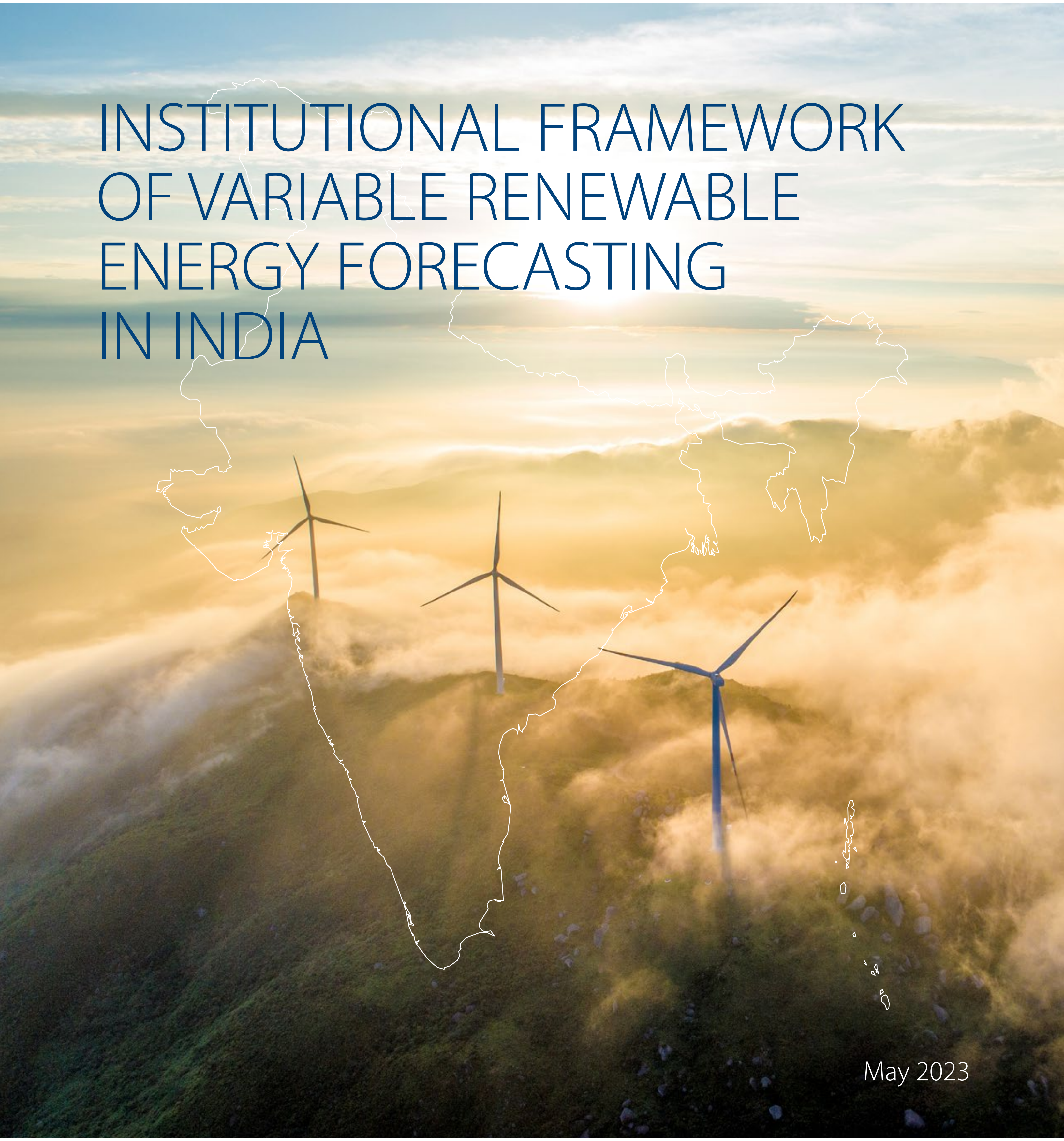
INSTITUTIONAL FRAMEWORK OF VARIABLE RENEWABLE ENERGY FORECASTING IN INDIA



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South Asia Group for Energy (SAGE)

INSTITUTIONAL FRAMEWORK OF VARIABLE RENEWABLE ENERGY FORECASTING IN INDIA

Authors
Mohit Joshi and Sarah Inskeep
National Renewable Energy Laboratory

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Abstract

The share of variable renewable energy (VRE) in India is growing rapidly, with a national goal of reaching 50% capacity from non-fossil fuel generation by 2030. One implication of this growth is the need for improved VRE forecasting methods. For this reason, the Ministry of New and Renewable Energy (MNRE) in India commissioned this study with support from the United States Agency for International Development (USAID), the National Renewable Energy Laboratory (NREL) in the United States, and the National Institute of Wind Energy (NIWE) in India. The objective of this study was to review the existing institutional framework for VRE forecasting and to present potential pathways for improvement, supporting plans for large-scale VRE integration in the country. To achieve that objective, the authors consulted local stakeholders about the status of VRE forecasting in India, reviewed existing studies, and examined VRE forecasting methods around the world to identify best practices. Based on those best practices, the study presents six potential approaches to improve the VRE forecasting framework in India. Approaches include incentivizing VRE forecast improvement and use of the most accurate VRE forecasts, creating an institution that will optimize VRE forecasts while maintaining and ensuring access to necessary data for forecasting, implementing a review and certification process for VRE forecast providers, forecasting closer to dispatch time and allowing for more frequent forecast revisions, increasing the frequency of weather forecasts, and aggregating VRE forecasts at the point of interconnection.

