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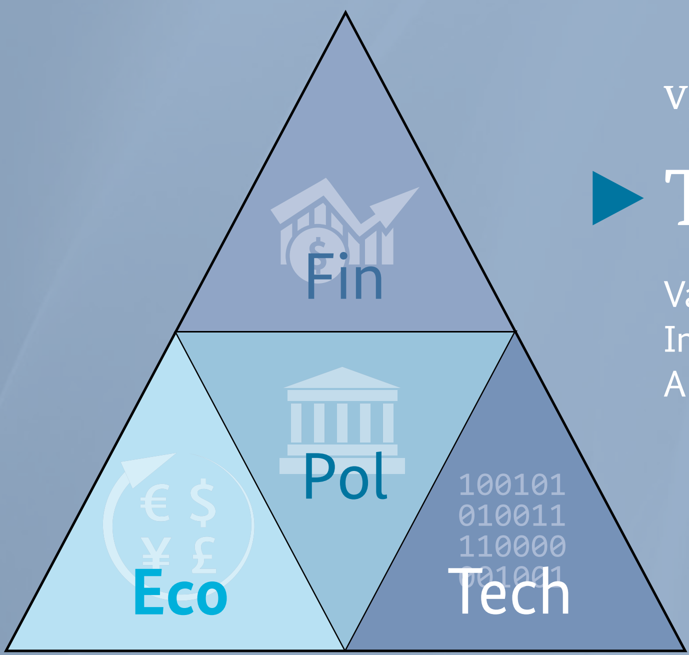

vRE Discussion Series – Paper # 06

TECHNOLOGY

Variable Renewable Energy Forecasting – Integration into Electricity Grids and Markets – A Best Practice Guide

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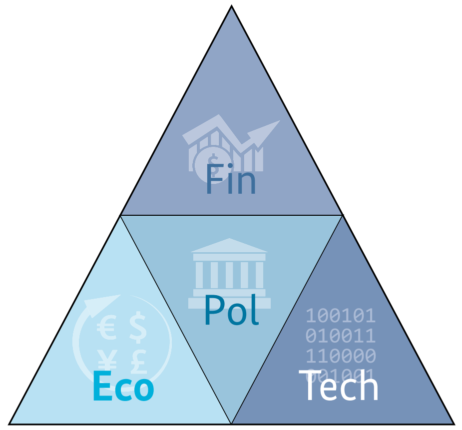

The GIZ TechCoop vRE Programme

Over the past decade, a "1st wave" of National Subsidy Programmes for variable/ fluctuating Renewable Energies (vRE) has (i) led to impressive growth in global cumulative installed capacity of wind and PV power and (ii) dramatic RE cost reductions. However, due to their typical "technology push" focus, most of these **1st wave national vRE programmes have not aimed at achieving an economically optimal pathway for national wind and PV development over time**. Naturally, this has led to suboptimal national RE deployment, resulting in (i) unnecessary losses of Government budget and credibility (subsidy schemes were too expensive or too slow, RE technologies were scaled up too early or applied at the wrong network nodes, lack of planning resulted in avoidable transmission losses or dispatch problems), and/or (ii) excessive private sector profits and/or massive insolvency waves after subsidy-driven vRE bubbles. None of this is intrinsic to vRE technologies or economics: it was simply ill-advised planning.

Increasingly, OECD and non-OECD Governments want to move beyond simple vRE technology-push policies, and shift to a new, 2nd wave of optimized national vRE pathways, by applying the same fundamental economic, financial and political goal functions that are used successfully for standard power system planning. To this end, vRE need to be analyzed as an INTEGRAL part of the national energy system and its growth in time and space, by applying methods which readily fit the toolkit already used by dispatchers, regulators and utilities.

Integrated vRE National Masterplans do not exist yet, though it is pretty clear what they would have to accomplish (IEA 2014, SMUD 2013). This has several causes, such as: (i) the inherent fluctuating character of vRE (wind and PV feed-in depends strongly on sunshine and wind availability at any given moment) poses a set of specific power planning and dispatch problems to established sector agents (dispatch, regulator, utilities) which may seem daunting initially (yet, a closer look reveals that they can be handled easily by these players with their existing processes, with a modest amount of training); (ii) existing studies have often focused on OECD countries and their results are not readily transferrable to GIZ partner countries (where grids can be weaker and demand grows faster and hydro can play a more positive role in vRE development); and (iii) few studies focus on pragmatic incremental steps based on the real-life generation mix, transmission system and fixed short-term capacity planning of specific countries (most look at long term vRE targets including smart storage >2030 instead, thus providing little guidance to pragmatic policy makers).

The GIZ vRE Discussion Series

Under the "vRE Discussion Series" we will continuously put forth emerging results and issues of special interest to GIZ partners, along the 4 main fields of our work: vRE policy, economics, finance and technology issues. As the series' title indicates, these are often based on work in progress, and we strongly encourage suggestions and ideas by mail to the contact below.

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Variable Renewable Energy Forecasting – Integration into Electricity Grids and Markets – A Best Practice Guide

Technology cooperation in the energy sector

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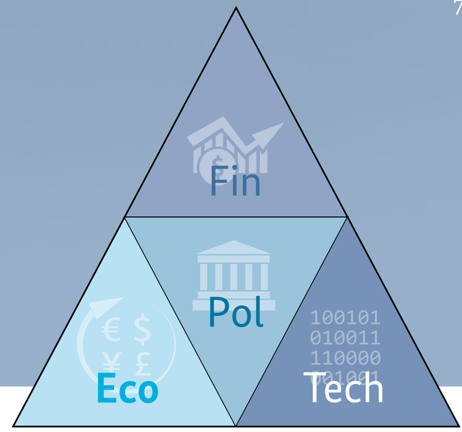
03/06/2015



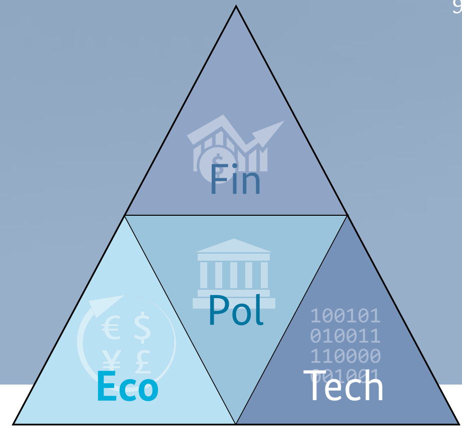
TECHNOLOGY

Table of Contents

TECHNOLOGY

List of abbreviations

2DACF	Two-Days-Ahead Congestion Forecast
ADME	Administracion del Mercado Electrico
AEGE	Sistema de Acompanhamento de Empreendimentos Geradores de Energia
AMA	Sistema de Acompanhamento de Medições Anemométricas
ANEEL	Agência Nacional de Energia Elétrica
DACF	Day-Ahead Congestion Forecast
DSO	Distribution System Operator
ECMWF	European Centre for Medium Range Weather Forecasting
EEX	European Energy Exchange
ENTSO-E	European Network of Transmission System Operators
EPE	Empresa de Pesquisa Energética
EPEX	European Power Exchange
ICE	Intercontinental Exchange
IEX	Indian Energy Exchange
IPP	Independent Power Producer
ISO	Independent System Operator
GMT	Greenwich Mean Time
MAE	Mean absolute error
MISO	Midcontinent Independent System Operator
MME	Ministério de Minas e Energia
MW / GW	Megawatt / Gigawatt
MWh / GWh	Megawatt hour / Gigawatt hour
NCEP	National Centers for Environmental Prediction
NWP	Numeric weather prediction model
OMIE	Operador del Mercado Ibérico Española
OMIP	Operador do Mercado Ibérico Portugal
ONS	Operador Nacional do Sistema Elétrico
PPA	Power Purchase Agreement
PXIL	Power Exchange India Limited
RMSE	Root-mean squared error
TSO	Transmission System Operator
UTC	Coordinated Universal Time
UTE	Administración Nacional de Usinas y Transmisiones Electricas
vRE	Variable Renewable Energy
WPPT	Wind Power Prediction Tool
XML	Extensible Markup Language



Glossary

Balancing group
A balancing group consists of metering points for generation units and/or withdrawal points of loads within a control area. Balancing groups have to be made known to the system operator responsible for the grid connection. Within a balancing group, a balance is to be maintained between the injections from the feed-in points and schedule-based supplies from other balancing groups, on the one hand, and withdrawals of the assigned withdrawal points and schedule-based supplies to other balancing groups. Balance responsible parties are in charge to keep the balancing group in balance.

Balancing power
Balancing power is activated to maintain the frequency within the control area. Balancing power is contracted via tenders, auctions or bilateral contracts for primary, secondary and tertiary reserve. Balancing power comprise upward and downward regulations at power plants as well as upward and downward regulations of consumption. The system operators activate these bids during the momentary operational situation.

Congestion forecast
A congestion forecast is a load flow calculation to predict critical situations in the transmission grid. In Europe, the Transmission System Operators have set up the so called Day-Ahead Congestion Forecast (DACF) to proactively provide information to ensure a secure electricity supply.

Congestion management
The congestion management is the sum of measures of the system operator taken to avoid or eliminate congestion. Possible measures are re-dispatch, counter trading or market splitting.

Curtailment
Curtailment means a reduction in the scheduled capacity or energy delivery.

Day-ahead market
At the day-ahead market, commercial electricity transactions are executed the day prior to the day of delivery of traded products.

Distribution System
The Distribution System is the high, medium or low voltage electricity grid for supplying end consumers. It is operated by Distribution System Operators (DSOs).

Feed-in tariff
A feed-in tariff is a policy mechanism designed to accelerate investment in renewable energy technologies. It offers long-term contracts to renewable energy producers, often based on the cost of generation of each technology.

Futures market
The futures market is a market on which commercial contracts are signed between two parties to buy or sell a quantified asset of electricity at a specified future date at a price agreed today.

Grid Code
A Grid Code is a technical specification in which parameters a facility connected to an electric network has to meet are defined to ensure safe and secure functioning of the electric system. A Grid Code also specifies the required behavior of a connected generator during system disturbances. It is specified by an authority responsible for the system integrity and operation.

Grid operator
A grid operator is a party that operates one or more electricity grids. Grid operators can either operate distribution or transmission grids.

Independent Power Producer
An Independent Power Producer is an entity, which is not a public utility, but which owns or operates facilities to generate electric power for sale to utilities or end users.

TECHNOLOGY

Independent System Operator
An Independent System Operator is an entity established to coordinate regional transmission in a non-discriminatory manner and ensure the safety and reliability of the electric system. In the United States of America, Independent System Operators are federally regulated.

Intraday market
At the intraday market commercial electricity transactions can be traded after the gate closure of the day-ahead market, but prior to the delivery of traded products, and until the intraday market's gate closure.

Net metering
Net metering is a service to an electric consumer under which electricity generated by the consumer from an on-site generating facility and delivered to the local distribution facilities may be used to offset electricity provided by the electric utility to the consumer during the applicable billing period.

Numerical weather prediction
A numerical weather prediction uses mathematical models of the atmosphere and oceans to predict the weather based on current weather conditions. Global and regional forecast models are run in different countries worldwide, using current weather observations relayed from radiosondes or weather satellites.

Outage
Outage means an unavailability of generating capacity. Outages can be scheduled, e.g. for maintenance purposes, or be unplanned, forced outages.

Plant operator
A plant operator is a person who supervises the operation of a power plant.

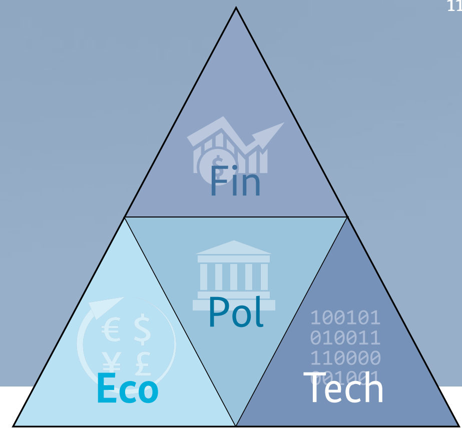
Power Purchase Agreement
A Power Purchase Agreement is a contract between one party who generates electricity and one who is looking to purchase electricity. A Power Purchase Agreement defines the commercial terms for the sale of electricity between the two parties.

Spot market
The spot market is a market on which commercial electricity transactions are settled within a period of two settlement days. Settlement can take place immediately (intraday) or the following day (day-ahead).

System operator
A system operator is a party that is responsible for a stable power system operation through a transmission grid in a geographical area. The system operator is also responsible for cross border exchanges.

Transmission System
The Transmission System is the electricity grid used to transmit electricity over long distances within one country and to connect up with foreign grids. It is operated by Transmission System Operators (TSOs). Transmission Systems are e.g. operated at the 220 or 380 kV voltage level.

Variable Renewable Energy
Variable Renewable Energy sources fluctuate during the course of any given day or season due to weather conditions. Variable Renewable Energy includes wind, solar, wave and tidal energy and is not-dispatchable, as opposed to controllable renewable energy sources such as hydroelectricity or biomass.



1 Introduction

The power production of wind farms and solar plants obviously depends on the weather. Their energy output strongly varies due to changes in wind conditions or in solar irradiation, which is why they are referred to as variable Renewable Energy resources (vRE). This variability is fundamentally different from other controllable production units - as in particular conventional power plants - and worries grid operators, utilities and market participants when they notice a rapidly increasing share of wind and solar plants in their power system.

Nevertheless, the electricity generation of wind and solar plants can be predicted by power forecasts based on numerical weather models. Wind and solar power forecasts have proven to be an indispensable source of information for many planning processes in the energy industry, such as unit dispatch or selling vRE to energy markets, as these forecasts provide the required production schedules for vRE over the next hours and days.

Over the last 20 years, significant experience has been achieved within several countries on how to effectively integrate vRE production into electrical grids and energy markets. This study gives an overview of state-of-the-art forecasting of wind and solar power as a key element in the integration of vRE units and presents practical experiences from countries with different regulatory frameworks and market environments on how forecasts are used on a daily basis. Examples from Europe, North and South America, South Africa and India highlight the way forecasts are embedded into operational decision processes of grid operators, system operators, market participants and plant operators depending on the design of the power system or the energy market.

