gujarat and India
- No additional balancing reserves may be needed on account of offshore wind in the RE mix

Avoided power procurement cost

- Savings in terms of avoided costs of power procured from the power exchange. Savings for both Gujarat and India
- Savings are likely to be higher in the monsoon months when offshore generation is at its peak

Reduced possibility of RE curtailment

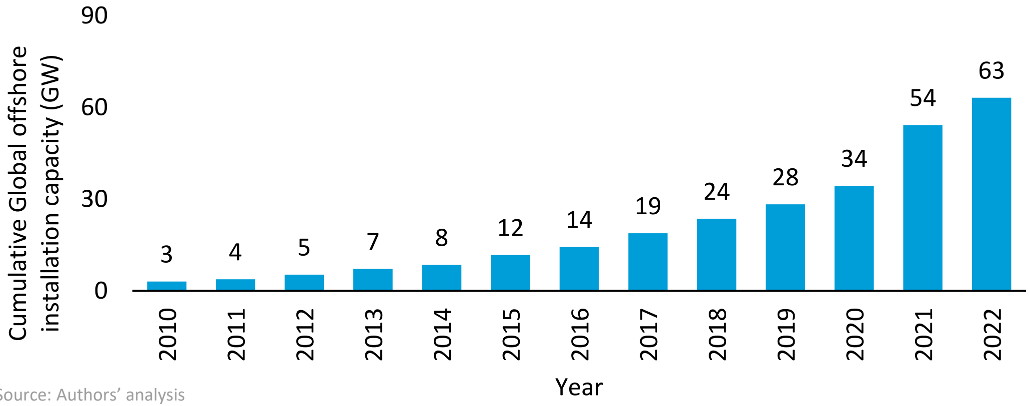
- Reduced over-generation in the system indicates lower chances of RE curtailment
- Reduction in RE curtailment greater at the all-India level than in Gujarat

Overview of the global and Indian offshore wind market

Global offshore wind capacity has increased 21 times since 2010

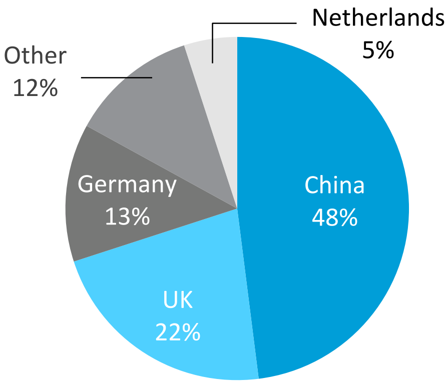
- 63 GW (gigawatts) installed in 2022. Projected to reach 380 GW by 2030[1,3]
- Top 3 deployers: China 48%, United Kingdom 22%, Germany 13%[1]
- Emerging markets offer growth prospects[2]
  - Brazil, India, Morocco, the Philippines, South Africa, Sri Lanka, Turkey, and Vietnam have a technical potential of 3.1 TW
  - New markets include - Japan, South Korea, and the United States

Figure 1 The cumulative offshore installation capacity increased by 21x from 2010 to 2022



Source: Authors' analysis

Figure 2 China, Germany, UK and Netherlands hold 88% share of installed offshore wind capacity



Source: Authors' analysis

Source: 1 IRENA 2023; 2 Berkeley Lab 2021; 3 GWEC 2023

Tariffs for offshore wind have declined steeply over the last decade

The global weighted average levelised cost of electricity (LCOE) declined by ~60% over 2010–2021, reaching $75/MWh in 2021 [2,4]

- Installations in China, Europe, and the UK contributed to this decline
- Denmark had the lowest weighted average LCOE for projects commissioned in 2021, at $41/MWh, followed by the UK at $54/MWh

Technological advancements, deepening of developer experience, greater product standardisation, the establishment of regional manufacturing and service hubs, and the benefits of economies of scale are important growth drivers.

Additionally, policy support for manufacturing and deployment have contributed to the sector's growth[2]

The global weighted average capacity factor increased from 38% in 2010 to 45% in 2017*.

This is mainly due to technological improvements (larger turbines, longer blades, higher hub heights, etc.) and the increased availability of better resources as wind farms expanded to deep shore sites*.

Source: 2 Berkeley Lab 2021; 3 GWEC 2023; 4 IRENA 2022

* The capacity Utilisation factor (CUF) dropped to 39% in 2021. The decrease in the global weighted average CUF is due to small turbines China deployed in their near-shore developments along coastal zones[4].

India aims to achieve 30 GW of offshore capacity by 2030

2013
The FOWIND (Facilitating Offshore Wind Energy in India) Project (2013–18) identified potential offshore zones through techno-commercial analysis and preliminary resource assessments for Gujarat and Tamil Nadu[5]

2015
India's offshore wind policy released, with a target of installing 5 GW by 2021 and 30 GW by 2030[6]

2016
The FOWPI (First Offshore Wind Project of India) Project (2016–18) enabled pre-financial-investment decisions and capacity building[7]

2018
Expression of interest for developing 1 GW in Gujarat. No tender was issued due to a lack of interest because of high capital expenditure (capex) and the absence of government support[8]

2018
Light Detection and Ranging (LiDAR) instrument installed for resource measurement at the Gulf of Khambhat, Gujarat coast[9]

2020
Bilateral agreement signed with Denmark – green strategic partnership for developing offshore capabilities[10]

2022
Strategy paper for establishing projects as per an auction trajectory proposed under different business models[11]

2022
Draft tender to lease sea-bed blocks for conducting surveys and the subsequent development of 4 GW of offshore wind projects across the Tamil Nadu coast[12]

2023
MNRE published the updated strategy paper and a tender for allocating seabed to develop 7 GW of open-access based or captive offshore projects off the Tamil Nadu coast

Source: 5 FOWIND 2015; 6 MNRE 2015; 7 FOWPI 2016; 8 NIWE 2018a; 9 Dash 2019; 10 MEA 2020; 11 MNRE 2022a; 12 MNRE 2022b

Challenges in adopting offshore wind in India

High capital costs and resultant LCOE[4,13,14,15]

No existing domestic supply chains[14]

Non-availability / inaccessibility of data[15]

Complexities in securing approvals and clearances[14,15]

Source: 4 IRENA 2022; 13 DEA and COWI 2022; 14 Mohan, Riya, Sandhya Sundararagavan, and Ashish Nigam 2015; 15 Gulia, Jyoti, and Shilpi Jain 2019

System operation parameters

Purpose of the analysis

Investigate the case for promoting offshore wind technology from the perspective of system operations

Determine the implications of adding offshore wind to the RE mix (onshore wind + solar PV) for the following aspects of system operations in Gujarat: (a) system adequacy and reliability; (b) operational reserves; (c) ramping capabilities; (d) balancing requirements

Capacity value

- Determines system adequacy and reliability in critical load hours
- Calculated as a weighted average capacity factor in peak load hours

Uncertainty

- Determines the requirement of operational reserves in the system
- Calculated as statistical variance in the generation profile

Variability

- Determines the ramping requirement of the system
- Calculated as ramps in the net load profile

Load following capability

- Determines system balancing requirements
- Calculated as the correlation coefficient between generation and load

Description of the parameters (1/2)

Capacity value

- It is a measure of the contribution that the RE generator makes to overall system adequacy and reliability by ensuring generation availability [16,17]
- The high capacity value of a generator during critical load hours (or high-risk periods) indicates a high effective load carrying capacity (ELCC) and low loss of load expectation (LOLE) [16,17]
- Capacity values are calculated as the sum of the weighted average capacity factor for the critical hours (Annexure A) [16]

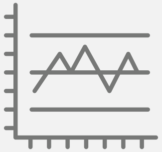
Uncertainty

- It is a measure of the randomness associated with the RE generation pattern owing to inaccurate forecasting or resource predictability errors at a particular time. This results in differences between scheduled and actual generation
- Statistical variance has been calculated to indicate the level of uncertainty associated with generation [18,19] (since forecasting of RE resource profiles is beyond the scope of this study)
- High variance in generation indicates a higher probability of forecasting errors, hence, higher uncertainty as well
- Operational reserves handle the uncertainty introduced by renewables in the system. Based on the level of RE penetration in the system, the requirement of operational reserves varies [19]

Source: 16 ICF International and Shakti Sustainable Energy Foundation 2014; 17 Milligan, Michael, and Kevin Porter 2005; 18 Stoutenburg, Eric D., Nick Jenkins, and Mark Z. Jacobson 2013; 19 Jain, Pramod, and Priyantha Wijayatunga 2016

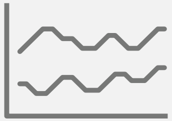
Description of the parameters (2/2)

Variability



- It is a measure of variation of net load (i.e., actual load – RE generation) resulting from changes in RE generation over a specified duration due to varying solar and wind profiles over the same duration. Hour-to-hour, day-to-day, and month-to-month changes in solar radiation and wind speed cause variability in energy production and hence in the net load[19]
- It has been calculated as ramps in the net load profile over the one-hour duration (MW/hr), i.e., rate of change in the net load from one hour to the next[18, 20].
- The ramping capabilities of existing generators handle the variability introduced by renewables in the system. Based on the level of RE penetration in the system, the requirement for ramping capabilities vary, which also affects the spinning reserves in the system[18, 20].

