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GRID INTEGRATION SERIES: VARIABLE RENEWABLE ENERGY FORECASTING

Scaling Up Renewable Energy Project

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GRID INTEGRATION SERIES: VARIABLE RENEWABLE ENERGY FORECASTING

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ACRONYMS, ABBREVIATIONS, AND GLOSSARY OF TERMS

APE	Absolute percentage error, a measure of error between actual and forecast
BPA	Bonneville Power Administration
CAISO	California Independent System Operator
CENACE	Centro Nacional de Control de Energía, Mexico's system operator
CERC	Central Electricity Regulatory Commission (India)
DA	Day-ahead
DOE	Department of Energy (United States)
ERCOT	Electric Reliability Council of Texas
Fx	Forecasting
GFS	Global Forecast System
HA	Hour-ahead
ICT	Information and communications technology
ID	Intraday
IEX	Indian Electricity Exchange
ISO	Independent system operator
IT	Information technology

kW	Kilowatt
kWh	Kilowatt hour
LDC	Load dispatch center
LIDAR	Light detection and ranging, a remote sensing instrument to measure wind speed
MA	Minute-ahead
MAD	Mean absolute deviation, a measure of error between actual and forecast
MAPE	Mean absolute percent error, a measure of error between actual and forecast
MW	Megawatt
MWh	Megawatt hour
NLDC	National load dispatch center
NREL	National Renewable Energy Laboratory (U.S. DOE)
NWP	Numerical Weather Prediction, a method for creating weather forecasts
O&M	Operations and maintenance
PPA	Power purchase agreement, an agreement between the seller and buyer of power
POSOCO	Power Systems Operations Corporation, a central-level entity in India for system operations
PV	Photovoltaic, a solar panel to convert solar radiation into electrical energy
QCA	Qualified coordinating agency
REST-API	Representational State Transfer Application Programming Interface
RMSE	Root mean square error, a measure of error between actual and forecast
RTO	Regional transmission operator
SCADA	Supervisory Control and Data Acquisition
SCED	Security-constrained economic dispatch, the lowest-cost dispatch of generators while respecting the limitations of the transmission system and unit operating characteristics
SCUC	Security-constrained unit commitment, the lowest-cost commitment (turning on) of generators to meet load while respecting all constraints
SERC	State Energy Regulatory Commission, the electricity regulator in each state of India
SLDC	State load dispatch center, an entity in each state of India to balance load and generation
SODAR	Sonic detection and ranging, a remote sensing instrument to measure wind speed
SURE	Scaling Up Renewable Energy (USAID project)
USAID	United States Agency for International Development
V-LEEP	Vietnam Low Emission Energy Program (USAID program)
VRE	Variable renewable energy
WA	Week-ahead
WMS	Weather measurement system
WRF	Weather research and forecasting
XM	System Operator and Market Administrator, Colombia

EXECUTIVE SUMMARY

In most grids worldwide, the cost of utility-scale variable renewable energy (VRE) has reached grid parity, matching or beating the cost of fossil fuel–based generation. In others, the cost of VRE is fast approaching grid parity. This phenomenon of falling VRE generation costs is likely to lead to an increase in the penetration of VRE in all grids.

High penetration of VRE is a new phenomenon, as is VRE forecasting. The California Independent System Operator was the first to implement forecasting in 2004.[1] Grid operators and policy makers believed high VRE penetrations could be achieved only by having a large amount of reserves, and some even contemplated requiring an amount of reserves equal to the amount of VRE in the grid. The thinking was that since VRE is variable and uncertain, a full backup would be required (making the cost of integrating VRE extremely high).

Fortunately, this did not come to pass, and VRE forecasting can take the bulk of the credit. In advanced VRE markets with accurate forecasting, the increase in statutory reserves is modest, thereby ensuring a modest cost to integrate VRE. For example, the Electric Reliability Council of Texas (ERCOT) reduced its operating reserve requirement through a variety of interventions. These included reducing the forecast lead time and the intervals between dispatches from 15 to 5 minutes.

VRE forecasting has emerged as a cost-effective method for reducing the impact of VRE integration on the grid, and it provides four key benefits that are essential to emerging market grid operators and regulators:

- **Reduces reserve requirements** needed to manage deviations between dispatched generation and demand, helping supply-constrained systems;
- **Improves system flexibility** by providing to the system operator accurate VRE generation forecasts, allowing it to optimize the entire generation fleet, which is often unutilized or underutilized;
- **Reduces curtailments**, allowing more renewables to be economically scheduled; and,
- **Increases system reliability** because better forecasting allows for significantly lower levels of volatility in the supply-demand balance, resulting in higher overall reliability levels.

VRE forecasting is also a least-cost solution to enhance grid flexibility—a requirement for increased VRE penetration. With accurate day-ahead (DA) and intraday VRE forecasting, decisions about committing, de-committing, or reducing the capacity factors of conventional generators can be made while maintaining high-reliability and low-cost generation. Without VRE forecasting, or with less accurate forecasting processes, it is not possible to adjust the level of production from inflexible conventional generators, leading to the curtailment of VRE. VRE forecasting provides the tools to exploit the flexibility of all conventional generators and thus reduce curtailments and increase VRE penetration.

[1] Bird et al., 2013.

VRE forecasting has become an indispensable tool for system operators in grids with modest to large amounts of VRE, with and without a real-time power market. The focus of this white paper is on emerging VRE markets with no real-time power market. In such markets, VRE forecasting improves the core functions of system operations: unit commitment, economic dispatch, real-time balancing of supply and demand, and reserves planning. Indeed, VRE forecasting is part of a portfolio of tools and processes that enable the greening of the grid.[2]

For countries that are new to VRE or have not implemented a comprehensive VRE forecasting program, a road map informed by best practices should include:

- Development of policy and regulatory design;
- Addition of VRE forecasting requirements to the grid code;
- A centralized VRE forecasting system pilot project;
- Migration to faster dispatching; and,
- Improvements in weather forecasting.

Since VRE is likely to be a primary source of generation soon, it is recommended that these countries adopt VRE forecasting as a key tool for integrating new or additional VRE into the grid.

[2] Other tools and processes included in the portfolio are fast dispatching (short lead time and short dispatch interval) processes, higher accuracy load forecasting and conventional generation scheduling, demand response, and a variety of market incentives.

INTRODUCTION

Power systems operate by instantaneously balancing supply and demand. Every power system contains uncertainty and variability, such as daily/hourly/moment-by-moment variations in load and the uncertainty associated with unplanned generator or transmission outages. Energy output from wind and solar generators can increase this variability and uncertainty, since wind speed and solar irradiation depend on inherently variable and uncertain weather conditions. Integrating a small amount (two percent to five percent of peak load) of VRE into an electricity grid may have little to no impact, but larger amounts of penetration can become challenging from the standpoints of grid management, reliability, and stability. However, given that VRE prices are falling and the cost of production is reaching grid parity, VRE penetrations will inevitably increase.

The forecasting of VRE generator output, referred to as VRE forecasting, is the act of predicting generator output on a day-ahead (DA) or intraday basis. This information is used by the system operator in making scheduling and dispatch decisions. VRE forecasting has now emerged as a cost-effective method that system operators deploy to reliably and economically integrate higher penetrations of VRE on the grid. VRE forecasting makes four key contributions:

REDUCES RESERVE REQUIREMENTS. By forecasting VRE generator output and incorporating these forecasts into dispatching decisions, there is a significant decrease in additional reserve requirements. The more accurate the VRE forecast and the faster the dispatch interval, the greater the reduction in reserve requirements. This is because regulating reserves are required to manage deviation between dispatched generation and demand, and with no forecasting the deviations are larger. Through VRE forecasting, this deviation can be reduced, leading to a reduced reserve requirement.

IMPROVES SYSTEM FLEXIBILITY. VRE forecasting enables the exploitation of the flexibility of the entire generation fleet, which is often unutilized or underutilized. Conventional (baseload) fossil fuel–based generators are typically operated without flexibility, and any changes in output must be scheduled DA. With no VRE forecasting, this generation flexibility cannot be exploited; instead, the burden falls on the more expensive spinning reserves (often non-baseload, fossil-based plants).

REDUCES CURTAILMENT. A grid operator may choose to curtail VRE generation under certain conditions, such as when the load is low, VRE production is high, the conventional baseload generators are operating at scheduled levels, and the remaining load-following generation fleet is operating at minimum output. In these situations, DA and intraday VRE forecasting allow the scheduling of inflexible conventional generators at the lowest allowable levels in anticipation of peak VRE generation, resulting in a far smaller amount of VRE curtailment.

INCREASES RELIABILITY. Higher penetrations of VRE generation can cause congestion, more area control errors, and sharp downward ramping of VRE (due to sudden cloud cover or reduction in wind resources). These can cause reserves to be overloaded and, in extreme situations, lead to reduced grid reliability. When sub-hourly (for example, five minutes) VRE forecasting is combined with fast dispatching systems, system operators can use the flexibility of all the generators to ensure reliable operations.

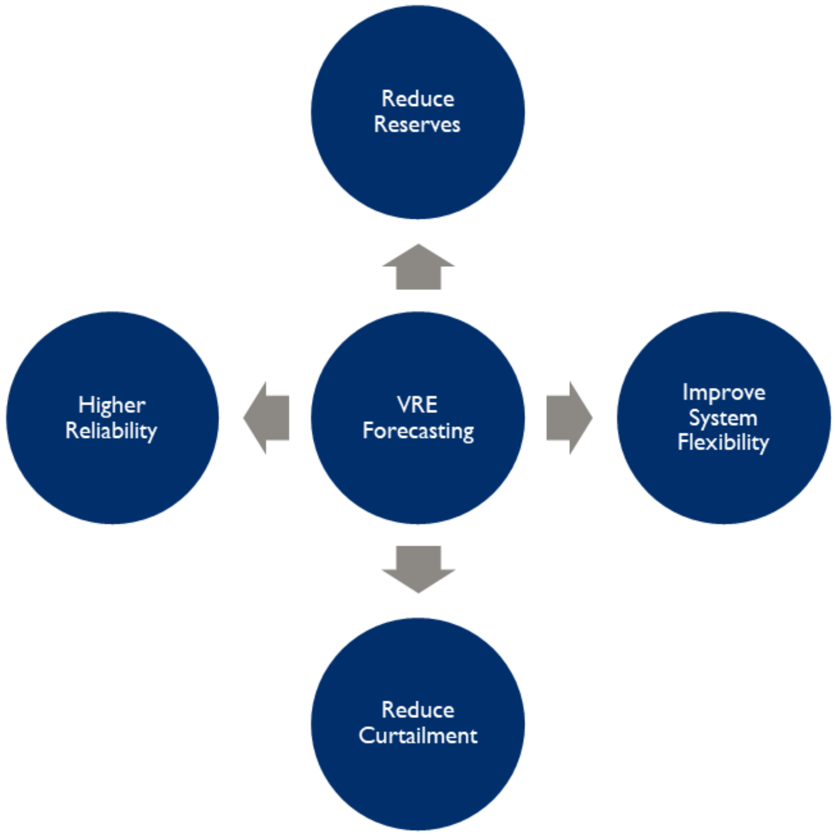


Figure 1. The Benefits of VRE Forecasting

The benefits of VRE forecasting are now well documented, and an increasing number of high-VRE countries have adopted policies and regulations to guide forecasting, while rethinking all aspects of system operations that are related to dispatch and reserves planning. In most cases, the goal of this effort is to maximize the contribution of non-fossil-based generation, leading to the maximization of grid flexibility. This paper explores the status of VRE forecasting and develops a best practice-based approach for emerging markets.

WHAT IS VARIABLE RENEWABLE ENERGY FORECASTING?

VRE forecasting is the short-term prediction of future VRE power plant output, generally on week-ahead (WA), DA, or intraday (ID) timescales. Examples of ID time intervals are hour-ahead (HA), 15 minutes-ahead (15MA) and five minutes-ahead (5MA); the duration, or time-horizon, of ID forecasting may be for the following few hours or through the end of the day.

The purpose of VRE forecasting is to support system operators in performing dispatch planning. The purpose of dispatch planning is to develop a schedule that balances generation with load, while managing appropriate amounts of reserves (Figure 2).

This schedule covers production from all generators, power exchange with neighboring utilities, a schedule of sales/purchases from the market (or electricity exchange), and a schedule for reserves.