The report also derives some generic information by extracting universal key lessons that have been learned and are thought to be applicable to power systems where the massive increase of vRE plants is just starting.

2 State-of-the-art of short-term forecasting of vRE

2.1 General application of vRE 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 in the energy market by different stakeholders.

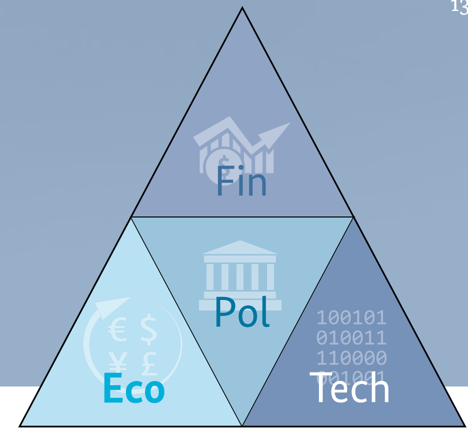
Forecasts of vRE units are needed in order to know in advance the amount of power that wind turbines or photovoltaic modules will feed into the grid over the next hours and days. The vRE forecasts are generally based on forecasts of the weather conditions at the site locations. In such a general application, the forecast can be used as an expectation of the vRE production for different stakeholders. 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.

Grid operators use medium-term forecasts for system security calculations, balancing power reserve planning and the planning of grid maintenance. Short-term forecasts are used for congestion forecasts, e.g. the Day-Ahead Congestion Forecast (DACF) for the European Network of the Operators for Electricity (ENTSO-E). Shortest-term forecasts are used for grid operations (congestion management, down-regulations), balancing unmeasured energy producing units, and in some markets for unit re-dispatch. In markets with fixed feed-in tariffs, the grid operators sometimes also have to sell the vRE on the spot market and use short- and shortest-term forecasts for the trade on the day-ahead and intraday markets.

Energy traders, who have a contract to sell vRE for the plant operators, also use the short- and shortest-term forecasts for the trade on the day-ahead and intraday markets. In some markets, energy traders can sell vRE also on the balancing power markets. Moreover, energy traders can use vRE forecasts to predict the influence of vRE on the spot market price.

Wind and solar plant operators use the forecast for their plants mainly to schedule maintenances. Owners of a roof-top Photovoltaic installation also plan the consumption of their households by means of the forecasts to raise the share of internal consumption of the produced energy.

To provide a general orientation, a selection of the main areas of state-of-the-art vRE forecasting, and the major stakeholders who use the forecasts for their purposes, are summarized in the following table where the information is ordered according to the time frames of the decision processes.



Time scale of forecast	Area of application	Stakeholder
Shortest-term (0 – 6 h)	Trading on intraday energy market	Traders
	Control of curtailment due to negative market price	
	Correct activation of regulation power (secondary and tertiary reserve)	
	Influence of vRE on market price	Speculators
	Balancing	Grid operators, load dispatch centers, independent system operators
	Unit re-dispatch	
	Curtailment of power plants	
Short-term (6 – 48 h)	Trading on day-ahead energy market	Traders
	Participation in regulation market	
	Influence of vRE on market price	
	Unit dispatch	Grid operators, load dispatch centers, independent system operators
	Load flow calculations	
	DACF congestion forecast	
	Day-ahead planning of maintenance	vRE operators
Medium-term (2 – 10 days)	Trading on long-term markets	Traders
	2DACF congestions forecast	Grid operators, load dispatch centers, independent system operators
	Week-ahead planning	
	Medium-term planning of maintenance	vRE operators

2.2 Organization of forecasting service and general data flow

In the majority of applications the vRE power forecasts are supplied to the user by specialized forecast service providers while only very few stakeholders have developed an in-house forecasting solution and continuously operate this. Nearly all commercial forecast service providers send out power predictions as a service similar to weather forecasts, i.e. the forecasting results are transmitted on a regular basis. Users can benefit from this service concept by contracting different service providers in parallel for a certain time, continuously check their performance and, if necessary, change forecast service providers. In contrast to this, in-house concepts, where the user is responsible for operating the forecasting system, require a lot of effort in terms of meteorological know-how and resources (human as well as IT infrastructure) to achieve a high forecasting accuracy.

To realize a service solution, it makes sense to establish a centralized approach where one responsible stakeholder, e.g. grid operator, ISO or trading company, receives forecasts for all vRE units of the portfolio from one or more forecast service providers. Hence, the forecasts are not collected from the individual vRE operators. Experiences from other countries show that only a centralized forecasting approach ensures high quality across all vRE units.

Especially for large portfolios it is good international practice that all required data from the vRE units, i.e. power production, availability information etc., are collected by the customer and are then made available

TECHNOLOGY

to the forecast service providers. The following scheme (Figure 1) illustrates the data flow (only for forecasting, no control signals shown from the dispatcher to vREs). The major advantage is that data from all vRE units can be retrieved in a standardized way and it is easier to implement effective quality control measures.

2.3 Forecasting techniques and accuracy

The technical reliability in wind and solar forecasting is dynamically advancing due to new developments where the major aim is always to produce a better forecast with greater accuracy. The drivers behind making progress in this field are mainly the commercial forecast service providers who seek to continuously improve their forecast methodologies due to the very competitive situation they find themselves in.

Over the last years, many forecasting concepts and systems have been set into operation by different service providers and institutions. From this, lessons have been learned how to produce accurate wind and solar forecasts. In the following, the basic facts and concepts as they are currently used in operational power forecasting of vRE are presented.

First of all, it is instructive to look at typical vRE forecasts. Wind and solar power predictions are schedules containing a number of values per day, e.g. 24 in an hourly resolution, for single plants or aggregates. The wind power forecast in Figure 2 was issued in the morning at 8:00 UTC (=GMT) covering the next five days, providing a schedule of the anticipated power production of the total of German wind farms with a fifteen minute time-resolution. The confidence bands indicate the expected uncertainty of the forecast due to the predictability of the weather conditions. Please note that when the prediction was produced the real production was, of course, only known up to this point of time.

This example already reveals a general fact: the accuracy of the forecast decreases as the look-ahead time increases. It can also be seen that the forecast uncertainty, which is expressed by the grey confidence band, depends on the predicted production level. In particular, it is asymmetric for both high and low production levels due to the fact that the production is limited between zero and installed power.

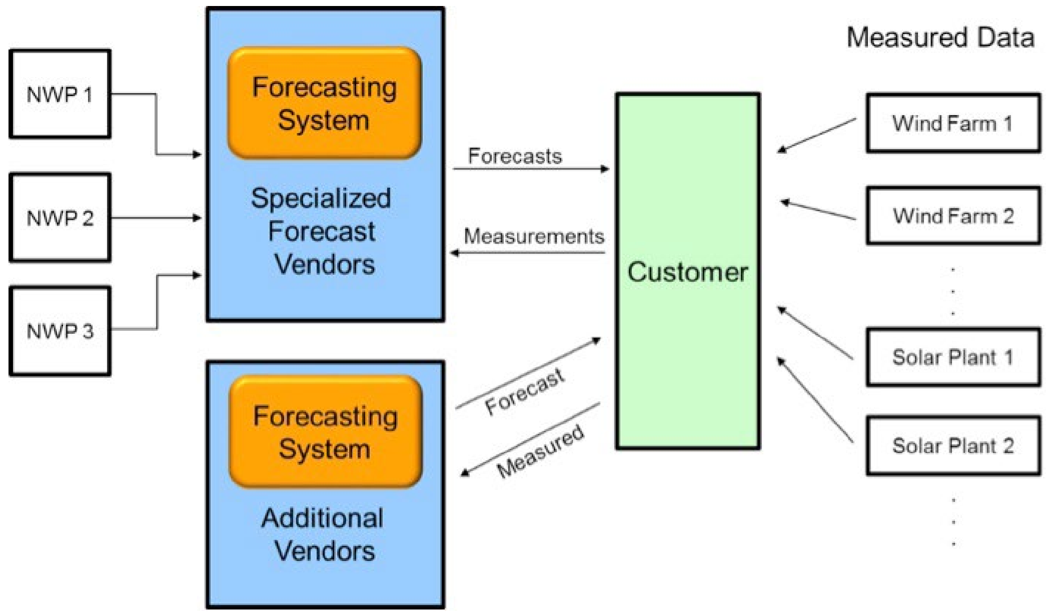


Figure 1: Data flow for a service solution concept where one or more forecast service providers provide forecasts for all vRE units and receive required data from vRE plants centralized through customer. "NWP" refers to numerical weather prediction. Source: energy & meteo systems.

The two days ahead solar power forecast in Figure 3 looks, as expected, different from the wind power forecast due to the highly visible diurnal variation of the sun. While the forecast is perfectly zero during the night, the steep increase in power after sunrise, and decrease before sunset, have to be predicted correctly to avoid large errors. To resolve these rapid changes, a temporal resolution of at least 15 minutes is required. For solar power forecasts confidence intervals are available, but not as widespread as for wind power forecasts.

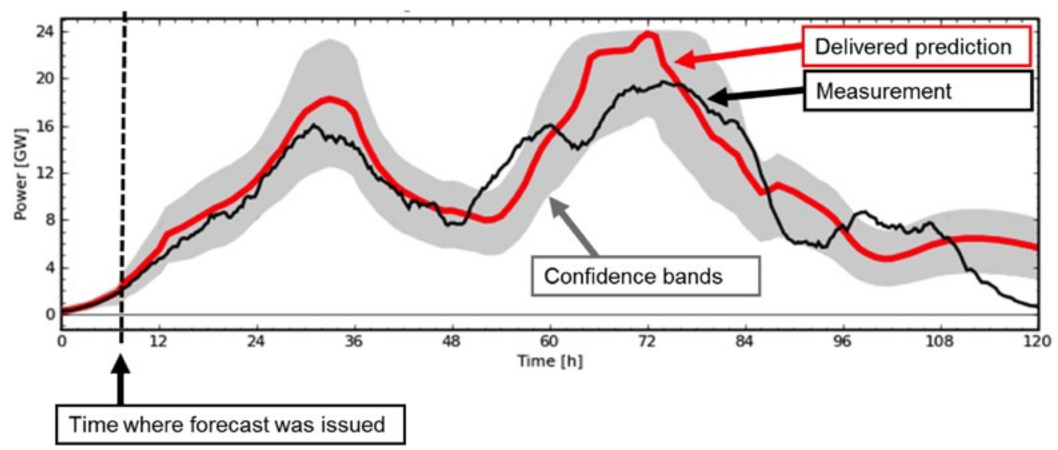


Figure 2: Wind power prediction with a horizon of 120 hours (5 days) into the future. Red: prediction produced at 8:00 UTC (=GMT), grey: confidence interval of prediction with pre-defined confidence level of 70 percent, black: measurement. Source: energy & meteo systems

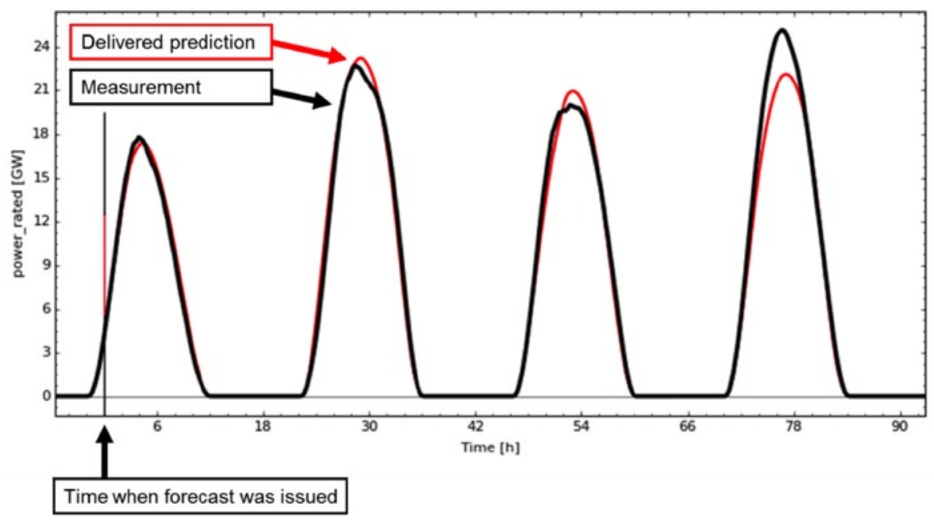


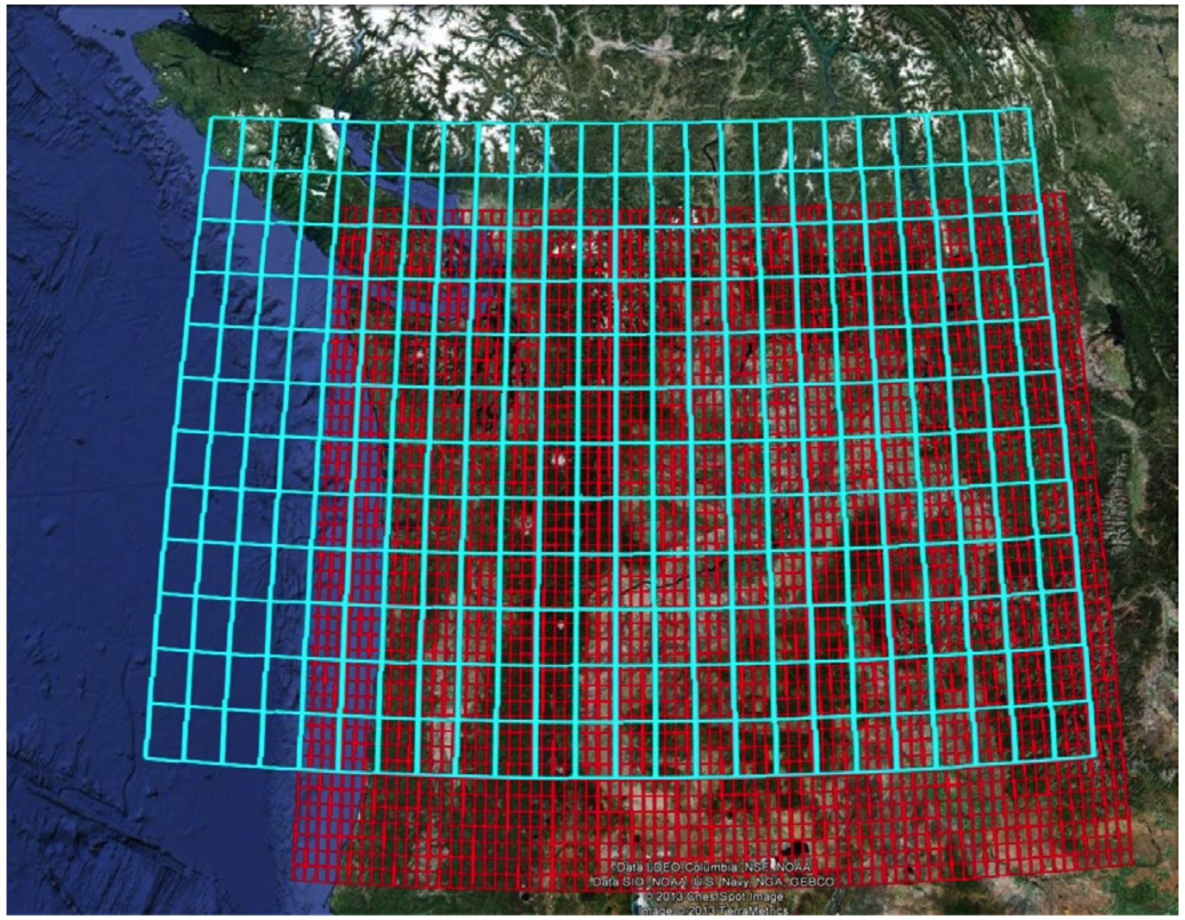
Figure 3: Solar power prediction with a horizon of 96 hours (4 days) into the future. Red: prediction produced at 8:00 UTC (=GMT), black: measurement. Source: energy & meteo systems

TECHNOLOGY

2.3.1 Numerical weather prediction models

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, concerning wind speeds and solar radiation. Forecasting methods that are purely based on observation data, e.g. power measurements, are only beneficial for very small time periods of a few minutes. Nevertheless, observation data is very useful for the forecasting process.