Load-following capability



- It is a measure of the ability of the RE generator to follow variations in load profile. Small changes in RE generation output can increase or decrease the balancing requirements of the system at every instant of operation[21]. It provides insights into the ramping requirements of the system (like variability) at a more granular level
- Also, it is useful in estimating the chances of RE generation curtailment in periods of low demand when the technical limits of other generating sources are exhausted
- It has been calculated as the statistical correlation coefficient between generation and load profiles[21]
- In general, there is no strong correlation between RE generation and load for the entire year; hence, most of the long-term analyses do not consider it important[21]

Source: 19 Jain, Pramod, and Priyantha Wijayatunga 2016; 18 Stoutenburg, Eric D., Nick Jenkins, and Mark Z. Jacobson 2013; 20 Ela, Erik, and Jason Kemper 2009; 21 Krich, A., and Michael Milligan 2005

Data requirements and approach

Offshore wind resource data for Gujarat (LiDAR)

Measured offshore wind resource data at 140 m at the Gulf of Khambhat off the Gujarat coast (Dec 2017 – Nov 2018)

Site coordinates (decimal degrees): 20.78, 71.67 in Zone B,[5] approximately 23 km off the Gujarat coast in the south-east direction [22]

Wind speed, direction, temperature, and pressure data at 10-minute granularity provided by MNRE and National Institute of Wind Energy (NIWE)

Turbine power curve

Publicly available turbine power curve in the NREL-SAM (National Renewable Energy Laboratory - System Advisor Model) tool for 5 MW offshore wind turbine

Onshore wind and Solar PV generation profiles

Real-time generation profiles for the inter-state transmission system (ISTS) connected onshore wind plant in Gujarat from Western Regional Load Dispatch Centre (WRLDC). Onshore wind plant capacity – 250 MW (Aug 2020 – Jul 2021)

Solar PV resource profile in Kutch, Gujarat (NREL National Solar Radiation Database) for a typical meteorological year (TMY#) [23]. Generation profile obtained using the NREL-SAM model for a mono-crystalline Si solar panel. Solar PV plant capacity – 38 MW_{AC}

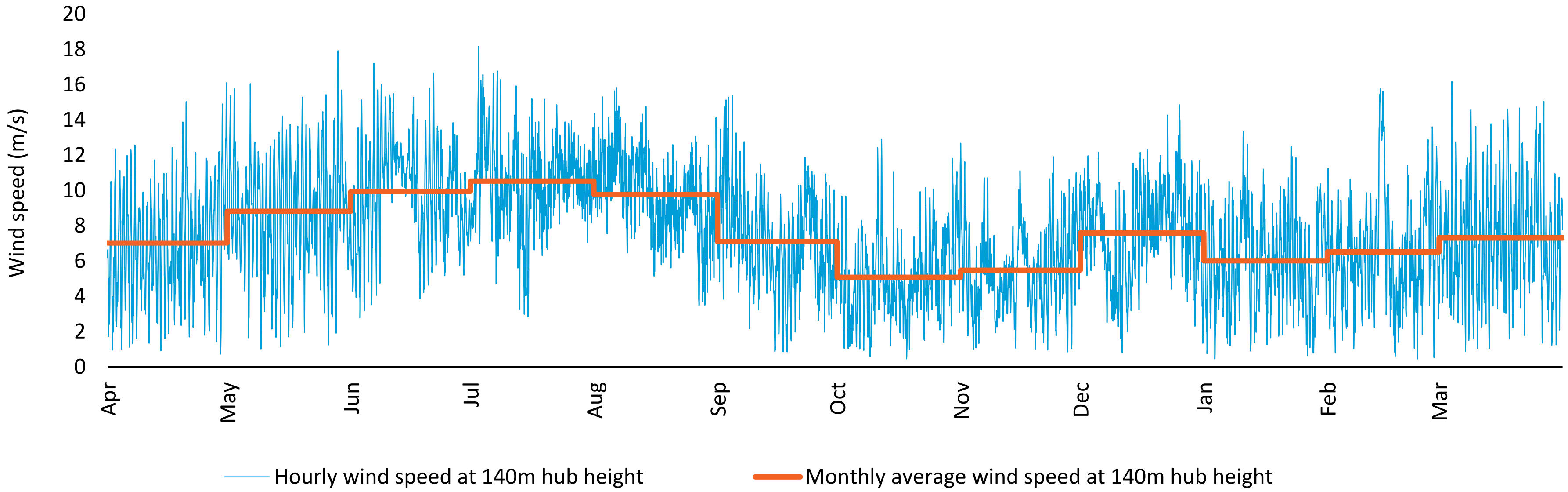
Load profile

The hourly load profiles of India and Gujarat for 2030 extracted from publicly available data (Energy Transitions Commission-India)[24]

Source: Measured wind resource data received from NIWE and MNRE; 5 FOWIND 2015; 22 NIWE 2018b; 23 NREL, n.d.; 24 TERI 2018
Note: # TMY contains one year of hourly data best representing median weather conditions over a multi-year period.

May to August show high average wind speeds

Figure 3 High offshore wind speeds were observed during May to August*



Source: Authors' analysis

Average wind speed at the location: 7.61 m/s

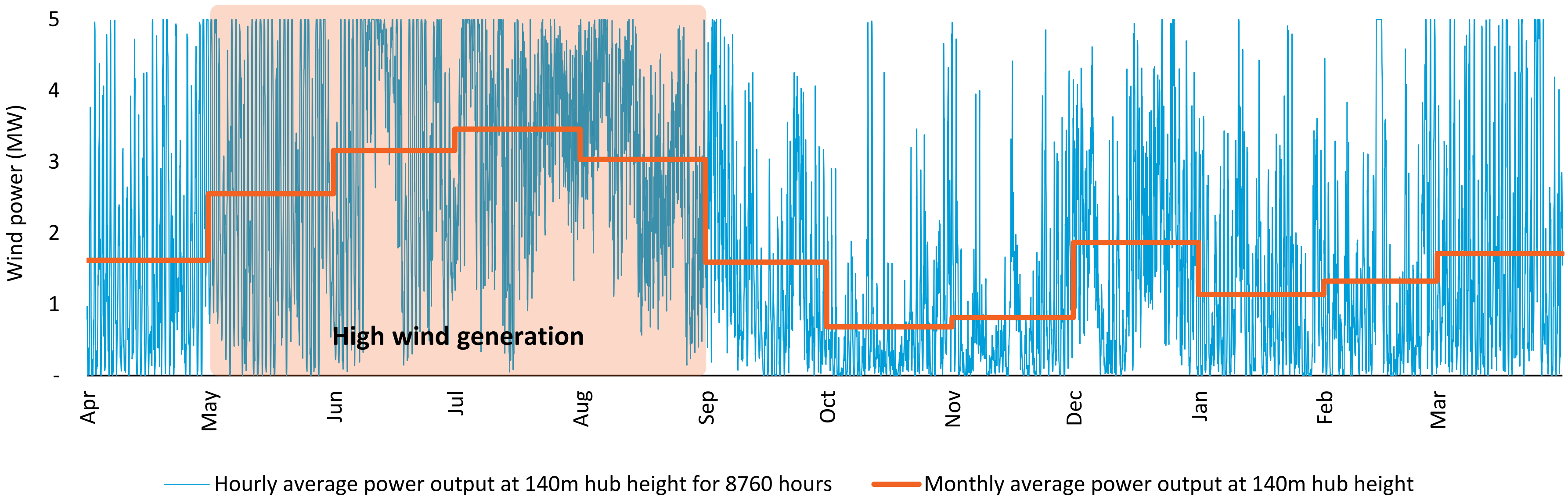
Peak wind speed at the location: 20.76 m/s

Source: Authors' analyses based on LiDAR data received from NIWE and MNRE

*Actual data is available at 10-minute time intervals. Hourly offshore wind speed data and monthly average wind speed data at 140 m for Dec 2017–Nov 2018 rearranged in the financial year format (i.e. April to March).

Over 50% of the total annual generation is concentrated across four months

Figure 4 High offshore wind generation is expected between May and August



Source: Authors' analysis

Note: A single turbine with a rated capacity of 5 MW is used for obtaining the generation profile. The power curve is shown in Annexure B. Source: Authors' analysis based on the LiDAR data received from NIWE and MNRE

Impact of offshore wind on system operations

Pool A and Pool B have a wind share of 12% in the overall generation mix in 2030

The share of solar PV and wind in the electricity generation mix is expected to be 19% and 12% in 2030[25]

Based on India's target of establishing 30 GW of offshore wind by 2030, we developed two distinct hourly hybrid generation profiles

Pool A
Onshore wind + solar PV

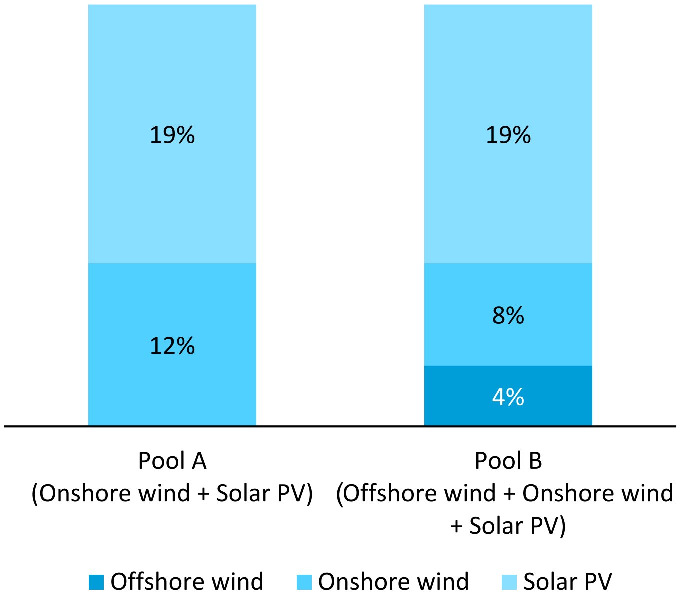
Pool B
Offshore wind + onshore wind + solar PV