List of Acronyms

AEMO: Australian Energy Market Operator
CAISO: California Independent System Operator (U.S.)
ENTSO-E: European Network of Transmission System Operators
ERCOT: Electricity Reliability Council of Texas (U.S.)
FSP: forecast service provider
IPP: independent power provider
MISO: Midwest Independent System Operator (U.S.)
MNRE: Ministry of New and Renewable Resources (India)
NERC: North American Electric Reliability Corporation (U.S.)
NIWE: National Institute of Wind Energy (India)
NREL: National Renewable Energy Laboratory (U.S.)
POSOCO: Power System Operation Corporation (India)
SLDCREMC: Renewable Energy Management Center (India)
RLDC: Regional Load Despatch Center (India)
SLDC: State Load Despatch Center (India)
SRLDC: Southern Region Load Despatch Center (India)
TSO: transmission system operator
USAID: United States Agency for International Development
VRE: Variable Renewable Energy

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1 Introduction

India has recently announced plans to achieve 50% capacity from non-fossil fuel generation by 2030 (PIB 2022). This implies a large share of non-fossil fuel capacity would come from variable renewable energy (VRE). As of March 15, 2023, the current installed capacity of VRE (wind and solar) in the country stands at approximately 110 GW, which is 26% of total capacity. Installed capacity of non-fossil generation (VRE, hydropower, biomass, and nuclear) stands at approximately 179 GW, which is 43% of the total (Ministry of Power, 2023).

Scaling up the share of VRE by 2030 has implications for the grid that need to be understood and addressed appropriately. One such implication is the VRE forecasting error, which creates the requirement for reserves and balancing power in the grid. Forecasting error is the difference between forecasted generation and actual generation. Forecasting is an important and cost-effective tool for VRE integration into power systems. However, excess forecast errors can lead to a significant and costly increase in the need for balancing power. If, on the other hand, forecasting accuracy improves in line with the growth of VRE shares, the need for balancing power can be maintained or even lowered. Thus, there is a need for improved forecasting methods and frameworks.

With this objective, the Ministry of New and Renewable Energy (MNRE), which is responsible for development of renewable energy resources in India, commissioned this study with support from the United States Agency for International Development (USAID) India, the National Renewable Energy Laboratory (NREL) in the United States, and the National Institute of Wind Energy (NIWE) in India.

Considering the 2030 target, the purpose of this study was to present potential pathways for improvements in the institutional framework of VRE forecasting based on current best practices. The study included a review of the existing institutional framework for VRE forecasting in India, of existing studies, and of international experience. In addition, consultations were held with key Indian stakeholders, including renewable energy management centers (REMCs), system operators, qualified coordinating agencies, and VRE developers to understand their perspectives and challenges in VRE forecasting. This report is a culmination of this study, summarizing the main findings and potential methods for improving the VRE forecasting institutional framework.

2 VRE Forecasting Framework in India

The VRE forecasting framework at the central level is governed by the regulations of the Central Electricity Regulatory Commission. The framework for forecasting, scheduling, and imbalance for VRE was introduced in 2015. REMCs have also been set up in the country to improve forecasting, scheduling, visualization of VRE, and situational awareness of the system operators. These REMCs (total 11) are co-located with the national load despatch center, regional load despatch centers (RLDCs) of VRE-rich regions, and state load despatch centers (SLDCs) of VRE-rich states. REMCs provide forecasts for RLDCs and SLDCs. The salient features of the VRE forecasting framework at the central level in India are listed below (CERC 2017; SRLDC 2021).