The leading numerical weather prediction models (NWP) are developed and operated by national weather centers such as the European Centre for Medium Range Weather Forecasting (ECMWF) or the National Centers for Environmental Prediction (NCEP). These organizations use a wide range of model approaches making the NWP slightly differ in the way they simulate the weather conditions of the future.



Underlying map: ©Google Earth

Figure 4: Horizontal resolution of numerical weather models shown by the centres of the grid cells. Red: 2.7 km, cyan: 15 km. Source: energy & meteo systems.

This difference is a considerable advantage for power forecasting since input from different NWP can be combined to produce an improved forecast.

NWP models see the world on a grid, i.e. they divide the atmosphere into little boxes (grid cells) with finite spatial extension. The meteorological parameters are calculated for the center of each grid cell and they represent on average what is happening inside this box. This means that the NWP cannot simulate all details inside the grid cell, e.g. variations of the wind speed.

In horizontal direction, the size of grid cells can vary between a few hundred meters and 20 kilometers. In Figure 4, two NWP with horizontal resolutions of 2.7 km and 15 km are shown for an area in the United States. To produce a forecast for a location not at the center of a grid cell, the parameters are interpolated from neighboring grid cells.

Also, in vertical direction the model resolution varies between NWP. 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. For wind power forecasts it is very crucial to calculate the wind speed at hub height of the wind turbines as precisely as possible. The forecasting systems differ widely in the way they perform this vertical interpolation (see chapter 2.3.2).

It is important to note that a higher resolution of the NWP in horizontal or vertical direction does not always lead to better power forecasts. The main reason is that models with higher resolution simulate more details, e.g. fluctuations due to changing wind conditions or broken clouds. However, if the forecasts get the timing of these fluctuations wrong, the accuracy gets worse.

The good news is that for any location in the world several good NWP models are available. As these weather models have not the same quality for every region in the world it requires some expertise to select the best models for a given area. In the context of power forecasting of vRE, the most practical experiences with NWP models have been made in the Northern hemisphere between the 30th and 60th parallel. Here it is very well known which areas and terrains are challenging and what performances can be expected at what time of the year. For other climate zones of the world, in particular tropical regions, the forecasting experiences with NWP are limited.

2.3.2 Approaches to convert meteorological forecasts into power forecasts

The core of wind and solar power forecasting is, of course, the conversion of the meteorological variables, e.g. wind speeds or solar irradiance, into power output of vRE units.

In the brief history of power forecasting two main approaches to carry out this conversion have emerged (i) the statistical approach on the one hand, and (ii) the 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 calculate the right meteorological input, 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 a higher accuracy.

To get an understanding of how these two approaches are implemented examples from two established wind power prediction systems are briefly described.

An example for a commercially successful statistical system to predict wind power is called Wind Power Prediction Tool (WPPT) and was developed by the Technical University of Denmark (Nielsen et al. 1998). It is now being operated and has been further enhanced by the Danish company ENFOR. The general scheme of WPPT in Figure 5 shows the basic idea that the constant data flow of NWP and production data is

TECHNOLOGY

used to continuously calibrate the system with methods from artificial intelligence. This permanent calibration is clearly an advantage of statistical systems as they are able to follow slight changes and climatological drifts. One disadvantage however, is that unknown weather situations that have not been previously observed by the system or occur very seldom might not be covered correctly by the forecast.

An example for a commercially successful physical system to predict wind power is called Previento and 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. The general scheme of Previento is shown in Figure 6. The physical model is based on a horizontal spatial refinement of the NWP data. It calculates the wind speed at hub height by using different height levels of wind speeds from the NWP according to the current vertical wind profile.

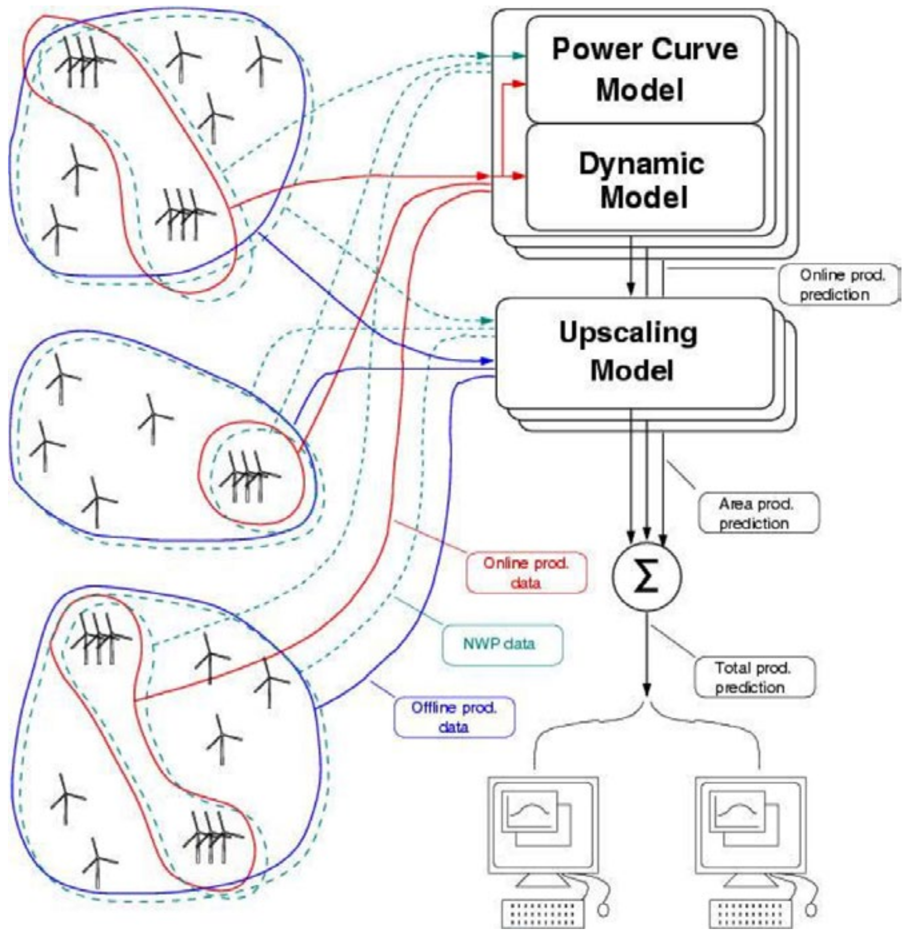


Figure 5: General scheme of the statistical wind power prediction system WPPT for forecasts of aggregated regional output. The „power curve model" and „dynamic model" are built on artificial intelligence where the system automatically calibrates to the observed situation. Source: ENFOR.

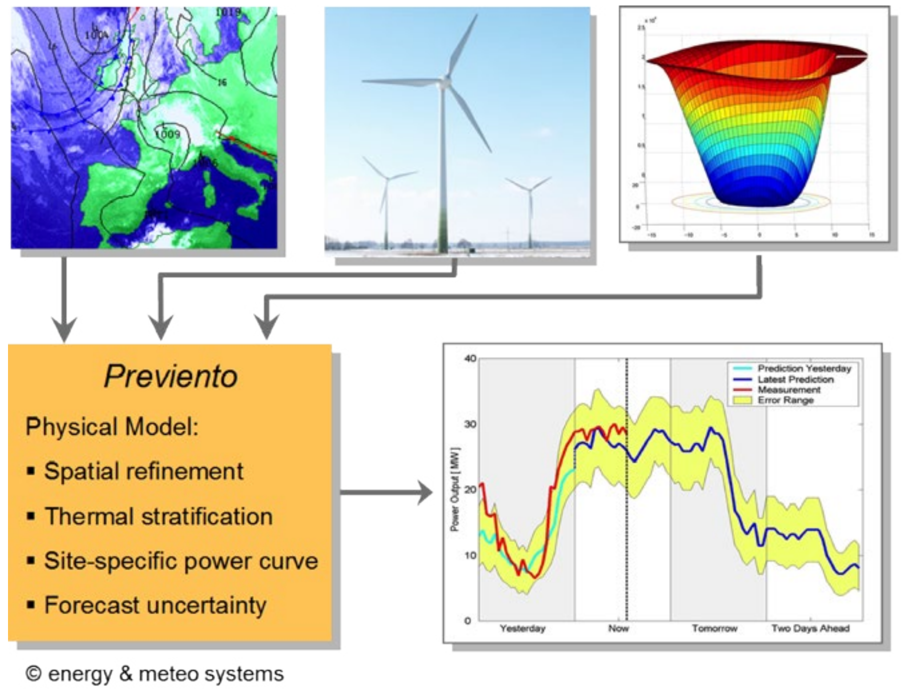


Figure 6: General scheme of the physical wind power prediction system Previento for forecasts of the power output of single wind farms or regional aggregates based on the ingredients NWP data, standing data and direction dependent power curve. Source: energy & meteo systems.

The vertical wind profile describes the change of wind speed with height (Figure 7). The shape of the wind profile strongly depends on the meteorological conditions. If during the day the ground is heated by the sun, warm air rises and this leads to turbulent mixing in the lower atmosphere. As a consequence, the wind speeds do not increase much with height (unstable situation). In contrast to this, as the ground cools during a clear night the atmosphere becomes very stable, thus leading to low wind speeds on the ground and high wind speeds at hub height. These phenomena are considered in physical systems to provide an accurate wind speed at hub height, which is then converted into power by a suitable power curve.

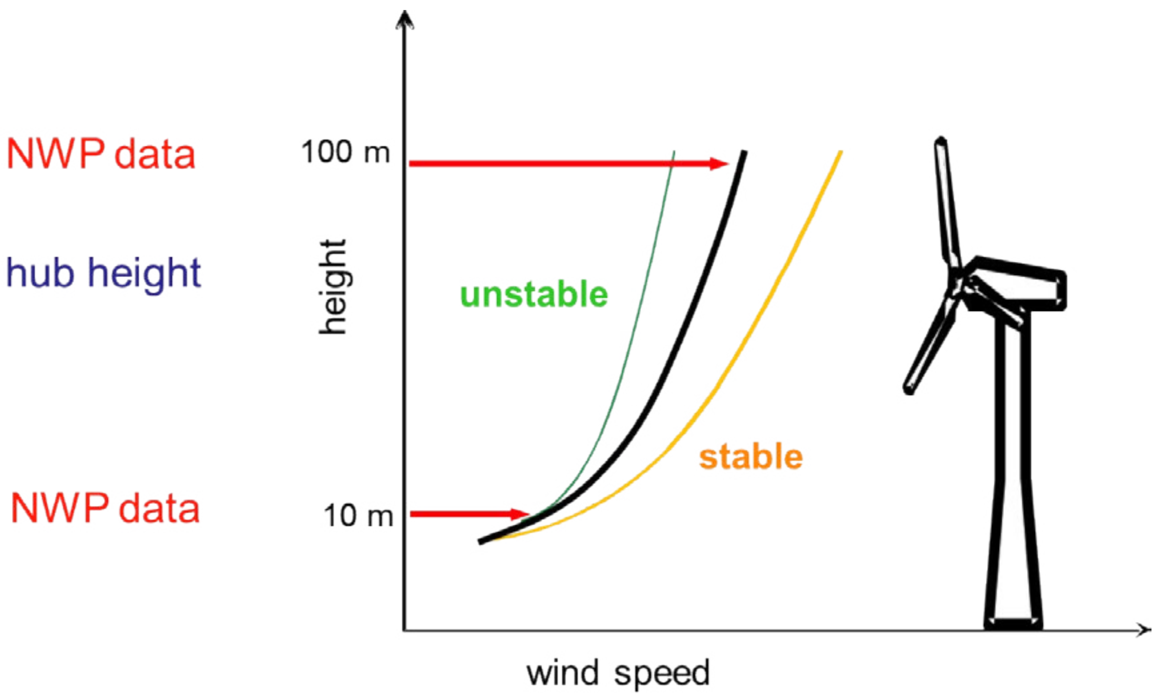


Figure 7: The vertical wind profile changes with the atmospheric conditions. Source: energy & meteo systems.

2.3.3 Combination of forecasts

It is an established protocol 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 commercially used forecasting systems use several NWP models as input and 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 sizeable reduction of the overall forecast error, it works particularly well in situations where extreme events occur. The accuracy of the combination forecast is generally greater than the accuracy of each individual forecast based on a single NWP.