Derived capacity utilisation factors (CUFs) for the three technologies

Offshore wind	Onshore wind	Solar PV
38%	33%	27%

In both pools, the share of wind energy remains at 12%. The desired RE generation levels are obtained by linear scaling the hourly MW output of the chosen RE plants.*

Figure 5 Offshore wind, onshore wind and solar generation share in 2030 for Pool A and Pool B



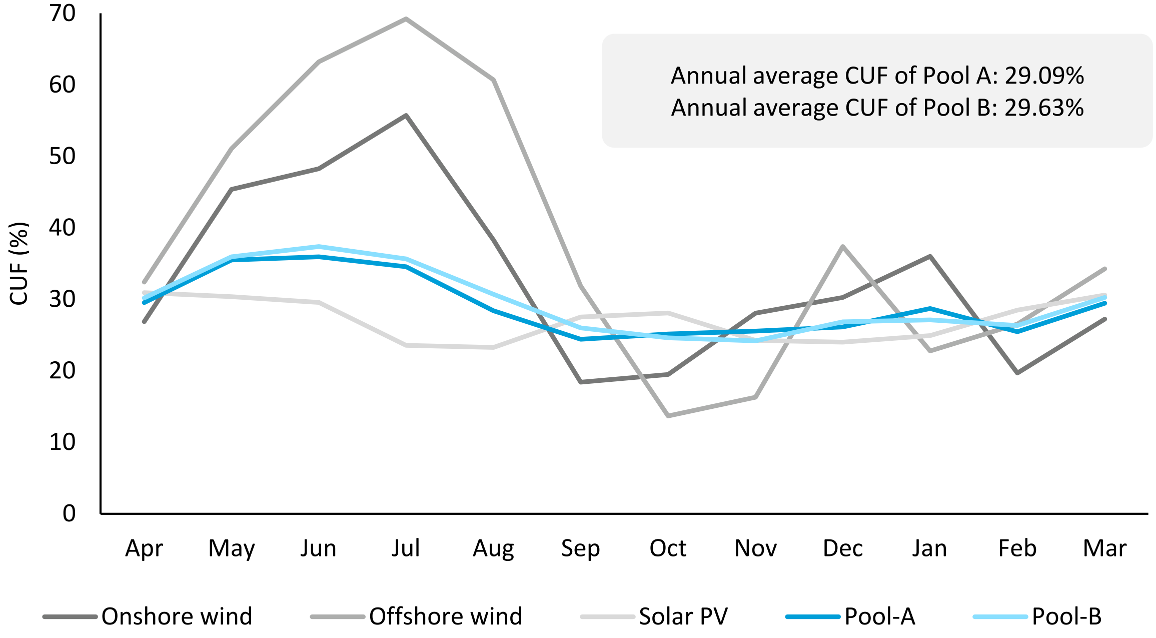
Source: Authors' analysis

Source: 25 CEA 2020

*Linear scaling adds a margin of variability that may not exist in reality for a plant spread across a large area. However, the same may be somewhat negated due to hourly averages under consideration.

Pool B has a slightly higher CUF than Pool A in the monsoon months

Figure 6 Higher CUF of offshore wind results in marginal improvement of CUF in Pool B, in 2030



Source: Authors' analysis

- The average CUF of Pool A and Pool B in the monsoon months is 31% and 32%. For non-monsoon months, the CUF of both pools is 28%
- Offshore wind CUF is beyond 50% in May–August. Onshore wind CUF exceeds 40% for the same period
- Monthly CUFs for Pool A and Pool B do not differ widely due to the low share of offshore generation in Pool B
- Increasing the share of offshore wind, tapping resource-rich zones of Gujarat and Tamil Nadu, and deploying turbines suited to India's offshore resources will drive up the CUF

Assessment of parameters across geographies and timescales helps understand the impact on system operations

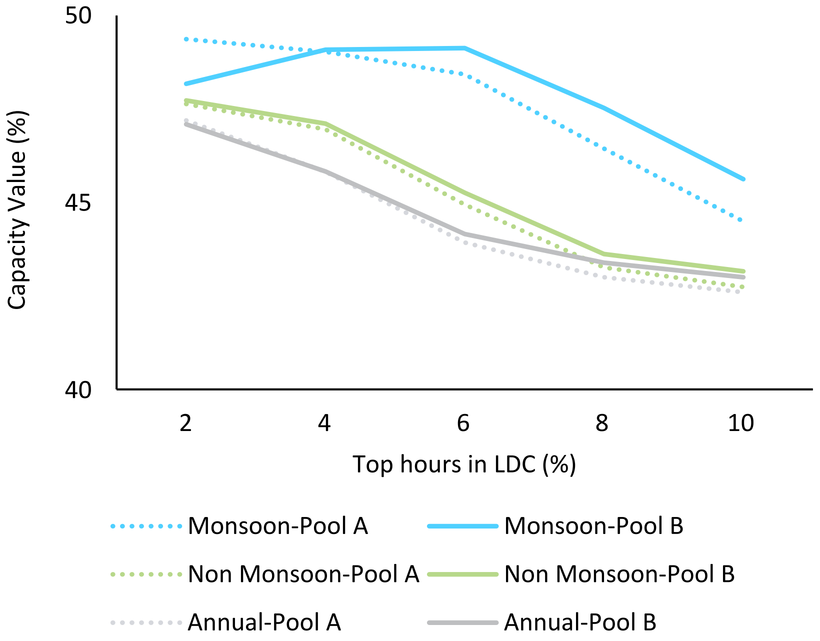
Parameters	Gujarat	All-India	Solar generation hours	Non-Solar generation hours	Monsoon months	Non-monsoon months
Capacity Value	✔	✔	✔	✔	✔	✔
Uncertainty	Not applicable*		✔	✔	✔	✔
Variability	✔	Not applicable#				
Load following capability	✔	✔	Not applicable##		✔	✔

- For Pool B, avoided cost of power procurement from the exchange is also computed
- For net load profiles in Pool A and Pool B, we also assessed the impact on RE curtailment in the system

* Uncertainty is calculated for the generation profile and is independent of demand profiles.
# Change in hourly net load at an all-India level would not qualify as a ramp due to its large magnitude. Further, the ramp requirement for Gujarat is assessed for all hours across the year.
Load following capability is derived on a daily basis, irrespective of solar and non-solar generation hours.

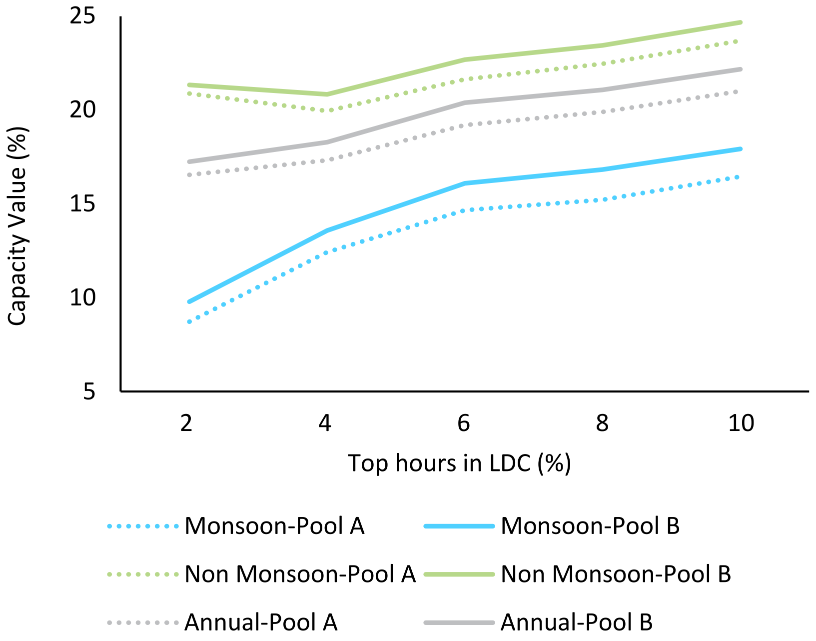
Offshore wind could improve the capacity value of the RE mix

Figure 7 Gujarat - Pool B has higher capacity value than Pool A for monsoon months, in 2030



Source: Authors' analysis

Figure 8 India - Pool B has higher capacity value than Pool A for monsoon and non-monsoon months, in 2030



Source: Authors' analysis

Load duration curve (LDC) for the monsoon and non-monsoon months and the entire year

Offshore wind can enhance system adequacy and reliability at an all-India level

Observations for Gujarat

- Capacity value is higher in the monsoon months than non-monsoon months – more than 40% for Pool A and Pool B. Offshore wind starts adding higher value beyond the top 4% of the hours in the LDC
- Beyond the top 4% hours, a nearly 1% improvement is seen in the capacity value for the monsoon months. In the non-monsoon months, improvement in capacity value is up to 0.42%
- Pool B has a higher capacity value for the monsoon months compared to Pool A because
  - Offshore wind generation has high CUF in the months of June, July, and August
  - High generation in the monsoons coincides with peak demand in Gujarat

