GET.transform
Transforming Energy Sectors Globally

International Best Practices in Solar and Wind Power Forecasting

GET.transform Technical Brief

GET.transform is supported by

Norad
Ministry of Foreign Affairs of the Netherlands
Sweden Sverige
Austrian Development Cooperation

Prepared by
Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Registered offices
Bonn and Eschborn, Germany

GET.transform
Friedrich-Ebert-Allee 32 + 36
53113 Bonn, Germany
T +49 228 44601112
E info@get-transform.eu
I www.get-transform.eu
I www.giz.de

Place and date of publication
Bonn, November 2023

Responsible
Daniel Cumpa Exebio, GET.transform

Author(s)
Ulrich Kaltenbach, emsys
Matthias Lange, emsys
Isabell Sonntag, emsys

energy & meteo systems is an internationally leading provider of sophisticated IT solutions (solar and wind power forecasts, Virtual Power Plants, redispatch platform) for an efficient integration of distributed energy resources into power systems. With its consulting services the German-based company shares its in-depth energy transition expertise on a global level.

Photo credits
Cover © iStock/OnurDongel

GET.transform is a European programme which offers developing and emerging countries comprehensive advisory services to advance their energy sector transformations. It is hosted on the multi-donor platform GET.pro (Global Energy Transformation Programme), and supported by the European Union, Germany, Norway, Sweden, the Netherlands, and Austria.

GET.transform is supported by

GET.transform
Transforming Energy Sectors Globally

Table of Contents

Table of Figures

Table of Tables

1 Introduction

A main challenge of the energy transition is the weather dependent power production of wind farms and solar plants. Varying wind speeds and solar irradiation directly translate to rapid and significant changes in electricity generation. This specific characteristic of solar and wind power is fundamentally different from other generator technologies.

With increasing shares of solar and wind power in a power system it is therefore indispensable to precisely predict their future production schedules. This ensures the stability of the power system and an economic integration of variable renewables in the electricity supply. Since some countries started to expand variable renewable energies already some 20 years ago a lot of experience has been gained in the field of power forecasting until now.

The goal of this forecast brief is to provide a concise overview of the best practices in power forecasting and shares international experiences with predicting solar and wind power production. Fundamental techniques and data requirements to set up and improve power forecasts are described and the most important factors that influence their accuracy levels are presented. The market design plays a decisive role in determining forecasting responsibilities among the market participants and how predictions are embedded in operational processes. These structural conditions often significantly influence the quality and limitations of power forecasts. This is illustrated in brief country studies which present international experiences in Mexico, the Dominican Republic and Chile. In particular, the respective country experiences with centralized and decentralized forecasting systems are highlighted. The question if penalty schemes are an appropriate measure to achieve more accurate power forecasts is examined with India as an example.

This forecast brief represents an extract from an extensive study of GET.transform on the power forecasting system in Peru which was elaborated with the support of energy & meteo systems. The report includes a comprehensive analysis of the current forecasting system and of the provided prediction and measurement data from wind and solar parks. The findings culminated in 11 concrete short- and long-term recommendations. Their implementation is considered to significantly improve the quality of solar and wind power forecasts in Peru and to enable a more seamless integration in operational processes.

2 Best Practices in Solar and Wind Power forecasting

2.1 Application of solar and wind power forecasts

After wind turbines and solar plants have been built and connected to the grid, the power production has to be accommodated into the power system and, depending on the circumstances, also into the energy market by different stakeholders. Forecasts of variable Renewable Energy (vRE) units are needed in order to know in advance the amount of power that wind turbines or photovoltaic modules will feed into the grid over the next hours and days. The vRE forecasts are generally based on forecasts of the weather conditions at the site locations. The forecast can be used as an expectation of the vRE production by different stakeholders. The main stakeholders are:

— System operators
— Power traders
— Aggregators that trade electricity from their own and third parties´ vRE plants
— Wind and solar plant operators

The stakeholders use power forecasts for their respective needs in various operational processes. In order to match the different requirements, several time-scales of forecasts are used: Medium-term forecasts of the following two to 20 days, short-term forecasts of the next six to 48 hours, and shortest-term forecasts of the next minute to the next six hours. **TABLE 1** gives an overview on the application of vRE forecasts by the main user-groups according to different time horizons.

TABLE 1. Application of vRE forecasts in different processes of electricity sector stakeholders

TIME-SCALE OF FORECAST	AREA OF APPLICATION	STAKEHOLDER
Shortest-term (0-6 hours)	Trading on intraday energy market Control of curtailment due to negative market price Correct activation of regulation power (secondary and tertiary reserve)	Power traders
	Impact of vRE on market price	Speculators
	Balancing Unit redispatch Curtailment of power plants	Grid operators, load dispatch centres, independent system operators
Short-term (6-48 hours)	Trading on day-ahead energy market Participation in ancillary services market Impact of vRE on market price	Power traders
	Unit dispatch Load flow calculations Day-ahead congestion forecast	Grid operators, load dispatch centres, independent system operators
Medium-term (2-10 days)	Trading on long-term markets	Power traders
	Two days-ahead congestion forecast Week-ahead planning	Grid operators, load dispatch centres, independent system operators
	Medium-term planning of maintenance	vRE operators

Source: energy & meteo systems

Depending on the market design, or individual operational needs of the forecast user, the configuration of the predictions is further specified. For instance, this includes the update frequency of power forecasts (e.g. one update per day, or hourly updates) and their resolution (e.g. hourly or 15 minute values).

2.2 Basic forecasting technique

Due to international efforts in the last 20 years to continuously improve the quality of predictions the technical skill of wind and solar forecasting has been dynamically advancing. This progress is mainly driven by the commercial forecast service providers who seek to continuously improve their forecast methodologies due to the very competitive situation they are exposed to.

Different forecasting concepts and modelling systems have been tested and set into operation by service providers and institutions. From the experiences with different approaches, best practices have emerged on how to produce fine-tuned wind and solar power forecasts. In the following, the basic facts and concepts, as they are currently used in operational power forecasting of vRE, are presented.

Established wind and solar power prediction systems generally use numerical weather models as input. This is necessary to cover forecast horizons of several hours or days, because only numerical weather models can simulate what will happen in the atmosphere in the future, in particular as far as wind speeds and solar radiation are concerned. Forecasting methods that are purely based on observational data, e.g. power measurements, are only beneficial for very small time periods of a few minutes or, in very special weather situations, with reliably reoccurring patterns. Nevertheless, observational data is very useful for the forecasting process.

The leading numerical weather prediction (NWP) models are developed and operated by national weather centres, such as the European Centre for Medium Range Weather-Forecasting (ECMWF), or the National Centres for Environmental Prediction (NCEP). These organisations use a wide range of model approaches which make the NWP models slightly differ in the way they simulate the weather conditions of the future. Hence, they deliver slightly different results for the same points in time of the future. Due to the increase in computational power over the last 20 years, NWP models have greatly advanced in quality.

In order to solve the relevant physical equations, NWP models divide the atmosphere into three dimensional boxes (grid cells). The meteorological parameters, such as wind speed or solar radiation, are then available with the spatial resolution of these grid cells for each point in time. In the horizontal direction, the size of grid cells varies between a few hundred metres and 25 kilometres, depending on the scope of the model. In order to gain wind speed or solar radiation values at a specific location, these meteorological parameters have to be interpolated from the neighbouring grid cell data. This is why vRE forecasts are always limited in accuracy. Another reason for this is the fact that processes inside the grid cells, e.g. variations of the wind speed, cannot be directly simulated. Assumptions have to be made in order to include these processes on the larger scale. The same is true for the detailed surface structure inside the area of a grid cell that typically induces additional sub-scale processes. The model resolution also varies in a vertical direction. In general, the lower levels, which are important for vRE forecasting, are covered by non-equidistant steps, typically around 10 m, 30 m, 100 m or 200

m. The number of height levels, and the exact positions, vary from model to model. Since wind speeds greatly change with height in the lower atmosphere, it is crucial to calculate the wind speed at the hub height of the wind turbines as precisely as possible. The power forecasting systems differ widely in the way they perform this vertical interpolation.

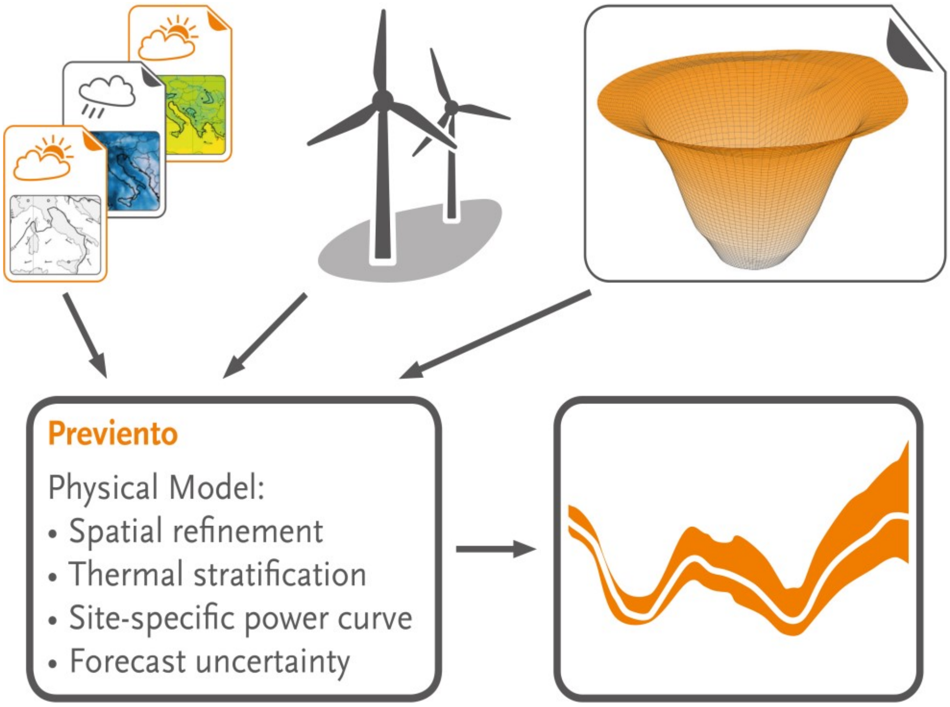
It is important to note that a higher resolution of the NWP models, in a horizontal or vertical direction, does not automatically lead to better power forecasts. High resolution models potentially simulate more details, e.g. fluctuations due to changing wind conditions, the extent of clouds or fog or developing clouds which models of coarser resolution could not display in such detail. However, if the high resolution forecast gets the timing of these fluctuations wrong, the accuracy suffers dramatically. Models of coarser resolution are better at describing the bigger picture. It turned out to be very beneficial to combine the model output from these two types of models: global NWP models with a coarser resolution on the one hand, and regional NWP models with a finer resolution on the other. More details on the method of combination forecasts can be found in **section 2.4**.

As soon as there is a prediction of the needed meteorological parameters, in particular wind speed and solar irradiation (typically surface solar radiation downwards, abbreviated as SSRD), the next step is to convert this data into power output of vRE units. In the history of power forecasting, two main approaches have emerged for this conversion: (i) a statistical approach on the one hand, and (ii) a physical approach on the other. In statistical systems, a mathematical relation between numerical weather predictions as input and measured power output is 'trained' or 'learned' based on the available data. In contrast to this, physical systems use methods from boundary layer meteorology and irradiance transfer schemes to recalculate the meteorological input based on the NWP data, e.g. wind speed at hub height, and then use power curves to transfer it into power. Recent developments of modern forecasting systems show that both approaches converge in the sense that physical and statistical methods are combined where necessary to achieve higher accuracy.

In order to get an understanding of how these two approaches are implemented, examples from two established wind power prediction systems will be briefly described here. An example of a commercially successful statistical system to predict wind power is the Wind Power Prediction Tool (WPPT) which has been developed by the Technical University of Denmark (Nielsen et al. 1998). It has been further enhanced for an operational purpose under the trademark, WindFor, by the Danish company, ENFOR. The basic idea of WPPT is the continuous calibration of the system by artificial intelligence methods, given a constant data flow of NWP models and vRE plant production data. This permanent calibration enables the statistical forecasting system to adapt the power forecasts e.g. to the plants' technical condition or seasonal variations of the meteorological resource. One disadvantage, however, is that weather situations which have not been previously observed by the system, or that only occur very seldom, are less well covered by the forecast.

An example of a commercially successful physical system to predict wind power is called Previento which was developed by the University of Oldenburg in Germany (Lange/Focken 2005). It is now being operated and has been enhanced by the German company, energy & meteo systems.

FIGURE 1. Basic scheme of an NWP based power forecasting system



Source: energy & meteo systems

The general scheme of Previento is shown in **Figure 1**. To set-up a power forecast for vRE units, the physical model requires at least the standing data of the solar and wind power plants (installed capacity, location, hub height, or inclination angle of solar modules, etc.) and meteorological forecasts provided by NWP models.