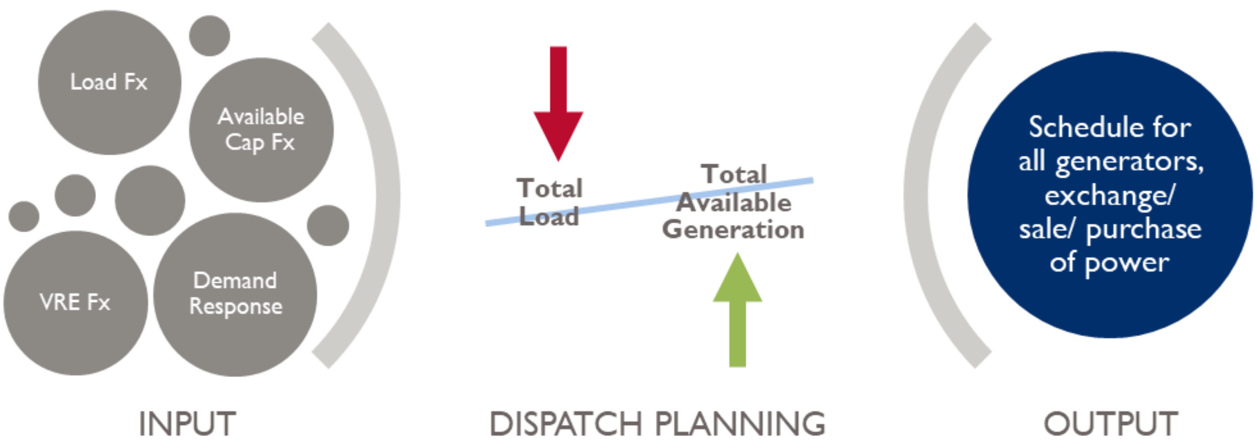


Figure 2. Illustration of Dispatch Planning

Key inputs required for dispatch planning are the forecast of load, available capacity of all generators, demand response, cost-capacity curves of generators, minimum operating capacity of generators, and the subject of this paper—forecasted output from VRE generators. In addition to the input forecast data, which are updated regularly (say every five minutes), many cost and other contractual static data are used as inputs.

The term “fast dispatching” describes five-minute or shorter dispatch intervals. Typically, dispatching that is shorter than five minutes is done only under certain grid conditions.[3] Most grids in the United States dispatch in five-minute intervals; however, other common intervals around the world include 15-minute and hourly dispatching.

[3] http://www.caiso.com/market/Pages/MarketProcesses.aspx.

DEFINITIONS

FORECAST TIME BLOCK is the granularity of the forecast, which is the smallest time interval for which the forecast is created. For example, if the forecast time block is 15 minutes, then the forecast is for the following time intervals: 00:00-00:15, 00:15-00:30, and so on. Other commonly used forecast time blocks are 30 minutes and one hour.

FORECAST TIME HORIZON is the span of the forecast into the future, which is the total duration for which the forecast is created. For example, if the time horizon is one day and the time block is 15 minutes, then the forecast is for the following intervals: 00:00-00:15, 00:15-00:30, …, 23:45-00:00. Such a forecast would generate predictions for 96 (=24 hours x 4 blocks per hour) time blocks. Other commonly used forecast time horizons are WA and ID.

FORECAST LEAD TIME is the amount of time between the forecast's first time block and the forecast submission time to the system operator. For example, if the dispatch center requires that a DA forecast be submitted by 10:00 a.m., then the lead time is 14 hours (=0 hours of the next day – 10 a.m. of today).

FORECAST REVISION is the process of altering a forecast, which is typically done in response to changes in weather conditions. For example, regulations in India allow one forecast revision of a DA forecast per time block. The revision must be submitted with a lead time of at least one hour. In most markets, hourly forecast revisions are allowed. This is also called intraday forecasting.

The above concepts are illustrated in Figure 3, where the forecast for all time blocks of day 1 is submitted at 10 a.m. on day 0.

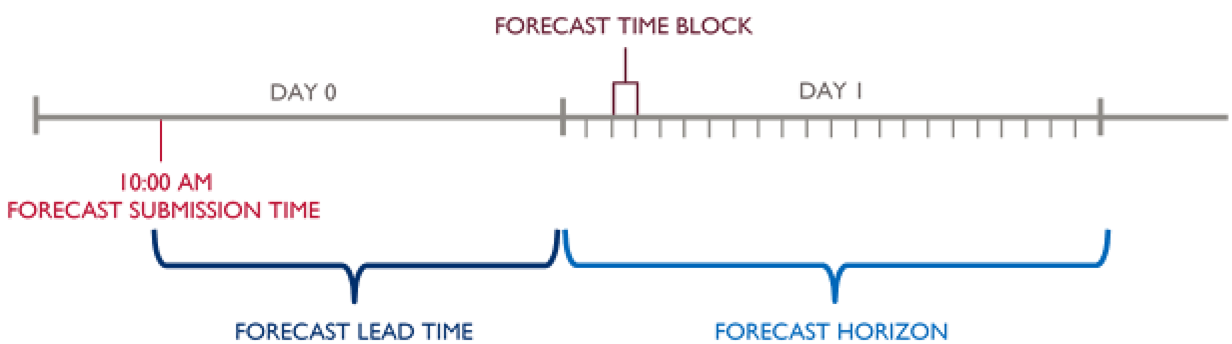


Figure 3. Illustration of the Forecast Terminology

FORECAST ERROR is a measure of the deviation between the predicted and the actual. There are three popular measures of forecast error:

- *Root Mean Square Error (RMSE)*, where t is a time block, f_t is the forecast for time block t, a_t is the actual observation for time block t, and n is the number of time blocks for which the error is computed.

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}(f_t - a_t)^2}{n}}$$

- *Mean Absolute Deviation (MAD)*, where $|f - a|$ is the absolute value of the difference between the forecast and the actual observations. RMSE is always greater than or equal to MAD. Large differences between RMSE and MAD indicate larger variances between individual deviations.

$$MAD = \frac{\sum_{t=1}^{n} |f_t - a_t|}{n}$$

- *Mean Absolute Percent Error (MAPE)*, where C is the available capacity of the VRE facility, and available capacity = installed capacity – capacity under maintenance.

$$MAPE = \frac{MAD}{C} \times 100$$

THE PROCESS OF VRE FORECASTING

The inputs to generate a VRE forecast include weather forecasts, historical data, generator details, and generator availability. The output—the VRE generation forecast—is the predicted generation for the desired time blocks and time horizon. The generation forecast may be an energy forecast (in kilowatt hours (kWh) or megawatt hours (MWh)) or power forecast (in kilowatts (kW) or megawatts (MW)). The inputs and outputs are illustrated in Figure 4.

WEATHER FORECAST is the primary input. For wind energy, forecasts of the following weather parameters are of interest: wind speed, wind direction, and air density—all preferably at the generator hub height. For solar energy, forecasts of the following weather parameters are of interest: irradiation, temperature, cloud cover, and precipitation.

HISTORICAL DATA pertaining to generation and weather are the second input and are used in algorithms to infer seasonality, trends, and conditions in the immediate past.

GENERATOR PLANT DETAILS are static data about the VRE generating plant, such as total installed capacity, number of units (number of wind turbines for wind plants or number of inverters and number of modules for solar plants), the capacity, latitude/longitude, and characteristics of each unit (power production versus wind speed, power production versus solar radiation and temperature), overall plant losses, on-site weather measurement stations (list of parameters measured), and others.

GENERATOR AVAILABILITY FORECAST is the last input and is the amount of installed capacity[4] available for production for each time block in the forecast horizon. This input is provided by the VRE generation facility and depends on the scheduled and unscheduled maintenance of the VRE plant, planned curtailments, and other factors. The inputs and outputs are the same regardless of whether the VRE forecast is plant-level or substation level. For the substation level, the VRE forecast would require input data from each of the connected VRE plants.

[4] In some cases, VRE plant developers will install a plant with capacity that is higher than the capacity contracted with the interconnecting utility or transmission provider. In such cases, the maximum amount of power this plant can inject is the contracted capacity. Hence, the generator availability forecast should be contracted capacity minus capacity under maintenance.

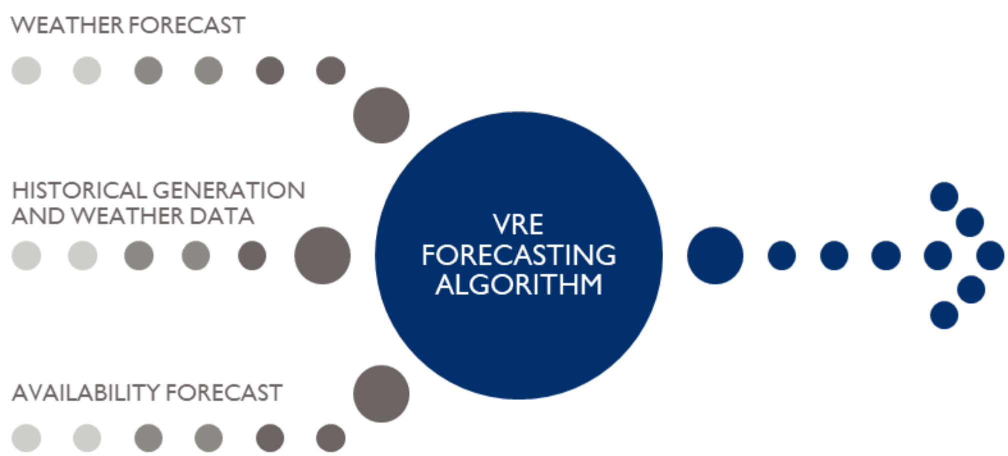


Figure 4. Inputs and Output of the VRE Forecasting Process

TYPES OF FORECASTING MODELS

VRE forecasting is essentially an exercise in converting weather forecast data (*i.e.*, appropriate meteorological variables) into a prediction of the power or energy generated by the available capacity of a VRE power plant. Weather forecast data are typically obtained from a variety of meteorological services or in-house numerical weather prediction (NWP) systems. NWP systems typically consist of three layers: global weather forecasts, downscaling, and statistical bias removal.

Global weather forecasts are produced by the Global Forecast System (GFS) of the U.S. National Centers for Environmental Prediction,[5] European Center for Medium Range Weather Forecasting System,[6] Unified Model of the UK Met Office,[7] and others. These low-resolution forecasts are then downscaled to finer spatial and temporal resolutions with detailed terrain and roughness information, using tools like Weather Research and Forecasting (WRF)[8] to create higher-resolution weather forecasts. The final layer of processing is statistical bias removal in which downscaled weather data are statistically corrected with ground-based measurements. In the case of wind generation, the accuracy of forecasts of wind speed and direction at each turbine location and at hub height are key to accurate generation forecasts. Similarly, the accuracy of tilted global solar irradiance and temperature at the photovoltaic (PV) panel location are key to accurate solar power generation forecasts.

Since real-time and location-specific weather forecasts are computationally expensive and often inaccurate, two approaches have emerged for energy generation forecasting: statistics-based and physical model–based.[9] In statistical models, it is assumed that weather forecasts of the desired characteristics (*i.e.*, exact location, hub height, tilt global irradiance) are not available, but a close approximation is available. For example, a global model may report the wind speed and direction forecast for a grid point that is eight kilometers from the desired location and at a height of 50 meters. In the statistics-based

[5] https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-forcast-system-gfs.
[6] https://www.ecmwf.int/.
[7] https://www.metoffice.gov.uk/research/modelling-systems/unified-model/weather-forecasting.
[8] https://www.mmm.ucar.edu/weather-research-and-forecasting-model.
[9] Zieher et al., 2015.

model, a relationship between the past weather forecast (from a global model) and past VRE generation is derived using historical data, and this model is then used with weather forecasts as input to generate VRE generation forecasts.

In the physical model–based approach, the focus is on obtaining weather forecasts of the desired characteristics using sophisticated meteorological models that cover the region where plants are located. Transfer functions are then applied to these forecasts to produce output generation forecasts. In the case of wind, the transfer function is the power production curve of the wind turbine; in the case of solar, it is the PV production curve.

Most system operators and VRE plant operators procure licenses to one or more VRE forecasting tool(s) or subscriptions to VRE forecasting software-as-a-service(s). In both cases, forecasters have access to a suite of generation forecasting algorithms and integration with multiple weather forecasting services. A list of VRE forecasting tool vendors is presented in Appendix C.

The Wind Power Prediction Tool[10] is an example of a statistical model, and Previento[11] is an example of a physical model. In most cases, a mix of statistical and physical models is used for VRE forecasting.

ACCURACY OF VRE FORECASTING

The following properties of VRE forecasting are useful to keep in mind when creating policy or designing detailed processes for integrating VRE forecasting into system operations:

- The accuracy of a VRE forecast improves with shorter forecast time blocks and reduced lead time, which is also called faster forecasting.[12] Only a grid with fast dispatching can capitalize on the higher accuracy from faster forecasting.
- The accuracy of the aggregated VRE forecast for the entire system increases as the number of VRE plants and the geographical diversity increase.
- The amount of total regulation required depends on both VRE forecast accuracy and dispatch interval; greater accuracy and faster dispatch intervals lead to the need for fewer regulating reserves.
- The accuracy of the VRE forecast depends primarily on the accuracy of both the weather forecast and available capacity forecast data (scheduled and unscheduled maintenance and expected downtime).