Observations for India

- Capacity value is higher in the non-monsoon months than monsoon months and is under 25% for Pool A and Pool B
- Offshore wind improves the capacity value by 1%–1.5% across the LDC range
- Improvement in capacity value is more for the monsoon months than non-monsoon months (same reasons as Gujarat's)
- The improvement in capacity value for non-solar hours lies in the range of 1.5%–2.0%

Gujarat has a higher capacity value than India, but *the improvement in capacity value due to offshore wind is higher for India than for Gujarat*

A comparison of the high capacity value of Pool B and Pool A indicates:

- Offshore wind could add to system adequacy and reliability requirements during peak load hours
- It is likely to improve the Effective Load Carrying Capability (ELCC) and lower Loss of Load Expectation (LOLE)
- Lower chances of curtailment during peak generation season

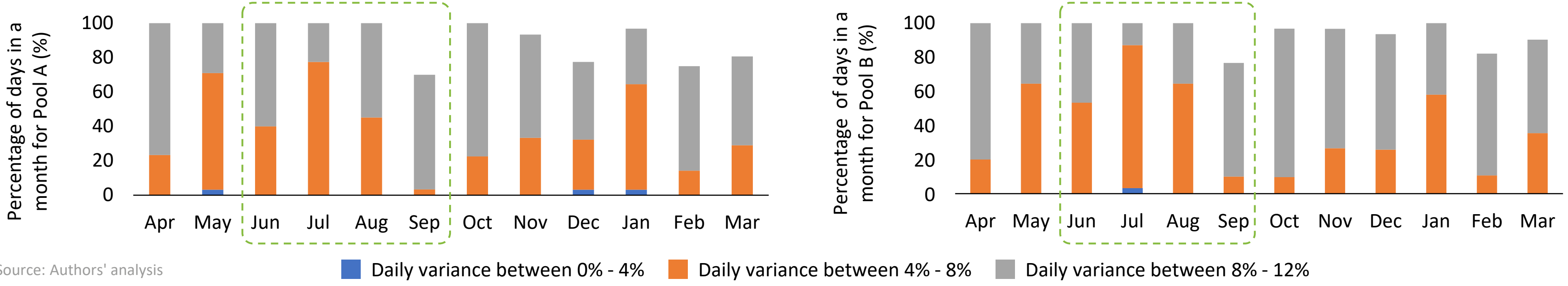
Uncertainty is computed for solar and non-solar generation hours

- We computed the variance measure of uncertainty
- To measure uncertainty, we normalised the daily generation profiles of Pool A and Pool B with respect to the daily peak generation across solar generation and non-solar generation hours
- Uncertainty for solar generation hours and non-solar generation hours was assessed separately as the distribution of the pooled generation profile in day hours is different from that in night hours*
- We then assessed uncertainty levels across days and months
- We found that most months have 100% of the days within 12% variance (daily variance is classified within these ranges: 0%–4%, 4%–8% and 8%–12%)

* During non-solar generation hours, Pool A is equivalent to only onshore wind. Pool B contains an equal share of onshore and offshore wind.

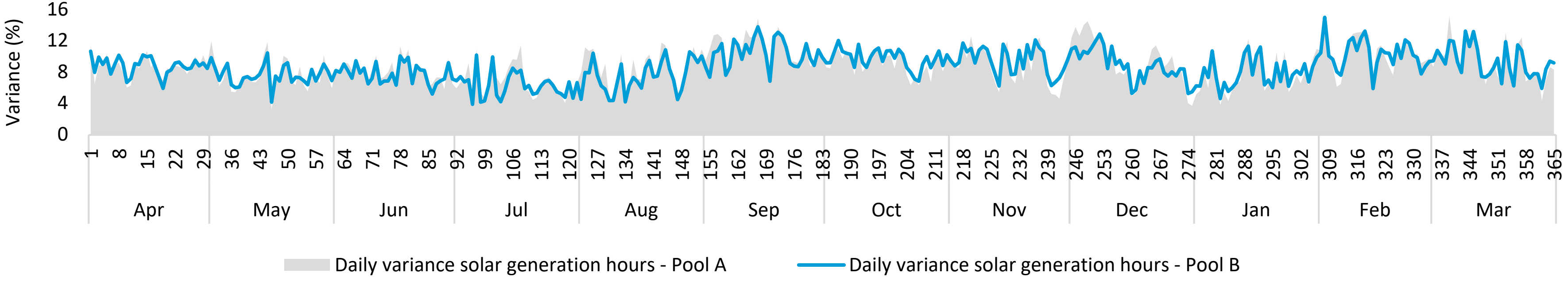
Pooling offshore wind can lower reserve requirements in solar generation hours

Figure 9 Pool B has increased number of days with lower variance for the monsoon months, compared to Pool A in solar generation hours, in 2030



Source: Authors' analysis

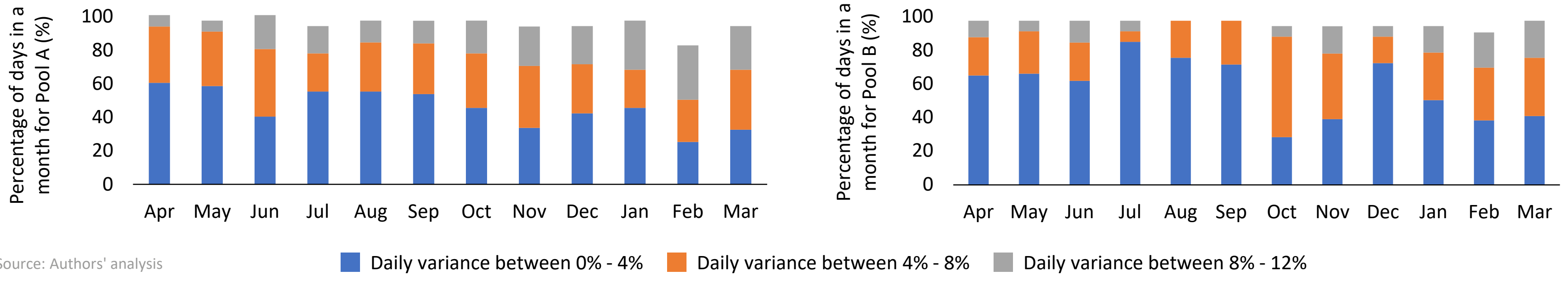
Figure 10 Majority of days in Pool A and Pool B have variance within 4% - 12% for solar generation hours, in 2030



Source: Authors' analysis

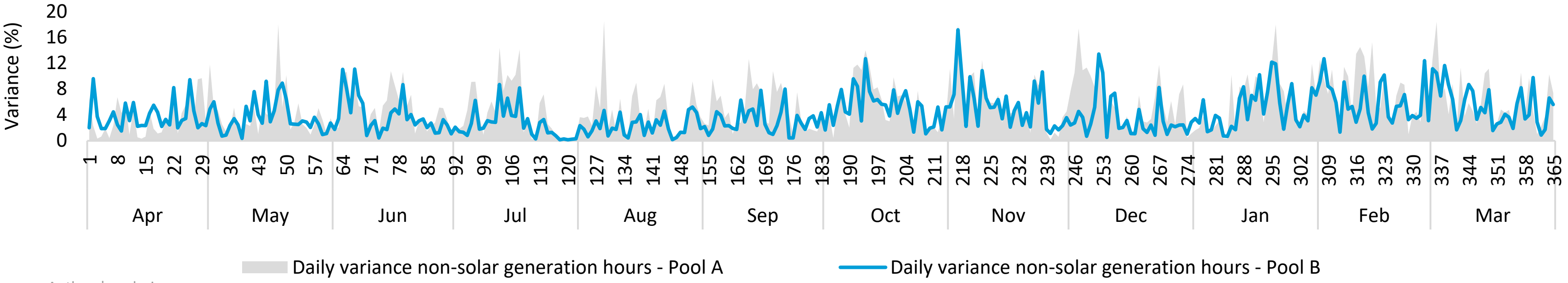
Pooling offshore wind can lower reserve requirements in non-solar generation hours

Figure 11 Pool B has increased number of days with lower variance throughout the year, compared to Pool A in non-solar generation hours, in 2030



Source: Authors' analysis

Figure 12 Majority of days in Pool A and Pool B have variance below 4% for non-solar generation hours, in 2030



Source: Authors' analysis

Pooling offshore wind can lower reserve requirements in the system

Solar generation hours

Overall variance in solar generation hours is more than in non-solar generation hours

Pool B had a higher number of days with a lower variance range (4%–8%) compared to Pool A during the monsoon period June–September. For example, in figure 9, for Pool A, 77% of the days in July had a variance between 4% to 8%. However, for Pool B, 84% of the days in July had a variance between 4% to 8%. **This means high offshore generation can reduce variance in the system**

During the non-monsoon months (low offshore generation period), Pool B had a higher variance than Pool A as the number of days in the range of 8%–12% variance increased primarily due to solar PV generation.