Experience shows that NWP models have indeed different capabilities according to the current weather situation where, for example, one NWP is very good in forecasting storm fronts and another in forecasting high pressure situations or morning fog. If the forecasting system is able to automatically classify weather situations relevant for wind and solar power prediction, specific weighting factors can be applied allowing for an optimal combination of different NWP inputs (Figure 8). The weather classes are typically different for combinations of wind and solar power forecasts.

As a result of a weather dependent combination, the solar power forecast in Figure 9 shows that the weighting can be very different. 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.

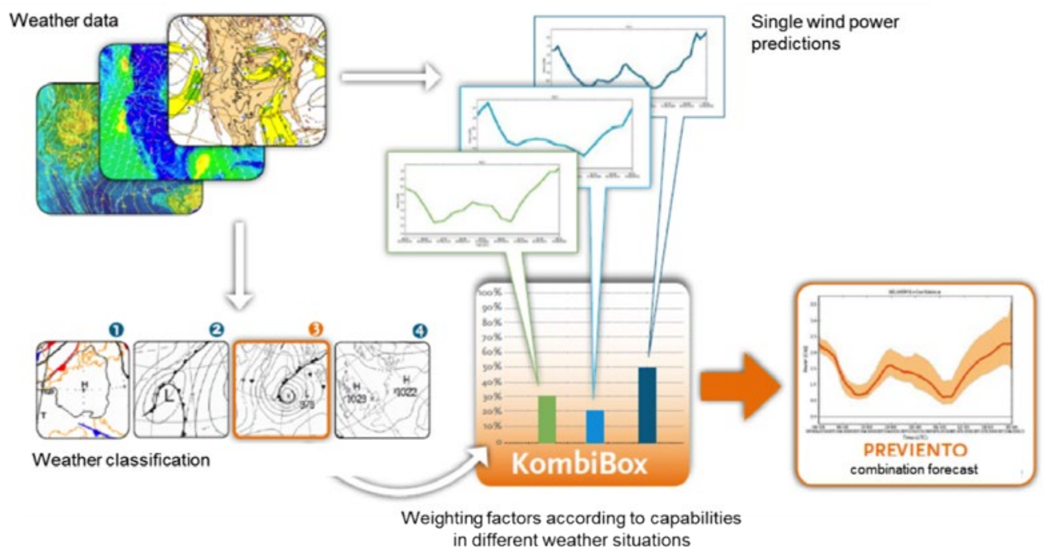


Figure 8: Example for combination of wind power forecasts with weighting of NWP input according to the weather situation. For wind and solar predictions different weather classes are used. Source: energy & meteo systems.

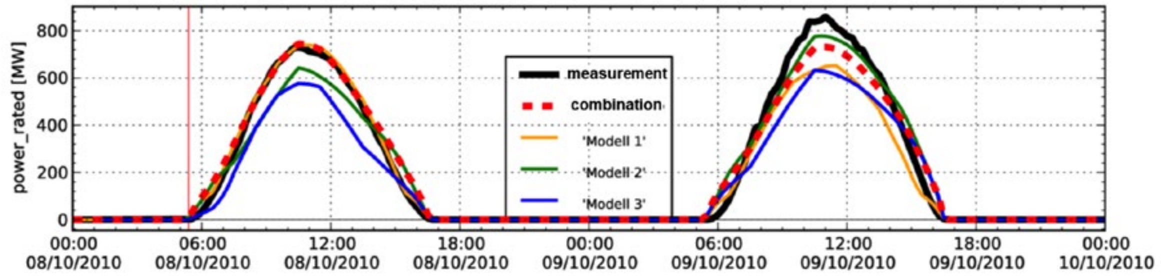


Figure 9: Solar power forecast for two days based on weather dependent combination. The dashed red line is the combination forecast, the thin coloured lines are single NWP models. The black line is the observed production. Source: energy & meteo systems.

2.3.4 Power plant outages and curtailments

A power forecast based o n 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. Hence, the forecasting system has to consider real-time availability, scheduled outages, planned curtailments of wind farms, and grid capacity limits directly, 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 10 shows power forecast for a large wind farm with 200 MW of installed power, where 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 system before the forecast was produced, the forecast that was delivered took this in to consideration (red curve). It is therefore clear from this example that it is indispensable for a high forecasting accuracy to include outage and curtailment information into the forecasting process.

In practice, setting up and maintaining the data flow related to outage information requires some effort. It has to be taken into account that outages of vRE units are mainly known to the operator, whereas outages due to 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 provider of the power forecasts. The most effective way to organize this is by collecting the outage information centrally, e.g. through grid operator or regulator, such that the complete information can be retrieved by the forecast provider.

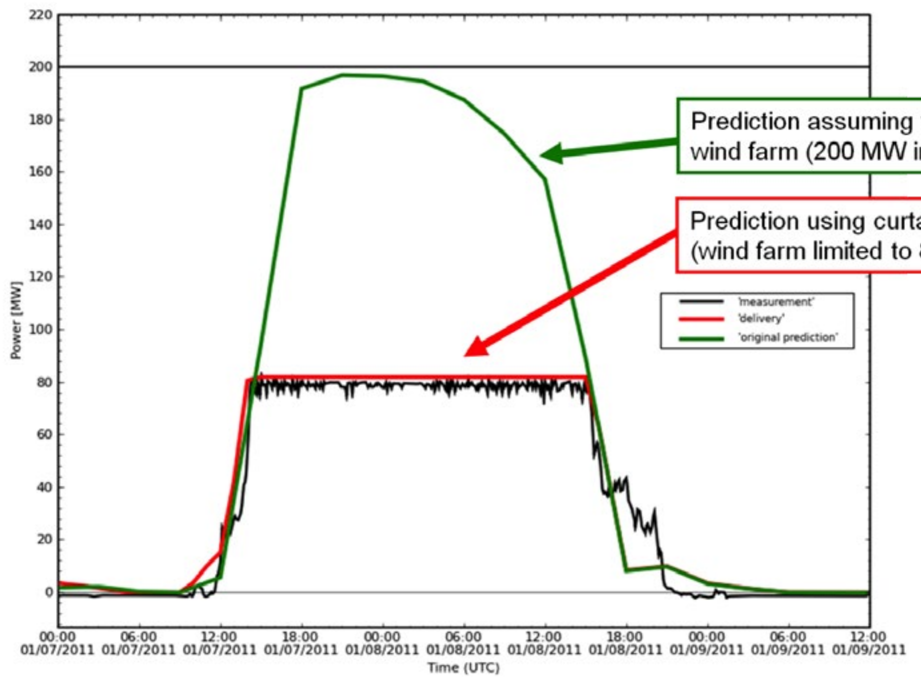


Figure 10: Time schedules for planned outages or curtailments are considered in the forecast (red curve) if announced in a timely manner. The prediction assuming full availability (green curve) can be provided as well. Source: energy & meteo systems.

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

2.3.5 Benefit of shortest-term forecasts based on real-time data

For very short-look ahead times of 0 to 6 hours the wind and solar power forecasts can be strongly improved by using real-time production data from the vRE plants. In particular, in 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 11 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 quite obvious.

The requirements on the real-time data that is used for shortest-term vRE forecasts are very high. The most crucial part is that the delay between collecting the data from the plans 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 minutes 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

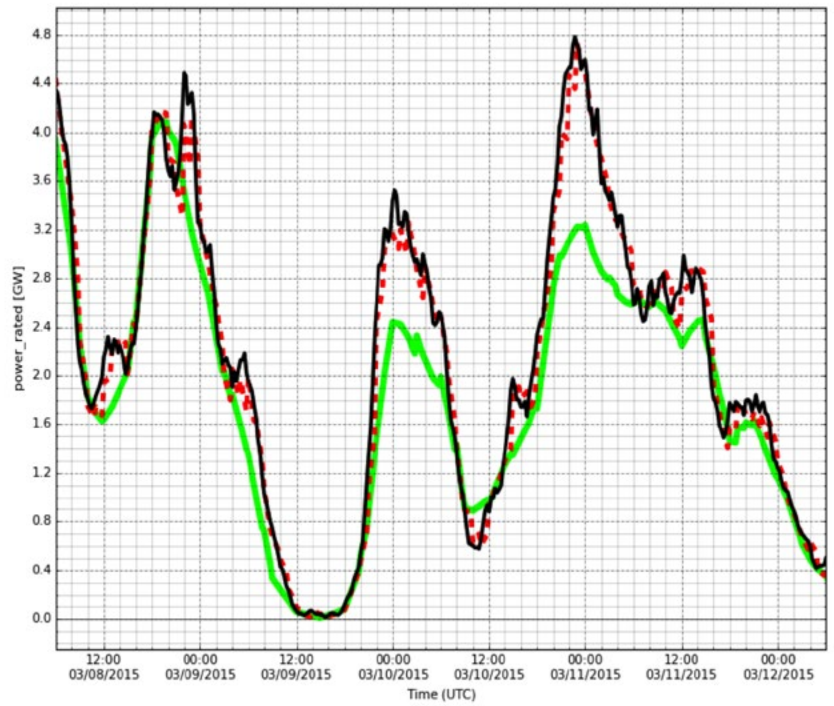


Figure 11: Benefit of shortest-term prediction based on real-time data in a difficult weather situation: the shortest-term prediction for 1 hour ahead (red line) is far closer to the real production (black line) compared to the most recent forecast only based on meteorological forecasting data (green line). Source: energy & meteo systems.

TECHNOLOGY

are less than a minute. For forecasts that are used for intraday trading or unit re-dispatch shortest-term forecasts are indispensable.

2.3.6 Forecast accuracy

The forecast accuracy is normally evaluated by considering the deviations between what was predicted and what really happened. 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 TSO.

- 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.

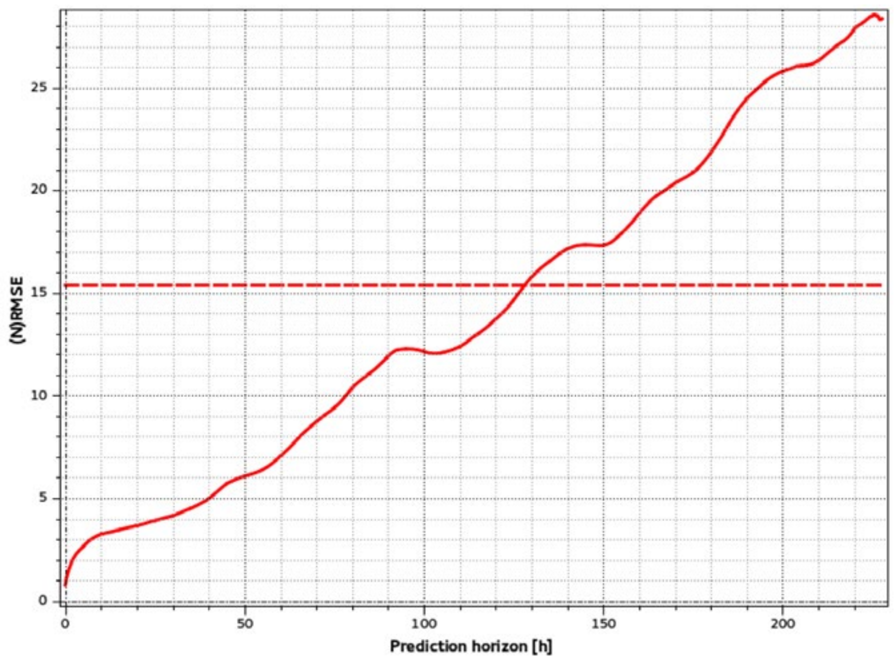
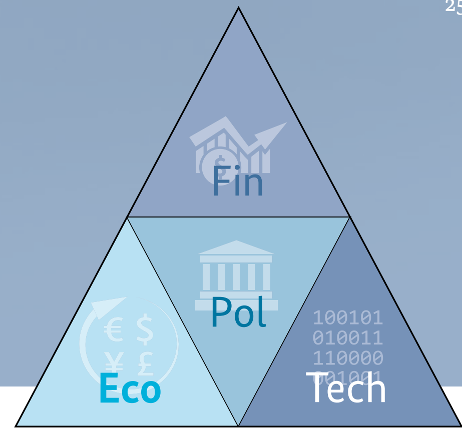


Figure 12: Increase of the forecasting error (RMSE / installed power) of a medium sized regional wind portfolio over the prediction horizon of 240 hours (10 days). For the first few hours the benefit of real-time production data leads to a small forecasting error. After 10 hours the forecasting error increases nearly linearly. Source: energy & meteo systems.



In addition, 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 normalization of the error metrics is a further important issue 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 forecasting values. It is up to the user to decide which normalization is required. For example many traders prefer MAE normalized to average power output while TSO prefer RMSE normalized to installed power.

The accuracy of wind and solar forecast strongly depends on several basic factors leading to some general rules:

- The simplest rule is that the forecasting error increases with prediction horizon, i.e. the further the forecast looks into the future, the lower the forecasting accuracy. Except for the first forecasting hours which benefit from the shortest-term predictions the forecasting error increases nearly linearly shown for a portfolio of wind farms in Figure 12.