1. VRE has a must-run status, which means the generation cannot be curtailed unless required for grid security.
2. A hybrid approach toward forecasting is adopted, wherein RLDCs and VRE generators are required to forecast VRE generation. REMCs' VRE forecasts for RLDCs are from the perspective of secure grid operation; forecasts are created for each of the VRE generators, then aggregated to arrive at state and regional forecasts. VRE generators can forecast on their own, acquire forecasts from private forecast service providers, or use RLDCs' forecasts for a fee.
3. Three external forecasts are available for REMCs, along with an internal forecast based on weather data, actual generation, and AVC. These four forecasts are aggregated with appropriate weight. An AI-based forecasting tool is also being developed.
4. Forecasting is done by REMCs at multiple time horizons. This includes week-ahead forecasts with hourly resolution and day-ahead forecasts for each 15-minute time block.
5. REMCs' forecasts are based on various parameters and weather data obtained by the Indian Meteorological Department or from a forecast service provider.
6. VRE generators can revise the day-ahead forecast/schedule by giving 60 minutes notice. A maximum of 16 schedule/forecast revisions are allowed to VRE generators each day.
7. VRE is given more flexibility for real-time deviations in comparison to other generators. VRE generators are allowed under injection up to 10% without any penalty. There is no penalty for over injection.
8. Forecast errors are currently managed internally to each state by SLDCs and through changes to the import/export schedule. If forecast error is expected or known before the gate closure for the real-time market, states do participate in the real-time market as well as reschedule conventional interstate generating station thermal plants to balance their portfolio apart from internal conventional generation based on merit order. If the time available is less than seven time blocks (each time block is 15 minutes long), efforts are made to manage internal resources. Further, reserve shutdown of conventional plants is done based on requirement.

2.1 Current Forecasting Method Error Metrics

Considering the accuracy of forecasts for solar and wind from available providers in 2020, the Power System Operation Corporation (POSOCO) and the Southern Region Load Despatch Center (SRLDC) report that the developers' forecasts are most accurate, while the various forecasting service providers' (FSPs) forecasts have greater error, as shown in Figure 1 (POSOCO and SRLDC 2021).

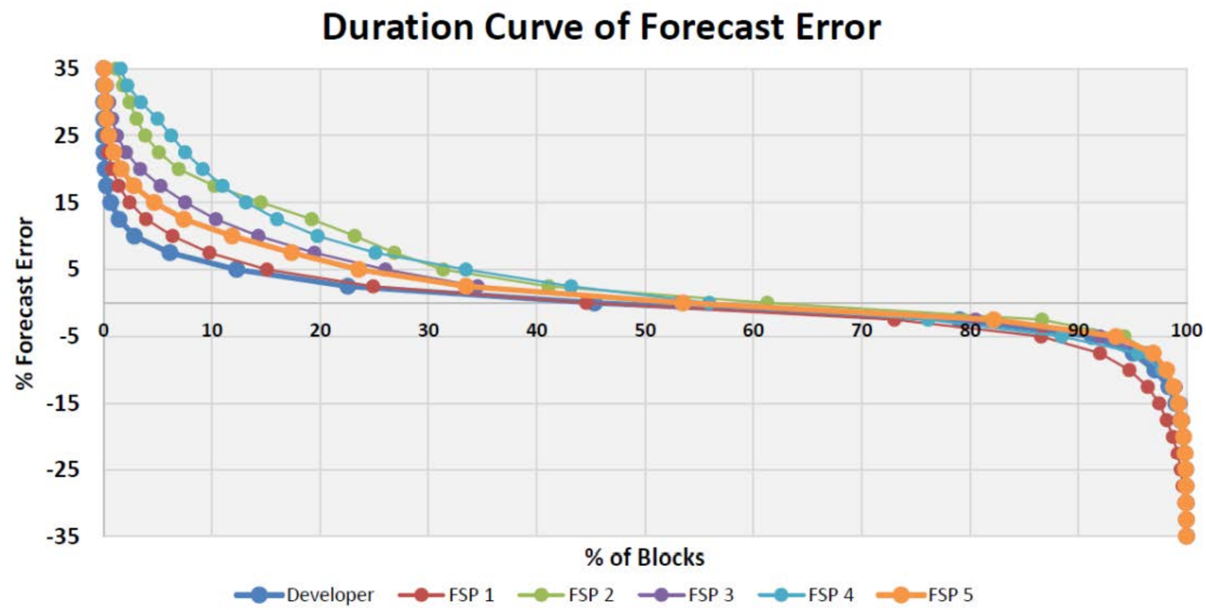

Figure 1. Duration curve of forecast error for Southern Region renewable energy (solar and wind) connected to the Inter-State Transmission System (POSOCO and SRLDC 2021)

The forecasts represented in this data are for all solar and wind plants connected to the Inter-State Transmission System in 2020. As of March 2021, total wind capacity in the Southern Region was 18,651 MW and total solar capacity was 19,332 MW (POSOCO and SRLDC 2021).

The average absolute forecast error statistics based on the same data from POSOCO and SRLDC's report, for all solar and wind plants connected to the Inter-State Transmission System in the Southern Region, are shown in Table 1. The absolute error is calculated for each 15-minute time block period.

Table 1. Forecast Error Statistics for Southern Region VRE Connected to the Inter-State Transmission System (POSOCO and SRLDC 2021)

Average Absolute Forecast Error Statistics Based on Blockwise Data					
Developer	FSP 1	FSP 2	FSP 3	FSP 4	FSP 5
3.35%	4.40%	6.59%	5.18%	7.30%	4.57%

To further understand the differences in forecast errors from different providers nationally, the existing framework and practices, and what improvements might be made, we met with some of the stakeholders involved in the VRE forecasting process. Important points coming out of these discussions are described below.