Non-solar generation hours

Pool B had a higher number of days with minimum variance ranging from 0%–4% throughout the year

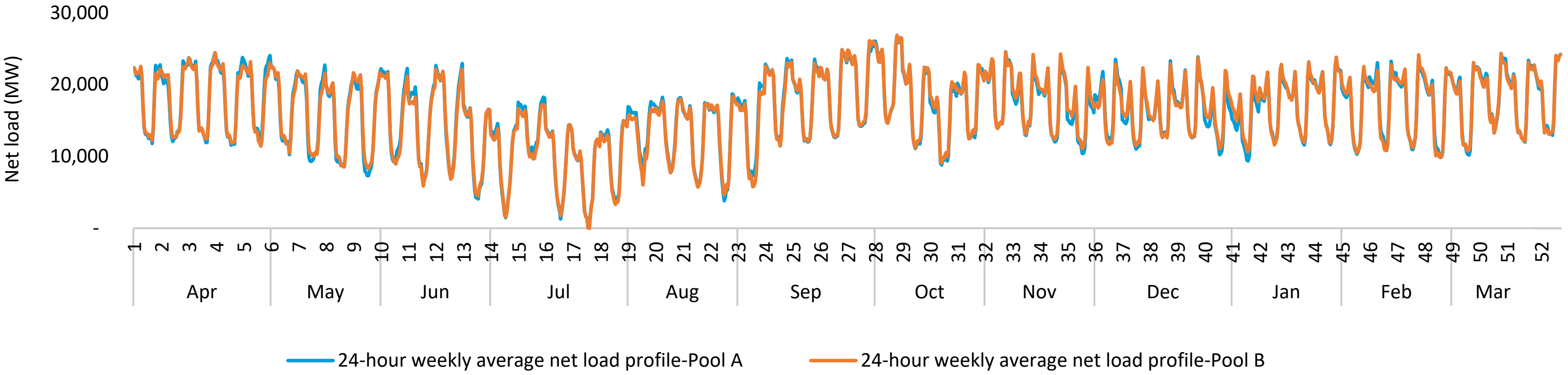
Except for October, all months have reduced uncertainty with more number of days having less than 4% variance

Adding offshore wind to the existing pool of onshore wind and solar PV is likely to lower reserve requirements to handle uncertainty in the system during solar and non-solar generation hours.

Offshore wind introduces negligible change in the net load profile of Gujarat

- To compute the variability introduced by offshore wind in the Gujarat power system, we assumed an RE penetration of ~25 GW (the capacity equivalent of 19% solar PV and 12% wind generation) in Pool A and Pool B. We consider net load profiles under both pools
- The graph shows 24-hour weekly averaged net load profiles with Pool A and Pool B in the system*
  - Net load profiles are nearly the same; negligible change in variability due to offshore wind
  - We validated the same by calculating the number of ramps using a histogram

Figure 13 Pool A and Pool B have nearly same net load profiles for Gujarat, for 2030



Source: Authors' analysis

* Graph for representation purposes only. Actual analysis was conducted on 8760 hours of data and not on 24-hour weekly average net load profiles. 24-hour weekly average means each week is represented by 24 hours by computing the average of each hour in a week.

The number of ramps in net load profiles helps measure variability

- Variability in the net load profiles of Pool A and Pool B is computed by calculating the change in the net load (MW) between two consecutive hours. MW per hour is a ramp observed by the system operator

- If the net load increases between two consecutive hours, then the ramp value is positive (up-ramp). If the net load decreases, then the ramp value is negative (down-ramp)

- The size of up-ramps and down-ramps is not constant. Therefore, the number of up-ramps and down-ramps is counted through a histogram
  - X-axis: various bins of fixed size
  - Y-axis: number of ramps in each bin
  - Bin size assumed as 1000 MW/hour, i.e., the difference between the upper limit and lower limit of the bin
  - A bin of (2000, 3000] depicts that it contains ramps greater than 2000 MW/hour and up to 3000 MW/hour

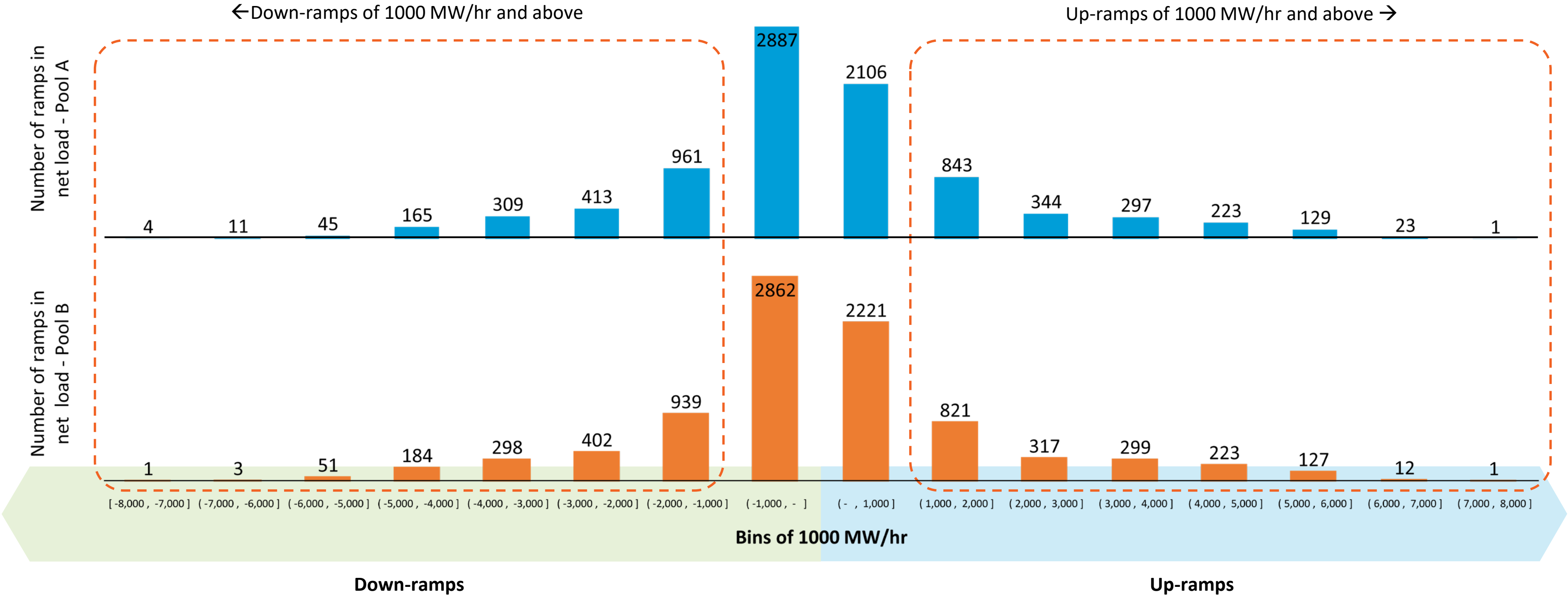
- Ramp size ≥ 250 MW per 15 min is of interest to the system operator.* Since this analysis is at the hourly level, we have taken a 1000 MW per hour ramp size as critical from a systems operation perspective

- The number of ramps in each bin for Pool A and Pool B was compared to measure the increase or decrease in the variability of the net load

*Based on inputs received from stakeholders

Offshore wind reduces the number of ramps in the system

Figure 14 Number of ramps in Pool B is slightly lower than number of ramps in Pool A



Source: Authors' analysis

Existing ramping capabilities may handle the variability in the system

On assessment of the ramps of size 1000 MW/hour and above, we find that

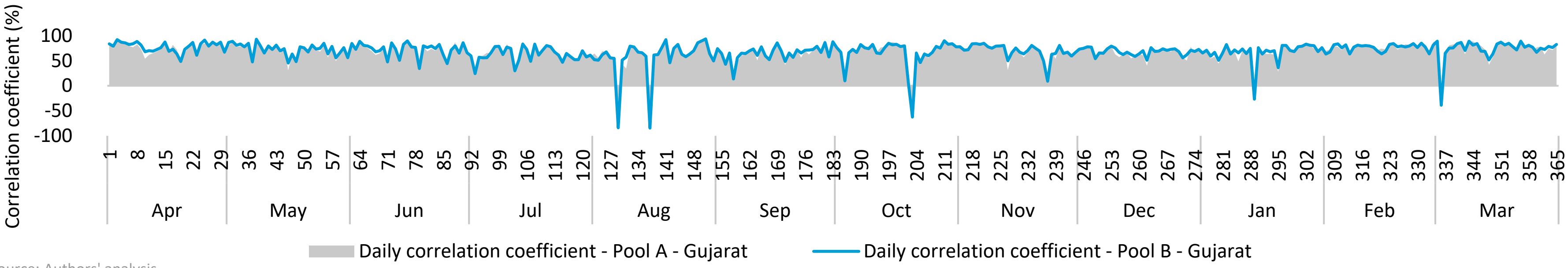
The number of up-ramps in Pool B either decreased or remained almost the same compared to Pool A in all bins

The number of down-ramps in Pool B either decreased or remained almost the same compared to Pool A in most bins except for bins (–6000,–5000] and (–5000, –4000]

This indicates that introducing offshore wind generation does not impact the variability of the system, and the existing ramping capabilities of the system may be sufficient to handle it.