Figure 5 illustrates the reduction in average total regulation (MW) described in the first three items: the total regulation needed decreases with faster dispatch and shorter forecast lead time. The relative reduction will vary for each system.

[10] http://henrikmadsen.org/software/wppt/.
[11] https://www.energymeteo.com/products/power_predictions/wind_power_prediction.php.
[12] Bird et al, 2013.

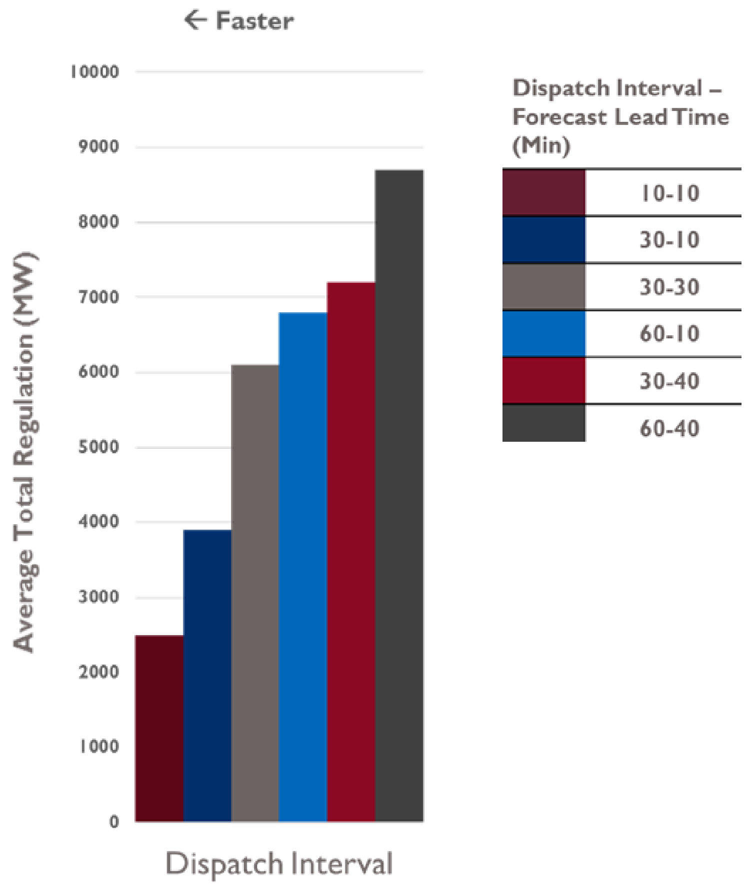


Figure 5. Illustration of Decrease in Average Total Regulation Reserves

VRE FORECASTING ECOSYSTEM

There are three types of VRE forecasting systems: centralized, decentralized, and hybrid.

IN CENTRALIZED FORECASTING, the system operator generates a forecast for all VRE generation on the system. In most cases, the forecasting is done for aggregate renewable energy generation at transmission pooling substations. The California Independent System Operator (CAISO) has adopted this approach. Its advantages include a consistent forecasting methodology, greater accuracy, and economies of scale. Since the cost of forecasting is spread across many VRE projects, investments can be made on sourcing higher-quality weather data from multiple providers and continuously improving the forecasting method, thereby leading to greater accuracy. In addition, errors are smoothed out because of geographic diversity, because forecasts are for all VRE plants in the system. This method of forecasting may be less expensive if there are a larger number of VRE plants and the cost is shared by the plants on a per MW basis.

IN DECENTRALIZED FORECASTING, individual VRE generators are required to submit forecasts to the system operator. Decentralized forecasting leads to diversity in forecasting algorithms/tools and weather sources, which in effect creates an ensemble forecast when the individual plant forecasts are aggregated by the system operator. In addition, if the incentives are properly set up for generators to produce accurate forecasts, then the decentralized approach can lead to higher accuracy due to (1) more innovation, (2) more accurate modeling of local weather phenomenon and equipment performance, and (3) better ensemble forecasts compared to the output of a limited ensemble of a centralized system. This type of forecasting is likely to incur higher system-wide costs because each VRE plant would individually bear expenses.

IN A HYBRID APPROACH, a combination of centralized and decentralized forecasting is used. For example, in India, the regulator requires the state load dispatch center (SLDC) to produce a DA or ID forecast at the transmission pooling substation level, and that all eligible VRE plants submit a forecast to the SLDC. The SLDC uses its forecast to produce schedules/dispatches for each VRE plant. The VRE generator then has the option of using the schedule from SLDC or its own forecast as the generation schedule. The effectiveness of the hybrid approach has not been fully evaluated in India, as it was only introduced in July 2018. In the United States, all regional transmission operators and independent system operators (RTO/ISO) use centralized forecasting, while some individual VRE plants generate forecasts for market offers.[13]

HOW ARE VRE FORECASTS USED IN SCHEDULING AND DISPATCH DECISIONS?

The most common forecast horizons are DA and intraday, and the time block is one hour or less. The system operator uses the DA VRE forecast to generate a security-constrained unit commitment (SCUC) for all generators in the grid, and a schedule for power transfers, purchases, and sales from neighboring grids. SCUC is the least-cost solution that specifies which generators should be online. "Security-constrained" means the plan respects all constraints (*e.g.*, the limitations of the transmission system and the operating characteristics of all the generators).

Security-constrained economic dispatch (SCED) is the more granular-level plan generated by the system operator near execution time (*e.g.*, SCED may be generated one hour ahead of execution time). SCED uses the intraday VRE forecast. It specifies the amount of generation that is assigned to each committed generator. Additionally, SCED specifies the amount of power that should be exchanged with neighboring grids and bought and sold on the electricity market. Another output of SCED is a schedule of primary, secondary, and tertiary reserves. Most modern systems do SCUC and SCED simultaneously, so depending on the time horizon for a SCUC and SCED run, DA or intraday VRE forecasts are used.

VRE forecasts are used by SCUC and SCED as a fixed schedule for power that should be dispatched with high priority. VRE has the lowest marginal cost of production because there is no fuel cost, and the operations and maintenance (O&M) cost attributable to each unit of production is low (normally less than $0.01 per kWh). Given this, VRE becomes the lowest-cost, must-run generation. Thus, dispatching is done for "net load," which is the difference between the load forecast and VRE forecast. Exceptions arise when the system operator assigns a negative marginal cost to large inflexible fossil-fuel or nuclear generators (traditionally called baseload generators) because the cost of shutting down and restarting them is so high that these plants are given the highest dispatch priority.

Large errors in VRE forecasts cause the SCUC- and SCED-generated dispatch to rely on more expensive options, such as (1) use of reserves, which is the most expensive form of generation; (2) changes to generator schedule, which lead to higher fuel and O&M costs because of unplanned deviations in schedule; (3) last-minute purchases of power at a high price; (4) last-minute sales of power

[13] Ahlstrom, Mark, 2016.

at a low price; (5) curtailment of VRE; and (6) in extreme cases, brownouts. Poor forecasting accuracy increases the cost of operating the electricity grid. In the rest of this paper, "dispatching," "dispatch planning," and "economic dispatch" will be used synonymously with SCUC and SCED.

In U.S. grids with large penetrations of VRE, system operators are starting to treat wind and solar plants as dispatchable during SCUC and SCED planning. The system operator optimizes the whole system by using the VRE forecasts to compute a dispatch for the VRE plants that is less than or equal to the individual VRE plant's forecast. In this mode of planning, the concept of net load is irrelevant because VRE plants are treated as dispatchable.

SYSTEM ARCHITECTURE OF VRE FORECASTING

A high-level architecture of the operational, information, and communication systems is shown in Figure 6 (this diagram presents only those systems and data transfers that are relevant to this report). The most common communication protocol used for data transfer from plants to the system operator is the Representational State Transfer Application Programming Interface (REST API). A plant's systems consist of:

- **Operational systems to collect data** use real-time power production parameters from individual turbines, inverters, revenue meters, and a variety of plant sensors and diagnostics systems. These systems send data to the central plant Supervisory Control and Data Acquisition (SCADA) system.
- The **weather measurement station** collects weather parameters from a variety of sensors that are of interest to the wind or solar plant. These data are sent to the centralized SCADA system.
- The **plant availability forecasting system** combines data from the following to deliver a prediction of the block-wise total available capacity out of the total installed capacity of the plant: (1) data from the SCADA system on the operating status of individual units of the VRE plant, (2) maintenance schedule, and (3) estimated time of completion of ongoing scheduled and unscheduled maintenance.
- The **VRE forecasting system** can be a decentralized regime, with forecasting occurring only in the VRE plant; a centralized regime, with forecasting only in the system operator; or a hybrid regime, with forecasting existing in both.
- The **plant IT system** is responsible for managing the secure transfer of data from the plant systems to the system operator (among other things). The data streams would include VRE forecasts for future time blocks, changes to the plant availability forecast, plant production in the previous time block, and plant weather parameters in the previous time block. The most common standard for data communication is REST API.
- **Weather forecasting services** provide predictions of weather parameters of interest for future time blocks. The most commonly used data transfer protocol is REST API.

- The **data ingestion system** is part of the system operator's IT system for ingesting multiple data streams from multiple plants. It manages the interface with plant systems and the insertion of the incoming data into the system operator's data store.

- **SCUC and SCED systems** are short-term planning systems described in the previous section.

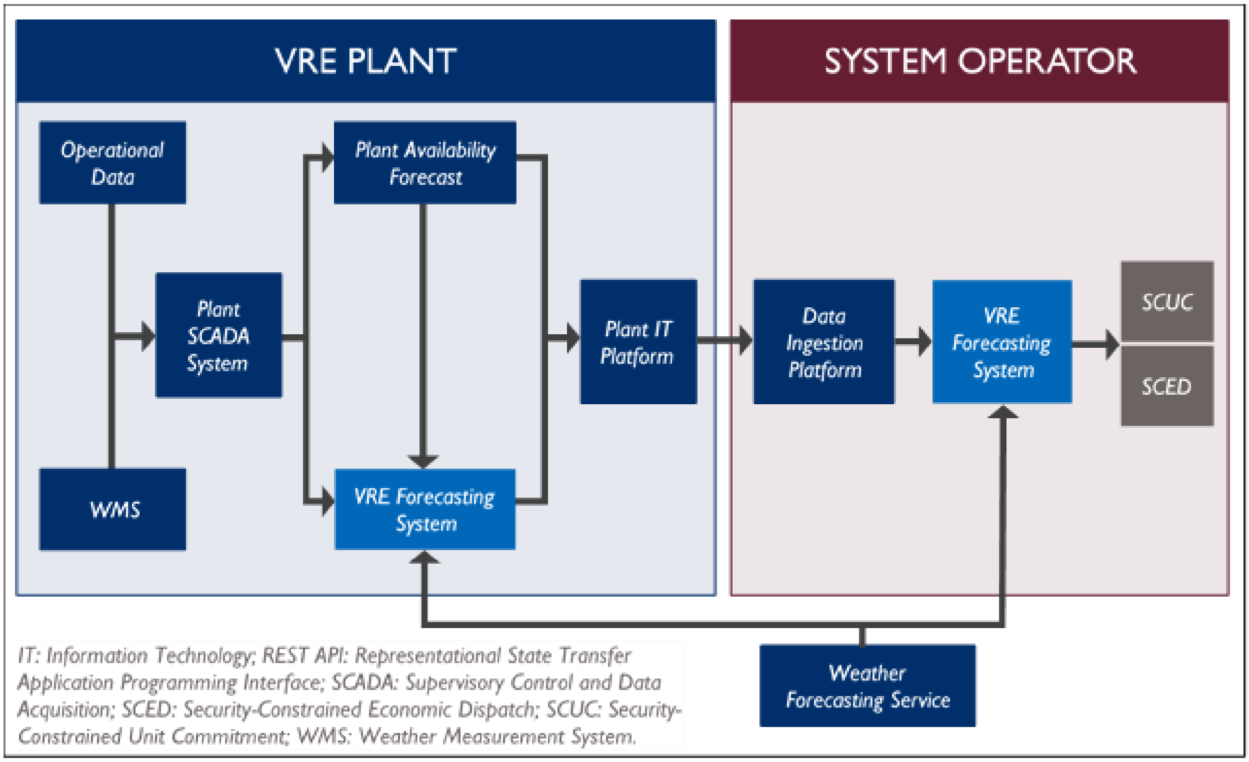


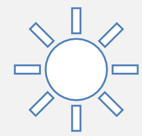
Figure 6. Operational Technology, Information Technology, and Communication Architecture of the Major Forecasting Components.