The physical model is based on a horizontal spatial refinement of the NWP model data. It calculates the wind speed at hub height by using different height levels of wind speed from the NWP model according to the current vertical wind profile. This profile describes the change of wind speed with height. Its shape strongly depends on the meteorological conditions. The consideration of these physical phenomena enables physical systems to provide an accurate wind speed at hub height for the same time horizon that the NWP models offers. The wind speed at hub height is then converted into power by a suitable power curve.

At the end of this process, wind and solar power predictions for the individual locations have been computed for equidistant time steps, e.g. of 15 to 60 minute width. This is not only possible on a single farm level, but also for different aggregations of vRE farms, either a regional portfolio, or for a trading portfolio containing plants from various regions. The forecasts cover up to 10 days into the future, with increasing uncertainty. They are then delivered and used as power schedules by different stakeholders.

2.3 Evaluation of forecast errors

The forecast accuracy is normally evaluated by considering the deviations between predicted and actually measured electricity production. On a daily basis, this is often done by visual inspection of the prediction schedule versus the real production. Visual inspection is very helpful, because by observing the forecasting error, users are able to learn about typical deviations and relate these observations to certain forecasting situations, e.g. timing errors in wind power due to an earlier arrival of a weather front, or amplitude errors in solar power due to fog.

To evaluate vRE power forecasts in the long run, a variety of measures is used which nicely summarize the forecasting error over certain time periods. Very popular statistical error measures are the **mean absolute error (MAE)**, **the root-mean-squared error (RMSE)** and the **mean error (bias)**:

— The MAE provides a good overview of the average deviations that occurred. It is, in particular, useful if the cost function for imbalances, i.e., the penalties for forecast errors, is linear. This error measure is widely used by traders and in the U.S. market.
— The RMSE gives a higher weight to large forecast errors, i.e., few large deviations dominate this error measure. As in many energy systems large imbalances are indeed more costly, the RMSE is often used, e.g., by the German TSOs.
— The bias indicates systematic errors, i.e., it can show a drift towards general over- or underestimation. It is, for example, very useful to detect unannounced curtailments because this leads to a permanent overestimation by the forecasts.

There are far more error measures, correlations and skill scores available. But they are mainly used for rather special analyses of the forecasting errors by experts.

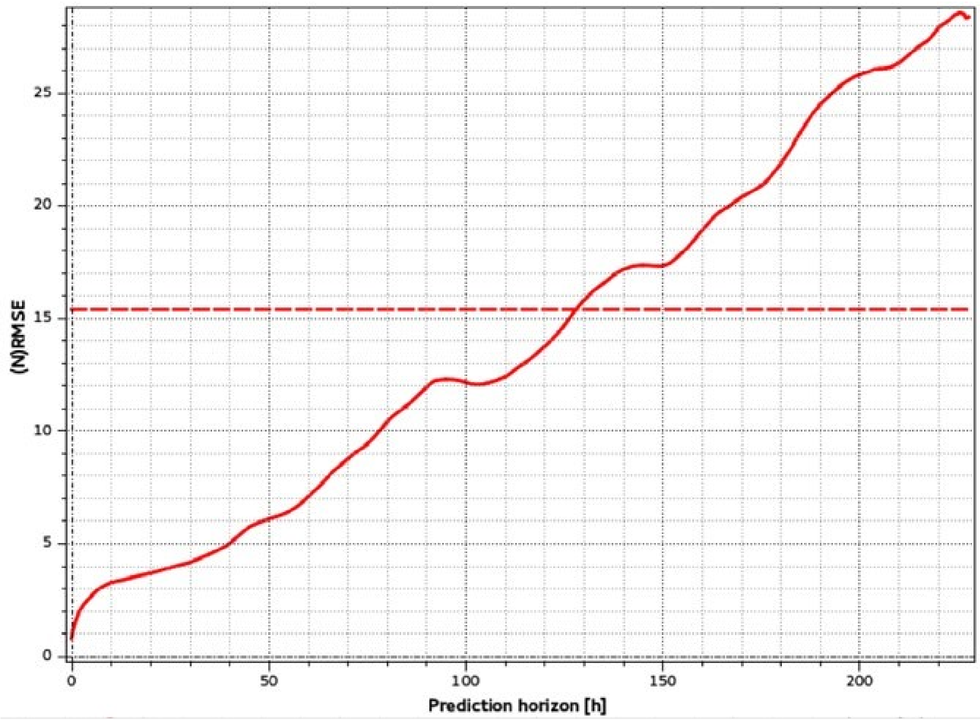
The normalisation of the error metrics is important to be able to compare the forecast accuracy of different sites or portfolios. For this purpose, the error measure can be divided by installed capacity, average output, or actual forecast values. It is up to the user to decide which normalisation is required. For example, many traders prefer MAE normalised to average power output, while TSOs often prefer RMSE normalised to installed power.

In general, the accuracy of wind and solar power forecasts strongly depends on several basic factors, leading to some general rules which are listed in the following.

i) The simplest rule is that the forecast error increases with **prediction horizon**, i.e. the further the forecast looks into the future, the lower is the forecasting accuracy. That means the intraday forecast will potentially be more accurate than the day-ahead forecast, and the day-ahead forecast is on average better than the week-ahead forecast. As shown in **FIGURE 2** for a portfolio of wind farms, the forecast error increases nearly linearly with the prediction horizon. In this example, the error during the first hours is even further decreased by a shortest-term correction based on live production data.

FIGURE 2. Development of the forecasting error with increasing prediction horizon

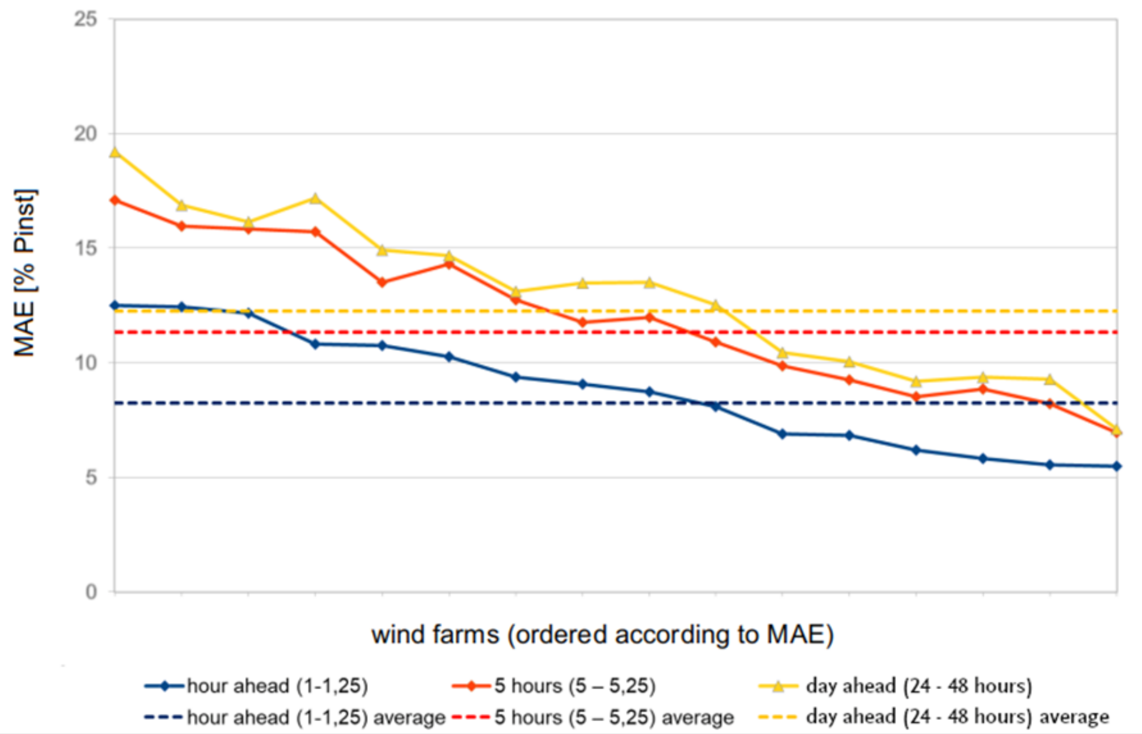
RMSE normalised by installed power, (in values of %) of a medium-sized regional wind portfolio over the prediction horizon of 240 hours (10 days). For the first few hours, the benefit of real-time production data leads to a very small forecasting error. After 10 hours, the forecasting error increases nearly linearly.



Source: energy & meteo systems

ii) The forecast error generally rises with the increasing complexity of the terrain, i.e. surrounding hills and mountains spoil the accuracy, as does close proximity to a shoreline. This is mainly related to the fact that the NWP models cannot detail surfaces and processes below the model's spatial resolution, e.g. wind speed deviations due to channelling effects, or a changed solar irradiance due to the occurrence of fog in valleys. Varying forecasting challenges at individual sites influence the possible accuracy levels of power predictions. **FIGURE 3** shows MAE values of power forecasts for single wind farms spread over Mexico, averaged over the period of 10 months and for different time horizons. The wind farms are sorted by the size of the MAE of the shortest-term forecast (blue line). As can be seen, the MAE values of single wind parks show quite a broad range in forecasting accuracy, spanning a range from 7% to 19% for the day-ahead forecast.

FIGURE 3. MAE values for single wind farms spread over Mexico



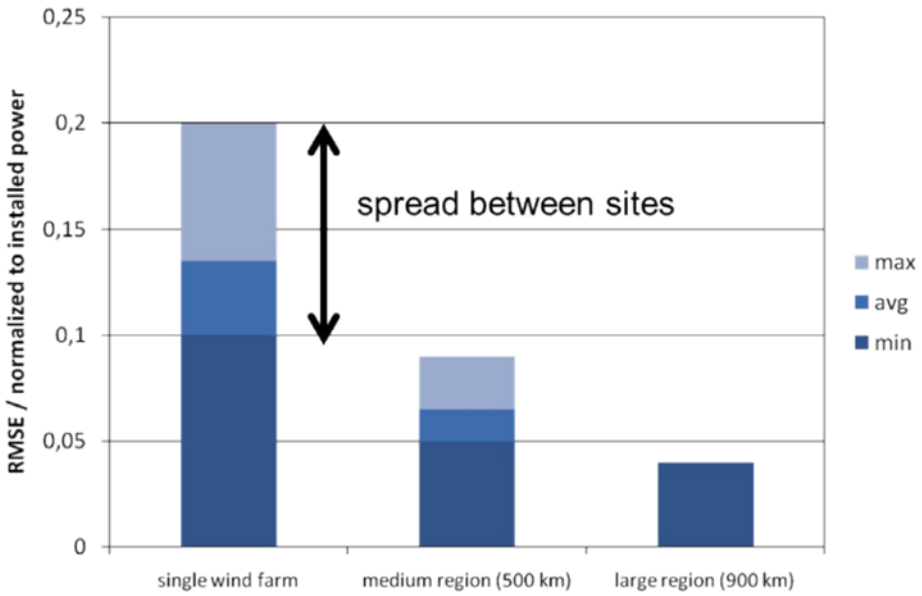
Source: energy & meteo systems

The addition of an NWP model with far less than 10 kilometres horizontal resolution into the process can help resolve these complex atmospheric conditions and therefore improve the power forecasting result. A well-known framework for the set-up of these so-called regional, or local weather models is the free of charge WRF model framework (https://www.mmm.ucar.edu/weather-research-and-forecasting-model).

iii) Forecasts for regional aggregates are always far better than forecasts for single sites due to the fact that weather prediction errors between different locations partly level each other out. This is why the RMSE for the area forecasts (mid and right column in **FIGURE 4**) drops with the size of the region. This spatial smoothing effect is very powerful (Focken et al. 2001), especially with a large geographical spread between the sites. In **FIGURE 4**, the large spread of forecasting accuracy for single sites (left column) between 10 and 20% RMSE normalised to the installed power mainly results from the wind farms' different locations. Especially high RMSE values of 18% or more characterise wind farms located in complex terrain. Please note that the weather conditions also influence the evaluation results. In weather situations that are especially difficult to predict, wind farms with a very good wind resource can generate a higher RMSE even in flat terrain or offshore.