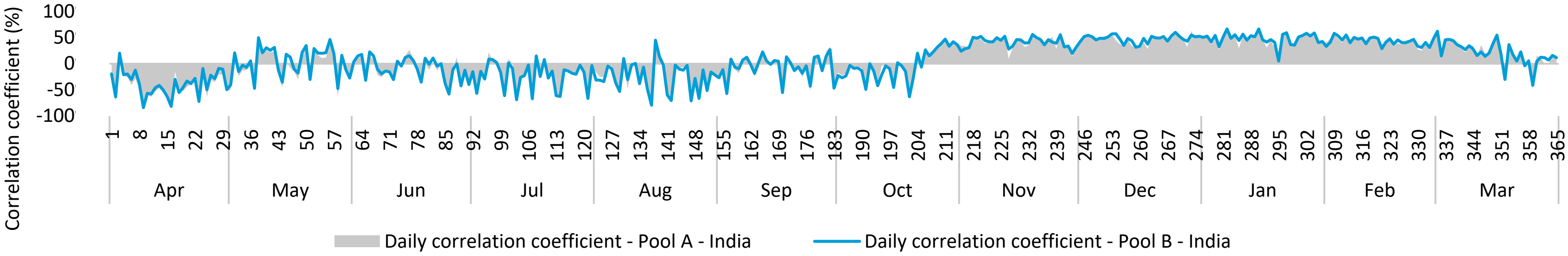
Gujarat demand is better correlated with generation than all-India demand

Figure 15 Gujarat demand profile is well correlated with Pool A and Pool B generation profiles, for 2030



Source: Authors' analysis

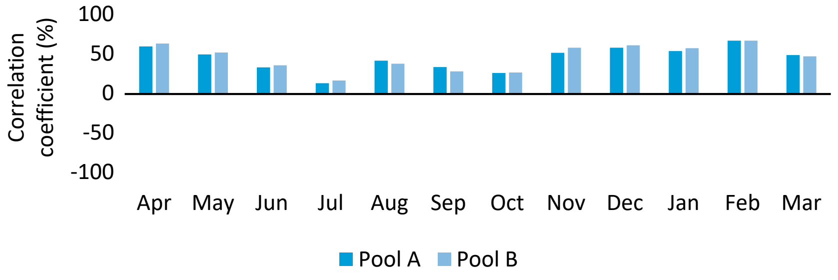
Figure 16 India demand profile is not well-correlated with Pool A and Pool B generation profiles, for 2030



Source: Authors' analysis

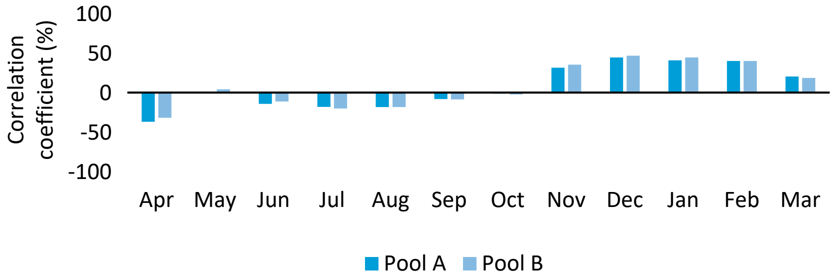
Negligible additional balancing requirements on account of offshore wind

Figure 17 Pool A and Pool B have similar correlation coefficients for Gujarat, in 2030



Source: Authors' analysis

Figure 18 Pool A and Pool B have similar correlation coefficients for India, in 2030



Source: Authors' analysis

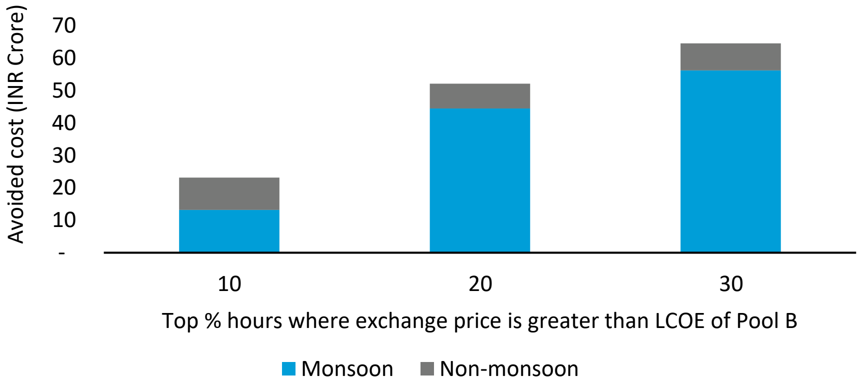
- To compute load-following capabilities, the correlation coefficients of Pool A and Pool B were compared on a monthly and daily basis (Figures 15 to 18)
- Load-following capability against Gujarat demand is better than for all-India demand. Pooling with offshore wind marginally improved the correlation coefficient in most months

Offshore wind does not impact the load-following capability of the existing pool of onshore wind and solar PV. Therefore, no additional balancing reserves may be required due to offshore wind generation.

Due to the positive coefficient for Gujarat, there are likely fewer chances for RE curtailment in Pool B in low-demand periods, provided the technical limits of the other generators are not reached.

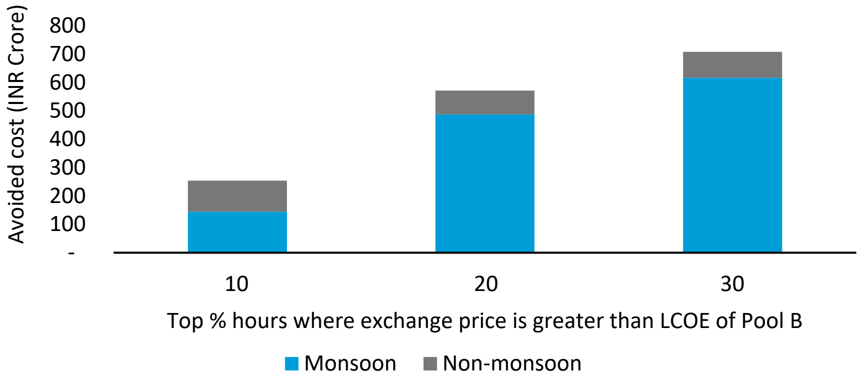
Pool B leads to avoided power procurement costs from the power exchange

Figure 19 Avoided cost in monsoon hours is higher than in non-monsoon hours for Gujarat in 2030



Source: Authors' analysis

Figure 20 Avoided cost in monsoon hours is higher than in non-monsoon hours for India in 2030



Source: Authors' analysis

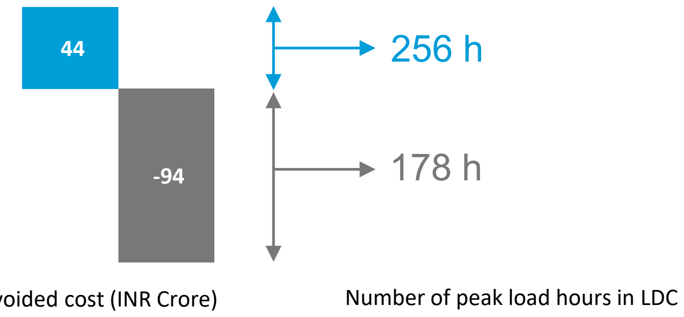
How much can we save in Pool B due to the 'avoided power procurement cost from the exchange'?

- The avoided cost is the price differential between the hourly average clearing price on the exchange and the LCOE of Pool B in 2030. The methodology for the calculation of the avoided cost and the LCOE of Pool B is explained in Annexure C
- In 2030, in nearly 60% of hours, the LCOE of Pool B is lower than exchange prices. However, the majority of potential savings accrue in the 30% of hours where the price differential between the exchange price and LCOE is maximum
- In 2030, the avoided cost for Gujarat and India estimated as INR 65 crore and INR 708 crore

Note - All cost numbers expressed as 2020 real

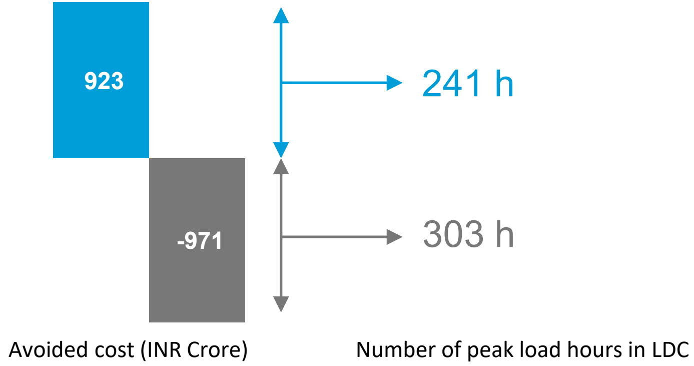
However, for peak load hours, the net avoided power procurement cost is negative

Figure 21 Avoided cost and corresponding peak load hours when price delta is maximum (Gujarat, 2030)



Source: Authors' analysis

Figure 22 Avoided cost and corresponding peak load hours when price delta is maximum (India, 2030)



Source: Authors' analysis

- We determined the avoided power procurement cost for the peak load hours that lie within 30% of the hours where the price delta (the differential between the exchange price and LCOE) is maximum. These peak load hours lie in the range of 0% to 10% of LDC hours
- During these hours, Pool B had lower generation than Pool A at the aggregated level. Therefore, the net avoided cost is negative. The figures 21 and 22 show the positive and negative avoided costs and corresponding peak load hours
- A similar analysis was conducted for select states in the northern region (Uttar Pradesh and Delhi). The results show the net positive avoided cost due to the demand pattern of the states. These states can potentially save from Pool B in the monsoon months as well as their peak load hours

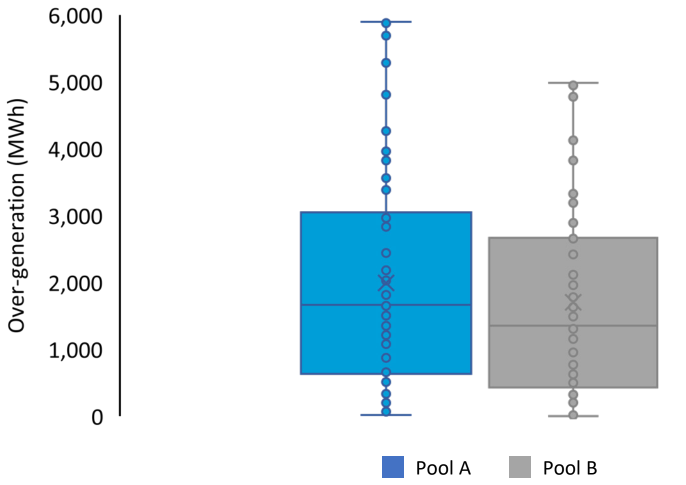
Note - All cost numbers expressed as 2020 real

Offshore wind can lead to a reduction in likely RE curtailment

We analysed the net load profiles for Gujarat and all-India for Pool A and Pool B and identified hourly timestamps when the net load is negative, i.e., over-generation* from solar PV and wind, which may likely get curtailed, unless stored for later use.