ILLUSTRATIVE EXAMPLE: USING THE SHORT-TERM UNCERTAINTY OF VRE FORECASTING TO IMPROVE DISPATCHING AND RESERVE PLANNING

Consider an example of solar generation forecasting done at 6 a.m. for time blocks between 10 a.m. and 10:15 a.m. under two weather forecasts:

Forecast 1: 40 percent chance of thunderstorms

Forecast 2: Clear skies



For the two cases, assume that a VRE forecasting algorithm produces a generation forecast of 70 MW and 100 MW, respectively. In most systems, the most likely estimator of VRE forecast is sent to dispatching and the fact that the first forecast has higher uncertainty is not captured. Hence, the information about uncertainty is not used in dispatching.

Sophisticated dispatching methods use the uncertainty associated with the weather forecast to plan dispatching and reserve capacity. Forecast uncertainty is expressed in terms of the standard deviation associated with the estimation. If the forecast of VRE generation is assumed to be distributed normally, then:

- Probability that generation > mean of the forecast is 50 percent
- Probability that generation > (mean minus standard deviation) is 84 percent
- Probability that generation > (mean minus 2x standard deviation) is 97.7 percent
- Probability that generation > (mean minus 2.33x standard deviation) is 99 percent

This approach, which uses exceedance probabilities, should form the basis for planning reserves. As an illustration, consider a grid with 15-minute time block dispatches that has, for a specific time block, 1,000 MW of load and a VRE generation forecast of 100 MW. Further assume that the load uncertainty is three percent of mean load and the VRE forecast uncertainty is five percent of the mean generation forecast. In this case, mean VRE generation = 100 MW, and standard deviation = 5 MW. A dispatch schedule that plans for 11.65 MW (= 2.33 x 5 MW) of reserves would yield a 99 percent probability that the planned generation would meet the average load.

In this simple illustration, it was assumed that the reserve is exclusively assigned to VRE generation; however, that is never the case. The grid plans for reserves across all generation while considering the uncertainty of load and all types of generation. In this illustration, three percent uncertainty in load would require a grid to plan for 70 MW (= 2.33 x 1,000 x 3%) of reserves. Here, the reserve requirement for load is much higher than for VRE generation.

In most grids, the reserves required for VRE are subsumed in the reserves required due to load uncertainty, and any additional reserves required because of VRE are small. As a final note, grids perform extensive probabilistic simulations to arrive at the amount of reserves that should be scheduled for different values of forecasted VRE generation.

VRE FORECASTING AT THE DISTRIBUTION LEVEL

VRE plants at the distribution level include all VRE generation resources that are connected to the distribution network, including those connected to businesses and homes. Central dispatchers face significant challenges with VRE generation at the distribution level because in most grid codes and regulations, VRE plants are not required to register with the system operator or submit a forecast to the dispatch center. For lower levels of distributed VRE penetration, the approach of forecasting net load is acceptable. However, for greater VRE penetration, the accuracy of net load would be poor without explicitly forecasting VRE generation from all generators on the distribution network. As prices of solar PV fall, this problem will become acute because of the large numbers of small PV installations.

The net load approach also presents challenges in deregulated markets where generation is settled at the nodal price and load is settled at the zonal price (*i.e.*, tariff paid by customers). This problem is still being discussed in mature markets—no clear solution is in sight yet that stakeholders can agree upon. It is therefore imperative to develop VRE forecasting models to account for VRE at the distribution level, and to develop regulations requiring the registration of all VRE generation.

WHY IS VRE FORECASTING IMPORTANT FOR GRID INTEGRATION OF VRE?

WHY IS VRE FORECASTING A KEY COMPONENT OF "SYSTEM FLEXIBILITY"?

One of the key enablers of increasing VRE penetration in a grid is system flexibility. Flexibility is a system's ability to respond to the variability and uncertainty of supply and demand.[14] Greater system flexibility can be achieved in several ways. Figure 7 illustrates different options for increasing grid flexibility with relative cost.[15]

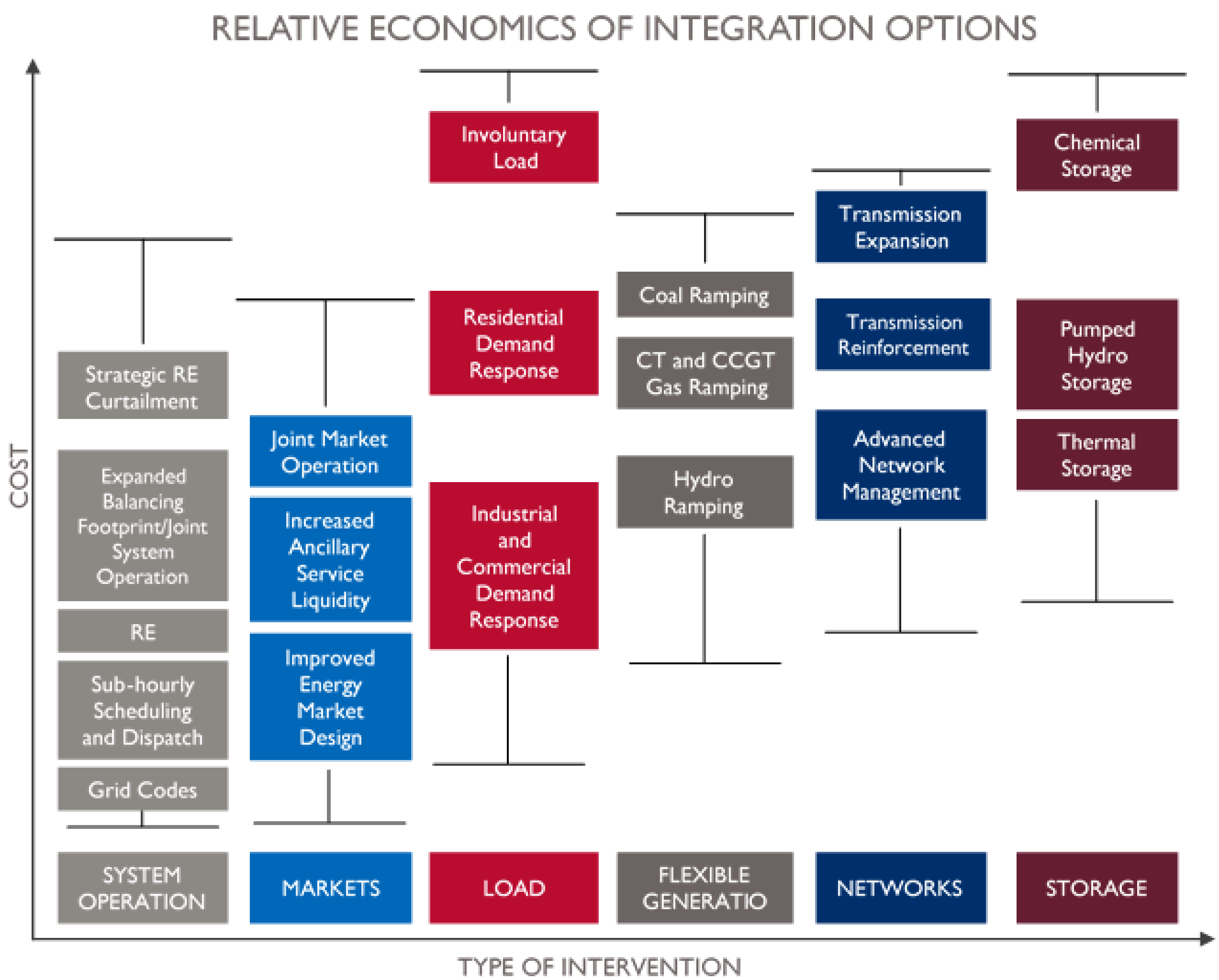


Figure 7. The NREL Flexibility Matrix

Making changes to system operation (and, within it, VRE forecasting) is the most cost-effective way to enhance system flexibility. As explained in in the following section, VRE forecasting, along with SCUC and SCED, provides the blueprint for exploiting the full flexibility of conventional generation at the lowest cost and without sacrificing system reliability.

[14] https://www.nrel.gov/docs/fy16osti/64864.pdf.
[15] Cochran et al., 2014.

It is important to note that VRE forecasting is an enabler; it alone does not enhance grid flexibility. Instead, it needs to be used intelligently with the other components. For instance, enhanced system flexibility requires a combination of VRE forecasting, short dispatch intervals, and sufficient conventional fleet flexibility—the ability of generators to change output levels several times a day in a short amount of time in accordance with signals from SCUC and SCED.

HOW DOES VRE FORECASTING AFFECT MARKET OPERATIONS?

Fast market operations—scheduling and dispatching with a frequency of five minutes or less—significantly improve grid flexibility and allows increased VRE penetration. Fast VRE forecasting within fast market operations yields lower amounts of reserves and less curtailment of wind power. Figure 8 illustrates a case study from the Bonneville Power Authority (BPA) in the United States, in which fast market operations are able to accurately follow load and generation changes while using fewer spinning and supplemental reserves.[16] Similarly, the ERCOT moved from 15- to 5-minute dispatches and achieved a significant reduction in wind power curtailment.[16]

VRE forecasting is key for VRE generators' full participation in DA markets. Accurate VRE forecasts enable these generators to schedule production in the DA market with a reasonable amount of certainty. Since intraday fast VRE forecasting is much more accurate, a better alternative is to combine it with DA forecasting. The latter type of forecasting allows the inflexible conventional generators to be scheduled ahead of time at appropriate levels of dispatch, while allowing enough room for VRE. Intraday fast VRE forecasting allows for the continuous update of generation schedules and specifically allows the flexible generators to be dispatched while ensuring there is minimal imbalance between dispatched generation and anticipated load. It also allows for trading of VRE in real-time markets.

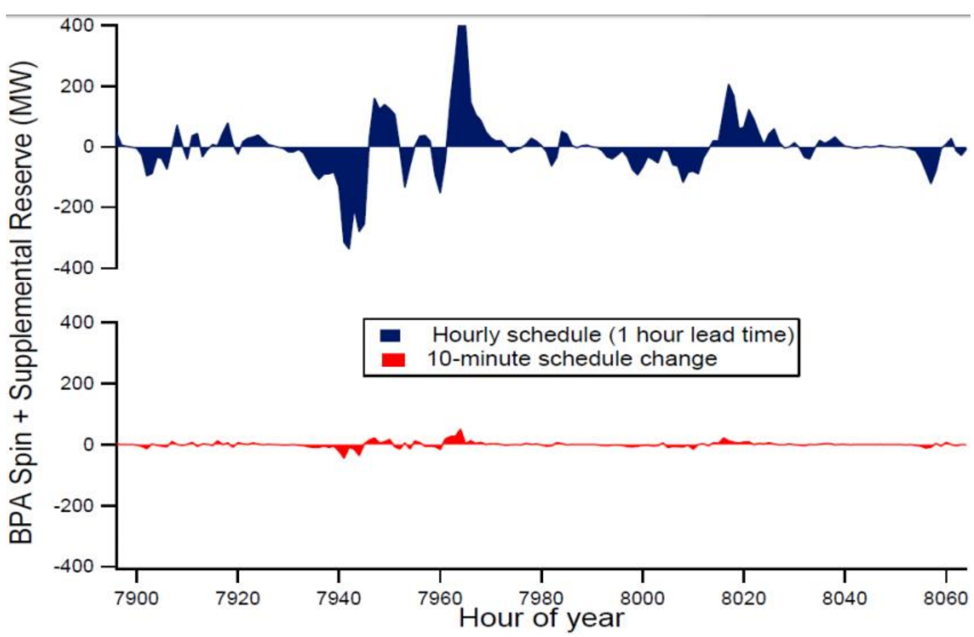


Figure 8. Impact of Fast Schedule and Dispatching on Reserve Requirements (Illustration from a case study of scheduling wind in the Bonneville Power Authority system (Bonneville Power Authority)).

[16] https://www.nrel.gov/docs/fy14osti/60983.pdf

BEST PRACTICES IN VRE FORECASTING

The current best practices for VRE forecasting are derived from experiences and lessons learned from grids that are successfully operating with high penetrations of VRE. The best practices are presented in six categories:

1. Early Actions
2. Policy and Regulatory Design
3. Data Provision in Grid Code Interconnection Requirements
4. Centralized Forecasting
5. Operationalization and Fast Dispatching
6. Improved Meteorological Services

EARLY ACTIONS

Activities proposed for system operators who are new to VRE forecasting include:

- Conduct a pilot by inviting the leading VRE forecasting vendors to participate. In preparation for the pilot, the system operator should:
- Design a preliminary DA and intraday forecasting process that specifies time block, lead time, and horizon;
- Seek the participation of VRE plant owners, who would provide historical and real-time production and weather data, as well as plant availability forecasts; and,
- Set up IT systems to receive the data from the forecasting vendors and VRE plant owners, compute the forecasting errors, and compare the vendors.
- After the pilot is completed, initiate centralized forecasting with a vendor chosen from the pilot.
- Integrate VRE forecasting with the current SCUC and SCED planning processes. Reduce the planning cycle and dispatching period only after sufficient experience has been gained with the entire process.
- In the VRE interconnection guidelines, develop a section on VRE forecasting in which the requirements for data exchange related to VRE forecasting are specified. This would include data types, frequency of transfer, data transfer protocol, and others.