2.2 Stakeholder Engagement Summary

A stakeholder engagement meeting took place on July 15, 2022, facilitated by NIWE and NREL. Approximately 40 individuals attended, representing system operators (RLDCs, SLDCs) and VRE generators (independent power providers [IPPs]). The team from NREL prepared and presented a set of guiding questions for system operators and VRE generators around the current forecasting framework and its challenges. Afterward, each stakeholder was given time to respond. Key takeaways from this session are noted here.

Challenges to All Stakeholders

- Many stakeholders requested a central agency to collect and store data (real-time, forecast, historical, meteorological, wind/solar generation) that will be made accessible to all forecast providers for forecast improvement.
- Many stakeholders expressed that day-ahead forecasts are particularly challenging. Qualified coordinating agencies or forecast providers' performance are assessed based on intraday forecasts, and, as a result, there is not much focus to improve day-ahead forecasts.
- Many stakeholders spoke about the challenge of weather data only being updated twice a day. Increasing the availability of weather data would allow for improved forecasting.
- Lack of real-time communication about outages is a challenge for many stakeholders.
- Accurate forecasts are particularly challenging to create during cloud cover.
- Several stakeholders spoke about the challenge posed by being limited to 16 forecast revisions per day.
- Stakeholders noted that forecasting error in certain regions is highest during certain seasons/months. For example, Karnataka faces challenges with high forecast error and high renewable deployment in monsoon season. Stakeholders expressed that the lack of accurate forecasts in these circumstances leads to additional challenges in other areas of work—wind and hydro have must-run status, and at times the excess generation from these sources leads to energy market prices dropping or agricultural load crashing.

Challenges Specific to System Operators

- Congestion and frequency are difficult to manage with high forecasting errors.
- Many system operators spoke about the challenge of "black box" forecasting methods. Everything is automated, so they are unable to troubleshoot and revise to create more accurate forecasts.
- VRE curtailment is not known to RLDCs in real time.
- REMCs are only a few years old, and are still getting their AI-based forecasts tuned. Increased availability of weather data and improved day-ahead forecasts are necessary to increase accuracy.
- System operators would like to have increased granularity of forecasts temporally, ideally to 5-minute time blocks. However, this is likely not useful until forecasts are more consistently accurate. The spatial granularity currently used (forecasting each renewable energy generation/pooling station and aggregating to the state and regional levels) seems to work well, though there is some interest in the possibility of aggregating large VRE-rich areas.

Challenges Specific to RE Generators

- Many IPPs expressed that they are strained by the money spent on forecasting, and feel that they should not be solely responsible for forecasting errors, because they cannot do much beyond procuring the best available forecast. At present, there are only four options for forecast service providers—in some areas, only one is available—so penalties from IPPs to providers for inaccurate forecasts are not possible; if facing penalties, the providers just refuse service.
- IPPs' procured forecasts are still more accurate than the forecasts provided to them by REMCs. Thus, most IPPs do not use REMCs' forecasts. This follows the trend in the Southern Region, described in the report from POSOCO and SRLDC and noted previously in Section 2.1.

- IPPs suggest that there is no need for charges for deviation from forecasts.
- IPPs are interested in forecast aggregation at the state or regional level to improve accuracy.

3 Review of International Experience, Best Practices, and Other Related Work

3.1 Best Practices and Other Related Work

A lot of work on VRE forecasting frameworks has been done around the world, and in India as well. In this subsection, we will discuss some of this work and highlight best practices recommended to date.

1. **NERC IVGTF Task 2.1**: This work was completed by the North American Electric Reliability Corporation (NERC) in 2010 to understand the impact of VRE forecasting on operations, to provide recommended measures to reliably integrate VRE, and to improve the reliability of power systems. Some of the conclusions related to forecasting from this work are quoted below (NERC 2010):
    A. Aggregate forecast accuracy improves with the size of the region forecast, and aggregation across broad geographical regions can significantly reduce output variability and associated operating reserve requirements.
    B. Electrical (power, availability, curtailment) and meteorological data from wind and solar plants, delivered to the forecaster and system operator on a timely and reliable basis, are critical for forecast accuracy.
2. **USAID's report on VRE forecasting:** This work highlights the best practices related to VRE forecasting in emerging VRE markets based on international experience**.** Some of the best practices described in this paper are quoted below (USAID 2020):
    A. VRE plants should provide forecasts, real-time generation, and on-site weather parameters for improved forecasting.
    B. Centralized forecasting is a best practice to help dispatchers make better decisions.
    C. Because VRE forecasts are more accurate close to dispatch, it is important to move to faster dispatching, in which forecast interval and lead time are short and multiple revisions to forecasts are required.
    D. Establishing new institutions to conduct research to improve forecasting accuracy for weather parameters that are important for VRE forecasting can be impactful.
3. **NREL's factsheet on forecasting wind and solar generation:** This work was published under USAID's Greening the Grid program. The main takeaways from this work are listed below (Chernyakhovskiy and Tian 2016):
    A. Centralized VRE forecasting is considered a best practice approach, as it provides greater consistency and lower uncertainty.
    B. Aggregate the results from different forecasts provided by multiple forecast providers.
    C. VRE forecasts in different time horizons can help in better scheduling, reserve assessment, regulation, market clearing, and real-time dispatch.
    D. Distributed photovoltaic forecasts can be integrated with load forecasting to obtain net load forecasts.
4. **GIZ work on forecasting, concept of renewable energy management centers, and grid balancing:** This work was done for India to understand the existing VRE forecasting capabilities and to recommend how forecasting services can be implemented with the establishment of REMCs. Some of the recommendations important for this work are listed below (Richts, Strauß, and Heinemann 2015):