FIGURE 4. Accuracy (RMSE) of day-ahead forecasts (24 to 48 hours)

Normalised by installed capacity for single wind farm, medium size region and large region

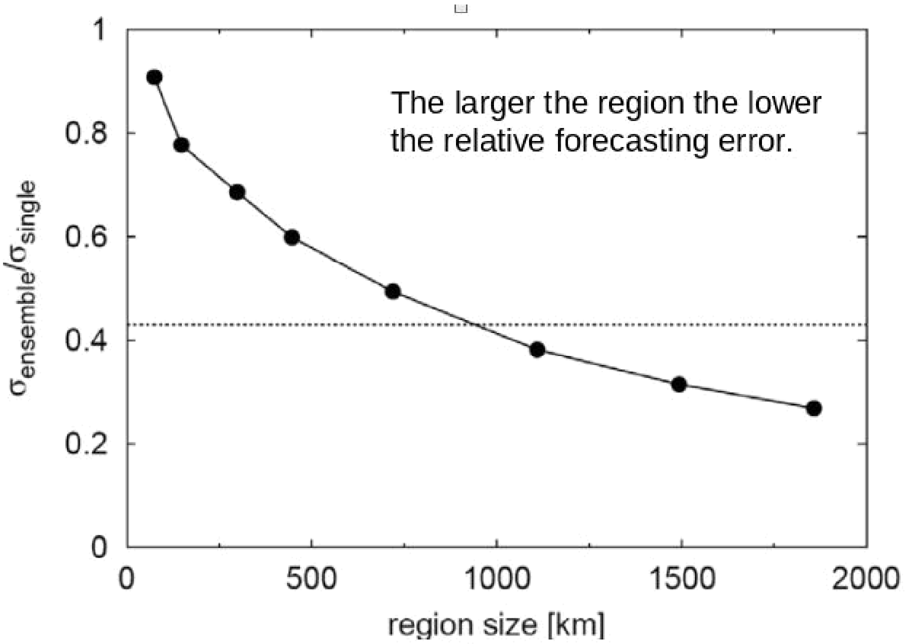


Source: energy & meteo systems

Figure 5 illustrates the general relation between region size and the decrease of the forecast error based on a statistical analysis. It should be noted that averaging the forecast errors from single vRE farms does, by that effect, always lead to a larger error value than a forecast based on a portfolio of the same vRE farms.

FIGURE 5. Decrease of relative forecasting error

For a regional forecast (aggregate) compared to single sites

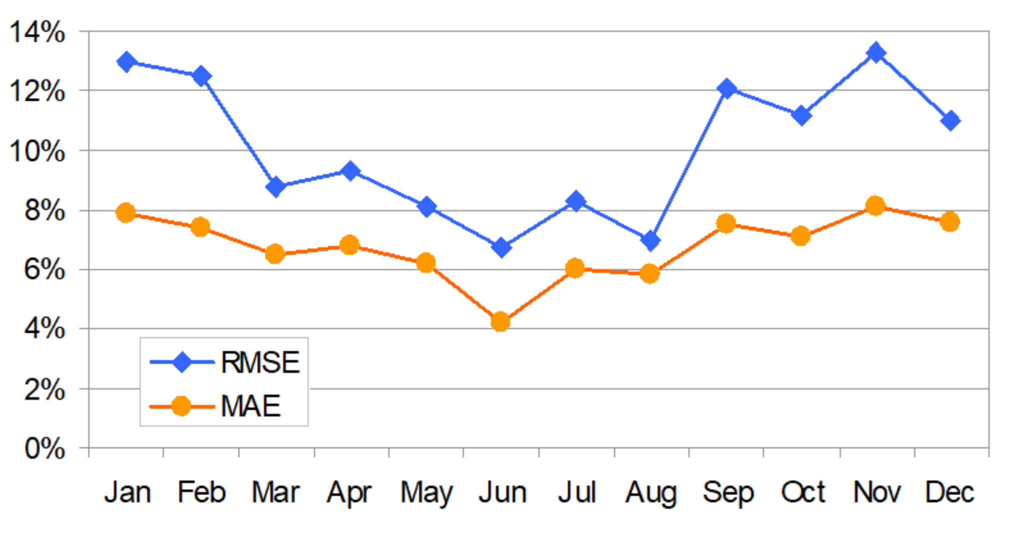


Source: energy & meteo systems

iv) The forecast error **varies by the time of year**. There exist typical months with meteorological conditions that are more difficult to forecast. This seasonal aspect affects all climate zones in its own way. An example for the seasonal variation of forecast errors in Europe is shown in **FIGURE 6**. Sudden decreases or increases of vRE production, so-called ramps, are generally difficult to forecast. Months with an increased occurrence of these ramps hence show larger error values. Time and magnitude of a ramp in the NWP model forecast always have some uncertainty.

FIGURE 6. Development of RMSE and MAE day-ahead forecast values

Of single wind farms in Europe in the course of the year



Source: energy & meteo systems

In Europe, North America and Argentina, for instance, wind power predictions during the winter season have a greater uncertainty because of the increased occurrence of storms. For solar power, a more frequent occurrence of drifting cloud bands, snow or fog situations enlarge the forecast error. Additionally, increased convection activity, i.e. the spontaneous development of clouds over an area, is an issue that not only complicates a good solar power forecast in the mid-latitudes during summertime, but also affects the tropics and subtropics during the rainy season, monsoon season or tropical thunderstorms.

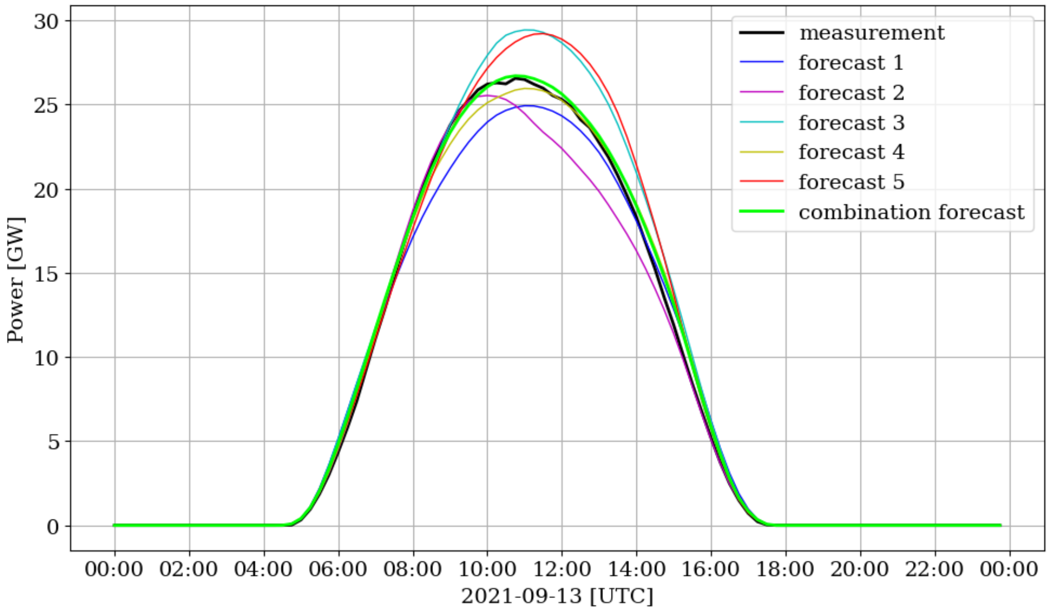
2.4 Methods of advanced power forecasting

The following techniques have become a standard in the business of forecast providers. The wording 'advanced' only indicates that these techniques are additionally applied on the basic forecasting scheme that has been described before. Especially in countries with low vRE status and forecasts that are not created within a competitive market, e.g. when they are delivered by the plant operators, international experience shows that these techniques are commonly not in place, but would certainly lead to a remarkable improvement of the existing forecasting scheme.

— **Combination of forecast**

It is state-of-the-art in wind and solar power forecasting to not trust solely one opinion as far as the weather situation in the near future is concerned. Hence, most of the commercial forecasting systems use several NWP models as input to generate a combination forecast by weighting the weather models according to their performance. Various strategies have been developed to find the best weighting of the models under specific conditions. The combination approach not only leads to a remarkable reduction of the overall forecast error, it works particularly well in situations when extreme events occur. The accuracy of the combination forecast is generally better than the accuracy of each individual forecast based on a single NWP. In **Figure 7**, a solar power forecast for 24 hours is shown where the coloured lines represent power forecasts calculated from different NWP models' output; the green line represents the combination forecast and measurements are depicted in black. The different power forecasts demonstrate that the combination forecast is the most accurate over the given time span.

FIGURE 7. Effect of combining several NWP models for a power forecast



Source: energy & meteo systems

The reason for the different performances is that each numerical weather model has its own way of

- solving the system of differential equations that describe the atmosphere's physical processes,
- resolving sub-scale processes (processes below grid resolution) using different parametrisations and
- feeding-in atmospheric measurement data, depending on model resolution, grid style and area they cover, leading to slightly different atmospheric status from where the computation can be started.

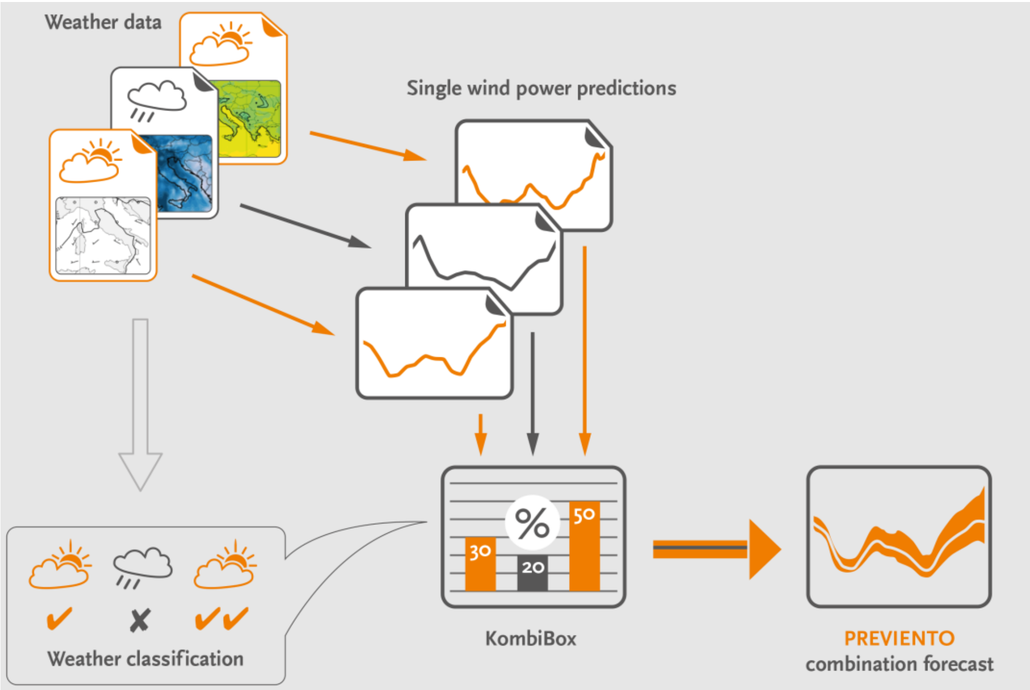
These differences lead to different model output for the same location and time, which is used as a strength in the combination forecast. A statistical analysis (not included here) showed the error to become minimal with the use of five to six different NWP models. Different spatial and temporal resolutions of the NWP models, as well as different update frequencies are beneficial in order to cover a broader range of weather phenomena.

There are two general types of NWP models. Global NWP models cover the whole globe with less temporal and spatial resolution. Typical mesh-widths are 10 to 25 kilometres, the finest global weather model today has a mesh-width of 9 kilometres. Regional NWP models only cover a defined area, are fed by a global NWP model at their edges and can deliver a finer spatial and temporal resolution, as well as a higher update frequency. Typical mesh-widths of regional models range from 3 to 7 kilometres. Global NWP models typically update either every six or every 12 hours, while some regional or local NWP models can deliver a new forecast every hour, depending on their configuration. By combining these two model types, a more accurate approximation for the meteorological parameters at a certain location can be reached as the advantages of one model type partly make up for the disadvantages of the other model type. As a result, at least one global NWP model and one regional NWP model should be combined if resources are limited. Please note that a regional NWP should not be used as a standalone, but should always be combined with a global NWP model because a better resolution does not automatically lead to a better forecast. Should a regional NWP model not be available, and its set-up and maintenance would be too costly, the use of two global NWP models already improves the power forecast a lot compared to a single NWP model forecast. Even though regional NWP models are not available for all locations in the world, there are several good global NWP models to cover all areas of the world. This situation guarantees the creation of a good worldwide combination forecast. Some weather forecasting agencies even offer some products free of charge, such as the German Weather Service (called DWD) which openly publishes the latest results of its global 'ICON' model on its open data platform (https://www.dwd.de/EN/ourservices/opendata/opendata.html).

Experience shows that NWP models do indeed have different capabilities according to the current weather situation where, for example, one NWP is very good at forecasting storm fronts, and another in forecasting high pressure situations or morning fog. This enables the opportunity to let the power forecasting system automatically classify weather situations relevant for wind and solar power prediction, and apply specific weighting factors to allow for an optimal combination of different NWP inputs (**Figure 8**).