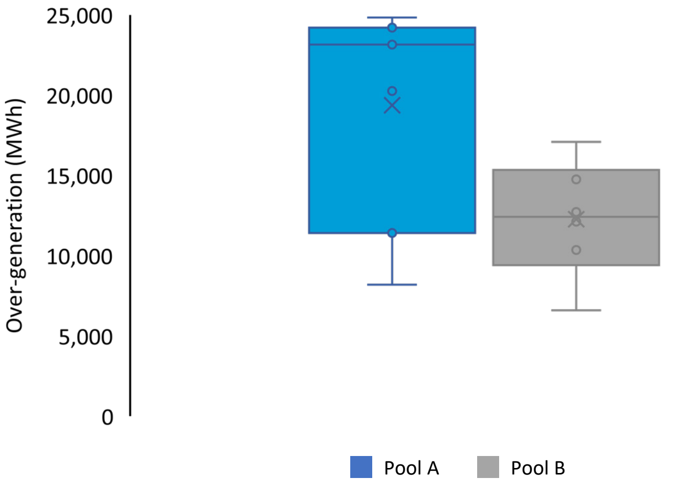
Pool B has relatively low over-generation in the system compared to Pool A. The reduction is marginal at the state level. Possible curtailment may significantly reduce at the national level.

Figure 23 Pool B has low over-generation than Pool A for Gujarat, in 2030



Source: Authors' analysis

Figure 24 Pool B has low over-generation than Pool A for India, in 2030



Source: Authors' analysis

*Actual over-generation in the system may be higher than shown in the figures due to the operational constraints (like technical minimum) of non-RE sources. Over-generation is evaluated considering the must-run status for RE.

Takeaways and limitations

Key takeaways (1/2)

Capacity value for Gujarat and India

For Gujarat, Pool B improves the capacity value during the monsoon months beyond the top 4% hours of the LDC. A slight improvement was observed at the annual level. For India, Pool B improves the capacity value across the year, with the maximum improvement seen in the monsoon months. This reduces the chances of curtailment during peak generation

- Offshore wind may improve system adequacy and reliability requirements during peak load hours and improve the ELCC (and lower LOLE), primarily in the monsoon months

Uncertainty

We assessed the uncertainty introduced by Pool B for solar generation hours and non-solar generation hours. Pool B reduces uncertainty, and the extent of reduction is higher during non-solar generation hours

- Offshore wind may lower the daily reserve requirements to handle uncertainty in the system across the year

Variability for Gujarat

We computed the variability introduced by Pool B in the net load profile of Gujarat by calculating the number of ramps of size 1000 MW/hour and beyond

- Offshore wind may have a negligible impact on the variability of net load, and the existing ramping capabilities in the system may be sufficient to handle it

Key takeaways (2/2)

Load following capability

The Gujarat load profile is better correlated with Pool A and Pool B compared to the all-India load profile. Pool B marginally improved the correlation coefficient for Gujarat and all-India

- Offshore wind may remove the need for additional balancing reserves in the system

Avoided power procurement cost

The avoided cost was computed to determine the potential savings with Pool B for Gujarat and India

- Offshore wind may result in avoided power procurement costs when compared to prices at the exchange. The avoided procurement cost is negative for peak load hours within high-price hours at the exchange for Gujarat and India; but it is positive for states in northern India

Reduced RE curtailment

Pool B has lower over-generation compared to Pool A. The extent of reduction in RE curtailment is greater for India than for Gujarat

- Offshore wind may reduce the amount of possible RE curtailment

Limitations of the analysis

The analysis is specific to selected Gujarat sites

Parameters vary across sites depending on the site layout, local climate and weather patterns, geographical diversity, land topography, the technical characteristics of wind plants, wind resource forecast, etc. [19,16,17]

Non-availability of commercial offshore wind turbine power curve

Without commercial turbine power curves, a general offshore turbine power curve was used from NREL-SAM. Actual power curves can add make the results more robust

Non-availability of data across a common time period

The availability of all datasets spanning the same time period can make the results more robust

Unmet demand is not captured in the demand profile

The demand profiles are that of met demand due to a lack of data on unserved energy. A more accurate assessment of load following capability can be done with unrestricted demand profiles. Sub-hourly demand projections would improve the results related to uncertainty

Source: 16 ICF International and Shakti Sustainable Energy Foundation 2014; 17 Milligan, Michael, and Kevin Porter 2005;19 Jain, Pramod, and Priyantha Wijayatunga 2016

Annexures

A. Capacity value formulation

Capacity value was calculated using the following formulae [16]:

$$Capacity\ value = \frac{\sum_{i=1}^{n} HD_i * CUF_i}{HD_{max} * n}$$

where,

HD_i is the load of the i^{th} peak hour

n is the number of critical hours considered as peak load hours in the LDC

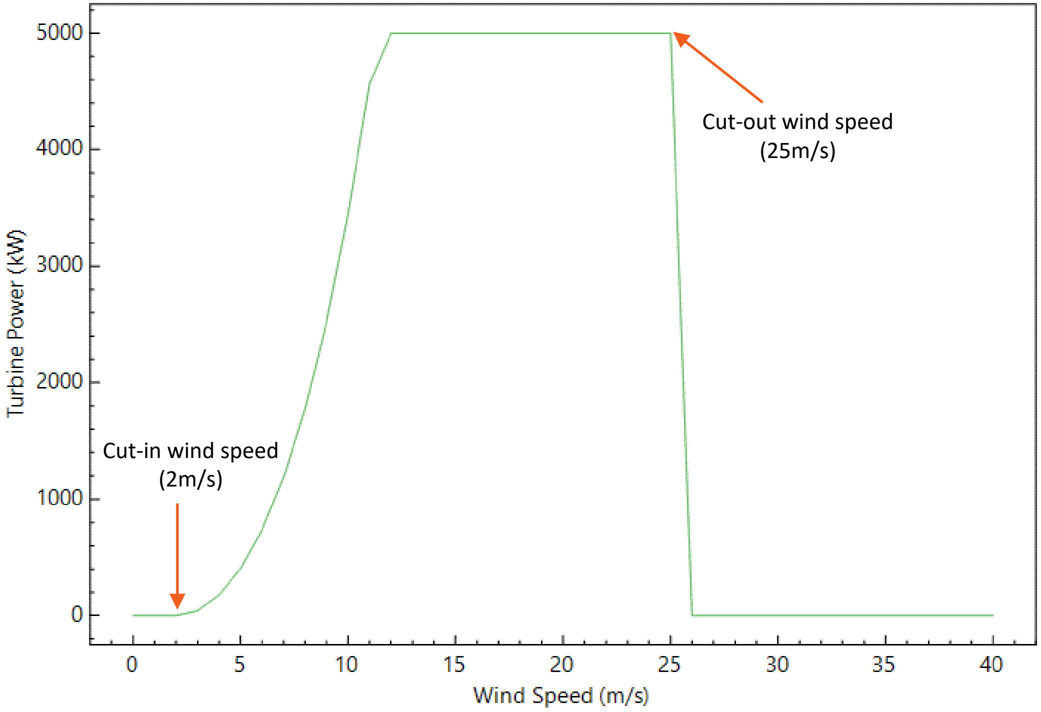
HD_{max} is the maximum of ($HD_1, HD_2, HD_3, \ldots\ldots, HD_n$)

CUF_i is the capacity factor of the generator in the i^{th} hour

Source: 16 ICF International and Shakti Sustainable Energy Foundation, 2014

B. Turbine power curve is used to derive offshore wind generation profile

Figure 25 5 MW turbine power curve used for conversion of offshore wind speed to offshore wind generation



Source: 26 NREL 2022

Publicly available offshore wind turbine curve for 5 MW in NREL-SAM[26] was used to convert wind resource data at 140 m hub height to wind generation

C. Methodology for estimation of avoided cost of market procurement (1)

Step-by-step approach of avoided cost estimation

Estimation of average clearing price on the exchange

We considered the weighted marginal clearing price (weighted MCP) and scheduled volume from the DAM and RTM market segments at the hourly level for financial year, FY2021–22. The volume weighted average price (VWAP) was calculated for the total cleared volume in the market segments at every hour. The VWAP was sorted from high to low