POLICY AND REGULATORY DESIGN

VRE forecasting is imperative, even for grids that have a modest amount of VRE in the system.[17] The policies and grid codes that pertain to VRE should specify (1) design details like centralized/ decentralized/ hybrid, forecast time block, horizon and lead time for DA and intraday and others, as described earlier, and (2) the obligations of these plants to provide the data required for VRE forecasting, as described below.

[17] U.S. Agency for International Development and National Renewable Energy Laboratory, 2016.

Policies and regulations should take a broader view of system operations because other aspects need updating. VRE forecasting policy in isolation is not effective unless it is synchronized with the requirements for forecasting load, faster dispatching, and others that increase grid flexibility, such as demand response, pricing of ancillary services, and pricing for curtailment.

Policymaking can take a significant amount of time; this process should be started early. In India, it took the Central Electricity Regulatory Commission (CERC) about two years to develop, finalize, and implement its VRE forecasting policy. For countries that are embarking on VRE forecasting policy development, Figure 9 provides an outline of the steps.

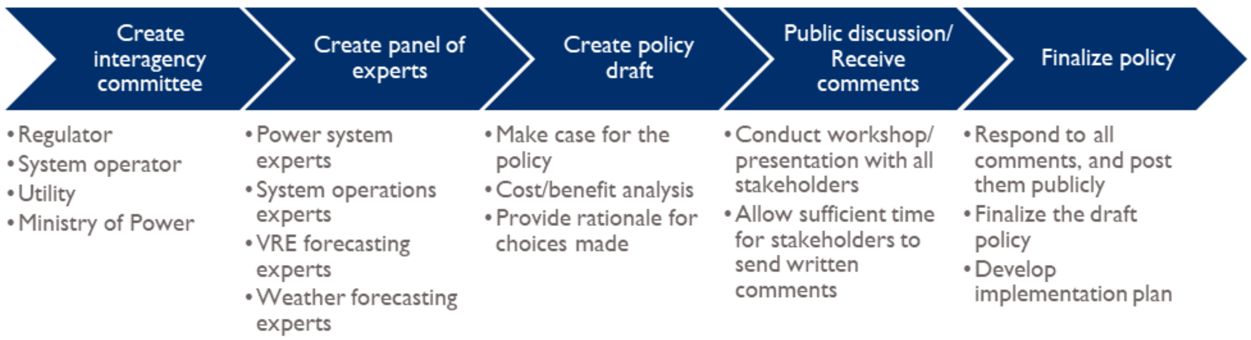


Figure 9. Outline of the Process for Formulating Policy for VRE Forecasting

DATA PROVISION REQUIREMENTS IN VRE INTERCONNECTION REQUIREMENTS

As VRE interconnection requirements are normally an attachment to the power purchase agreement (PPA), the requirements should become a specification in the design of the data collection and communications infrastructure of the VRE plant. VRE plants should be obligated to provide the data described below for VRE forecasting (and should follow the operationalization procedures described in the Operationalization and Fast Dispatching section of this paper:

- **Master data on the plant** (or static data) such as total installed capacity, capacity of each generator, physical and technical properties of each generator (wind turbine or PV module), geographic location, point of interconnection, and expected annual average energy production. Note that this is not just for utility-scale VRE plants but also for smaller commercial and residential units. As has been observed in southern Germany, the penetration of rooftop solar PV has reached a level that leads to a reverse flow of energy—the flow from distribution to the transmission system. If system operators are unaware of all the generation in the grid, they will be handicapped in their efforts to manage reserve requirements and plan the dispatch of generators in the most economical manner.

- **Near real-time data to system operators** like power production (active and reactive), renewable energy resource (wind speed and direction or solar radiation and temperature), available capacity, curtailment, and other data, for each time block. The VRE plant owner should also be required to provide the available capacity forecast for the time blocks that correspond to WA and DA forecasts, which would inform the system operator about the maintenance schedule and when equipment currently under maintenance will be available to generate power. VRE plants should be required to provide such data using direct data transfer methods like web-based application programming interfaces. If centralized forecasting is adopted, the best practice is to implement a SCADA feed from VRE plants to provide (1) available capacity forecasts, which may be in the form of start and finish times of scheduled and unscheduled maintenance; (2) active and reactive power production in the past time block; and (3) weather parameters from on-site weather measurement station(s).

CENTRALIZED FORECASTING

Centralized forecasting by the system operator is a best practice. The primary benefit is that the entity that uses the forecast is the one that generates it, which should lead to a tight integration between the VRE generation forecast and SCUC and SCED. The tight integration should allow the dispatcher to make better decisions. As an example, a centralized forecasting system that generates a generation forecast containing not just the mean value but also the uncertainty would be immensely useful and effective. Uncertainty provides information about the level of confidence in the forecast, which can be used to better plan dispatches.

For instance, if the forecasting model indicates that the forecast uncertainty is skewed towards the lower side (that is, the probability is much higher that the generation will be lower than the mean), then the dispatcher may plan for large amounts of up-reserves. Although it is possible to obtain information like uncertainty and skewness in decentralized systems, it is difficult to ensure consistency and quality unless all VRE plants are required to use similar methods of forecasting. The other advantages of centralized forecasting include (1) the ability to dedicate more resources to procure multiple high-quality weather forecasts; (2) the ability to hire the right mix of personnel; and (3) the ability to experiment with a larger number of algorithms to ultimately significantly enhance the quality of the forecast—something that a typical VRE plant owner cannot do.

To accomplish centralized VRE forecasting, the system operator should conduct a pilot with multiple vendors and choose one based on results of the pilot. Homegrown or software bootstrapped from open source components is not a recommended solution for most system operators because of the very high level of skill and expertise required for such a system. The vendor's solution chosen for this task should bundle weather services, algorithms for forecasting, detailed reporting, and data integration with the system operator's dispatching systems.

OPERATIONALIZATION AND FAST DISPATCHING

This best practice deals with detailed timelines, desired accuracy, penalties, and other aspects of operationalizing VRE forecasting. Given that VRE forecasts are more accurate as the time horizon shrinks, it is imperative that system operators move to faster dispatching in which the forecast interval and lead time are short and multiple revisions to forecasts are required. Forecasts for short time blocks (*e.g.*, a five-minute time block) that are updated very frequently (*e.g.*, revisions every five minutes) are ideal. This would provide the dispatcher accurate VRE generation forecasts that when combined with fast dispatching would lead to lower generation costs and higher grid reliability.

VRE forecasting cannot work in isolation; it is part of a portfolio of tools and processes that enable the greening of the grid. Other tool and processes in the portfolio are fast dispatching (short lead times and short dispatch intervals) processes, load and conventional generation forecasting, demand response, and a variety of market operations. VRE forecasting impacts the core functions of system operations—SCUC and SCED, real-time balancing of supply and demand, and reserves planning. A comprehensive approach should be adopted to upgrade all elements of the fast dispatching system.

IMPROVED METEOROLOGICAL SERVICES

In countries with poor weather forecasting services, highly accurate wind speed and radiation forecasts may not be available or can be prohibitively expensive. In such countries, it is good practice for governments or regional organizations to use existing meteorological research institutions in the region or establish new institutions to conduct research to improve forecasting accuracy for weather parameters that are important to VRE generation forecasting. These institutions would install meteorological stations, create weather models, downscale global weather data, perform statistical analysis for bias removal, model local weather phenomena, and generate accurate weather forecasts.

THE FUTURE OF VRE FORECASTING

Machine learning or any other algorithm that uses weather forecasts as input and computes energy forecasts cannot provide a high level of accuracy unless weather forecasts are accurate. It is impossible for any algorithm to consistently deliver energy forecasts that are more accurate than the underlying weather forecast. Significant improvements to the accuracy of VRE forecasting will be achieved only when there is significant improvement in weather forecasting with time horizons that range from minutes to days. There are four key areas for improvement:

- Higher-quality NWP models, including global forecasts, downscaling (WRF models), and statistical bias removal done at a spatial scale of 50m x 50m or less and a temporal scale of 15 minutes or less. These models are computationally expensive and can take hours to run, even on super computers. Research into enhancing the speed of models for VRE forecasting would lead to multiple forecast revisions. Currently such models generate only two forecasts: one at midnight and one at noon.

- Given the higher uncertainty of HA weather forecasts during unstable atmospheric conditions, real-time measurements using a variety of sophisticated instruments can provide improvements to forecasts in the five-minute to one-hour timescale. This would be useful for ramp rate forecasting. Technologies currently being explored include:

    – Satellite-based, real-time cloud cover and cloud movement data for the accurate prediction of solar irradiation at solar plant sites.

    – Short-term forecasting of wind speed based on data from weather radar, and more sophisticated remote measurement sensors like light detection and ranging (LIDAR) and sonic detection and ranging (SODAR).

- As stated earlier, shorter dispatching will lead to more accurate VRE forecasts and lower-cost dispatches. While real-time forecasting can yield the best results, for most grids in developing markets, VRE forecasting with a time block and lead time of 5 minutes would yield good results with a provision to increase speed when warranted by weather conditions.

- Other improvements to the forecasting methods are being explored. See the textbox on the following page: "DOE Research Initiative to Improve Solar Forecasting." This initiative is under development and its details and application are not fully known.

Department of Energy Research Initiative to Improve Solar Forecasting[18]

As part of the U.S. Department of Energy's (DOE) SunShot program, DOE is funding the Watt-Sun subprogram, "A Multi-Scale, Multi-Model, Machine-Learning Solar Forecasting Technology." This is a universal platform with open architecture and is independent of proprietary weather or solar radiation models. It is based on the concept of creating an ensemble forecast by blending multiple forecasting algorithms. The blending is done by assigning weights to different models, where the weights are tuned using deep machine learning. The weights depend on weather conditions and a variety of other parameters.

DOE describes the program's accomplishments as follows: "The noticeable feature of the Watt-Sun forecast system is that a set of appropriately chosen parameters is used to create different weather situation categories in which the input models exhibit different error characteristics. This approach (*i.e.*, situation-dependent, machine-learnt, multi-model blending) has been demonstrated to advance the accuracy of the next best standard bias corrected model by more than 30% and by more than 15% compared to a DiCast (dynamic integrated forecast) approach."

[18] https://www.osti.gov/servlets/purl/1395344

CHALLENGES IN SOLAR AND WIND GENERATION FORECASTING IN DEVELOPING MARKETS AND THE WAY FORWARD

VRE forecasting is a relatively new advancement in developing VRE markets. The following challenges and ways forward apply to both vertically integrated and deregulated electricity sectors:

TABLE 1. CHALLENGES TO VRE FORECASTING AND WAYS FORWARD

CHALLENGE	WAYS FORWARD
Lack of a regulatory framework: Among the greatest challenges for VRE forecasting are the (1) lack of requirements related to communications on available capacity, actual production, actual weather measurement, and other data; and (2) lack of penalties for poor forecasts or transmission of inaccurate data about available capacity.	• Specify design details in policies and grid codes pertaining to VRE forecasting: (1) forecasting to be adopted: centralized, decentralized or hybrid; (2) forecast time block, horizon and lead time for day ahead, intraday or other; (3) obligation of plants to provide data required for VRE forecasting • Synchronize VRE forecasting policy with the requirements for forecasting load, faster dispatching, and others that increase grid flexibility, such as demand response, pricing of ancillary services, and pricing for curtailment
Lack of capacity at system operations: For a centralized forecasting model, the system operator requires experience and skill in a variety of areas such as IT, data analytics, statistics, and algorithms. In addition, the system operator requires control systems and IT systems to capture data and to ingest data from multiple sources.	• Centralized forecasting • Procuring VRE forecasting services from experienced vendors
Dispatching practices at system operations: The current system operations practices can pose a serious hinderance to utilizing higher accuracy VRE forecasting for dispatching. These include use of hourly or multi-hour intervals of forecasts and dispatch frequencies and use of spread-sheet-based dispatching tools. Way forward: Institute operational reforms that include sub-hourly dispatching, integration of VRE forecasting with the dispatching process, and use of sophisticated tools for dispatching that are part of energy management systems.	• Operational reforms that include sub-hourly dispatching • Integration of VRE forecasting with the dispatching process • Use of sophisticated tools for dispatching that are part of energy management systems
Unavailability of accurate weather forecasts: Since the uncertainty of weather forecasts is the largest component of VRE forecast uncertainty, it will be a major challenge in obtaining accurate generation forecasts.	• Use existing meteorological research institutions in the region or establish new institutions to conduct research to improve forecasting accuracy • Install meteorological stations, create weather models, downscale global weather data, perform statistical analysis for bias removal, model local weather phenomena, and generate accurate weather forecasts

Developing a road map is a key first step in avoiding or overcoming the challenges facing VRE forecasting. Figure 10 outlines a comprehensive road map.