FIGURE 8. Example for combination of wind power forecasts

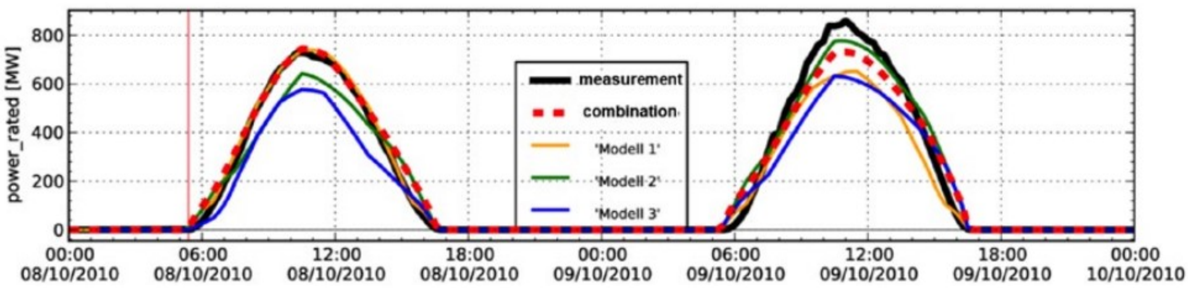
With weighting of NWP input according to the weather situation. For wind and solar predictions, different weather classes are used



As a result of a weather dependent combination, the weighting of NWP models can be very different, as shown in **Figure 9**. On the first day, the weighting factors prefer model 1, such that the combination forecast nearly corresponds to this model. On the second day, which had a different weather situation, the weighting of model 2 is very high, whereas model 1 has a lower weight. This weather classification is a very advanced step in the process of combination forecasts and is therefore not regarded as obligatory.

FIGURE 9. Solar power forecast for two days based on a weather dependent combination

The dashed red line is the combination forecast, the thin coloured lines are power forecasts based on single NWP models. The black line is the (later) observed production



Source: energy & meteo systems

— **Intraday forecast updates**

Frequent updates of power forecasts are beneficial, e.g. they enable improved redispatch management within the day. The standard practice of vRE power forecast providers is to issue new power forecasts as soon as an NWP model update reaches their server. Again, the reason for this is that shorter look ahead times of the NWP model deliver better results on average. With these updates, all stakeholders profit from the most recent and accurate power forecasts on the basis of weather model results.

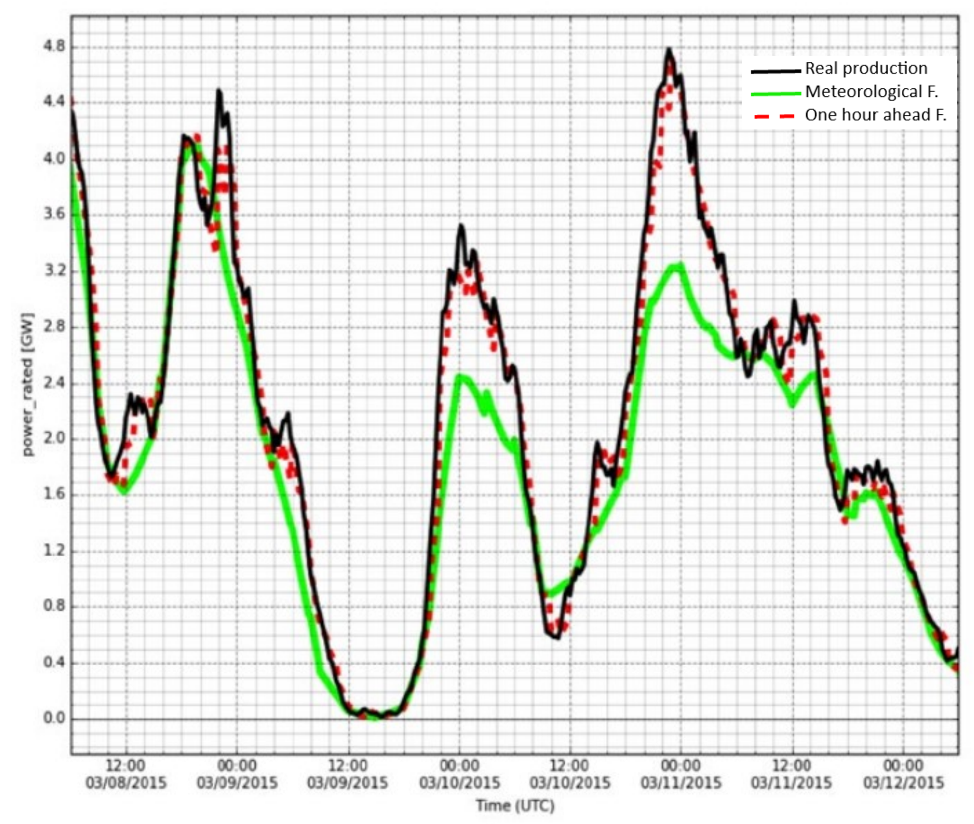
When real-time measurements from the vRE sites are included in the power forecasting process, shortest-term updates can be issued which can offer an even better picture of the forthcoming hours. Here, power forecasts based on NWP models are combined with live measurement data in a highly frequent forecast generation process and delivery, e.g. every 30 minutes. Particularly during weather situations with forecasting errors of the NWP models, the incorporation of real-time data into the forecasting process strongly reduces the deviations in the forecast over the next few hours.

In the example of a regional wind power forecast in

FIGURE 10, the shortest-term prediction was generated every hour based on recent production data of the last fifteen minutes before the hour and the original combination forecast. The advantage in terms of accuracy of this shortest-term forecast compared to the original forecast is obvious.

FIGURE 10. Benefit of shortest-term prediction based on real-time data

In a difficult weather situation, the shortest-term prediction for one hour ahead (red line) is far closer to the real production (black line) compared to the most recent forecast only based on meteorological forecasting data (green line).

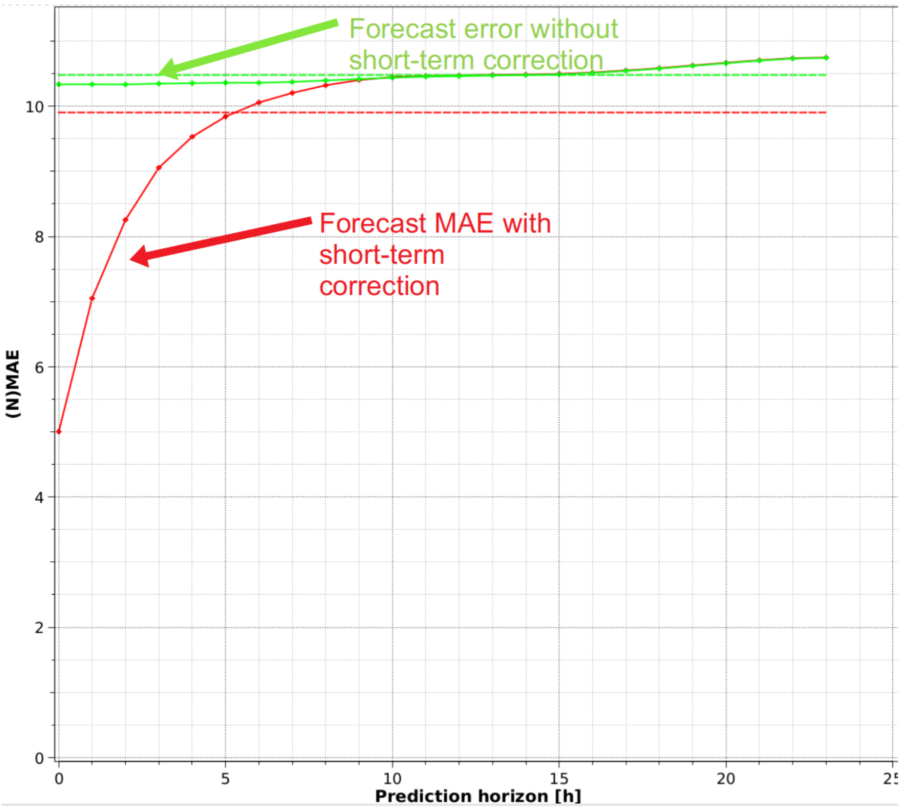


Source: energy & meteo systems

Figure 11 illustrates that this method substantially reduces deviations between forecast and measurement for the forthcoming few hours.

FIGURE 11. Improvement of the power forecast corrected with live production data

The figure shows the result for a random single wind farm, by values of MAE normalised by installed power. This correction is most powerful for the next few forthcoming hours.



Source: energy & meteo systems

The requirements for the real-time data which is used for shortest-term vRE forecasts are very high. The most crucial part is that the delay between collecting the data from the plants, and processing them in the forecast, is as small as possible, because every minute of additional delay leads to higher forecasting errors. For example, if fifteen minute updates are needed, the age of the measurement value should not exceed ten minutes. With modern information technology, this is generally not a big issue, the processing times that can currently be achieved without enormous efforts are less than a minute. For forecasts that are used for intraday trading or unit redispatch, shortest-term forecasts are indispensable.

BOX 1. Use of weather data for improving power forecasts

When only global weather model data is available to produce power forecasts at the site, the typical problem is the low spatial resolution of the weather model which can introduce a large error to the on-site power forecast. The idea to improve the weather data before creating the power forecasts is therefore legitimate. It is important to note that only meteorological measurements taken at the parks' location can be of any help in the process. Data with larger distance to the park should not be used.

Shortest-term correction

Concerning corrections in the intraday, the correction of the power forecast by directly using measured power output from the park will lead to better results compared to improved weather data input. The reason is that weather data has to be converted into power output using the special characteristics of the park which itself has an uncertainty. The measured power data already includes the reaction of the park to any conditions at the site, as well as interactions within the park. When updating the forecasts every three-hours, for instance, it is therefore simpler, and less error-prone, to rely on some temporal mean of the measured power output from the time just before the correction is performed. This is international standard.

Shortest-term corrections using on-site weather data are currently part of international research. In any application, they would be performed additionally, or simultaneously, to a correction based on power measurements and only at very short time-scales (minutes ahead). Applications are the detection of advancing ramps in wind energy or using pictures of the sky/clouds in solar energy.

However, in case meteorological data are available at the site, and power data cannot be transmitted frequently or reliably enough to be included into correction processes throughout the day, the meteorological data would certainly help in improving the power forecast. However, in comparison, the conversion from meteorological resource into power is one computation step more to take place.

Short-term correction

Concerning corrections for the day(s)-ahead horizon, live meteorological data cannot help as they are valid for today and not the days-ahead. However, an idea can be to take a large amount of live meteorological data, e.g. the last six months of on-site measurements and model them against the data from the roughly resolved global weather model (interpolated to the location of the park). This self-created model can be used to correct future data from the global weather model by adapting the meteorological data to the local site conditions. It is expected that this method can - but not necessarily will - lead to improved power forecasts when looking days-ahead.

It shall be noted that, in case a regional weather model is available, the combination of global weather model data (rough spatial resolution) and regional weather model data (fine spatial resolution) is always the recommended option for the creation of state-of-the-art power forecasts, making the inclusion of live meteorological data dispensable.

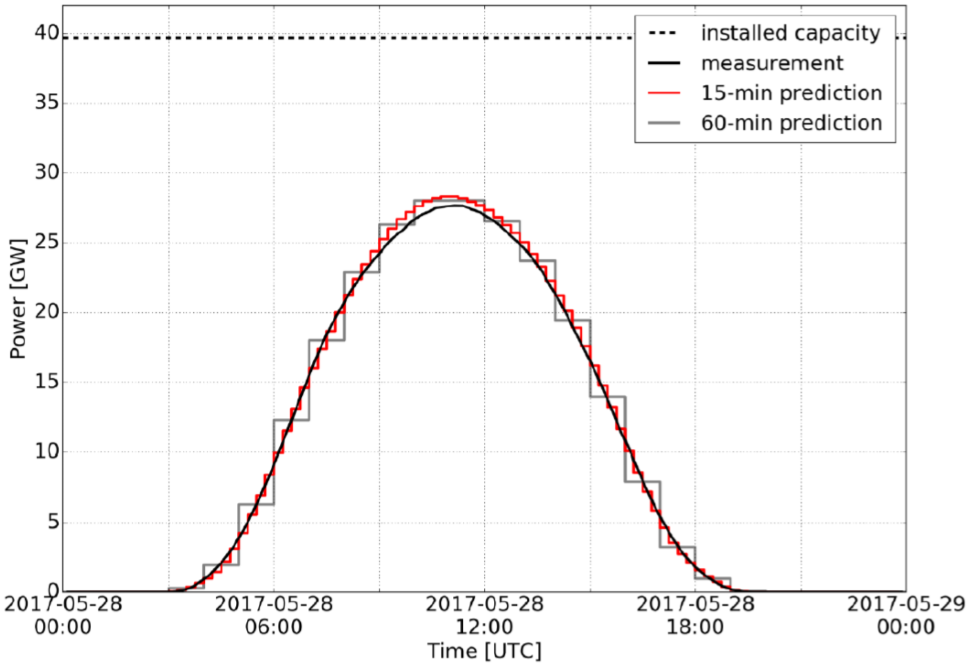
— **Frequent training of the model onto measurement data**

Power forecasting systems need to keep track with the seasonal changes of the wind and solar resource, and to consider site-specific production patterns. Power forecast providers have developed their own techniques to frequently train their forecasting systems onto measurement data of the vRE farms. A proper training on measurement data at different stages of the forecasting process is key for the creation of high-quality power forecasts. Additionally, profound meteorological expertise and a consistent quality control process are necessary to keep forecasting quality high during these seasonal changes, and in order to include local effects in the model training. For the initial training of a forecasting system, at least one year of historic measurement data of the vRE plants is required.