A. Larger areas need to be considered in forecasting at the state level, as it smooths out variability and lowers uncertainties.

B. Update forecasts on an intra-day time scale.

C. Continuously evaluate forecasts.

D. Forecasts can be provided by multiple service providers.

E. At a later state, a central organization can forecast by making use of several VRE forecasts.

5. **USAID's Grid Integration Toolkit under Greening the Grid platform**: This is an online platform created to help various stakeholders by compiling resources and best practices on various VRE grid integration topics. Some of the best practices related to VRE forecasting listed on this platform that are relevant for our work are as follows:

   A. Forecasts can be improved by more frequent measurements and observations of the weather and atmospheric conditions.

   B. More frequent updates to numerical weather prediction models can also help in improving forecasts.

   C. Provide system operators with access to forecast-relevant data from generation resources or a national network for the development of centralized forecasts that are designed to minimize reliability risks.

   D. Facilitate a national network of weather stations to create historical meteorological datasets that are useful for characterizing renewable resources and forecasting future power generation.

   E. Adopt administrative or market rules that incentivize VRE generators to submit accurate estimates of resource availability at all market time scales. When taken in combination with centrally aggregated forecasts, these resource-specific forecasts may help minimize the costs associated with reliably serving demand.

   F. Shorten the time-step of forecasts to the minimum interval in which system operators can make actionable economic dispatch decisions.

   G. Consider using multiple forecasting sources, also known as ensemble forecasting.

   H. Exchange data and forecasts among balancing authorities within the same interconnection.

6. **The International Renewable Energy Agency's work on advanced forecasting of VRE**: This work was completed as part of the International Renewable Energy Agency's "Innovation landscape for a renewable-powered future" project, which maps relevant innovations, identifies synergies, and formulates solutions for integrating high shares of VRE into power systems. This brief provides an overview of weather forecasting for VRE integration, with emphasis on both short- and long-term forecasting for renewable generators and power system operators. A checklist of requirements for improved forecasting can be found in this work. Some key recommendations are also listed below (IRENA 2020):

   A. Increase time granularity of regulatory and electricity market arrangements—the dispatch and scheduling time interval, the pricing of market time units, financial settlement periods, and the time span between gate closure and real-time delivery of power should be reduced.

B. Incentivize VRE generators and system operators to produce accurate generation forecasts at different time scales, at the same time granularity used in electricity markets.

C. Consider automatization of communication between system operators and VRE generators for real-time sharing of weather, forecast, and other data.

D. Consider open-source systems for weather data collection and sharing, which can foster rapid advances in data analytical techniques and consequently in weather forecasting.

3.2 International Experience

This subsection will review the forecasting framework of the systems that either have a high-percentage share of VRE comparable to targets in India or are planning to achieve it in the near term.

3.2.1 California Independent System Operator (CAISO)

CAISO is one of the leading system operators in the United States, managing high shares of renewable energy. At present, it is managing around 26 GW of VRE, out of which solar is around 15 GW and wind is around 8 GW (CAISO 2022). In 2021, VRE use on an annual energy basis was around 31%, with instantaneous shares reaching up to around 95% (CAISO 2021). CAISO plans to achieve annual energy shares of 60% VRE by 2030 and 100% by 2045 (Hildebrandt 2021). Some of the salient features of CAISO's forecasting system relevant for this work are listed below (CAISO 2022; Stewart 2021):

1. **Forecasting Agency:** VRE generators can choose to provide their own forecast, or to use the forecast provided by CAISO's forecast service providers. VRE generators are required to provide meteorological and outage data to CAISO.
2. **Forecast Method/Model:** Not specified.
3. **Forecast Temporal Resolutions:** Hourly day-ahead forecasts for the next 4 days are provided for each VRE generator. In addition, real-time forecasts are maintained for the next 8 hours at 5-minute granularity and are updated every 5 minutes. Hourly day-ahead forecasts are used in all reliability studies. Real-time forecasts are used for real-time dispatch.
4. **Forecast Spatial Resolutions:** Forecasts are provided for each VRE generator. Generators at the same point of interconnection to CAISO can be aggregated as one resource.
5. **Methods Used to Increase Forecast Accuracy:**
   - VRE generators can take part in the participating intermittent resource program to receive protective measures that allow deviations between the resource's actual energy output and the hourly schedule to be netted over each month. Generators participating in this program are required to use CAISO's forecast.
   - An internal persistence forecast is used in real-time dispatch to improve accuracy 50% from FSPs.
   - Forecasting performance is continuously reviewed, and corrective measures are taken as needed.