- The forecasting errors increase on average with increasing complexity of the terrain, i.e. hills and mountains spoil the accuracy. This is mainly related to the fact that the NWP models cannot consider all details, e.g. wind speeds due to channeling effects or solar irradiance due to the occurrence of fog in valleys. In Figure 13 the large spread of forecasting accuracy (day-ahead forecast of wind farm) for single sites (left column) between 10 and 20 percent RMSE normalized to installed power mainly comes from their different location. Especially, wind

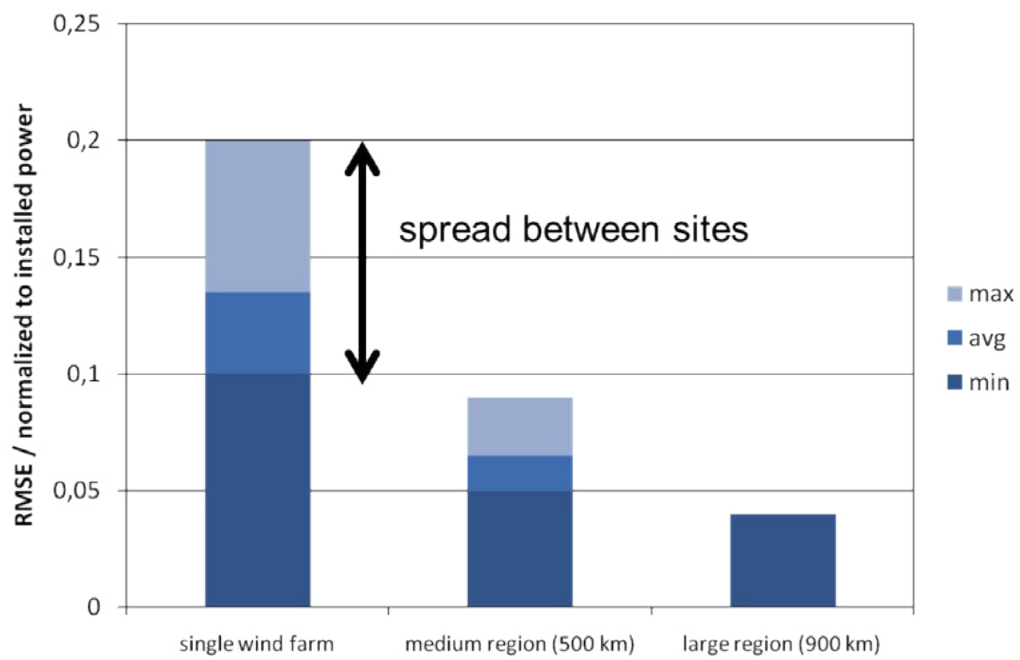


Figure 13: Forecast accuracy of day-ahead (24-48 hours) in terms of RMSE normalized to installed capacity for single wind farms, medium size region and large region. Source: energy & meteo systems.

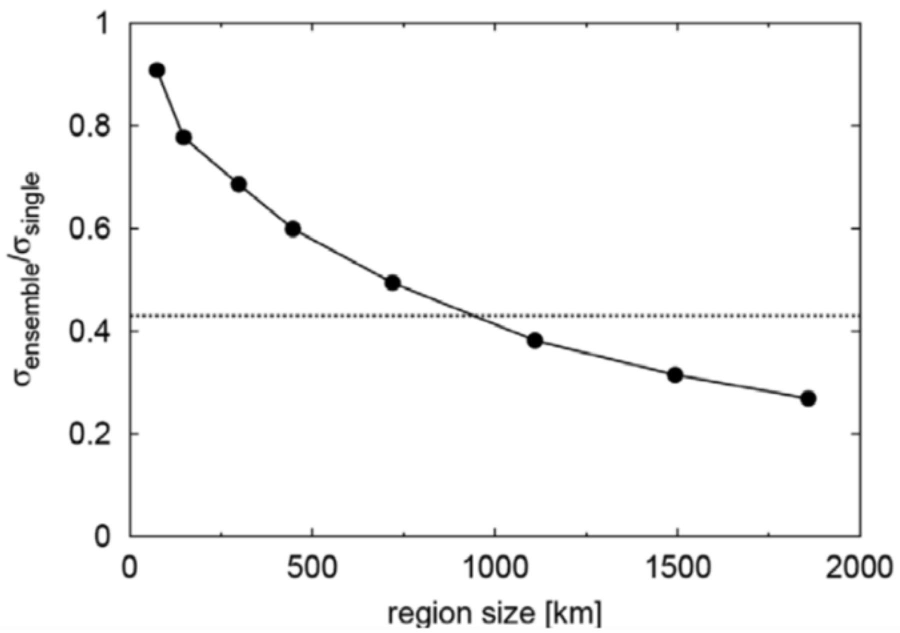


Figure 14: Regional smoothing effects, i.e. decrease of relative forecasting error for a regional forecast (aggregate) compared to single sites. For example, a forecast for region with a diameter of about 900 km has an RMSE/installed power which is only 42 percent of that of a single wind farm. Source: energy & meteo systems.

farms with a very high RMSE of 18 percent or higher are located in very complex terrain. Please note that, of course, the wind and solar conditions can also influence the evaluation results. In particular, wind farms with very good wind conditions can generate a higher RMSE even in flat terrain or offshore.

- Forecasts for regional aggregates are always far better than forecasts for single sites due to the fact that errors between different locations inside one region cancel out partly. This is why the RMSE for the area forecasts (mid and right column in Figure 13) drops with the size of the region. As this spatial smoothing effect (Focken et al 2002) is very powerful it is beneficial to have a large geographical spread between the sites. Hence, the larger the region the smaller the forecasting error of the portfolio. While Figure 13 shows this effect derived from the evaluation results for operational forecasts, the curve in Figure 14 illustrates the general relation between region size and the decrease of the forecasting error based on a statistical analysis.

3 Best practice examples from different countries

The following chapter will show examples of vRE forecasts from all over the world. The aim is to illustrate different market designs, institutional frameworks and the way forecasts are used to integrate vRE into grids and markets. The chapter takes into account that the physical need for forecasts of vRE is the same everywhere, but that e.g. the grid penetration of vRE or the institutional framework including the degree of unbundling make the implementation of forecasts very different. Thereby, this chapter describes regional specifications and which lessons can be learned from the examples of the different countries.

The examples are chosen to help to understand the situations under different market designs and institutional frameworks with the aim to cover all important use cases. The best practice examples will include experiences from Europe, South Africa, the United States of America, Brazil, Uruguay and India. Every analysis includes the question to which degree the experiences can be translated to other countries or regions as well. For every region the status of the extension of vRE, the market design and institutional framework, as well as the implemented forecast solutions, will be described. These descriptions shall generate awareness of how to best integrate vRE and forecast systems into different energy market schemes and institutional frameworks.

The examples have been selected to cover a broad range of different vRE forecast implementations. The European electricity market has been largely liberalized, with different stakeholders needing wind and solar forecasts. This is shown on the basis of the situation in Germany, Spain and Denmark. The United States of America has a partly liberalized market and in some areas a nodal pricing market with huge re-dispatch permissions for the Independent System Operators or Regional Transmission Organizations is used. This is shown on the basis of the Midcontinent Independent System Operator. The need for vRE forecasts for a vertically integrated public utility is shown for the case of South Africa. Brazil and Uruguay are examples for institutionalized forecast solutions, but currently smaller vRE grid penetrations. India is an example of benefit for discussions concerning the need of operators delivering forecasts individually to the system operator or Dispatch Center.

3.1 Examples from Europe

3.1.1 Status of the extension of variable Renewable Energy

In the European Union, electricity generated by Renewable Energy contributed to 23.5 percent of the gross electricity consumption in 2012. Hydro power plants produced 54.1 percent of the total renewable electricity generation, 30.4 percent by wind turbines and 10.5 percent by solar installations. Between 2002 and 2012, wind energy production increased more than fivefold, while solar power increased by 252 times (Eurostat 2014). In the following, the share of Renewable Energy will be shown for three of the biggest markets of vRE in Europe: Germany, Denmark and Spain.

Status of the extension of variable Renewable Energy in Germany

The extension of renewable energy production in Germany has been mostly influenced by the introduction of the Renewable Energy Sources Act in 2000. The law introduced guaranteed feed-in tariffs to different technologies. Before the introduction of this law, the share of Renewable Energy was only 5.2 percent of the gross electricity consumption, while in 2014 it was already 27.8 percent. Out of the 160.6 billion kWh of Renewable Energy, 34.8 percent have been produced by wind energy and 21.7 percent by photovoltaic installations in 2014 (Bundesministerium für Wirtschaft und Energie 2015: 4ff).

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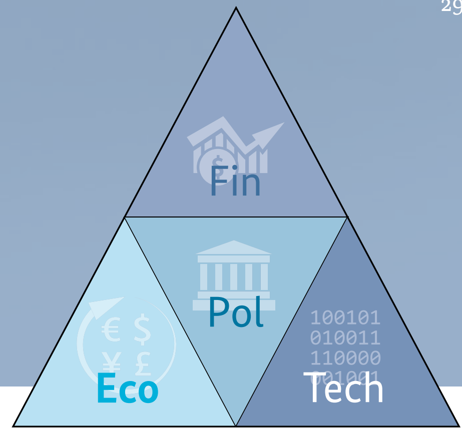

Status of the extension of variable Renewable Energy in Denmark

In 2010, Renewable Energy made up a share of 21.3 percent of the net electricity production in Denmark. In 2014 it was already 44.7 percent. Wind power accounted for 42.7 percent and solar power for 2 percent of the country's net electricity production (Danish Energy Agency 2015).

Status of the extension of variable Renewable Energy in Spain

In Spain, Renewable Energy contributed 42.8 percent of the electrical demand in 2014. Namely wind energy contributed 20.4, photovoltaic installations 3.1 and Solar Thermal installations 2.0 percent of the electrical demand of the country (RED 2014: 11).

3.1.2 Market design and institutional framework

In 1996, the European Parliament and the Council of the European Union decided upon a Directive concerning the harmonization towards a European domestic electricity market. The Directive required the member countries to liberalize their electricity markets regulating the access to transmission and distribution networks, the network connection requirements, the costs for network access and the unbundling of network operators. The aim was to remove market access barriers for energy producing units (European Union 1996).

Market design and institutional framework of Germany

In Germany, the liberalization was carried out in 1998 and changed the market design heavily. Until the liberalization, the customers were obligated to be provided electricity by the regional electricity supplier. The electricity prices had been controlled and had to be authorized (Heuck et al. 2007: 492). Today, Germany has a central energy-only day-ahead and intraday spot market based on the merit order principle, an over-the-counter futures market and a balancing power market. There is an open competition for end customers. The unbundled distribution networks, as well as the four control areas, which are operated by four Transmission System Operators (TSO), have a natural monopoly, but are regulated by the federal regulator (Bundesnetzagentur) (Crastan 2009: 142ff). The European Power Exchange (EPEX) Spot market contains a day-ahead auction market with tradable hour contracts in Euro per MWh and an order book close at 12:00 pm every day and a call-auction market with tradable quarter hour contracts in Euro per MWh and an order book close at 3:00 pm every day. Continuous intraday trading is possible until 45 minutes before delivery with tradable hour or quarter hour contracts (EPEX Spot 2015: 9ff).

In Germany, the Renewable Energy Sources Act introduced guaranteed feed-in tariffs to different technologies in 2000. This proved to be a reliable and predictable payment to plant operators and led to high investments into vRE. Moreover, a priority for the feed-in of Renewable Energies had been introduced. The energy is fed into the grid and is paid according to the feed-in tariff by the Distribution System Operator (DSO). The DSO transfers the energy to the balancing groups of the TSOs, which then must sell it at the EPEX Spot.

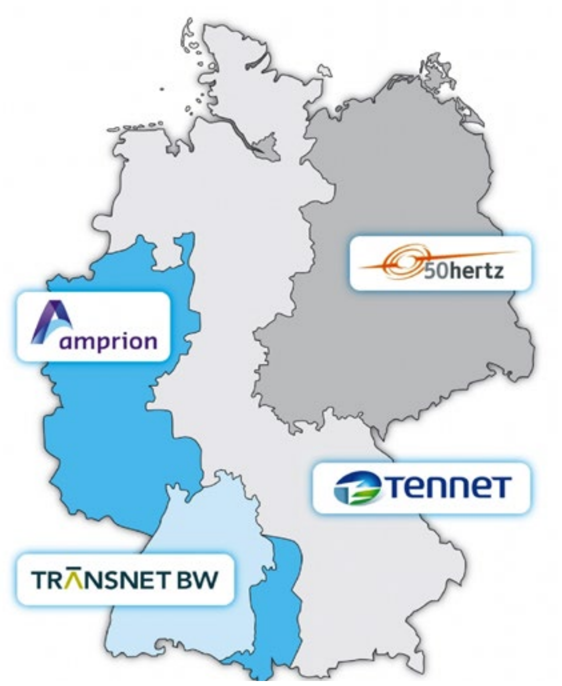

Figure 15: The four control areas and the respective Transmission System Operators in Germany (Source: SOPTIM 2015)

In 2012, the possibility for plant operators to have their energy be traded by electricity traders with the aim of more balanced balancing groups was introduced. To encourage the switch to this market option (Direktvermarktung), an economic incentive of a market premium was given, which is still paid by the DSO. Since then the TSOs, as well as traders, sell the energy at the day-ahead and intraday market. The difference between the market price and the feed-in tariff, as well as the market premium, are reimbursed through a surcharge to be paid by electricity consumers.

Since August 2014, new built generation units above an installed capacity of 500 kW have to be compulsory traded by electricity traders in the market option (Bundesministerium der Justiz 2014: 9ff). Out of a total installed capacity of 38.1 GW of wind energy plants and 38.2 GW of photovoltaic installations (Bundesministerium für Wirtschaft und Energie 2015: 4f), in March 2015, 35.5 GW of wind energy capacity and 6.2 GW of photovoltaic capacity have been part of the market option (50 Hetz et al. 2015: 1).

Market design and institutional framework of Denmark

The electricity market design of Denmark is similar to Germany. Renewable Energies can be sold at the electricity market for the market price and a price supplement (Danish Parliament 2008: 1ff). One major market difference is that wind energy power plants are allowed to take part in the balancing power market. A market participant offers the availability to regulate wind parks in specific hours one day ahead. The minimum activation bid size is 10 MW and a bid has to be handed in at the latest 45 minutes before the operating hour. To reach the minimum bid of 10 MW it is possible to aggregate wind turbines. The balancing power market is set up as a marginal price market with cost reflective penalties. The penalties for plants which have caused imbalances are equal to the prices for the energy units which have removed imbalances (Energinet.dk 2008: 6ff).

Market design and institutional framework of Spain

The electricity market design of Spain is also similar to Germany. As in Germany, the Spanish Government wanted to minimize the differences of the market access between conventional and Renewable Energies. That is why Spain also implemented an economic incentive to switch from a fixed feed-in tariff to a market-dependent premium-scheme. In 2009, 96 percent of all wind power capacities used the market-dependent system, compared to only 2.5 percent in 2004 (Bennerstedt et al. 2012: 33ff). However, in 2014 the feed-in tariff as well as the premium-scheme have been phased out (Boletín Oficial del Estado 2014: 1ff).