— **Short-time intervals in the forecast time-series**

In the case of ramps in the vRE production time-series, forecasts with smaller time steps perform better because they can better capture the fast increases or decreases of the power production. The solar production, for instance, has a very characteristic steep ramp which is not well described by using a 60 minute average. **FIGURE 12** below illustrates this effect by comparing 15 and 60 minute averages. Although the forecast is good at describing the middle value of the corresponding hour, a lower time resolution causes considerable deviations to the measured data. This behaviour particularly influences the intraday dispatch management. When preparing processes in the energy market and dispatch planning to include a higher share of vRE farms in the near future, or in case of frequent errors during ramping situations, this is an issue to consider.

FIGURE 12. Impact of higher temporal resolution on the accuracy of power forecasts



Source: energy & meteo systems

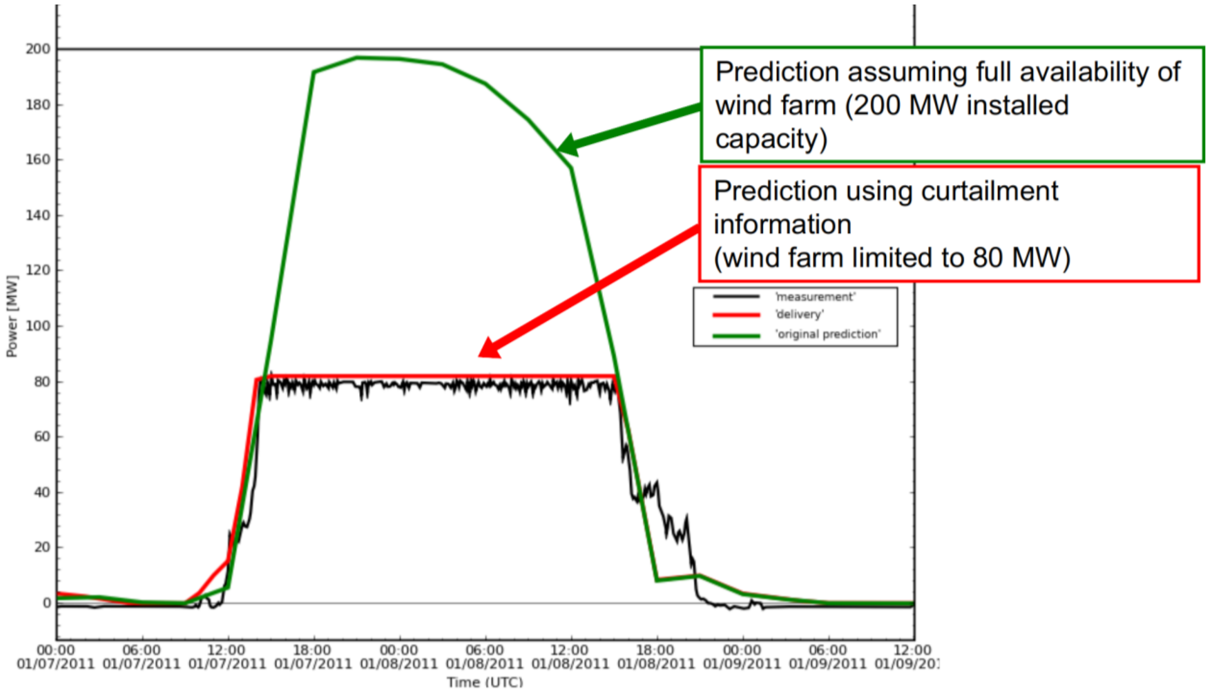
— **Include availability and curtailment information of vRE plants**

A power forecast based on pure meteorological data provides the power output of a wind or solar plant with full availability. However, in practice, the real power output of the plant can be reduced temporarily, or permanently, due to different reasons, e.g. maintenance work. Hence, the forecasting system has to directly consider real-time availability, scheduled shutdowns, planned curtailments of wind farms and grid capacity limits, in calculating the power predictions. For this purpose, suitable information has to be provided to the forecasting system.

From the point of view of the forecast user, it can make a significant difference if a plant is in full operation or not. The example in **Figure 13** shows a power forecast for a large wind farm with 200 MW of installed power, where an original prediction would see an increase of power output up to nearly full load (green curve). However, due to curtailment of the grid connection point by the grid operator, the maximum power output was limited to 80 MW. As the information of the curtailment had been known to the forecasting agent before the forecast was produced, the delivered forecast took this into consideration (red curve). From this example, it is clear that it is indispensable for high forecasting accuracy to include availability and curtailment information into the forecasting process.

FIGURE 13. Time schedules for planned partial/full shutdowns or curtailments

These outages can be considered in the forecast (red curve) if announced in a timely manner. The prediction assuming full availability (green curve) can also be provided.



Source: energy & meteo systems

In practice, setting up and maintaining the data flow related to this information requires some effort. It has to be taken into account that times of reduced availability of vRE units are mainly known to the operator, whereas time periods of maintenance of power lines or curtailments in the grid are known to the grid operator. These key pieces of information must be transferred to the power forecast provider. The most effective way to organise this is by collecting this information centrally, e.g. through the grid operator or regulator, such that the complete information can be retrieved by the forecast provider.

The first step is to establish a reliable system to collect schedules of reduced availability of the vRE units and related grid sections. The second step is to increase the temporal granularity. For practical purposes, it is desirable to have availability information at the same temporal granularity as the forecast, i.e. hourly for hourly forecasts, and every five minutes for five minute forecasts.

2.5 Benefits of an advanced power forecasting system

Weather dependent solar and wind power production can lead to unexpected and quick status changes which affect the efficiency of a power system. This, in turn, threatens the stability, safety and reliability of system operation. In addition, unforeseen fluctuating vRE production affects expenditures to keep the system in balance.

It is therefore critical to have an advanced power forecasting system that provides accurate information on future vRE production schedules. More visibility is key to enabling system operators to react early, and to prepare the most cost-effective solutions for vRE integration.

The importance of power forecast accuracy becomes increasingly noticeable with rising shares of fluctuating renewable energies. The International Energy Agency (IEA) categorises four different phases of vRE integration which are described in the following table.

TABLE 2. Phases of vRE integration

	ATTRIBUTES (INCREMENTAL WITH PROGRESS THROUGH THE PHASES)			
	Phase 1	**Phase Two**	**Phase Three**	**Phase Four**
Characterisation from a system perspective	vRE capacity is not relevant at the all-system level	vRE capacity becomes noticeable to the system operator	Flexibility becomes relevant with greater swings in the supply/demand balance	Stability becomes relevant. vRE capacity covers nearly 100% of demand at certain times
Impacts on the existing generator fleet	No noticeable difference between load and net demand	No significant rise in uncertainty and variability of net load, but there are small changes to operating patterns of existing generators to accommodate vRE	Greater variability of net load. Major differences in operating patterns; reduction of power plants operating continuously	No power plants are operating around the clock; all plants adjust output to accommodate vRE
Impacts on the grid	Local grid condition near points of connection, if any	Very likely to affect local grid conditions, transmission congestion is possible, driven by shifting power flows across the grid	Significant changes in power flow patterns across the grid, driven by weather conditions at different locations; increased two-way flows between high and low voltage parts of the grid	Requirements for grid-wide reinforcement and improved ability of the grid to recover from disturbances
Challenges depend mainly on	Local conditions in the grid	Match between demand and vRE output	Availability of flexible resources	Strength of system to withstand disturbances

Source: IEA (2017)

While in phase 1, the share of vRE production is low and goes unnoticed, the impact of fluctuating generation starts to become noticeable to the system operator in phase 2. In this phase – according to the IEA, the countries classified here had a share of between 3% and 13% - a few upgrades of the operational practices can usually easily integrate vRE generation. One of these upgrades is considered to be the implementation of an advanced power forecasting system to determine the net load and efficiently balance generation and demand. Although at this stage, the system can still be operated reliably without accurate power forecasts, it will be more costly due to inefficient scheduling and dispatch of non-vRE generators (IEA: Getting Wind and Sun onto the Grid. Insights Series 2017). In the following phases 3 and 4, with even higher levels of vRE penetration, solar and wind power forecasts are indispensable for a safe and economic operation of the power system.

The benefits of higher forecasting accuracy naturally vary significantly depending on the characteristics of the power system. These include, among others, power system size, the geographical and technical spread of vRE plants, robustness of the grid network technology, capacity and costs of generators, operational processes and constraints, etc. Yet, the international practical experience from advanced vRE markets, and findings from studies, allow the identification of the following positive impacts of a highly accurate power forecasting system:

— **Operational system security**

With increasing vRE penetration, the system security and reliability of electricity supply is challenged when no advanced forecasting system is in place. Large deviations between forecast and actual production can lead to overloads, load deviations, or network violations. Operational processes at the system operator are under stress when significant forecast errors need to be settled on an ad-hoc basis. International experience shows that it is advisable to implement a state-of-the-art forecasting system already at lower vRE penetration levels and not to wait until their share starts to pose serious operational challenges. For example, as a result of a consulting project carried out by GIZ and energy & meteo systems, the TSO of the Dominican Republic made various adjustments to the power forecasting system. Up to this point, the TSO had exclusively relied on power forecasts provided by the plant operators which lacked accuracy. The measures included contracting an external service provider to have more accurate, complete and consistent power forecasts. While the adjustments were implemented, the share of vRE generation had risen from 3.4% (271 MW of wind and PV) to 8.0% in 2021 (736 MW of wind and PV). With 5.2 GW of overall installed capacity, the size of the Dominican power system is rather small and, apart from vRE generators, the electricity is produced by small conventional units. Even a deviation of 100 MW between forecast and production can cause grid overload and voltage problems, requiring the rapid activation, or curtailment, of multiple gas-fired plants. OC reported in an interview that relying on more accurate forecasts has increased their confidence in taking correct dispatch decisions and that it reduced the stress in system operation. OC emphasised that serious operational problems would occur if they had to work with the previous power forecast uncertainty levels.

— **Improved generation planning**

A high degree of uncertainty in day-ahead power forecasts translates to wrong decision-making in the day-ahead planning process of the system operator, for example, in the case of under-predicting the vRE production, the day-ahead dispatch unnecessarily considers additional plants in the unit commitment. Vice-versa, when power forecasts overestimate vRE production, units quickly need to be activated in the intraday to meet demand. More accurate power forecasts reduce the uncertainty in the day-ahead planning process, and thus the need for short-term activation of conventional plants. In addition, faster and usually more costly generators committed in real-time need to be used less to compensate forecasting errors. The impact of more accurate power forecasts on generation planning was investigated in a study (**Martino-Anidez et al., 2016**) which analysed four forecast improvement scenarios (25%/50%/75%/100%) for four levels of solar penetration. The study shows that, at a 9% solar penetration level, a 25% improvement in the power forecasts would decrease the electricity generation from conventional units by 4.5%, and a 50% forecast improvement, by 7.5%. OC confirmed that a more efficient day-ahead dispatch planning, due to more accurate forecasts, means that, in the Dominican Republic, less unnecessary start-ups or shutdowns of fossil-based power plants now occur.

— **Reduced operating reserve**

The available operating reserve enables the system operator to respond to a sudden increase in electricity demand, or lower than scheduled generation. The incorporation of fluctuating solar and wind power potentially adds significantly more uncertainty to system operation, since errors in vRE prediction are higher in comparison to load forecasts. More accurate power forecasts – supported by the introduction of short-term intraday scheduling processes – are therefore key to reducing the need for operating reserve.

— **Decreased curtailments of vRE generators**

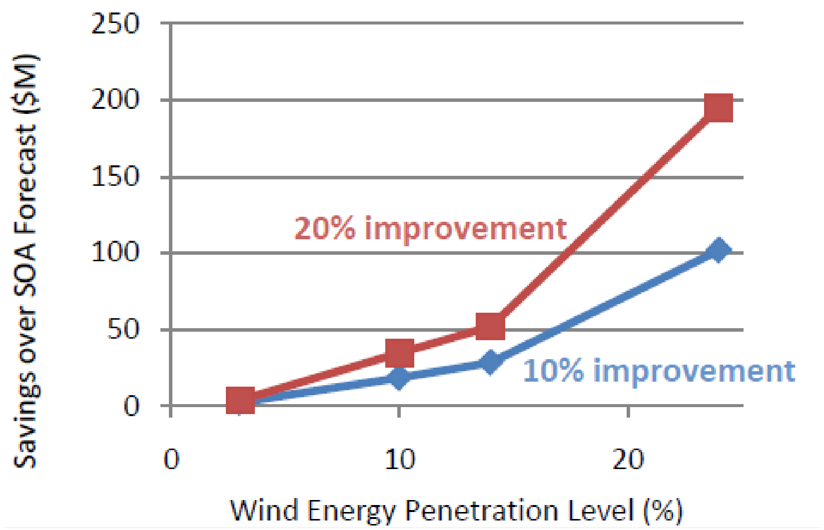
Unnecessary curtailments of solar and wind power plants occur when power production is higher than predicted, and cannot be compensated in the short-term by adjusting the power output of other units. Curtailments of vRE generators, due to forecasting errors, are costly since their low cost electricity production is replaced by much more expensive generators. In addition, the plant operator may need to be compensated for production and revenue losses. The previously cited study from Martinez et al. investigated the positive impact of forecast improvement at different solar penetration levels. In their power system model, at a 9% share of solar power generation, a forecast improvement of 25% would reduce curtailments by 2.3%, and a 50% forecast improvement, by 4%.