3.2.2 Electricity Reliability Council of Texas (ERCOT)

ERCOT is another power system in the United States with significant VRE deployment: around 35.7 GW of wind capacity and 11.3 GW of solar capacity are operational as of March 2021. The share of VRE in ERCOT was 43% in 2021, with maximum instantaneous deployment of over 70% (ERCOT 2022). Important aspects of ERCOT's VRE forecasting framework are summarized below (ERCOT 2021; 2020):

1. **Forecasting Agency:** Centralized VRE forecasting is done by two FSPs for ERCOT. Meteorological and outage data are required to be telemetered to ERCOT.
2. **Forecast Method/Model:** Meteorological tower data, resource telemetry, and outage data are used with local and regional physics-based weather models. Outputs from these models are used as inputs for statistical models; outputs from statistical models are in turn used in plant output models to create forecasts (ERCOT PVGR/Wind Forecasting Design Documentation).
3. **Forecast Temporal Resolutions:** Intra-hour forecasts for the next 2 hours at 5-minute resolution are updated every 15 minutes. Then, short-term rolling 168-hour forecasts for each VRE resource are maintained and updated every hour.
4. **Forecast Spatial Resolutions:** Forecasts are maintained by ERCOT for each VRE resource, as well as for resource regions and for the total system.

3.2.3 Midwest Independent System Operator (MISO)

MISO is another important power system operator in the United States in terms of installed VRE capacity. It has around 26 GW of wind capacity and a relatively small amount of solar (MISO 2021a). The annual energy share of wind and solar are expected to grow to 26% - 46% percent in the future (MISO 2021b). A high-level overview of MISO's VRE forecasting framework is given below (MISO 2019):

1. **Forecasting Agency:** Forecasts are maintained by MISO at the plant level. Each resource can also provide its own forecast for scheduling and dispatch. Resources using MISO's forecast are allowed to produce at their full potential unless being dispatched down.
2. **Forecast Method/Model:** Numerical weather prediction models.
3. **Forecast Temporal Resolutions:** Intra-hour forecasts for the next 6 hours are maintained at 5-minute resolution and are updated every 5 minutes. Then, hourly load forecasts are provided for the next 168 hours and are updated hourly.
4. **Forecast Spatial Resolutions:** Intra-hour and hourly forecasts are maintained at a farm level.
5. **Methods Used to Increase Forecast Accuracy:** There is continuous monitoring and reporting of large forecasting errors to market participants.

3.2.4 Australian Energy Market Operator (AEMO)

Looking to examples outside the United States, Australia has significant shares of wind and solar, with annual contributions of around 24% toward total generation in 2021 (CEC 2022). This share of VRE (including hydro) is expected to increase further to 50% by 2025 and 69% by 2030 (Mazengarb 2021). The forecasting framework followed by AEMO, the national electricity market operator of Australia, is discussed in brief below (AEMO 2016; 2022):

1. **Forecasting Agency:** AEMO maintains centralized forecasts of wind and solar. However, since 2018, VRE generators are encouraged and incentivized to self-forecast, as it is expected to reduce generation forecast error while providing greater autonomy. AEMO assesses the performance of each VRE generator's self-forecast.
2. **Forecast Method/Model:** Forecasts are produced by AEMO using various inputs such as: real-time data, numerical weather predictions from weather forecasts around the world, technical information of VRE generators, and standing data.
3. **Forecast Temporal Resolutions:** There are 5-minute ahead forecasts, hour-ahead forecasts at 5-minute resolution, and a 7-day ahead forecast at 30-minute resolution.

4. **Forecast Spatial Resolutions:** Forecasts are maintained for individual generators, for each region, and for the total system.

3.2.5 EIRGRID

EIRGRID is the system operator of Ireland. VRE accounted for 43% of electricity consumption in 2020 in Ireland. Under the program called "delivering a secure, sustainable electricity system" (DS3), Ireland is planning to achieve 80% annual VRE share by 2030 (EIRGRID 2022). Important aspects of EIRGRID's forecasting framework are (EIRGRID 2018):

1. **Forecasting Agency:** EIRGRID procures forecasts from two independent service providers.
2. **Forecast Method/Model:** Forecasts are produced based on various inputs, including coordinates for each VRE plant, real-time measurements, outage data, and site-specific meteorological data.
3. **Forecast Temporal Resolutions:** Forecasts of 15-minute resolution are updated every 6 hours for the next 96 hours. Forecasts from service providers are blended based on outage data and real-time conditions and interpolated to a 1-minute level forecast for use in scheduling and dispatch.
4. **Forecast Spatial Resolutions:** Forecasts are maintained for each wind/solar farm for the total system, along with uncertainty levels. Wind and solar farms of greater than 5 MW are individually forecasted.