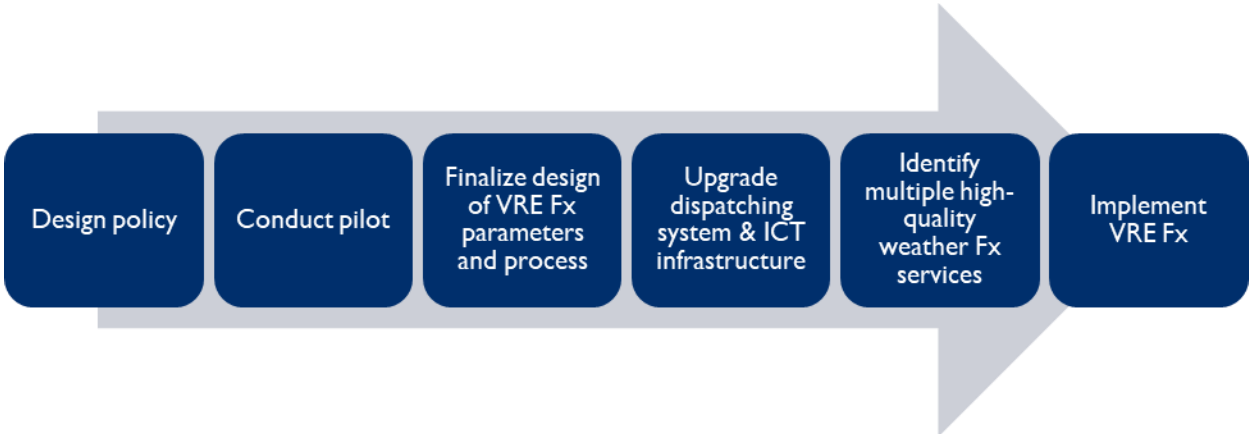


Figure 10. Outline of a Road Map for VRE Forecasting

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

VRE forecasting is essential to integrating VRE into the grid. When VRE forecasting is not performed or done inaccurately, the grid may experience reliability and economic issues, even when VRE penetration is modest. The consequences include VRE curtailment, frequency and voltage excursions due to over- or under-generation, negative market prices, price volatility, and dropped load.

An important unintended consequence of VRE forecasting is the rethinking of system operations with the goal of reducing the overall cost of generation, increasing decarbonization, and improving reliability. This rethinking can take the form of a comprehensive look at processes and subprocesses, including faster dispatching, improved load forecasting, improved generation forecasting for conventional generators, demand response, and better information and communications technology (ICT) infrastructure and decision support tools to integrate more almost real-time data streams.

The best practices for VRE forecasting in developing VRE markets are:

USE CENTRALIZED VRE FORECASTING WITH VRE FORECASTING SERVICES/SOFTWARE FROM EXPERIENCED VENDORS. Centralized forecasting is preferred because it eliminates the need for each VRE plant to purchase software and services for forecasting weather and VRE generation. It should also provide more accurate forecasts because the system operator can achieve scale by pooling resources and using multiple high-quality weather and generation forecasting services.

DEVELOP POLICY, REGULATIONS, AND GRID CODE (ENHANCEMENT SPECIFIC TO VRE) THAT ADDRESS IN A COMPREHENSIVE MANNER VRE FORECASTING AND RELATED ACTIVITIES IN SYSTEM OPERATIONS. The grid code should specify the design of VRE forecasting, deviation settlements for inaccurate forecasts, and its integration with dispatching. It should also mandate the sharing of data on available capacity, actual production, on-site measured weather data, and other parameters at a frequency and granularity that match the VRE forecast.

IMPLEMENT SHORT TIME BLOCK AND SHORT LEAD TIME FORECASTING TO INCREASE ACCURACY. In combination with fast dispatching, this would significantly enhance the flexibility of the grid, resulting in the ability of the grid to absorb larger amounts of VRE.

INVEST IN HIGHER-QUALITY WEATHER FORECASTING SERVICES. This is essential because it is the primary ingredient in VRE generation forecasting.

RECOMMENDATIONS

The analysis of data on VRE forecasting in Colombia, India, Mexico, the Philippines, and Vietnam (Appendix A) revealed varying levels of sophistication. summarizes the VRE needs of each of the study countries and makes recommendations for correcting the gaps.

TABLE 2. GAPS AND RECOMMENDATIONS RELATED TO VRE FORECASTING

COUNTRY	GAPS/RECOMMENDATIONS
India	Gaps: VRE plant owners and SLDCs are starting to implement VRE forecasting systems; however, dispatching systems are not ready in most SLDCs to fully exploit the benefits of VRE forecasting. Recommendations: • Enhance dispatching systems and integrate with VRE, load, and generation forecasts to fully exploit the value of VRE forecasting. • Ministry of Power should seek close partnerships with government-owned weather services and meteorological research agencies to significantly improve weather forecasting accuracy. • CERC should require the Indian Electricity Exchange (IEX) to enhance its platform to use intraday VRE forecasts, thereby aligning with SLDCs. • Use information about VRE forecasting uncertainty for improving dispatching and reserves planning.
Mexico	Gaps: There are no penalties for high-deviation forecasts. Recommendations: • Initiate modest penalties for large deviations to improve forecasting accuracy. • Use information about VRE forecasting uncertainty for improving dispatching and reserves planning.
Philippines	Gaps: There are no penalties for high-deviation forecasts. Recommendations: • Initiate modest penalties for large deviations to improve forecasting accuracy. • Use information about VRE forecasting uncertainty for improving dispatching and reserves planning.
Colombia	Gaps: Very small amount of installed VRE capacity compared to the high potential for VRE. A new VRE forecasting policy is currently in place, and a pilot is ongoing. Recommendations: • Work with weather services and meteorological research agencies to significantly improve weather forecasting accuracy specific to parameters of interest to VRE forecasting. • Use information about VRE forecasting uncertainty for improving dispatching and reserves planning.
Vietnam	Gaps: No policy is currently in place, although there are active discussions by the dispatch center regarding alternatives for the design of a VRE forecasting framework. Recommendations: • Design a fast dispatching framework that includes VRE forecasting policy and regulations, detailed design of the process, and data requirements from generators and others. • Conduct a pilot to assess the achievable accuracy of VRE forecasting, readiness of dispatch centers to integrate VRE forecasting into dispatching, and current level of weather forecasting accuracy of parameters like solar irradiation and wind speed at 50+ meters above ground level. • Upgrade dispatching systems to sub-hourly dispatches.

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APPENDIX A. SELECTED GLOBAL EXPERIENCES WITH VRE FORECASTING

The Scaling Up Renewable Energy (SURE) project assessed barriers to the grid integration of VRE through a study of five countries (Colombia, India, Mexico, Philippines, and Vietnam) with respect to VRE forecasting. These countries are in different stages of VRE development: Colombia has a very small amount of installed VRE capacity but it will increase rapidly as a result of first successful VRE auction in October 2019; India, Mexico, and the Philippines have sizeable VRE installations and high growth projections; and Vietnam has modest VRE installations with high growth potential. In assessing VRE forecasting in these countries, SURE identified gaps and made recommendations based on international best practices.

In the first phase of gathering information, SURE conducted an exhaustive search of publicly available sources. Next, it interviewed experts from the U.S. National Renewable Energy Laboratory (NREL), Tetra Tech, Vietnam National Load Dispatch Center (NLDC), and the United States Agency for International Development's (USAID's) Vietnam Low Emission Energy Program (V-LEEP) with knowledge about VRE forecasting in the five countries. Subsequently, SURE sent questionnaires to system operators in Mexico and the Philippines, where, for the latter, significant gaps in information remained. In most cases, the necessary information is extremely detailed, under development, and evolving, and in some cases not provided in publicly available documents. A questionnaire (see Appendix B) was therefore prepared and sent to systems operators in Mexico and the Philippines. The conclusions and recommendations from the five-country assessment are as follows:

- Colombia has very small amount (less than one percent of total generation capacity) of VRE in its grid and has no VRE forecasting program. However, it is now conducting a pilot. Since Colombia has a very large potential for VRE development, it is recommended the country initiate a program to develop a comprehensive policy for fast dispatching, to include VRE forecasting.

- India has a comprehensive VRE forecasting framework that is currently under implementation. It is recommended that (1) dispatching systems at the SLDCs and regional load dispatching centers be upgraded in a timely manner to fully exploit the value of VRE forecasting; (2) the Ministry of Power work to significantly enhance weather forecast accuracy through closer partnerships with government-owned meteorological research agencies; (3) the Indian Electricity Exchange (IEX) be required to upgrade its trading platform from DA to intraday VRE forecasting; and (4) dispatching and reserve planning be improved by incorporating information related to the uncertainty of VRE forecasts.

- Mexico and the Philippines have comprehensive VRE forecasting frameworks. A major gap is the lack of penalties for greater deviations between actual and forecast. It is recommended that (1) modest penalties be initiated for larger deviations to improve forecasting accuracy and (2) dispatching and reserve planning be improved by incorporating information related to the uncertainty of VRE forecasts.

- Vietnam has not formulated a framework for VRE forecasting. Current VRE generators are not required to submit a forecast. While requirements and policies are being developed for DA and WA forecasts, intraday revisions are not likely to be part of the initial design. The recommendations are to develop a comprehensive framework for VRE forecasting while migrating to sub-hourly dispatches.

Table 3 lists the experts used to obtain information from the five countries. Table 4 summarizes VRE forecasting-related information about these countries.

TABLE 3. EXPERTS WHO GATHERED INFORMATION ON VRE FORECASTING IN THE FIVE COUNTRIES

COUNTRY	EXPERT(S)
Colombia	Jairo Gutierrez, Tetra Tech ES, Inc.; Sebastian Ortega, XM, Colombia
India	Pramod Jain, IWE
Mexico	Ignacio Rodriguez and Adrian Paz, Tetra Tech ES, Inc.; Victor Hugo Cruz Rivera, Centro Nacional de Control de Energía (CENACE), Mexico
Philippines	Jessica Katz, NREL
Vietnam	Dinh Xuan Duc, Deputy Manager, Power System Analysis and Planning Department, NLDCer, EVN; Nghia Nguyen Trong, USAID V-LEEP program; Jessica Katz, NREL

TABLE 4. COMPARISON OF DIFFERENT ASPECTS OF VRE FORECASTING FOR THE FIVE COUNTRIES

VRE FORECASTING	COLOMBIA	INDIA	MEXICO	PHILIPPINES	VIETNAM
Policy	Initial	Mature	Mature	Mature	NA
Implementation Status	In progress	Initial	Initial	Initial	NS
Integration with SO	Initial	Initial	Initial	Initial	NS
Centralized/ Decentralized/ Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid
Forecast Interval	1 hour, 5 mins 5 mins*	15 mins	15 mins15 mins	30 mins	NS
DA/ Intraday	Both	Both	Both	Both	NS
Intraday Revisions	90 mins, 5 min**	Hour ahead	15 mins ahead	4 hours ahead	NS
Penalties	Yes***	Yes, for deviation > 15%	No	No	NS

NA: Not Available; NS; Not Started; SO: System Operations

*VRE plants are required to provides hourly forecasts DA and 90 min ahead; XM, the system operator and market administrator in Colombia, generates hourly and 5-min forecasts.

** VRE plants shall provide intraday forecast 90 mins ahead and only 4 revisions are allowed; XM shall generate intraday forecasts every 5 mins.

*** Based on two-tier deviation for DA and intraday.

COLOMBIA

The current share of generation capacity from wind, solar, small and mini hydro, and biomass power in Colombia is about three percent, while wind and solar is less than one percent of the total installed capacity.[19] Although the potential is large for wind power (3.1 GW[20] to 21 GW[21, 22]), currently there is only one 19.5 MW wind farm operating in Colombia, and there are just a few solar plants smaller than 20 MW, and only one solar plant above 80 MW which was inaugurated in early 2019. Colombia carried out its first successful renewable energy auction which awarded contracts that will boost the country's renewable energy capacity by 1,374 MW with 1,077 MW of wind and 297 MW of solar power generation at a historic low price. Results from this auction in October 2019 and a separate reliability auction in February 2019 will bring VRE participation to 12 percent in the generation mix by 2022. Building on this success, the Government announced recently that it was possible to reach a target of 20 percent of VRE by 2030.

XM, the grid operator in Colombia, is now piloting different wind, solar, and small-hydro forecasting methodologies with international vendors.[23] The Colombian grid code was updated in June 2019 to include modifications to address solar and wind generation interconnection requirements including forecasting.