Some studies have examined the impact of forecast accuracy levels on vRE integration costs.

— In a study by NREL, the value of more accurate day-ahead wind power forecasts was analysed for the Western Electricity Coordinating Council (WECC, extends from Canada to Mexico, and includes the provinces of Alberta and British Columbia, the northern portion of Baja California, Mexico, and all, or portions of, the 14 Western states in-between) for different wind energy penetration levels. For the analysis, the operating costs included fuel cost, start-up costs, and unit variable operation and maintenance costs.

FIGURE 14. Average annual operating cost savings versus wind penetration

For 10% and 20% wind forecast improvements



Source: NREL (2011)

As shown in **Figure 14**, at low penetration levels, the savings of 10% and 20% improved forecast increase slowly, and then drastically, when exceeding a 14% penetration level. At a 14% share of wind power savings, and a 20% improved forecast, the savings would amount to 52 million USD. As regards annual operating costs, at a 24% wind energy penetration level, a 20% improved forecast would lead to savings of 195 million USD.

— Another study, published by Berkeley Lab in January 2022, examined the costs of solar forecast errors by using day-ahead and real-time prices as an indicator for system costs. The study looked at over 600 plants, from 2012 to 2019, across five major electricity markets in the United States. The study compared two types of forecasts, a simple 'persistence' forecast approach, in which today's solar profile will repeat exactly tomorrow, and a publicly available NWP forecast (the North American Mesoscale Model, NAM). The study found that the average cost of the forecast errors using the NAM method was 1 USD per MWh, or less in all other years except 2016, while the persistence-based forecasts caused, at close to 1.5 USD/MWh, higher costs every year. This shows that even the use of a simple forecasting technique can provide value by reducing the cost of forecast errors. Additional savings, which can be expected when using a professional forecasting system, were not examined in the study.

It can be concluded that power forecasts play a crucial role for successfully integrating vRE production into various processes of power system operation. With rising shares of solar and wind power their importance becomes more evident. At a quite early stage of vRE expansion a powerful forecasting system is indispensable for a safe and economic operation of a power system.

2.6 Responsibilities in power forecasting: options and international trends

A main design option of a forecasting system is whether power forecasts will be administered centrally by the system operator, or provided decentralised by the solar and wind power plant operators. The decision for a centralised or a decentralised forecasting concept defines different roles and responsibilities of the plant operators and the TSO. However, both concepts are not mutually exclusive and are even combined in several countries.

In a **decentralised forecasting system**, the owners of solar and wind power plants are obliged to submit power forecasts to the TSO. The regulatory authority, or TSO, defines which plants (minimum size) need to send forecasts in a certain resolution, quality, update frequency, etc. The plant operators, on their part, either produce the power forecasts themselves, or contract a professional service provider. In cases where a quality control is established, combined with a penalty scheme, the plant operators will tend to contract a service provider to ensure a certain quality level.

The alternative concept is a **centralised forecasting system** where one central entity – most often the transmission system operator – directly administers the predictions. This can be done by either setting up an in-house solution, or by contracting a professional service provider (external solution).

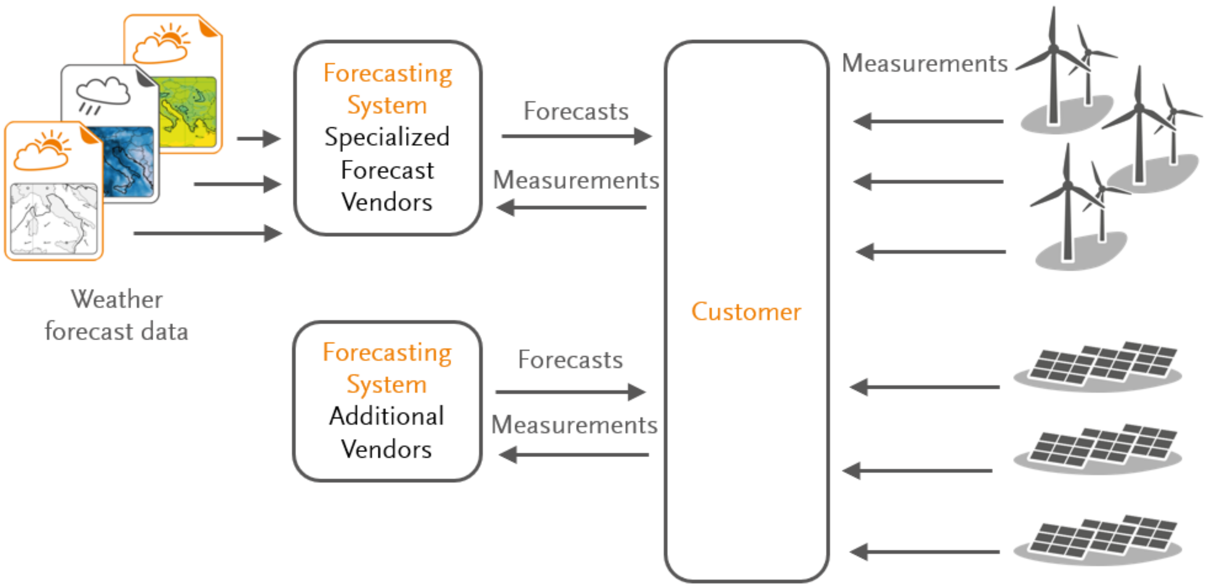
— The first option is to set-up an **in-house forecasting system**. In this case, the forecast user manages the entire forecasting process internally. This includes developing or purchasing a forecasting system, sourcing of NWP models, ensuring sufficient IT capacities to handle large data volumes, and hiring or specialising staff in forecasting issues. The advantage is that the user builds up their own experience in solar and wind power forecasting and has the possibility to control and improve all the processes. However, this approach involves high costs for purchasing, or developing, a forecasting system and for maintaining it. Usually only very large vRE markets with many plants can justify setting up an in-house forecasting system.

— In the **forecast-as-a-service model**, specialised service providers offer to provide solar and wind power forecasts. The forecasting system is completely managed by the service provider, including the selection of NWP models and the entire process of converting meteorological predictions into power forecasts. Since forecast providers reach out to many users, the fixed costs (forecasting system, purchase of NWP models) spread based on an economy-of-scale-effect. Costs significantly vary with the scope of customisation and the complexity of the requirements. A forecast service, which includes processing of real-time production data for very short-term power forecasts, will be more costly than a standard day-ahead forecast. In addition, the forecasting costs per unit tend to decline with an increasing number of assets, as set-up costs for the client-specific forecasting system are shared across a larger portfolio. Due to an increasing number of service providers, the international vRE forecasting market is characterised by a high level of competition. High-quality power forecasts are therefore accessible at low cost.

From the TSO's perspective, one major challenge in the decentralised approach is to ensure a high level of forecast accuracy. The TSO usually does not know the source of the forecasts and has no control over the forecasting process. Coming from different sources, the plant-level forecasts often have a wide range of quality levels. A systematic forecast bias can also be triggered by power market incentives, or even a penalty regime (see **section 2.7**). With an increasing number of vRE plants and diversity of operators, it becomes a time consuming task for the TSO to ensure complete and accurate power forecasts. The decentralised forecasting system is therefore more recommended for power systems with a smaller number of vRE plants and a lower share of vRE production.

In centralised forecasting systems, the vast majority of the TSOs choose external service providers instead of building up its own forecasting system, which is why the first option will not be discussed in detail. In the figure below, the data flow is visualised for the centralised forecasting system where a service provider is contracted. In this case, the power forecast user receives measurement data from the solar and wind power plants and provides them to the forecasting service provider. The service provider, in turn, selects weather predictions from different NWP models. Based on the standing data, measurement data, weather data and his/her own forecasting system, the service provider creates power forecasts and provides them to the user in the agreed format.

FIGURE 15. Data flow in a centralised forecasting system



Source: energy & meteo systems

Centralised forecasts provide system-wide forecasts for all vRE generators, e.g. in a balancing area. This leads to a greater consistency in results due to the application of a single methodology. The results are neutral and not distorted by other incentives. In contrast to the decentralised approach, small-scale vRE plants (e.g. rooftop PV plants) can also be covered cost-efficiently in the forecast. The contractual relationship is the basis for direct communication between the TSO and the service provider on quality issues and service needs.

Since the expansion of vRE into the electricity supply in the late 1990s system operators and regulatory authorities have gained experience with both forecasting approaches. Due to better prediction results and easier handling of the forecasts, the international trend shows an ongoing shift towards a centralised forecasting system.

Today, an estimated 80% of worldwide TSOs primarily rely on centralised power forecasts:

— All European countries
— All Independent System Operators in the United States
— All Independent System Operators in Canada
— The Market Operator of Australia

In Latin America, Asia and Africa both forecasting systems are in use and often combined. However, here, too, the overall trend shows a preference for the centralised approach, particularly in countries with higher or increasing shares of vRE.

Among the countries which have recently adopted a centralised forecasting system are:

— Asia: Vietnam
— Africa: Tunisia
— Latin America: e.g. Argentina, Uruguay, Chile, El Salvador, Dominican Republic

In many cases, these countries started with a decentralised forecasting system and later decided to introduce a centralised system, while continuing to request predictions from the plant operators (e.g. Chile, Dominican Republic, El Salvador). It has never been observed that a country dropped a centralised forecasting system to switch to a decentralised system.

BOX 2. Forecasting small-scale vRE generation

An important aspect of power forecasting is how to cover distributed vRE generation. This particularly refers to electricity generation from rooftop PV systems. In some power systems, these small-scale generators have been installed in large numbers and dominate solar PV generation. For example, at the end of 2021, Germany had two million installed solar power plants. Rooftop PV plants accounted for 75% of the entire solar power capacity of 59 GW. Due to economic reasons, data management challenges, and accuracy aspects it is not useful to require each operator – often private households, industry and commerce – to provide power forecasts. This is why purely decentralised forecasting systems are not an adequate solution for power systems with a significant share of rooftop PV systems. Centralised forecasts, by contrast, can easily also cover smaller generators. If a complete plant register - containing at least the installed capacity and location of each plant – is available, an NWP based power forecast for the entire installed capacity can be created. If predictions are needed for defined aggregation levels – for instance, for a balancing area or individual substations – the forecast can be tailored by assigning the plants accordingly.

With very few exceptions the, system operators rely on power forecasts provided by external service providers. The four German TSOs initially also supported the development of in-house systems 20 years ago and collaborated with research institutes. The in-house system was the primary system during the first years of rising vRE shares. However, more than 15 years ago, all German TSOs switched to commercial forecasting vendors. The main reasons for this were a higher accuracy of the power forecasts, lower costs, a high service quality and the flexibility to change forecast suppliers.

2.7 Experiences with penalty schemes: the case of India

In decentralised forecasting systems, where the system operator exclusively relies on power forecasts provided by the plant operators, an unsatisfactory quality of the predictions is a common problem. Typically, the plant operators receive a fixed feed-in tariff and do not need to take care of the integration of their fluctuating production. Their responsibility is limited to providing information on future production schedules of their plant(s) to the system operator. Often, this task is perceived by the plant operators as a mere cost burden, and not as an important contribution for a seamless vRE integration which benefits all of the market participants. This attitude may be changed if there is a dialogue with the system operator on forecasting issues to raise awareness of their importance.

When challenged by inaccurate power forecasts, a useful idea is to introduce a penalty scheme in order to incentivise the plant operators to dedicate more attention and resources to their forecasting responsibilities. However, implementing a balanced and effective penalty scheme involves numerous challenges.

One reason is that the accuracy level of power forecasts varies significantly with the generator technology (solar, wind) and the location of the plants, including their site-specific forecasting challenges. An exemplary span of prediction accuracy levels for different plants was shown in **Figure 3**. As a consequence, a fair penalty scheme necessarily has to be well-differentiated to take into account these individual forecasting conditions.

Furthermore, a penalty scheme should also take into account that the accuracy of power forecasts varies with changing meteorological conditions in the different seasons of the year. This was previously illustrated in **Figure 6**.

The question then arises of whether penalties can also be applied to already existing wind and solar power plants, or only to future plants added to the power system. Retroactive changes in the regulation may lead to disputes and undermine investors´ confidence in the reliability of a vRE market.