3.2.6 Germany

In 2021, renewable energy provided 41% of the electricity supply in Germany, with wind power being the most prominent energy source. Germany has four transmission system operators (TSOs)—Amprion, TenneT TSO, 50 Hertz Transmission, and TransnetBW—who collaborate with distribution system operators and the German Meteorological Department (DWD) to create and manage VRE forecasts with the following framework (Richts, Strauß, and Heinemann 2015; Zieher, Lange, and Focken 2015):

1. **Forecasting Agency:** Forecasts are maintained by DWD in partnership with TSOs and electricity traders.
2. **Forecast Method/Model:** Forecasts are created using numerical weather prediction and statistical methods.
3. **Forecast Temporal Resolutions:** TSOs and electricity traders create intra-day forecasts for the next 6 hours, as well as day-ahead forecasts, and 7-day-ahead forecasts.
4. **Forecast Spatial Resolutions:** Forecasts of feed-in for individual systems are maintained; these forecasts are also extrapolated and aggregated to form regional and national forecasts.
5. **Methods Used to Increase Forecast Accuracy:**
   - TSOs are incentivized to have accurate forecasts by a federal bonus system.
   - Regional and national forecasts are used for load-flow calculations to prevent congestion; TSOs inform distribution system operators about power requirements at certain transformer stations for certain periods of time.
   - TSOs have limited access to real-time data but use real-time estimates to improve the accuracy of the shortest-term (0–6 h) forecasts. These estimates are calculated for every control area and for the whole of Germany so TSOs can balance VRE in their balancing groups.

3.2.7 European Network of Transmission System Operators (ENTSO-E)

ENTSO-E is a network of European TSOs responsible for the secure and coordinated operation of Europe's electricity system. ENTSO-E consists of 39 members from 35 countries. In 2018, 36% (1,300

TWh) of the total electricity for these members came from renewable sources, and 48% (556 GW) of net generation capacity was renewable sources (ENTSO-E 2019). ENTSO-E contributes to VRE forecasting and scheduling through management of day-ahead congestion forecasts for the European grid (Zieher, Lange, and Focken 2015):

1. **Forecasting Agency:** ENTSO-E prepares day-ahead congestion forecasts by collecting and merging various data types (including load, generation, renewable energy forecasts, and grid aspects such as scheduled outages) for the agreed timestamps from every member TSO. After merging, security analysis is performed, and the day-ahead congestion forecast is provided to TSOs for scheduling.
2. **Forecast Method/Model:** Varies based on methods and models used by TSOs.
3. **Forecast Temporal Resolutions:** Both day-ahead and 2-day-ahead forecasts are maintained.
4. **Forecast Spatial Resolutions:** Regional only; the forecasts are intended to help member TSOs plan to avoid congestion.

3.2.8 National Grid ESO

National Grid ESO is the electricity system operator (ESO) for the United Kingdom. As of the end of 2020, the total installed generation capacity was 76 GW (U.S. Energy Information Administration 2022). In April 2022, wind energy accounted for 23% of monthly generation, and solar accounted for 6% (National Grid ESO 2022).

1. **Forecasting Agency**: National Grid ESO procures weather data, then creates and publishes two types of forecasts:
   A. System operator generation forecasts
   B. Embedded generation forecasts (National Grid ESO 2018b).[1]
2. **Forecast Method/Model:** Measurement data is assimilated by a physical model, which estimates output using information about installed capacity, location, and power curves. For embedded forecasts, capacity and location data are best estimates based on a range of publicly available information (National Grid ESO 2018a).
3. **Forecast Temporal Resolution:** Forecasts are created in half-hourly resolution for up to 14 days-ahead time scales and are updated every hour (NG-ESO User Guide). Values represent an average for the 30-minute time period, not an instantaneous amount (National Grid ESO 2018b).
4. **Forecast Spatial Resolutions:** System operator forecasts are aggregated to total operational capacity that is connected to the National Grid Transmission Network. Embedded forecasts are also estimated at the national level.
5. **Methods Used to Increase Forecast Accuracy:** In 2017, National Grid ESO partnered with researchers at the Alan Turing Institute to use machine learning techniques to improve solar forecasts, resulting in 33% more accurate day-ahead forecasts (The Alan Turing Institute 2019). A follow-up project is underway with Open Climate Fix to use AI to further improve solar forecasts (National Grid ESO 2021).

[1] Embedded generation is an estimate of national generation that does not have transmission system metering installed (e.g., rooftop solar) and is thus invisible to the ESO. This type of generation suppresses demand during periods of high wind and solar.