FORECASTING HORIZON, INTERVAL AND DELIVERY WINDOW

The Colombian grid code as of June 20, 2019[24] requires VRE plants of sizes greater than 20 MW connected to the regional or national transmission system (57.5 kV or greater) to submit the following:

1. DA forecast to be delivered at 8 AM of the previous day for the next day with hourly granularity.
2. Intraday forecast to be delivered 90 minutes ahead of execution hour with hourly granularity until the end of the day. Only four revisions are allowed.

In case of deviations between the generation forecast and actual, penalties are incurred based on a two-tier approach. Penalties are calculated using a complex formula that takes into account DA and intraday deviations. In addition the Colombian grid code requires XM to generate three types of VRE generation forecasts:

1. Short-term generation forecast, which has a horizon of one week (Monday to Sunday) and granularity of one hour.
2. Very short-term, day-ahead generation forecast, which has a horizon of 40 hours and granularity of one hour. The forecast delivery window is 8 a.m., and it should cover 16 hours of today and 24 hours of tomorrow.
3. Very short-term, five-minute-ahead generation forecast, which has a horizon of 60 minutes and granularity of five minutes. The forecast delivery window is five minutes prior to execution time and the forecast is generated every five minutes.

[19] https://colombiareports.com/the-promises-and-challenges-of-renewable-energy-in-colombia/.
[20] https://publications.iadb.org/handle/11319/8146.
[21] http://www.nortonrosefulbright.com/knowledge/publications/134774/renewable-energy-in-latin-america- colombia.
[22] http://large.stanford.edu/courses/2017/ph240/pinilla2/.
[23] Interview with J. Gutierrez, SURE Project Lead Colombia. (Interview based on XM information). June 2018.
[24] http://apolo.creg.gov.co/Publicac.nsf/1c09d18d2d5ffb5b05256eee00709c02/ca640edbe4b7b5100525842d0053745d.

FORECASTING ACCURACY REQUIREMENTS AND PENALTIES

In the current regulation, the formula for the error in forecasts of plant availability is:

$$error = \frac{actual\ -\ availability}{availability}$$

Deviations in availability forecasts of more than five percent are penalized.

The Colombian grid code as of June 20, 2019[25] has deviation penalties for VRE generation forecasting. DA forecasts with MAPE of greater than 15 percent incur a deviation penalty and intraday forecast with MAPE of greater than eight percent incur a deviation penalty.

STATUS OF IMPLEMENTATION AND PROCESS OF SUBMITTING VRE FORECAST

VRE forecasting implementation has not begun. XM is working on a forecasting pilot, and estimations of the MAPE for individual plants will be available soon.

INDIA

India has an installed capacity of 83.37 GW of renewable energy as of October 2019[26,27]: 37 GW of wind, 31.7 MW of solar, 9.8 GW of biomass, and 4.6 GW of small hydro. India has set a target of 175 GW of renewable energy capacity by 2022[27]: 100 GW from solar, 60 GW from wind, ten GW from biomass, and five GW from small hydro.

The country's CERC formulated a framework for VRE forecasting in 2015.[28] It stipulated the individual state electricity regulatory commissions (SERCs) develop state-specific regulations for VRE forecasting. States with significant VRE generation capacity have drafted regulations that follow the CERC guidelines. For VRE generating plants that operate at the inter-state level, the Power Systems Operations Corporation (POSOCO) released procedures in 2017 for the implementation of forecasting for renewable energy generating units.[29]

The framework for VRE forecasting applies to generating plants with an aggregate capacity of 5 MW in most states while in some states it applies to 1 MW plants as well. It requires DA forecasting with a forecast interval (in India it is called a "time block") of 15 minutes and allows for 16 updates to the forecast on an intraday basis. The VRE forecasting framework includes assessing penalties for large deviations in actual versus forecasted VRE generation. In the next phase of implementation, CERC is planning to reduce the forecast time block to five minutes.

[25] http://apolo.creg.gov.co/Publicac.nsf/1c09d18d2d5ffb5b05256eee00709c02/ca640edbe4b7b5100525842d0053745d.
[26] https://www.ibef.org/industry/renewable-energy.aspx.
[27] http://www.energetica-india.net/news/around-69784-mw-of-renewable-energy-capacity-has-been-installed-in-the-country-by-march-2018.
[28] http://www.cercind.gov.in/2015/regulation/SOR7.pdf.
[29] https://posoco.in/wp-content/uploads/2017/03/pro.pdf.

FORECASTING HORIZON, INTERVAL AND DELIVERY WINDOW

The CERC framework requires DA forecasts for a horizon of 24 hours with time blocks of 15 minutes, which implies that VRE forecasts are required for 96 time blocks per day (=24 hours x 4 time blocks per hour). Some states also require WA forecasts. Although the forecast delivery time is not specified in the regulation, DA forecasts are requested by POSOCO and SLDCs before 10:00 a.m. of the previous day.

Revisions to forecasts are also referred to as intraday forecasts. Such revisions must be made for at least six time blocks (90 minutes total). The forecast lead time is one hour, that is, revisions are effective after four time blocks (one hour) where the first time block is when the forecast is submitted. For instance, if a revision is submitted at 10:05 a.m. it must be for the time block that runs from 11:00 to 11:15 a.m., and it must be applicable for at least six consecutive time blocks, which would be from 11:00 a.m. to 12:30 p.m.

Revisions can be made only once for a specific time block. The maximum number of revisions that can be submitted in a day is 16. This implies that 16 revisions can be submitted in which each revision contains forecasts for six time blocks. Hence, all 96 blocks can be revised once. Since solar plants operate for about 12 hours, some states have reduced the maximum number of revisions for solar forecasting to nine.[30] Other than the number of revisions, there is no policy differentiation between wind and solar forecasting.

FORECASTING ACCURACY REQUIREMENT AND PENALTIES

The CERC framework specifies four accuracy bins and guidelines for associated penalties. POSOCO and SERCs have customized the deviation bins and penalties (see TABLE 5).

The metric used for accuracy is the absolute percentage error (APE):

$$APE = 100 * \frac{(Actual\ Power\ Injection - Forecasted\ Power\ Generation)}{Available_{Capacity}}.$$

APE is computed on the final revisions to the forecast and for each 15-minute time block.

TABLE 5. PENALTY FOR EXCESSIVE DEVIATION IN INDIA

ACCURACY BIN	PENALTY (PER KWH)	
	CERC/POSOCO	ANDHRA PRADESH
APE ≤15%	None	None
15% <APE ≤ 25%	10% of PPA	Rs 0.50
25% <APE ≤ 35%	20% of PPA	Rs 1.00
APE >35%	30% of PPA	Rs 1.50*
APE ≤15%	None	None

[30] http://www.aperc.gov.in/admin/upload/regulationNo4of2017.pdf.

Some states in India have changed the accuracy bins. For instance, Andhra Pradesh, Madhya Pradesh, Tamil Nadu, and Haryana use ten percent as the permissible deviation (no penalty), and Gujarat uses 12 percent for wind and seven percent for solar as the permissible deviations. In addition, each state uses a different penalty amount.

The penalty is computed for each time block on the shortfall or excess generation. As an illustration of computing penalties, consider the following example. If the available capacity of a VRE facility is one MW, the forecasted power generation is 0.62 MW, and the actual power injection is one MW, which gives:

$$APE = 100 * \frac{1 - 0.62}{1} = 38\%.$$

In the state of Andhra Pradesh, the deviation charges could be computed as a sum of three deviations. Deviation 1 is for APE more than 15 percent but less than 25 percent. In this bin, 0.1 MW of excess power was generated for 15 minutes, which is 100 kW*15/60 h = 25 kWh. In the next two bins, 0.1 MW and 0.03 MW of excess power were generated. The deviation charges are therefore:

$$Deviation\ 1 = \text{Rs } 0.50 * 100 \text{ kW} * \frac{15}{60} = \text{Rs } 12.5$$

$$Deviation\ 2 = \text{Rs } 1.00 * 100 \text{ kW} * \frac{15}{60} = \text{Rs } 25$$

$$Deviation\ 3 = \text{Rs } 1.50 * 30 \text{ kW} * \frac{15}{60} = \text{Rs } 11.25$$

$$Total\ Penalty = 12.5 + 25 + 11.25 = \text{Rs } 48.75$$

STATUS OF IMPLEMENTATION

The CERC order was to go into effect on January 1, 2018, for all VRE plants designated as interstate, which at the moment is only one plant. Each state regulator is customizing the CERC order and a few states have released the final order and started implementation. At this point, several states are mobilizing to implement VRE forecasting, so it is too early to determine which states are fully operational with VRE forecasting in terms of computing deviations and levying a penalty for excess deviations.

PROCESS OF SUBMITTING VRE FORECASTING

The VRE implementation framework requires that VRE forecasts be aggregated at a pooling substation and delivered by a qualified coordinating agency (QCA). The QCA is an agency registered with the SLDC or POSOCO and it acts as a coordinating agency on behalf of VRE generators that are connected to a pooling substation. QCAs collect VRE forecasts from individual generators, aggregate them by pooling substation, and submit them to the SLDC. The intent is to minimize forecasting errors through aggregation of renewable energy forecasts at one or more pooling stations. The deviation settlement also occurs at the pooling substation; it is the responsibility of the QCA to pay the deviation charges and subsequently to apportion (de-pool) the charges equitably to and collect the charges from the VRE plants that caused the deviation.

INTEGRATION OF VRE FORECASTING WITH DISPATCHING/MARKET OPERATIONS

Separate from forecasts submitted by the VRE generating plants, the SLDCs are also required by the regulators to generate VRE forecasts at the pooling substation level. The wind or solar generator or QCA has the option of accepting the SLDC forecast for preparing a schedule or providing the SLDC with a schedule based on its own forecast.

According to the VRE forecasting framework, the objective of centralized VRE forecasting is to enable SLDCs to secure the grid operation by DA and HA planning for requisite balancing resources. At the SLDCs, conventional generation and load forecasting are undergoing a similar transition to DA forecasts and intraday revisions, and to 15-minute time blocks. This is all to conduct optimal dispatches and market operations based on integrated and timely views of load and generation from all sources.

ACCURACY OF VRE FORECASTING

In 2014, a pilot wind power forecasting project was conducted in the state of Gujarat in which five leading international vendors participated.[31] The pilot ran from November 2014 to February 2015. The reported accuracy was poor, within the +/-30 percent range for 60–65 percent of the time blocks during high wind scenarios, and even poorer during low wind scenarios. The reason for poor accuracy was that the pilot was implemented without historical weather and generation data. A complete performance of VRE forecasting service providers currently operating in India is not available. The following presents a few available data points as of mid-2019 about performance in terms of average penalty per kWh of energy generated by the VRE plants:

- Rs 0.07 per kWh (~0.001 USD per kWh[32]) penalty for solar forecasting in the state of Karnataka[33]
- Rs 0.10 to Rs 0.12 per kWh (~0.0014 to 0.0017 USD per kWh) penalty for solar forecasting[34]
- Rs 0.20 to Rs 0.25 per kWh (~0.0028 to 0.0035 USD per kWh) penalty for wind forecasting[34]

MEXICO

At the end of 2017, Mexico had 4 GW[35] of wind and 539 MW[36] of solar power. The Secretariat of Energy expected the total installed solar capacity by 2019 to be 5.4 GW, and the total installed wind capacity to be 12 GW[37] by 2024. In 2017, the German Development Agency, GIZ, started a program called *develoPPP* for wind and solar power predictions in El Salvador and Mexico.[38] Other than this announcement, no information is available about this program's work on VRE forecasting. Basic data were obtained by interviewing the Tetra Tech team in Mexico.

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[31] https://mnre.gov.in/file-manager/UserFiles/draft-report-fscb-remcs.pdf.
[32] An exchange rate of 1 USD = Rs 70 is used for the calculation.
[33] http://www.cercind.gov.in/2019/expert-group/Stakeholders%20Comments/National%20Solar%20Energy%20Federation%20of%20India2.pdf.
[34] https://mercomindia.com/harsh-penalties-deviation-settlement-solar-wind/.
[35] http://gwec.net/global-figures/graphs/.
[36] http://www.iea-pvps.org/fileadmin/dam/public/report/statistics/IEA-PVPS_-_A_Snapshot_of_Global_PV_-_1992-2017.pdf.
[37] http://www.rechargenews.com/wind/1444141/clear-path-to-tripling-of-mexican-wind-by-2024-energy-secretary.
[38] https://www.energymeteo.com/products/case_studies/giz_latin_america.php.

Subsequently, additional data were received in response to the questionnaire in Appendix B, which was sent to CENACE (the National Center for Energy Control, a part of the national utility) on this topic. Additional information was obtained from a manual of forecasting[39] published by Mexico's Department of Energy.