A penalty scheme requires the system operator to constantly monitor forecasts and actual production for each vRE plant, and to calculate error measures. Plant operators need to be confronted with evaluations and resulting penalties which may lead to (legal) disputes. Maintaining a penalty scheme therefore requires substantial effort.

Finally, the fee structure needs to be well dimensioned in order not to stall the vRE development in a market. If the penalties are high – and permitted forecasting errors difficult to comply with – companies may refrain from investments at all, or not exploit available wind and solar resources in locations where vRE generation is difficult to forecast.

An important example for a country which decided to introduce a penalty scheme is India. With 48 GW of installed wind power, and 40 GW of installed solar power by the end of 2021, the country is one of the largest international vRE markets. Back in July 2013, India had already implemented a regulation that imposes fees when vRE plant operators submit inaccurate power forecasts. It is mandatory for vRE plant operators to send day-ahead power forecasts to the TSO. Additionally, up to 16 intraday forecast revisions are allowed in the intraday. Absolute forecast errors are then calculated for each 15 minute time block. If the absolute error is below 15%, no penalties apply. If the error is higher, different penalties apply according to the extent of the deviation (15%-25%, 25%-35%, above 35%). The penalty scheme does not consider seasonally, or site-specific, varying forecasting challenges.

It is not known if the penalty scheme has improved the accuracy of power forecasts. However, its introduction has prompted legal and operational consequences.

First of all, solar and wind power producers oppose the regulation and have taken legal action against it. The main reason is that penalty fees are up to 1.5% of the IPP´s revenues, and therefore have a noticeable economic impact on their investment.

In addition, it has been observed that plant operators in India tend to optimise their power forecasts in order to minimise penalty risks, rather than aiming to achieve a high degree of accuracy. For instance, if full production of a solar or wind power plant (100% of installed capacity) is predicted, the plant operator only faces a penalty risk if the actual production is lower. To minimise the risk, the plant operator will tend to submit a lower forecast (ca. 87%). This penalty-orientated optimisation of the power forecasts leads to distorted forecasts which are not conducive with the system operator’s objective to utilise them for an efficient integration of vRE in the power system.

The described complexity of developing a balanced penalty scheme, and the experiences in India, show the inherent difficulties of this approach to improving the accuracy of power forecasts. Drawing from international experience it is more advisable to focus instead on working with centralized forecasts.

3 International Lessons Learnt from Power forecasting

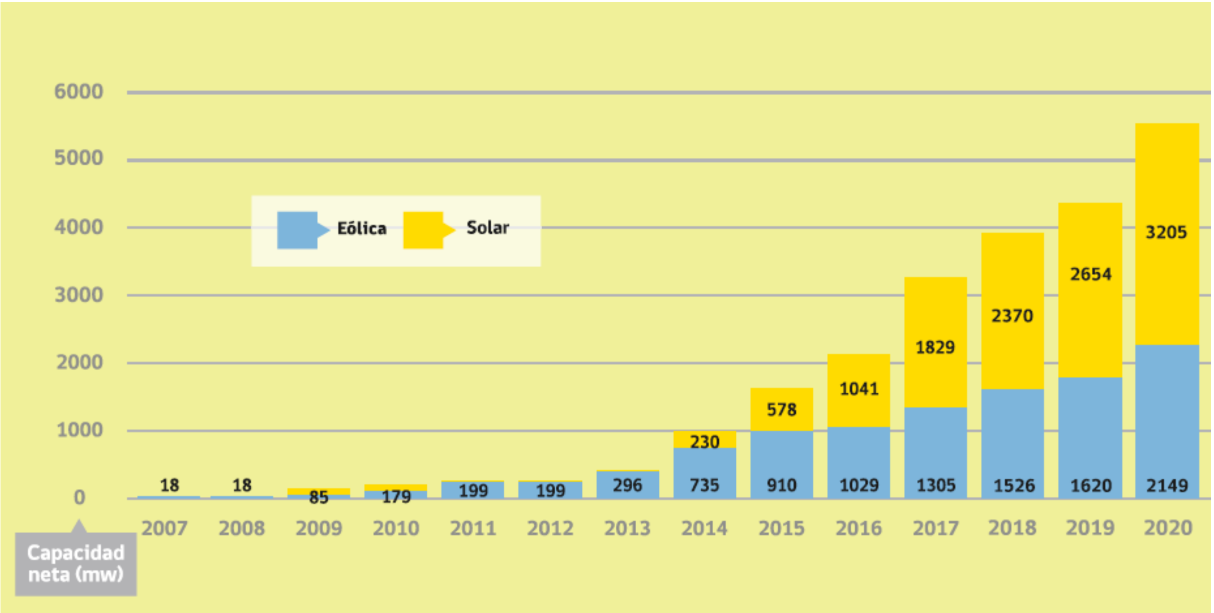
The idea of this section is to share international experiences with solar and wind power forecasting. The following case studies present challenges that different countries faced with power predictions and how they reacted to them. The selected countries – Chile, Mexico, Dominican Republic – are from Latin America but the fundamental observations and insights are useful and valid for any power system regardless of the geographical location.

3.1 Country brief: Chile

Chile is a pioneer and strong advocate for the use of solar and wind energy in Latin America. Since 2014, Chile has supported a dynamic growth of variable renewable energies which achieved a share of 16,8% of the national electricity supply in 2020. Due to the successful and accelerated growth, Chile now aims to reach the 70% vRE target by as early as 2030, originally scheduled for 2050. The expansion of vRE is part of a comprehensive plan to convert Chile into a carbon-neutral country by 2050, which includes the shutdown of carbon-fired plants, a strategy to improve energy efficiency and to convert Chile into an important international supplier of hydrogen.

According to the Chilean National Energy Commission (CNE), the installed capacity at the end of 2020 was 24,714 MW out of which 3,205 MW was solar, and 2,149 MW was wind energy. Solar energy accounted for 9.7%, and wind energy for 7.1% of the entire electricity production in Chile. Despite the dynamic growth of these technologies, 78% of the generation is still covered by conventional thermal and hydroelectric units, owing also to the continuously rising demand (CNE 2022).

FIGURE 16. Development of solar and wind power capacity in Chile



Source: GIZ (2021)

The bulk of the wind and solar power plants are utility scale projects which resulted from public tenders. In addition, the Chilean net billing law also allows the installation of smaller vRE, or cogeneration assets up to 300 kW for self-consumption and feed-in of exceeding electricity. At the end of 2020, 6946 plants, with an installed capacity of 56 MW, were installed across Chile, most of them being very small solar plants with an installed capacity of less than 5 kW.

The system operator, Coordinador Eléctrico Nacional, dispatches the power plants based on a centralised economic operation of the power system, taking into account the marginal costs of the units. As a consequence, vRE units in the national electric system (Sistema Eléctrico Nacional, SEN) with no, or very low, marginal costs are dispatched first, followed by carbon, gas and diesel fired plants.

Initially Chile had a purely decentralised forecasting system where Coordinador relied on the power forecasts provided by the solar and wind plant operators. The forecasts showed large deviations, in some cases, the plant operators had simply sent a forecast based on the previous day's generation.

A study, conducted by GIZ in 2016, analysed the results of the forecasts generated by plant operators and recommended taking measures to improve the forecast accuracy, including the introduction of centralised vRE forecasts for the system operator (GIZ 2016).

Supported by the GIZ, Coordinador received centralised forecasts from a professional service provider in a pilot phase between April 2018 and December 2018. The service covered 26 wind parks and 33 solar parks with a combined capacity of 3425 MW. Coordinador received intraday forecasts (0-24 hours), and day-ahead forecasts with a horizon of 240 hours, both with hourly time resolution. After the end of the project, Coordinador continued to contract an external service provider to submit centralised forecasts.

As a consequence of the gained insights, Coordinador proposed new forecasting requirements which the regulatory authority implemented in the Regulation of the Operation and Coordination of SEN. (Reglamento de Operación y Coordinación del SEN). Regulation 125, approved in December 2019, introduced the requirement for the system operator to have centralised power forecasts. In addition, the regulation further specified the plant operators' forecasting obligations. Among others, the plant operators had to try to minimise the prediction error; however, there is no quantification of the permitted deviation from the forecast.

The regulation established the following characteristics for the forecasts provided by the plant operators:

— Wind and solar photovoltaic plants generate a day-ahead forecast with a 48 hour horizon and a forecast with a one week horizon
— The forecasts are updated every hour and every six hours respectively. The wind power plants also send an intraday forecast with a 12 hour horizon wind speed forecast, a temperature and atmospheric pressure forecast with a 12 hour horizon
— Forecasts need to be provided for temperature and atmospheric pressure with a 48 hour horizon, and a ramp forecast with a 48 hour horizon
— All forecasts have an hourly resolution

Over the past years, Coordinador has also built up in-house capacities to evaluate and process power forecasts. In addition, since 2020, the network operator has also received meta-forecasts from a service provider (called 'Sistema Experto'). The objective of these meta-forecasts is to create an optimised forecast by combining and weighting the predictions from the plant operators and the external service provider. The result is an improved forecast which is, on average, more accurate than forecasts from single sources.

The invested efforts resulted in a notable improvement of the accuracy of the power forecasts. In 2017, the MAE for solar and wind power forecasts plants submitted by the plant operators was, on average, 13%. By 2019, the error value had declined to 9-10%. The MAE of the forecasts of the external service provider also improved over this period, and reached average values of about 9% in 2019 (Coordinador, 2019).

3.2 Country brief: Mexico

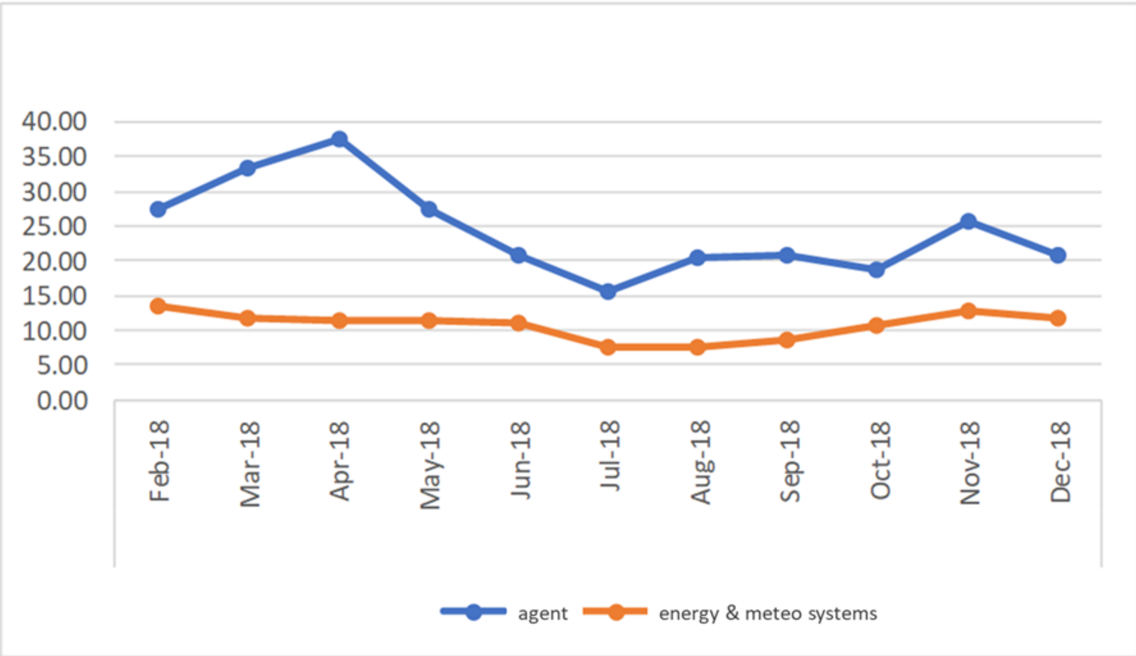
Mexico aims to rapidly diversify its energy supply. By 2024, power generation from renewable energies is set to reach 35%. The long-term target is to achieve a share of 50% by 2050. In the process of liberalisation of the energy market, and unbundling of the public utility, CFE, private companies are now also allowed to participate in the generation of energy. Driven by public auctions, large scale solar and wind farms have been commissioned. At the end of 2021, out of 86 GW of installed generation capacity, wind power accounted for more than 7.6 GW and solar power for 7 GW.

Within a Public Private Partnership (develoPPP), executed with the GIZ in Mexico, energy & meteo systems transferred know-how in power forecasting. The project included a one-year pilot phase during which energy & meteo systems provided the system operator, CENACE (*Centro Nacional de Control de Energía*), with predictions for selected solar and wind power plants which accumulated to more than 3 GW of installed capacity. By then, CENACE was only receiving power forecasts from the plant operators which were used for dispatch planning.