One major market difference is that Spain has a capacity bonus for conventional power plants. Investors who built new power plants or undertake significant retrofits, get over ten years a maximum capacity bonus of 28 Euro per kW and year. The bonus is lower if the secured capacity exceeds the year's peak load by more than ten percent and turns zero if the capacity exceeds the peak load by more than 30 percent. The bonus is only paid for new power plants if they add at least 50 MW of installed capacity (inagendo 2013: 3).

3.1.3 Implementation of variable Renewable Energy forecasts

In Europe, vRE forecasts are used for several use cases. The variety of use cases is due to the high liberalization and unbundling of the electricity market. The market designs of the countries led to the need of several stakeholders to have vRE forecasts. In the following, these use cases shall be described mostly at the example of Germany, but also with references to Denmark and Spain or in regard of whole Europe.

Trading forecasts on regional and portfolio levels

The introduction of the market option in Germany led to the situation that both the TSOs and electricity traders sell vRE energy of their portfolios at the day-

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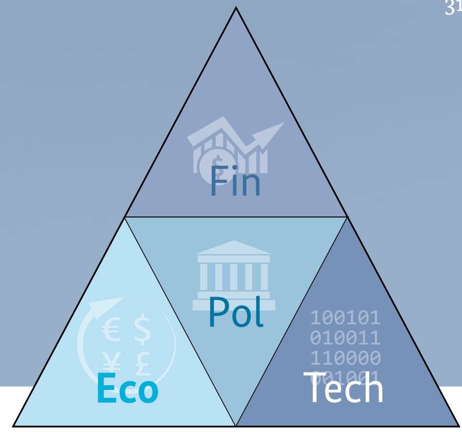

ahead and intraday market. To submit trading schedules they need to use accurate day-ahead forecasts as well as shortest-term forecast updates for the 24/7 intraday market.

The TSOs incentive for accurate forecasts is a bonus system introduced by the German government. Apart from that, TSOs have only moderate interest in accurate vRE forecasts, as the costs of balancing energy are reimbursed through the surcharge paid by electricity consumers (Bundesnetzagentur 2012: 35). The traders' incentive for accurate forecasts in the market option is mainly to diminish the payment for balancing power of which is not reimbursed to them. The larger a portfolio, and the more regionally distributed the generation units, the better a portfolio is predictable. The better the forecasts are, the better the balancing groups can be balanced. Thus, balance energy payments can be diminished and profits can be gained. Traders moreover use intraday forecasts to create curtailment schedules in the case of negative spot market prices. To enlarge the portfolio, a competition between traders developed to contract great shares of vRE capacities. Due to the need of accurate forecasts, traders in the market option are highly driving forecast improvements.

According to the German federal regulator, the TSOs have to publish the day-ahead trading forecast until 6:00 pm in an hourly resolution in the Internet. Moreover, they have to publish the amount of energy they have bought or sold in the intraday market and the amount of balance power that was needed to balance their balancing group. The federal regulator also discussed if the set-up of a meta forecast based on forecasts by different providers should be mandatory for the TSOs. The agency, however, decided not to make this mandatory as the TSOs already use different forecast providers to calculate a meta forecast (Bundesnetzagentur 2009: 3ff).

The participation in the market-dependent premium-scheme in Spain required the trader of a forecast production, with penalties applied if the actual production deviates from the forecast. Nevertheless, the premium-scheme was introduced with beneficial economic conditions compared to the feed-in tariff. The penalties and the partly market-based profits led to the need of highly accurate forecasts (Bennerstedt et al. 2012: 33ff).

The promotion scheme of vRE in Denmark, with price supplements on top of the market price, led to the same need for accurate forecasts as the introduction of the market options in Germany an Spain. In Denmark the need for accurate forecasts is also driven by the possibility of wind energy power plants to take part in the balancing power market.

Regional forecasts

The TSOs in Germany use forecasts not only for trading purposes, but also for grid information and security analysis. For these reasons, forecasts are calculated on a regional level. There are e.g. forecasts calculated for whole Germany, for the four control areas or for federal states.

The German-wide forecasts, i.e. the aggregate wind and solar forecast, are also used by electricity traders, even if they do not have vRE portfolios. The national wind and solar forecasts are used as a spot market price indicator as vRE production strongly influences the spot market price. The forecast can be used for speculators who need to determine when energy is best bought or sold.

Load flow calculations at the level of grid nodes

Forecasts of vRE production are also used for load flow calculations at the level of grid nodes. The need for such calculations is driven by the changed grid situation due to the high feed-in of renewable energies into the distribution grid. In Germany, the once one-directional electricity flow in the grid has been changed towards a bi-directional one. This change brought some fundamentally new tasks for the DSOs as well as the TSOs. Huge loads of electricity that must be transformed to higher voltage levels towards the transmission grid have to be handled in the transformer stations and the grid capacity has to be monitored. Furthermore, the DSOs lack detailed information about power injection, as the generators are only required to provide actual power measurements with an installed capacity above 100 kW. According to the Renewable Energy Sources Act, renewable energies have an unlimited priority to feed electricity into the grid. Hence, the DSO is only allowed to curtail production from vRE units if congestion is foreseeable and the production of conventional power plants is limited a minimum in order to ensure grid security (Bundesministerium der Justiz 2014: 9f).

To keep track of the load in the grid, and especially at the transformer stations between the transmission and distribution grid, an accurate and detailed forecast of the vRE production is essential to ensure grid stability. Therefore, wind and solar power predictions are set up at the level of grid nodes to provide information about the expected amount of wind and solar power coming from lower grid levels. By accumulating the forecasts of all transformer stations of the distribution grid transformer station, forecasts for the transmission grid can be generated. Load flow calculations can then prevent congestions by pro-active measures. The TSO can inform the DSO about the required amount of power that has to be curtailed at a certain transformer station as well as the time period of curtailment. The TSO 50 Hertz Transmission and the DSO avacon e.g. cooperate at this level. Congestions at transformer stations towards the transmission grid occur frequently. The TSO 50 Hertz Transmission sets working points of 100, 60, 30 and zero percent. The grid control center of the DSO avacon sends out the command to the directly connected transformer stations with a telemetric installation which can give a feed-back if the signal was delivered or not. The DSO avacon moreover sends out coded radio signals to Renewable Energy plants that are connected to this transformer station. This procedure allows for a regional curtailment of renewable generation units. As the load at a transformer station is predicted and the actual load is recorded the curtailment can be confirmed (cf. avacon et al. 2014).

European-wide congestion forecasts

Load flow calculations are not only needed for the control areas of single countries, but also internationally, e.g. to predict the import or export of electricity from one country to another. In Europe, the TSOs have set up the so called Day-Ahead Congestion Forecast (DACF). The main mission of the Day-Ahead Congestion Forecast is to proactively provide information to the TSOs to ensure a secure electricity supply in Europe. The basis for the forecast are data from the TSOs. In Germany, the TSOs get the final balanced day-ahead schedule after gate closure at the EPEX spot market until 2:30 pm by the balance responsible parties. The balance responsible parties use accurate day-ahead power forecasts for wind and solar portfolios to balance volatile production in the balancing group schedules (Verband der Netzbetreiber 2007: 62).

The DACF data sets are generated every day by the TSOs after the gate closure of the markets and comprise the changes of topology for the predicted day. Every TSO from the European Network of Transmission System Operators (ENTSO-E) collects the forecast data for the agreed timestamps and adjusts a suitable selected load flow dataset with all necessary technical data in the corresponding transmission grid. This includes information about load, generation and grid aspects as scheduled outages, topology and electrical data. To create his own set of data, every TSO with a higher share of vRE in the grid also uses the latest renewable energy power forecasts. Furthermore, the overall balance, and therefore the expected load flows on the tie lines, is calculated in correspondence with market data. After having collected all the data sets from the TSOs they are then merged. In the end, a security analysis on the merged datasets is performed. With the Day-Ahead Congestion Forecast possible, congestion at the interconnectors due to unforeseen transmission flows is detected prematurely and can be avoided. Beneath the Day-Ahead Congestion Forecast there is also calculated a Two-Days-Ahead Congestion Forecast (2DACF) (ENTSO-E 2010: 2ff).

Real-time estimations for TSOs and traders

Besides forecasts, real-time estimations are also used to integrate vRE into grids and markets. These estimations can be used for grid operational information as well as for the shortest-term improvement of intraday forecasts. For real-time estimations it is crucial to have access to actual measurements. For traders in the German market option, the share of measured generation units increased heavily as the remote control possibility and the delivery of actual measurements to the trader became a requirement for the market option since April 2015, as defined by the newest Renewable Energy Sources Act. The actual measurements are in most cases read out from the plant computers or the metering points via Virtual Private Network connections (Bundesministerium der Justiz 2014: 22ff).

Based on the knowledge of the estimated actual situation, short-term forecasts can be adjusted to be able to trade the best possible estimate of vRE production. Moreover, if traders have adjustable conventional power plants in their balancing group, they can regulate these power plants in real-time to balance the balancing group according to the actual feed-in of vRE.

The German TSOs have only very limited access to real-time measurements of vRE, not even to generation units they trade on the spot market. Only the DSOs are provided with actual measurements from vRE with an installed capacity above 100 kW. Nevertheless, the TSOs are allowed to make contracts with plant operators to use their plants as representative reference sites, so that service providers can set up a real-time estimation. Moreover, the TSOs can contract real-time estimations by service providers which therefore use their own dataset. The German Renewable Energy Sources Act even forces the TSOs to publish continuously a real-time estimation of the actual produced electricity by wind power plants and photovoltaic installations in at least an hourly resolution for transparency reasons (Bundesministerium der Justiz 2014: 65).

Real-time estimations are used by the TSOs to estimate the actual situation in the grid. That's why there is a real-time estimate calculated for every single control area. Moreover, an estimation for the whole of Germany is calculated as this estimate is more accurate due to the larger area. The Germany-wide estimation is also the basis for the horizontal compensation between the TSOs. The horizontal compensation is a mechanism which balances the amount of Renewable Energies to the balancing groups of the TSOs according to predictions of customer demand in the control areas. The apportionment of demand between the control areas accounts for the division of energy to the own or to the balancing group of the other TSOs. The exchanged amount is then invoiced with the average spot market price for either wind or solar energy between the TSOs. The horizontal compensation moreover divides the financial costs to the four TSOs according to the share of demand between the control areas (BDEW 2013: 110).

3.2 Examples from the United States of America

3.2.1 Status of the extension of variable Renewable Energy

Renewable Energy accounted for 13.2 percent of the net electricity generation in the United States of America in 2014 with hydroelectric power plants being responsible for almost half of the Renewable Energy generation. Wind energy accounts for 4.4 percent of the total electricity generation and Solar Thermal and photovoltaic for 0.4 percent (U.S. Energy Information Administration 2015: 12).

In the United States of America individual states can set up Renewable Portfolio Standards to increase the generation of electricity from Renewable Energies. These require electricity producers to supply a minimum share of their electricity from renewable sources. Thirty states and the District of Columbia had enforceable Renewable Portfolio Standards, as of January 2012. Seven states had voluntary goals for renewable generation. Although several proposals have been discussed in the U.S. Congress, there is currently no national-wide Renewable Portfolio Standard (U.S. Energy Information Administration 2012).

3.2.2 Market design and institutional framework

In the United States, only 16 states have deregulated their electricity markets to restructure the monopolist vertically integrated electric utilities to an unbundled competition between sellers. Seven states began

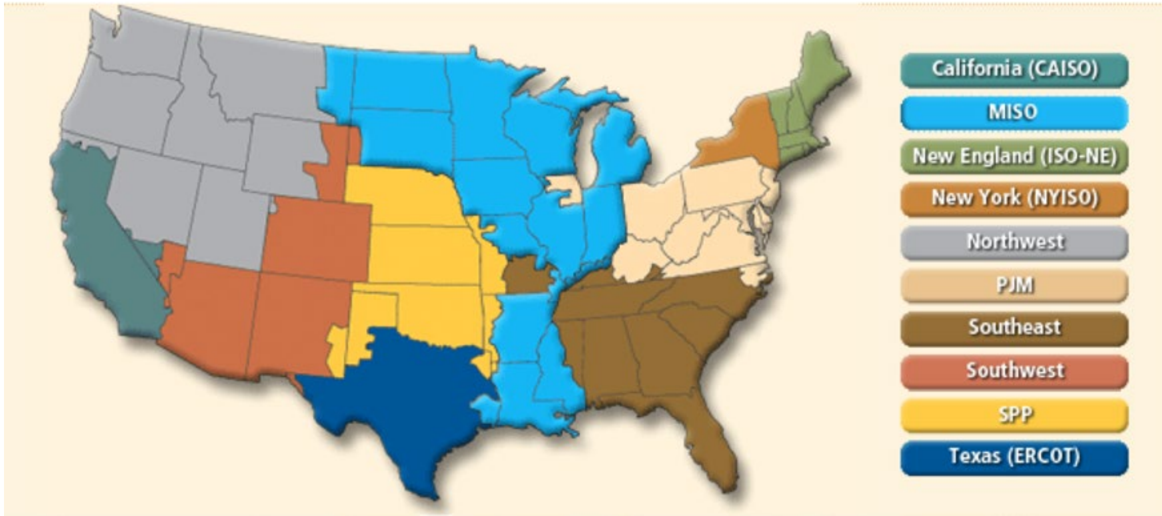

Figure 16: Electric Power Markets in the United States of America (Source: Federal Energy Regulatory Commission 2015)

restructuring their electricity markets, but suspended it (U.S. Energy Information Administration 2010). Nevertheless, wholesale markets are established and utilities are required to provide network services on a non-discriminatory basis. There are four Regional Transmission Organizations and three Independent System Operators (ISO) that are both responsible to coordinate, control and monitor electricity transmission grids and move electricity over large interstate areas. All of these entities established a power market. Moreover, there are three power markets in the Northwest, Southwest and Southeast region (Federal Energy Regulatory Commission 2015).

The Energy Policy Act of 2005 required all public electric utilities to facilitate net metering upon request by customers to allow homes and businesses with distributed generation to pay only the net cost of electricity from the grid. In other words, homes and businesses have to pay for the electricity used minus the electricity produced locally and sent back into the grid (U.S. Congress 2005: 370).