4 Conclusions

Based on the review of international experience, best practices, and work done by various experts and institutions (including NREL) in this area, the following potential pathways could improve the existing forecasting framework in India:

1. **Forecasting agency**: Although centralized forecasting is considered a best practice, a mix of centralized and hybrid forecasting approaches have been adopted by many systems with high VRE share around the world. Both approaches have their pros and cons. Centralized forecasting can provide greater consistency in results, lower uncertainty, and reduced financial burden on VRE plants. On the other hand, hybrid forecasting provides greater autonomy to VRE plants for forecasting their own generation but may make the jobs of system operators more difficult if not done correctly. Generally, system operators use ensemble forecasting methodology where multiple VRE generation forecasts provided by service providers are aggregated.

   Adoption of hybrid and ensemble forecasting methodologies in India appears to be consistent with international practices. However, large forecasting errors are a matter of concern for both system operators and VRE developers. It is therefore important to first identify who can provide the best forecast—system operators, VRE generators, or any other agency—and to consider incentivizing use of that forecast. These incentives could be either in the form of less penalty for deviation, netting of deviations over a period, or another approach that encourages use of the best available forecast for scheduling and dispatch.

2. **Improvement of system operator forecasts**: As mentioned above, REMCs in India use aggregated forecasts based on their own forecast and on three additional forecasts from external providers. System operators may have limitations to improve these forecasts beyond a certain level. If needed, a new institution could be created to support system operators in improving their forecast or to provide forecasting services to them. Something similar was described by GIZ in their report on REMCs—to expand the forecasting service to a centralized organization who can make use of several VRE forecasts to yield an optimized forecast for each state (Richts, Strauß, and Heinemann 2015). This institution could take up some or all of the following activities:

   A. Research and development of forecasting models and tools.

   B. Capacity building of system operators in VRE forecasting.

   C. Provide forecasting service to system operators and VRE developers along with other forecast service providers.

   D. Review and certification of VRE generators forecast.

   E. Maintain a database of real-time and historical data for weather and generation that is accessible by all forecasting stakeholders for the creation of more accurate forecasts.

   F. Vendor development to ensure that multiple forecast service providers are available for system operators and VRE developers.

   Availability of meteorological and real-time generation data from VRE generators are also critical to the accuracy of the forecast. VRE generators could support this by giving priority to the data telemetry; this could be encouraged through incentives for timely provision over a period of time. Consistent default in providing these datasets could likewise be discouraged. Other suitable measures could be considered with involved stakeholders to ensure that the required data for forecasting is made available to system operators.

3. **Review and certification of VRE generators forecast:** Most VRE generators in India at present use their own forecast for scheduling and dispatch. Though VRE generators are responsible for

their forecasting errors and deviation penalties settlement, inaccurate forecasts have implications for reliable operation of the grid. Autonomy to forecast their own generation can be good if errors are within limits. To ensure this is so, other international operators continuously review and evaluate the accuracy of forecasts provided by VRE generators; something similar could be considered for India. The system operator or any other institution with expertise in VRE forecasting could review forecasts and provide feedback for improvements as necessary. If no improvements are seen after some time, VRE generators' forecasts may be decertified and asked to switch to the system operator's forecast.

4. **Forecasting time horizon:** VRE forecasts are more accurate if they are provided closer to the dispatch period. Though VRE generators are allowed a maximum of 16 revisions during the day, these revisions are required to be provided to the system operators at least 45–60 minutes in advance. Options may be explored to reduce this lead time and to allow more frequent revisions so that forecasts are available closer to dispatch time.
5. **Improvement of weather forecasts:** At present, the Indian Meteorological Department provides weather forecasts to RLDCs only twice a day. In the international systems reviewed for this report, those with lowest forecast error have FSPs with access to much more frequent weather updates. CAISO, for example, notes the use of real-time telemetry for meteorological information used in near-term forecasts. In addition to more frequent weather data, use of multiple sources of weather forecasts is beneficial. Most forecast service providers reviewed here rely on aggregation of multiple weather forecasts from different providers using different weather forecast models.
6. **Forecast aggregation**: VRE forecast aggregation may improve the forecast accuracy and smooth out associated variability. Many systems around the world allow aggregation at the point of interconnection to their system and provide aggregated forecast at the zonal, regional, and national level. However, only the aggregated forecast at the point of interconnection is generally used for scheduling and dispatch. Use of aggregated forecasts at a larger geographical area for scheduling and dispatch has implications on transmission line loading, which can create network congestion in the system and can be considered only if the transmission system permits. Aggregation at a higher geographical level can be used for assessment of reserves, ancillary services, etc.

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Monali Hazra
U.S. Agency for International Development
Email: mhazra@usaid.gov

Adarsh Nagarajan
National Renewable Energy Laboratory
Email: Adarsh.Nagarajan@nrel.gov

Meredydd Evans
Pacific Northwest National Laboratory
Email: m.evans@pnnl.gov

Nikit Abhyankar
Lawrence Berkeley National Laboratory
Email: NAbhyankar@lbl.gov

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