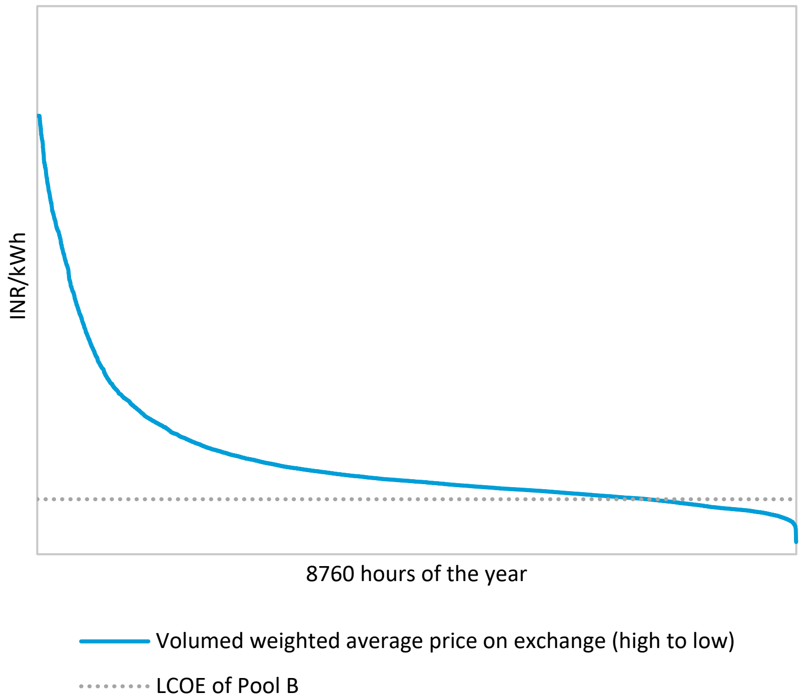
Estimation of LCOE of Pool B

We calculated the LCOE of Pool B in 2030 @3.08 INR/kWh based on 2030 projections for offshore wind, onshore wind, and solar PV as provided by Financial Modelling of Offshore wind in India (FIMOI)[13] and Lawrence Berkeley National Laboratory (LBNL)[27]

Estimation of avoided cost

Change in generation, i.e., Pool B(gen) – Pool A(gen) multiplied by the price differential between VWAP and LCOE

Figure 26 Comparison of VWAP and LCOE of Pool B, for 2030



Source: 13 DEA and COWI 2022; 27 Abhyankar, Nikit, Shruti Deorah, and Amol Phadke 2021

C. Methodology for estimation of avoided cost of market procurement (2)

Four possible profit and loss combinations for the avoided cost calculation

Quadrant 1: *Pool B (gen) > Pool A (gen), and VWAP > LCOE*
The additional generation from Pool B is procured at a relatively low-cost LCOE resulting in profit

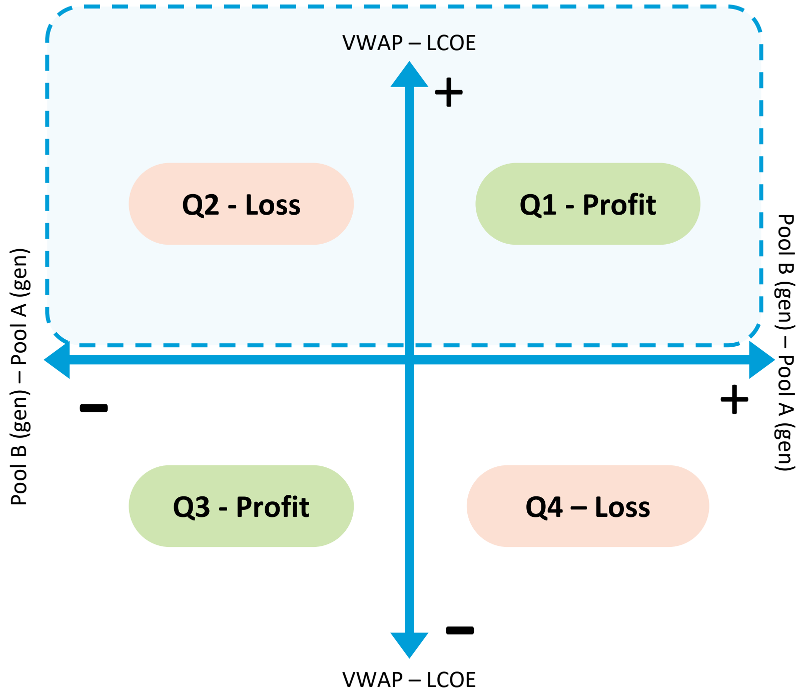
Quadrant 2: *Pool B (gen) < Pool A (gen), and VWAP > LCOE*
The generation shortfall from Pool B is procured from the exchange at a relatively high VWAP, resulting in loss

Quadrant 3: *Pool B (gen) < Pool A (gen), and VWAP < LCOE*
The generation shortfall from Pool B is procured from the exchange at a relatively low VWAP, resulting in profit

Quadrant 4: *Pool B (gen) > Pool A (gen), and VWAP < LCOE*
The additional generation from Pool B is procured at a relatively high LCOE, resulting in loss

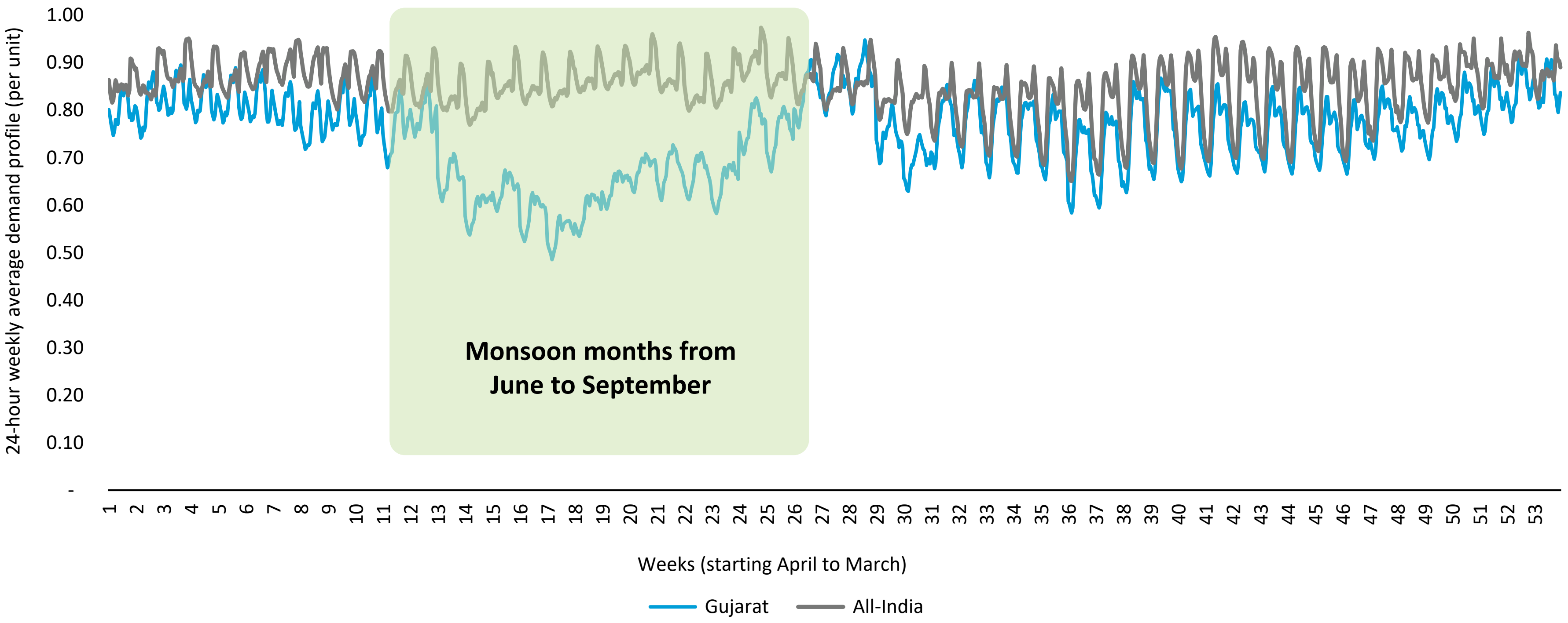
For our analysis, we considered hours when VWAP > LCOE. Hence Quadrant 1 and Quadrant 2 were used for the calculation of avoided cost.

Figure 27 Different combinations for avoided cost of market procurement



D. Per unit demand profile for Gujarat and All-India in 2030

Figure 28 Demand profile of Gujarat and India, for year 2030[24]



Source: 24 TERI 2018

Acronyms

$	United States Dollar
Capex	capital expenditure
CEA	Central Electricity Authority
CUF	capacity utilisation factor
DAM	Day-ahead Market
ELCC	effective load carrying capacity
FOWIND	Facilitating Offshore Wind in India
FOWPI	First Offshore Wind Project of India
FY	financial year
GW	gigawatts
GWEC	Global Wind Energy Council
INR	Indian Rupees
IRENA	International Renewable Energy Agency
ISTS	inter-state transmission system
LCOE	levelised cost of electricity
LDC	load duration curve
LiDAR	light detection and ranging
LOLE	loss of load expectation
MCP	Market Clearing Price
m/s	Metre per second
MNRE	Ministry of New and Renewable Energy
MWh	megawatt-hour
NIWE	National Institute of Wind Energy
NREL	National Renewable Energy Laboratory
PV	photovoltaic
RE	renewable energy
RTM	Real Time Market
SAM	system advisory model
TMY	typical meteorological year
VRE	variable renewable energy
VWAP	volume weighted average price
WRLDC	Western Regional Load Dispatch Centre

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