Electricity produced by vRE is mostly sold via Power Purchase Agreements (PPA). The merchant must utilize the ISO administered markets to enact power sales. This implies that the power has to be bid into ISO markets at zero Dollar as compensation will come from the buyer and not the ISO. Net metering is also considered as a PPA, without the need to bid into markets, but implying that an on site meter has to be utilized to track the output (GP Renewables & Trading 2009: 13ff).

In some markets of the United States there is a price component which takes the state of the grid in terms of congestions into account. To consider the level of congestion, a model of Locational Marginal Pricing is implemented. The pricing is a bid-based computational model that determines the optimal generation unit dispatch as well as local energy and transmission congestion prices. The marginal price at a specific location is related to the generation marginal cost, the transmission congestion cost and the cost of losses. The model calculates an electricity price and transmission congestion price for each node on the grid. Only under unconstrained conditions without any congestions is the price equal at every node (MISO 2015: 1ff). The idea of this nodal pricing market design is a result of the historically weak electricity grid in the United States.

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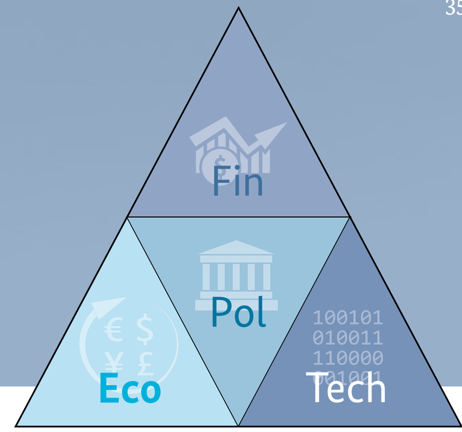

Market design and institutional framework of MISO

The Midcontinent Independent System Operator (MISO) is a non-profit member based organization regulated by the Federal Energy Regulatory Commission. As a Regional Transmission Organization, MISO provides electricity to consumers in 15 states. There is an open access to the MISO transmission grid through a nodal pricing tariff regulated by the Federal Energy Regulatory Commission. MISO administers a day-ahead and a real-time energy market and monthly financial transmission rights allocations and auctions. Bilateral options and futures trading is active on the Intercontinental Exchange (ICE) market (Federal Energy Regulatory Commission 2015). In the MISO transmission area are state legislated Renewable Portfolio Standards in Montana, Minnesota, Wisconsin, Iowa, Missouri, Illinois, Michigan, Ohio and Pennsylvania. These Standards require varying percentages of electrical energy to be produced by renewable sources (Electric Power Research Institute 2011: v).

3.2.3 Implementation of variable Renewable Energy forecasts

In most of the United States market participants have to deliver schedules in a five minute resolution. Regarding Renewable Energy schedules, the first Independent System Operator in the United States introduced wind power forecasts for system operation in 2004. Wind power forecasts in the United States are used differently for system and market operations. MISO followed in 2008 to set up wind energy forecasting procedures (Botterud et al. 2009: 6ff). As of June 30th, 2013, there had been 12.2 GW of registered wind capacity in the MISO transmission grid (MISO 2013: 4).

Implementation of variable Renewable Energy forecasts in the MISO market

In the MISO market, the market operations for wind energy producing units are being done in an automated procedure. Therefore, the provision of a day-ahead forecast is required by market participants. Imbalances are settled at the real time price, but there are no further deviation penalties (Botterud et al. 2009: 10).

In the MISO market, market participants have to submit real time bids 30 minutes before delivery. MISO, moreover, uses short-term forecasts in a five minutes resolution based on real-time measurements to dispatch the system. Due to the high update interval, there are high requirements on the data processing, forecast calculation speed and data backup for MISO's service provider. MISO defines the maximum capacity for Dispatchable Intermittent Resources like wind power to automatically dispatch the generation based on offer prices and system conditions (Ruud 2014: 12ff). For outage and availability information, MISO offers an operational XML API and a web interface (MISO 2014: 27). By integrating these accurate outage and re-dispatch information, the forecast accuracy can be highly increased. MISO collects actual production data and outage information and provides it to market participants and forecast service providers.

The maximum capacity re-dispatch signals have to be used differently for fast and slow reacting wind turbines. Both the dispatch schedules and the power forecasts have to take the reaction time of the wind turbines into account. Otherwise forecast errors can be possible, as the measured value some minutes after a re-dispatch can still be very low, leading to low forecasts for the next minutes although the wind turbines then are possibly running again. The dispatch schedules have to take the reaction time into account to prevent dispatching slow reactions to already sent dispatching signals.

As regulations require utilities to allow net metering, the TSOs will also have to deal with the distributed surplus-feed-in of roof-top photovoltaic installations in the future. This will become of a larger importance when the extension of solar energy capacities will progress leading to the need of forecasts of the production and also of the load profile change of households and businesses (cf. chapter 3.3).

3.3 Examples from South Africa

3.3.1 Status of the extension of variable Renewable Energy

South Africa is the largest producer of electrical energy in Africa and the 16th largest in the world. Up to 90 percent of all generation in the country comes from coal fired power plants. With the "Integrated Resource Plan for Electricity 2010 to 2030" the Government approved an addition of 17.8 GW of new installed electric power capacity from vRE plants by the year 2030: 8.4 GW from wind farms, 8.4 GW from photovoltaic and 1 GW from Concentrated Solar Power installations (Department of Energy South Africa 2013: 12).

In 2009, South Africa introduced a renewable energy feed-in tariff, but has switched to a tender process with a competitive bid on price in 2011. The objective is that Renewable Energies will contribute 42 percent to South Africa's new generation capacity by 2030 (Saylor et al. 2011). With the "Renewable Energy Independent Power Producer Procurement Program," South Africa has set up a competitive bidding process for Renewable Energy. Until June 2014, wind farms with a capacity of 254 MW and photovoltaic installations with a capacity of 397 MW have been installed during the first Bid Window. Still to be connected to the grid are 772 MW from Bid Window 1. Projects from Bid Window 2 are supposed to be complete around 2016 (Department of Energy South Africa 2014: 2ff).

3.3.2 Market design and institutional framework

South Africa has a vertically integrated public utility, called Eskom. It is responsible for 95 percent of the country's generation, and owns and operates the country's national transmission system. Eskom also provides electricity to 45 percent of all end users, whereas the other 55 percent are provided for by redistributors, including municipalities. South Africa is struggling with high demand and limited reserve margin and is using demand-side management to avoid load-shedding. The attempts to enable private participation in the country's energy system have not been very successful thus far, but the Integrated Resource Plan clearly formulates the need of Independent Power Producers (IPP) (Saylor et al. 2011).

Eskom is the only buyer and only one of few sellers of power. However, there is currently a debate whether or not to establish an Independent Systems and Marker Operator to create a more open and transparent process in South Africa. The establishment would form a single buyer model (Saylor et al. 2011).

3.3.3 Implementation of variable Renewable Energy forecasts

As South Africa has a vertically integrated public utility, the system operator Eskom uses power forecasts to plan schedules for conventional generation units and to predict the generation of vRE generation units. Therefore, Renewable Power Plants above an installed capacity of 1 MW have to produce and submit week-ahead and day-ahead hourly production forecasts to the system operator. The forecasts have to be provided by the generator at 10:00 am every day by means of an electronic interface (Eskom Transmission Division 2014: 37). As Eskom is the only buyer of power, unit dispatching or curtailing is being done based on economic principles while considering technical constraints, but without market price indicators. Moreover, Wind Power Plants have to provide wind speed and wind direction information within 75 percent of the hub height and photovoltaic Power Plants have to provide solar radiation information, both updated every minute (Eskom Transmission Division 2014: 35ff). With this information, Eskom will be able to set up power curves for every generator to be able to calculate confidence indicators for the delivered power forecasts. Nevertheless, there is no incentive for accurate forecasts for the plant operator, as no imbalance costs have to be paid. In addition to the forecasts provided by the Renewable Power Plants itself, Eskom is considering the provision of portfolio forecasts by service providers. Portfolio forecasts are usually much more accurate because of regional smoothing effects.

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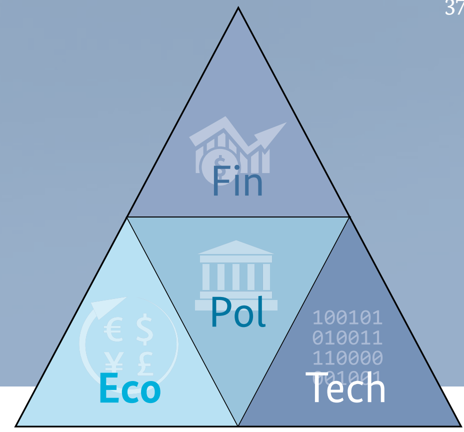


To make the dispatching or curtailment process more accurate, the Grid Code in South Africa is very clear on what the generators have to deliver besides power forecasts. Every Renewable Power Plant above 1 MW in South Africa has to provide the actual power in MW at the Point of Connection to the communication gateway equipment of the system operator or the Network Service Provider. Moreover, it has to provide a signal including availability estimates for the next six hours, updated hourly on the hour, and feedback that the plant is responding to a curtailment when requested by the system operator (Eskom Transmission Division 2014: 35ff). With this information, Eskom can set up schedules and knows all the actual information of the generators to be able to undertake unit dispatching or curtailment. IPPs are expected to sign a PPA. The buyer shall buy all the energy generated by the units. The output is determined by the unit operator on a self-dispatch basis. The National Control Centre still can apply curtailments. The National Energy Regulator of South Africa is envisaging declaring Renewable Energies of IPPs as must-run facilities in the future (National Energy Regulator of South Africa 2013: 1).

At present, South Africa is planning small-scale embedded photovoltaic generation units within municipal boundaries to be allowed only by a registration instead of a licensing process until an installed capacity of 1 MW. These units shall be allowed to export surplus electricity to the electric grid. For these units there shall be no need to deliver forecasts to the system operator or the Network Service Provider (National Energy Regulator of South Africa 2015: 17f). Regarding the high solar radiation, it is possible that South Africa will have to deal with the challenge of a high penetration of roof-top photovoltaic installations. As Eskom will not have access to the actual power of these installations, a forecast or an upscale will have to be implemented by Eskom itself or by a service provider. Beneath the provision of a physical production forecast, there will also be the need to update the load profiles for the households with photovoltaic installations as only the surplus is exported to the grid. The reason is that it is easier to generate production forecasts than surplus-feed-in forecasts, as predictions of production and demand need very different basis information and are better calculated separately. This does however makes the grid management more complex, as the residual load has to be determined.

3.4 Examples from India

3.4.1 *Status of the extension of variable Renewable Energy*

The Indian electricity sector is the 5th largest in the world, with over 258 GW installed capacity, currently dominated by coal-fired power plants (Central Electricity Authority 2015: 7). The "Indian Electricity Act" of 2003 facilitated the development of Renewable Energies. The Indian government through its "Renewable Purchase Obligation" policy made it mandatory for each state to have a fixed percentage of Renewable Energy in the grid. At the end of 2014, wind farms with an installed capacity of 22.5 GW and photovoltaic installations with an installed capacity of 3.1 GW have been connected to the grid (Ministry of New and Renewable Energy 2015). In 2011, the National Solar Mission set the goal of 20 GW installed capacity of solar power by 2022. This was revised to 100 GW in 2014 (Business Standard 2014).

3.4.2 *Market design and institutional framework*

To pay energy producers, India has a system of Availability Based Tariffs. These comprise a capacity charge to cover the fixed costs of a power plant, an energy charge to cover the fuel costs for scheduled generation and a schedule deviation charge to cover deviations dependent on the frequency. By 9:00 am every generation station informs the Load Dispatch Center how much power it will produce the next day. The regional and national Load Dispatch Centers decide then a schedule for the generating stations. By 5:00 pm these schedules have to be given to the stations and the schedule is applicable by midnight (Central Electricity Regulatory Commission 2000: 4ff).

Generation and transmission at the interstate level has already been unbundled in 1991 and to date the unbundling of generation, transmission and distribution in states has, to a large extent, been achieved. The regional and national Load Dispatch Centers have been prohibited from trading electricity and the regional Load Dispatch Center is also prohibited to generate electricity. Open Access to the Inter State Transmission System was implemented in 2004 to promote non-discriminatory usage of the transmission system by customers (Pandey 2007: 4ff).

In India, electricity is to 89 percent sold in the long term through PPAs. Short-term trading on weekly, daily or intraday basis has only a minor market share. The most important spot market is the Indian Energy Exchange (IEX), which manages short-term markets including day-ahead and intraday (Indian Energy Exchange 2014: 4ff).

3.4.3 *Implementation of variable Renewable Energy forecasts*

In India, power forecasts are being used to let the regional and national Load Dispatch Centers know which amounts of Renewable Energy are predicted to be fed into the grid. But the Dispatch Centers cannot adjust the schedules of wind and solar generation units, since all renewable energy power plants except biomass power plants are treated as must-run power plants in India and are not subject to the merit order dispatch. Thus, the Load Dispatch Centers shall aim at utilizing available wind and solar energy fully. That said, the system operator can chose to instruct solar and wind generators to back down generation for grid security (Central Electricity Regulatory Commission 2010: 38ff). To increase the quality of the forecasts, the Central Electricity Regulatory Commission imposed an order in 2013 that force wind farms of 10 megawatts or more to predict their generation for the following day in fifteen minutes steps. If the forecast deviates by more than 30 percent, penalties do take place. Solar parks are ordered to submit a forecast as well, but are not fined (Central Electricity Regulatory Commission 2013: 2ff).

This order has been challenged in several Indian courts by the Indian wind power association, the Wind Independent Power Producers' Association and Gujarat Mineral Development Corp to review the rule's legality and feasibility. They claimed that the order would significantly reduce their profits. The Central Electricity Regulatory Commission is thus currently in a review process with possible changes to the forecast requirement. In the beginning of 2014, the Commission moreover postponed the introduction of penalties (Central Electricity Regulatory Commission 2014: 6).

In a report, the Central Electricity Authority refers to create Renewable Energy Management Centers at state, regional and national levels, co-located with respective Load Dispatch Centers. These Centers shall have the function of forecasting Renewable Energy generation in jurisdiction areas on month-ahead, week-ahead, day-ahead and hour-ahead basis'. The forecasting is to be done cluster-wise for determination of power flows in and between states (Central Electricity Authority 2013: 35ff).