The centralised day-ahead forecasts showed an overall significantly higher accuracy than those provided by wind and solar plant operators. CENACE compared both forecasts during the pilot phase and analysed that the MAE of the wind park operators' forecasts was 17%, in comparison to 13% for energy & meteo systems. The power forecasts of the solar park operators showed an average deviation of 9%, while energy & meteo system's forecasting error of 6% was one third lower. The data analysis particularly revealed that plant operators tended to submit very low production forecasts. As an example, **FIGURE 17** shows the comparison of MAE values for power forecasts provided by plant operators (agents) and energy & meteo systems for wind parks in Baja California.

FIGURE 17. Comparison of MAE values for day-ahead forecasts

Provided by agents (plant operators) and energy & meteo systems for wind parks in Baja California.



Source: CENACE (2019)

According to an analysis conducted by CENACE, upscaling the higher accuracies of the centralised forecasts from the pilot project on the entire wind and solar power capacities in Mexico would translate to 300 MW/hr corrected deviations, in comparison to the forecasting results of the plant operators. Considering the future expansion of solar and wind power plants by 2024, the avoided deviations would achieve 622 MW/hr according to CENACE.

CENACE came to the particularly important conclusion that the notorious underestimation of forecasted vRE production caused the dispatch of more expensive conventional power units in the merit order list. This ultimately leads to higher costs in system operation which are financed by the final electricity consumers.

Drawing from this experience, CENACE decided to launch an auction in order to obtain centralized and neutral power predictions from a professional provider.

3.3 Country brief: Dominican Republic

In 2019, energy & meteo system analysed the forecasting system of the Dominican Republic and provided expert advice to the GIZ and the system operator on how to improve the quality of the solar and wind power predictions. The motivation for the consultancy was to identify the reasons for the unsatisfying accuracy of the power forecasts provided by the plant operators, and to identify how to improve the quality.

As of October 2018, a total of 264.2 MW of wind and solar plants were installed in the Dominican Republic, representing 7.4% of the installed capacity in the National Interconnected Electric System (SENI). Both technologies combined contributed around 4.2% to the entire electricity production. According to the information provided for the preparation of the long-term operation programme of the SENI, it is expected that, in the forthcoming years, some 391 additional MW will be added to make a total of 662 MW, making up 12% of the total installed, and 8% in energy production, by the end of 2021.

The Dominican Republic had a decentralised forecasting system, obliging plant operators to submit power forecasts to the system operator, OC (Organismo Coordinador). The plant operators submitted their day-ahead forecast every day by 10 am, with an hourly resolution. The operator could have had an own estimation (in-house solution), or hired a provider, detailed information about where the forecast exactly came from was not available to OC. This forecast was used to plan the economic dispatch of the plant.

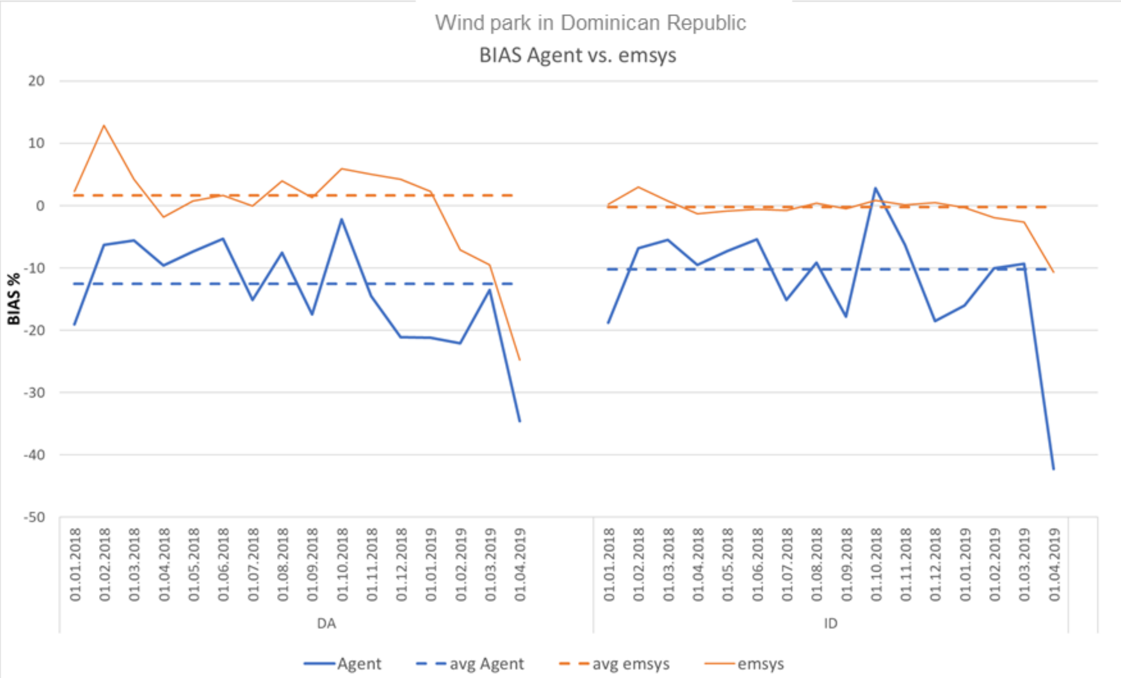
There was no incentive in the regulations of the Dominican Republic for the plant owners to submit accurate power forecasts. OC reported that, in some cases, the plant owners failed to provide forecasts and that several forecasts showed an unsatisfying level of accuracy.

Since the forecasts are used for the dispatch, OC reported that several problems were identified due to the low forecasting accuracy: mistaken planning of the plant economic dispatch, inaccurate planning of the reserve, inadequate results for nodal pricing and grid congestion. According to OC, these issues led to unnecessarily high costs.

By creating own power forecasts and comparing them with the predictions submitted by plant owners for their wind and solar parks, energy & meteo systems was able to evaluate the level of accuracy and potential for improvement.

FIGURE 18. Day-ahead and intraday BIAS for power forecasts

From plant owner/s and energy & meteo systems in the Dominican Republic.



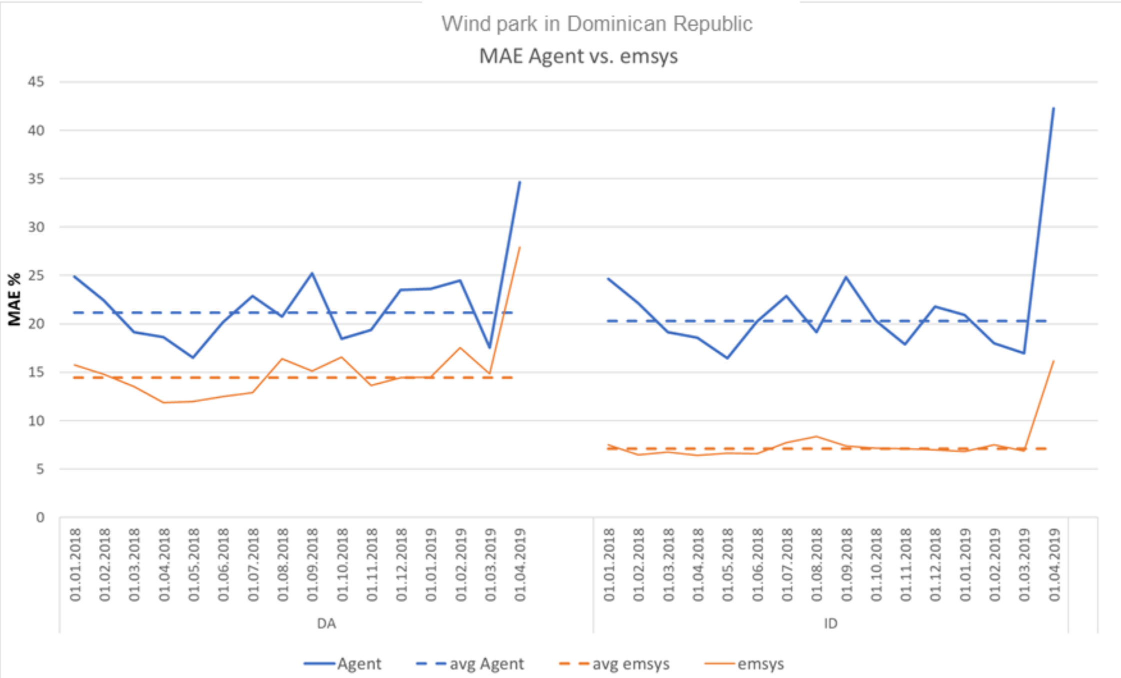
Source: energy & meteo systems

As can be observed in the comparison of the forecasts provided by energy & meteo systems and the plant operators (agents), in **Figure 18** the monthly averaged bias for day-ahead forecasts and intraday forecasts of the agents was continuously negative. This indicates that plants operators systematically underestimated the production output of their plants. The reason to submit lower than calculated predictions may have been triggered by market orientated incentives, which clearly contradicts the target to achieve a high degree of accuracy of the power forecasts.

The medium absolute error (MAE) of the historic power forecasts in the chart below shows that an unbiased centralised forecast leads to significantly better results in comparison to the forecasts provided by the plant operators.

FIGURE 19. Day-ahead and intraday MAE for power forecasts

From plant operators and energy & meteo systems in the Dominican Republic.



Source: energy & meteo systems

As a consequence of this analysis, OC contracted an external service provider to supply centralised power forecasts for all of the wind and solar power plants in the Dominican Republic. The operational predictions fully confirmed the results of the data analysis and justified the shift towards a centralised forecasting system. It is noteworthy mentioning that after a dialogue between OC and plant operators on the importance of accurate power forecasts the quality of the decentralized predictions improved. OC now receives both centralised and decentralised vRE forecasts.

4 Conclusion

The international energy transition requires new approaches in order to efficiently integrate a large number of distributed energy resources into the power system. One of them is forecasting the weather dependent electricity production from solar and wind power plants. Different market participants who deal with renewable energy generation – system operators, traders, plant operators – require customized power forecasts for their respective tasks. The need for power forecasts increases with the share of vRE production and its degree of impact onto the power system.

Efforts to improve the accuracy of power predictions are of utmost importance to efficiently integrate variable solar and wind power production. With rising vRE shares high-quality power forecasts help to minimize vRE integration costs, contribute to more reliable scheduling of generators and help reducing the reserve of ancillary services. At some stage, predictions simply become indispensable to maintain the stability of the power system.

Since the early 1990s, the international know-how in power forecasting has made tremendous progress. Best practices have emerged from testing different approaches through the years and have become common practice. The conversion of weather forecasting data into power forecasts under the use of vRE plant data (master data, historic measurements, real-time measurements), machine-learning technology and meteorological know-how from highly qualified experts today is the prevailing methodology to achieve accurate results.

Nevertheless, accuracy values of power predictions vary significantly. Resolution and precision of NWP models, generator technology (solar, wind), geography and site-specific meteorological conditions are some of the main factors which define the individual difficulty of a power prediction. The complexity makes general statements and expectations regarding the accuracy of power predictions very difficult. What reduces the forecast error in general is a combination of several NWP models, shorter horizon of the power forecast, a larger and geographically well distributed portfolio and the utilization of real-time data. However, it is not only about optimizing the power forecasts but also about adjusting traditional patterns of power system operation towards the characteristics of solar and wind power generators. Working with shorter lead times in intraday processes is one of these measures.

A crucial structural decision is to define forecasting responsibilities among the market participants. In countries where primarily the system operator - and not a liberalized wholesale market - is responsible for the integration of vRE production, power predictions can be supplied by plant operators and/or centrally organized. In contrast to this, due to numerous advantages the favoured solution today is working with forecasts that are centrally created. Among the benefits are a better control over the forecasting process, a higher reliability and consistency, a better accuracy level, the possibility to easily cover small-scale solar plants and lower forecast generation costs per plant. Considering the flexibility and low costs of a service solution inside this centralized system, system operators usually rely on forecasts from professional forecast vendors instead of setting up a costly in-house forecasting system themselves.

The case studies of Chile, Mexico and the Dominican Republic illustrate the experiences made with vRE forecasts in countries that are amid a phase of increasing vRE shares. All of them started with a decentralized power forecasting system, requiring the plant operators to provide power predictions for their solar and wind parks. Incomplete and inaccurate predictions – sometimes systematically over- or underpredicting the power production - have motivated the system operators to directly coordinate the forecasting process. Chile and the Dominican Republic have already contracted external service providers but continued to receive forecasts from the plant operators. The positive results have fully confirmed the expectations and have led to an improved day-ahead planning process for the generator fleet. The case of India shows that the introduction of a penalty scheme to improve the forecasts in decentralized systems is not the best option since often leading to strategic forecasting errors. However, as the cases of Dominican Republic and Chile show, it is useful to have a frequent dialogue with plant operators about the importance of their forecasts. This way, decentralized and centralized forecasting schemes can be combined.

GET.transform c/o Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH
Friedrich-Ebert-Allee 32 + 36
53113 Bonn, Germany
E info@get-transform.eu
I www.get-transform.eu
I www.giz.de

GET.transform is supported by