Mexico is using a hybrid approach in which VRE forecasts are generated by both the system operator and the VRE plant. VRE forecasts are required for all wind and solar plants of 0.5 MW or larger that are connected to a transmission network of 69 kV or higher.[40]

FORECASTING HORIZON, INTERVAL, AND DELIVERY WINDOW

WA, DA, and HA VRE forecasts are generated by the system operator and the generating plant. WA (which subsumes DA) forecasting is done for a time block of one hour and a horizon of one week; the delivery time is 10:00 a.m. Intraday forecasts are done for a time block of 15 minutes, a horizon of 10 time blocks (2.5 hours), a lead time of 15 minutes, and can be updated continuously during the day.

FORECASTING ACCURACY REQUIREMENT AND PENALTIES

According to the questionnaire results, the expected accuracy of intraday forecasts is four percent, and the current mean absolute deviations for wind and solar forecasts are about 17 percent. There are no penalties for higher deviations. In general, VRE forecasting is in the initial stages of implementation, including its integration with SCUC and SCED.

THE PHILIPPINES

The Philippines has 443 MW of wind and 978 MW of solar installed as of December 2019.[41] VRE forecasting is required as per the Philippines Grid Code 2016. It applies to all generators connected to the high-voltage (exceeding 34.5 kV) backbone system in Luzon, Visayas, and Mindanao. The system operator is responsible for producing aggregated VRE forecasts for each interconnected system it operates, and the individual VRE plants are responsible for producing forecasts for their own facilities.

FORECASTING HORIZON, INTERVAL, AND DELIVERY WINDOW

The grid code requires DA and intraday VRE forecasts to be generated by the system operator and the generating plant. The DA forecast covers a horizon of 36 hours, while the intraday forecast is for a horizon of one hour. The forecast time block is 30 minutes. The lead times for DA and intraday forecasts are 36 and four hours, respectively.

FORECASTING ACCURACY REQUIREMENTS AND PENALTIES

The Philippines grid code specifies two accuracy standards, one for the system operator and another for the VRE plant, as shown in Table 6.

[39] http://dof.gob.mx/nota_detalle.php?codigo=5505475&fecha=23/11/2017.
[40] Based on answers to questionnaire provided by Victor Hugo Cruz Rivera of CENACE, Mexico.
[41] https://www.doe.gov.ph/renewable-energy/summary-renewable-energy-re-projects-31-december-2019.

TABLE 6. SYSTEM OPERATOR VRE FORECAST ACCURACY REQUIREMENTS		
REQUIRED PERFORMANCE	FIRST AND SECOND YEAR AFTER SOFTWARE COMMITMENT	THIRD AND SUBSEQUENT YEARS AFTER SOFTWARE COMMITMENT
Forecasting Errors*	Mean Absolute Percentage Error	Perc95 Error
Short-Term Forecast (0–4 hours)	< 10%	15%
Medium-Term Forecast (4–36 hours)	<25%	35%

*Note: Calculated over a complete calendar year.

The MAPE is computed with respect to "actual average value of dependable capacity of VRE generation (integrated over one hour) at a particular interval *t*."

$Perc_{95}$ Forecasting Error (percentile 95 of the forecasting error) is the value of absolute forecasting error not exceeding 95 percent of the observations.

TABLE 7. VRE PLANT OWNER FORECAST ACCURACY REQUIREMENTS				
REQUIRED PERFORMANCE	FIRST AND SECOND YEAR AFTER SOFTWARE COMMITMENT		THIRD AND SUBSEQUENT YEARS AFTER SOFTWARE COMMITMENT	
	Mean Absolute Percentage Error	$Perc_{95}$ Error	Mean Absolute Percentage Error	$Perc_{95}$ Error
Short-Term Forecast (0–4 hours)	<18%	30%	<15%	20%
Medium-Term Forecast (4–36 hours)	<30%	40%	<25%	35%

Penalties are not specified in the grid code. However, it does specify that the system operator and VRE plant owners will achieve the required accuracy on a best-effort basis.

VRE forecasting has been implemented in the Philippines; however, research of publicly-available sources did not identify additional details about the status of implementation, integration with dispatching, and current level of accuracy.

VIETNAM

Vietnam had about 327 MW of wind[42] and 4,500 MW of solar capacity[43] installed as of the end of 2019. The total installed power generation capacity in the country was about 48 GW at the end of 2018. Vietnam has a target for renewable energy of 6.8 GW by 2020. VRE forecasting requirements in Vietnam are not clearly spelled out.

There are two circulars (regulations) that are relevant to renewable energy forecasting. The first is circular 25/2016/TT-BCT,[44] "Regulations on Electricity Transmission System." Its article 42, "Technical

[42] https://www.eco-business.com/news/gusty-growth-vietnams-remarkable-wind-energy-story/.
[43] http://documents.worldbank.org/curated/en/949491579274083006/pdf/Vietnam-Solar-Competitive-Bidding-Strategy-and-Framework.pdf.
[44] https://vanbanphapluat.co/circular-25-2016-tt-bct-regulations-electricity-transmission-system.

requirements of wind and solar power plants," does not mention VRE forecasting. In the second, circular 16/2017/TT-BCT,[45] "Regulating Solar Power Project Development and Standardized Power Purchase Agreement for Solar Power Projects," there is one mention of forecasting, which is in section "Article 10 Grid-Connected Solar power project." Item 2, Letter B in this section states: "Providing equipment connected to the SCADA or dispatching system in order to provide forecast information on generated electricity by hour to the Load Dispatch Center in charge of system dispatching." These are the only mentions of VRE forecasting. The second circular implies that provisions for transferring VRE forecasting data to the load dispatch center are present in the regulations.

According to Mr. Dinh Xuan Duc, of the NLDC, EVN, there are no policies for VRE forecasting, the current VRE plants in the grid are not providing forecasts, and no pilots have been conducted. NLDC is currently reviewing the forecasting solutions of various vendors. The plan is to start hybrid (centralized and decentralized) VRE forecasting on a DA basis with hourly time blocks and then migrate to intraday with 5-minute granularity. As of this paper's publication, no assessments have been made about forecast accuracy requirements and penalties.

FORECASTING HORIZON, INTERVAL, AND DELIVERY WINDOW

Preliminary information was also obtained from Nghia Nguyen Trong of the V-LEEP program.[46] According to Mr. Trong, VRE forecasting is likely to start with DA and WA VRE generation forecasts for one-hour time blocks that are submitted to the dispatch authority. The dispatch authority may be the regional or national load dispatch center.

PROCESS OF SUBMITTING VRE FORECAST

Vietnam has the following dispatch centers:

- National Load Dispatch Center (NLDC) - A0
- Northern Region Load Dispatch Center (NRLDC) - A1
- Southern Region Load Dispatch Center (SRLDC) - A2
- Central Region Load Dispatch Center (CRLDC) - A3

Wind plants would provide forecasts to their region's load dispatch centers, depending on their locations. The regional load dispatch center (*i.e.*, A1, A2, or A3) would then forward the forecasts to the NLDC - A0. Using load forecasting as a guide, the NLDC would require all forecasts for the next day's generation be received before 10:00 a.m. every day, so Ax (the respective region's center) would have to coordinate with wind plants accordingly.

There would be some cases wherein B-level dispatch centers at the provincial/city level are focal points for receiving forecasts and they would forward data to the respective A-level dispatch center. Forecast timing would be adjusted accordingly in these cases.

[45] http://rainer-brohm.de/wp-content/uploads/2017/10/2017_09_12_Circular-solar-PV-project_ENG.pdf.
[46] Email conversation with John Wells and Nghai Nguyen Trong of USAID V-LEEP program.

APPENDIX B. VRE FORECASTING DATA COLLECTION SHEET

1. Who are required to submit VRE generation forecasts:
   a. Size of wind plant: **20 MW**
   b. Size of solar plant: **20 MW**
   c. Connection voltage: **69 kV**
2. Who is responsible for generating VRE forecast?
   a. System operator ☒
   b. VRE plant owner ☒
   c. Third party ☒ **Enter name**
3. What is forecast granularity:
   a. One hour ☒
   b. 15 minutes ☒
   c. 5 minutes ☒
   d. Others ☐ **Enter in mins**
4. What is forecast horizon:
   a. Week-ahead ☒
   b. Day-ahead ☒
   c. Intraday ☐ **Enter hours**
5. What is lead time for forecast delivery:
   a. For day-ahead: **8:00 and 15 hours**
   b. For intraday: **One hour prior**
6. What is the formula for error:
   ☒ (actual-forecast)/actual
   ☐ (actual-forecast)/avail
7. Does regulation or grid code expect forecast accuracy:
   a. +/- 15% ☐
   b. Others: **+/-4% intraday**
8. Are there penalties for high deviation of forecast from actual?
   ☒Yes ☐No
   If yes: **Specify penalties**
9. What is the status of VRE forecasting?
   Initial Stage
10. What is the protocol for delivering VRE to system operator?
    Others
11. Is VRE forecasting incorporated into unit commitment and dispatching?
    Initial Stage
12. Is VRE forecasting used in market operations?
    ☒Yes ☐No
13. Currently what is the average error for wind forecasts?
    a. Mean absolute percentage error: %
    b. Other metrics: **Enter number**
14. Currently, what is the average error for solar forecasts?
    a. Mean absolute percentage error: **Enter number**
    b. Other metrics: **Enter number**

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APPENDIX C. VENDORS AND SOFTWARE

VENDORS

The table below represents a list of selected international vendors for VRE forecasting solutions.

TABLE 8. VENDORS AND SOFTWARE

VENDOR NAME	DESCRIPTION
AWS Truepower, UL Company, USA[47]	AWS provides wind and solar forecasting for about 70 GW of capacity worldwide, including 50 GW of capacity in North America. It uses atmospheric models and adaptive statistical techniques to produce forecasts.
DNV GL, UK[48]	Previously, Garad Hassan's GH forecaster, DNV's current short-term forecasting service comprises Forecaster Now, Forecaster Live, Forecaster Plus, and Forecaster Solutions. It uses downscaling and localizing of weather data from global forecast models to generate site-specific forecasts.
EMD International, Denmark[49]	EMD offers WindFor and SolarFor, self-learning and self-calibrating software systems based on a combination of physical models and advanced machine learning. Weather forecasts are obtained from external sources.
IBM, USA[50]	IBM owns the Weather Channel, which is a prominent source for historic and forecast weather data around the world. IBM Watson is one of the most well-known general machine learning platforms. It also provides solar and wind power forecasting services that combine weather data with deep machine learning.
Meteologica, Spain[51]	This firm provides wind and solar forecasting to 330 GW of capacity. It downscales and localizes global NWP models to generate site-specific power forecasts.
Meteotest, Germany[52]	Meteotest's Solar Web Service provides solar radiation and power forecasts. Its CloudMove product uses wind fields from weather models to propagate currently measured cloudiness to the future, which is then used to forecast radiation. The SolarForecast product uses GFS forecasts and statistically optimizes them based on measurement data from weather stations.
Vaisala, USA[53]	Previously 3Tier, Vaisala uses NWP models, neural networks, and real-time observations to predict weather parameters and then generation forecasts.
Vortex, Spain[54]	Vortex uses NWP models with downscaling and statistical training, along with several algorithms to provide power forecasts.
50 Hertz[55]	Active in India, 50 Hertz uses weather forecasting services, statistical and machine learning models.
Kreate Energy[56]	Active in India, Kreate uses NWP, weather forecasting services, statistical, and machine learning models.

[47] https://aws-dewi.ul.com/solutions/forecasting-grid-integration/.
[48] https://www.dnvgl.com/services/forecaster-introduction-3848.
[49] https://www.emd.dk/forecasting-solutions/.
[50] https://www.ibm.com/us-en/marketplace/weather-company-power-gen-forecasts.
[51] http://www.meteologica.com/services.html.
[52] https://solarwebservices.ch/.
[53] https://www.vaisala.com/en/products/data-subscriptions-and-reports/energy-forecasting.
[54] http://www.vortexfdc.com/forecast/.
[55] https://www.50hertz.in/.
[56] https://kreateglobal.com/energy.php.

TABLE 8. VENDORS AND SOFTWARE	
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EMD International, Denmark[59]	EMD offers WindFor and SolarFor, self-learning and self-calibrating software systems based on a combination of physical models and advanced machine learning. Weather forecasts are obtained from external sources.
IBM, USA[60]	IBM owns the Weather Channel, which is a prominent source for historic and forecast weather data around the world. IBM Watson is one of the most well-known general machine learning platforms. It also provides solar and wind power forecasting services that combine weather data with deep machine learning.

SOFTWARE

For VRE forecasting, the most commonly used software platforms are R and Python. Both platforms provide a rich collection of statistical and machine learning algorithms. In addition, these platforms have extensive data cleaning and manipulation capabilities.

[57] https://aws-dewi.ul.com/solutions/forecasting-grid-integration/.
[58] https://www.dnvgl.com/services/forecaster-introduction-3848.
[59] https://www.emd.dk/forecasting-solutions/.
[60] https://www.ibm.com/us-en/marketplace/weather-company-power-gen-forecasts.