With the review process of the forecasting order, and the possible creation of Renewable Energy Management Centers, it is unclear in which way the Indian government wants to implement wind power forecasts. In the future it may both be possible that every producer of wind energy is obligated to produce its own forecast and that the planned Renewable Energy Management Centers are also required to have the function of forecasting vRE generation. From the perspective of accurate system-wide forecasts, it is recommendable to generate forecasts not only on a wind-farm level, but also on a portfolio- or grid-wide level. Moreover, it can be a fragile implementation if thousands of independent producers have to submit individual forecasts, because the Load Dispatch Centers have to deal with numerous senders and likely different data formats. The costs of power forecasts also decline with the possibility of aggregating wind farms to a portfolio, rather than a forecast provider having many customers and the need of setting up a delivery to each of them.

TECHNOLOGY

3.5 Examples from Brazil

3.5.1 *Status of the extension of variable Renewable Energy*

As of April 2015 Brazil had an installed capacity of 89.6 GW of hydroelectric power, 5.7 GW of wind power and 15.2 MW of solar power out of a total installed capacity of 135.3 GW (ANEEL 2015). For 2023, Brazil estimates to reach an installed capacity of 112.2 GW of hydroelectric power, 22.4 GW of wind power and 3.5 GW of solar power out of a total installed capacity of 192.9 GW (MME 2014: 92).

Until now, Brazil always relied on its hydroelectric potential to satisfy the national electricity demand. However, currently licenses for hydroelectric power plants are not only hard to obtain, but they are frequently challenged in court after they are granted. This has resulted in construction delays and in effect no new reservoirs are being allowed. This creates a need for other electricity sources to complement hydroelectric power (Barroso 2012: 39).

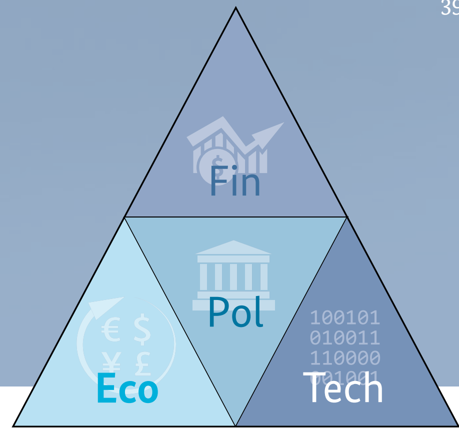
3.5.2 *Market design and institutional framework*

Every generator in Brazil receives a firm energy certificate by the Ministério de Minas e Energia (MME) with the maximum amount of energy the generator can sell in contracts. All consumers must be contracted at 100 percent, which is verified ex-post. If a consumer was under-contracted the year before, a penalty has to be paid. So the need to sign new contracts to cover additional load is the driver for new capacities. The market is divided in a regulated market, which accounted for 75 percent of the consumption in 2012, and a free market. In the regulated market, distributors contract energy through an organized investment market with tenders for energy contracts and reliability options. In the free market, large industry consumers can freely negotiate contracts with generators or trading companies. The only requirement is to remain covered by contracts at 100 percent. The regulated contract tenders include standardized offers for new energy between three and five years ahead of delivery or shorter-term contracts for existing generators between one and twelve months ahead of delivery, as well as reserve energy tenders to increase the system's security of supply. It is not a single buyer model, but PPAs are signed between generators and distributors after the tender (Barroso 2012: 6ff).

The sale of electricity in the national interconnected power system is enabled by Câmara de Comercialização de Energia Elétrica, a non-profit legal entity of private law under the regulation of the national regulator Agência Nacional de Energia Elétrica (ANEEL). Its purpose is to manage the contracts of purchase and sale of electricity, its accounting and liquidation. The national system operator Operador Nacional do Sistema Elétrico (ONS), another non-profit legal entity of private law, is coordinating and controlling the operation of generation and transmission (ONS 2014). ONS centrally determines the production schedule of each plant. Dispatch decisions are based on a stochastic optimization in a cost-minimization framework, where hydrology is the uncertainty parameter. There are no price bids as there is no spot market (Barroso 2012: 6).

In 1998, the distribution companies were privatized and the generation sector was transformed into a competitive market, whereas transmission and distribution remained regulated. Although transmission reinforcements are centrally planned, there is a strong private participation in the transmission expansion. In 2012, 45 companies were granted with a concession of transmission and 63 companies in charge of distribution (Barroso 2012: 7ff).

Any generation unit connected to the grid, whether by the regulated or the free market, needs to respect all the specifications and guidelines of the distribution procedures established by ANEEL (ANEEL 2012a: 6ff). Every entrepreneur who wishes to participate with his undertakings in the country's energy tenders, is obligated to register them in the Sistema de Acompanhamento de Empreendimentos Geradores de Energia (AEGE). The system allows each entrepreneur to access a database with all his undertakings that have participated in the energy tenders since 2009 (MME 2015c:



5ff). Wind farm planners have to provide to the AEGE system site appraisals, including historical weather and anemometric data for a period of minimum 24 consecutive months, done in ten minutes intervals. With this data, the planners have to make an estimation of the energy they can sell in the tender (MME 2015b: 7ff). Photovoltaic installation planners have to provide to the AEGE system site appraisals historical weather and solar radiation data for a period of minimum 12 consecutive months, done in ten minutes intervals. With this data also, the photovoltaic installation planners have to make an estimation of the energy they can sell in the tender (MME 2015b: 7ff).

In the case where energy from a wind farm is sold at an energy tender, the operator is required to start within six months after the initial operation to provide anemometric and meteorological measurements from the wind farm to Empresa de Pesquisa Energética (EPE), the energy research department of MME. The measurements are done in ten minutes intervals and include air pressure, temperature, relative humidity, wind speed and direction. The wind farm operator stores these measurements and transmits them to EPE every 15 days (MME 2011: 1f). To provide the measurements, the operator uses an interface called Sistema de Acompanhamento de Medições Anemométricas (AMA). The AMA database is used for wind energy studies about the development of technical instrumentation to plan, operate and integrate wind energy into the national electric system (MME 2013: 1ff). There are currently no requirements to submit meteorological data for photovoltaic installations in the regulated market. According to ONS, specific requirements should appear around 2017, when the contracted projects of the first energy tenders, including solar energy, start to operate. For distributed micro wind power generators connected to the grid through the free market, currently there are also no requirements regarding anemometric and meteorological data supply.

Net metering for micro-renewables up to 1 MW, which are connected to the consumer-side of the meter, has been possible since 2012. Energy supplied to the grid is remunerated in the form of energy credits, which can later be used by the producer to pay future consumption within 36 months, otherwise they expire (ANEEL 2012c: 2f). The distributors thus will have to deal with increasing variability in their networks, as consumers have incentives to displace their energy consumption, but not necessarily their load capacity (Barroso 2012: 44).

3.5.3 *Implementation of variable Renewable Energy forecasts*

ONS is responsible for the coordination of the national electrical system and for the dispatch of all generation units. It uses real-time measurements and forecast techniques to plan the dispatch of each electricity generation unit connected to the grid. Real-time measurements and forecast data are not publicly available.

The distribution companies perform real-time measurements from all generation units connected to the interconnected national grid, including wind farms and photovoltaic installations, and submit them automatically to ONS. The measurements are done in five minutes intervals and include active and reactive power, power factor, current, voltage and frequency (ANEEL 2012b: 3ff).

ONS employs a meteorological department for prognoses of the available amount of water for hydroelectric power plants including El Niño forecasts. Regarding variable wind energy, ONS is developing forecast models to predict the production of the wind farms connected to the grid through the regulated market for the next hours, days and weeks. ONS uses its own models to achieve an aggregated forecast to plan the dispatch of wind energy. According to ONS, the models still have limitations and result presently in significant deviations. For the northeast of Brazil for example, the models have to be optimized to better predict rain conditions, as rain usually leads to dramatic reductions in the wind power production in this area. To further develop the models, ONS is exchanging experiences with the GO15 group, an initiative of the world's 17 largest power grid operators.

For distributed micro wind power generators connected to the grid through the free market, currently there are no forecasts models implemented by ONS. For photovoltaic installations, given the fact that there is still no significant number of photovoltaic installations connected to the grid through the regulated market, there as well are presently no forecast models implemented by ONS.

3.6 Examples from Uruguay

3.6.1 *Status of the extension of variable Renewable Energy*

In 2013, Uruguay had an installed capacity of 3.12 GW, out of which 1.5 GW was from hydropower plants, 59 MW from wind farms and 2 MW from photovoltaic installations. Wind energy supplied one percent of the generated electricity in that year (Ministerio de Industria, Energía y Minería 2014: 2). In 2012, Uruguay announced a plan to bring 1000 MW of installed wind capacity onto its grid. Therefore, the national power company Administración Nacional de Usinas y Transmisiones Electricas (UTE) wanted to sign contracts to buy this energy. At that time 342 MW of capacity were already awarded to sell energy to UTE (Bloomberg 2012). In 2013, Uruguay undertook a tender for 200 MW of photovoltaic installed capacity at a maximal price of US Dollar 91.50 per MWh. Winners of the tender had the possibility to then sign a PPA with UTE (pv magazine 2013).

3.6.2 *Market design and institutional framework*

In 1997, generation, transmission and distribution were unbundled in Uruguay. The generation sector is organized on a competitive basis with independent companies either selling electricity at the administered market or by private contracts. Distribution and transmission is owned by UTE. But UTE is required to provide third parties an open access to the transmission system against a toll for transmission services. Regulation is undertaken by the Reguladora de Energía Eléctrica (Vignolo et al. 2001: 5f). In the spot market the price equals the marginal price of short term generation and is capped at 250 US Dollar per MWh.

Most of the installed capacity is owned by UTE, while the remaining share corresponds to the Salto Grande hydroelectric power plant and to small-scale IPPs. UTE is in charge of all the capacity and transmission expansion in the country (Administración Nacional de Usinas y Transmisiones Electricas 2003: 7ff), and while the Administracion del Mercado Electrico (ADME) is de-jure in charge of power dispatch, this remains under control of UTE.

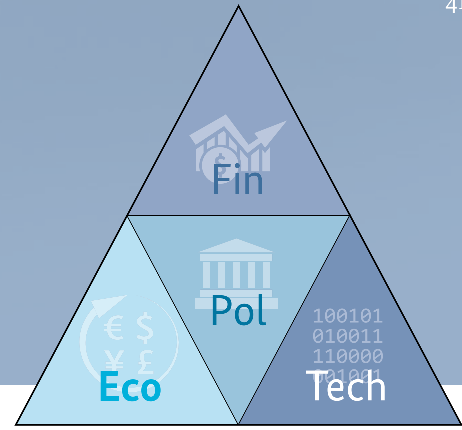
Uruguay allowed micro-generation in 2010 with the possibility of delivering the surplus of the generated energy to the grid. An approval by UTE is required. UTE will purchase the energy fed into the grid at the current pricing list on a 10-year contract term (Uruguay XXI 2014: 21).

3.6.3 *Implementation of variable Renewable Energy forecasts*

In 2011, UTE signed an agreement with the University of the Republic to develop a technique to implement a wind prediction technique with an hourly resolution. This project was based on the university's previous experience building up the country's wind-speed map and mapping exercise at the Emanuelle Cambilargiu wind farm, which included a forecast for generated power with confidence intervals. The forecast is made at 9:00 am for median schedules for wind power and covers a period of one week. It is published every day at around 3:00 pm (Universidad de la republica et al. 2011: 1ff).

3.7 Overview of the contemplated examples

The following table shows the contemplated countries with the used market design and institutional framework, important energy sales markets, vRE support schemes, the operator of the transmission grid, required vRE forecast types and forecast clients. In addition, it shows to which countries or grid regions the contemplated market designs, regardless the vRE support scheme, can be widely applied.

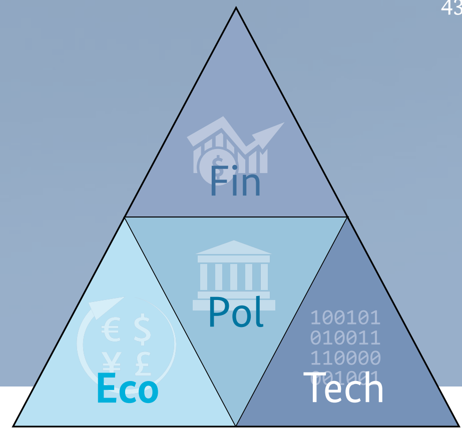


The table includes several forecast types. Trading forecasts are forecasts, where the operator or accordingly the signed trader is responsible for balancing the balancing group by trading the energy at the spot market. Production forecasts are forecasts, where the system operator or the Dispatch Center are responsible for balancing without trading incentives, although for India, penalties apply for deviations to the forecast quality criterion, which are not linked to balance energy prices. Grid node forecasts refer to the grid situation at the grid node, but also include regional forecasts like the Germany wind or solar forecast used for grid security. Real-time estimations are used by system operators, which do not have full dispatch duties, to have an idea about the actual power production by vRE, but are also used by traders for shortest-term improvements of intraday forecasts.

In most countries, it makes no different for vRE operators if there is a spot market or not because the energy does not have to be traded at the spot market, but rather is purchased via a PPA. That is why there are no trading forecasts needed.

One similarity between all contemplated examples is that PPAs are possible in every country by some means or another. Over the counter trading here is subsumed as a PPA. The fact of PPAs being possible in every country also leads to the fact that in every listed country there are IPPs.

TECHNOLOGY



	Germany	Spain	MISO (USA)	South Africa	India	Brazil	Uruguay
Market design and institutional framework	Energy-only market based on the merit order principle with physical and financial contracts	Energy market based on the merit order principle with physical and financial contracts; capacity bonus	Nodal pricing energy market with physical and financial contracts; capacity market with reserve requirement	Vertical integrated public utility with financial contracts to IPPs	Energy-only market based on the merit order principle with physical and financial contracts	Regulated market for financial contracts through tenders; free bilateral market; capacity market with forward reserve requirement	Energy-only market with physical and financial contracts with UTE as a strong vertical integrated public utility
Important energy sales markets	EPEX (Spot); EEX (Futures); PPAs	OMIE (Spot); OMIP (Futures); PPAs	MISO (Spot); ICE (Futures); PPAs	PPAs	IEX (Spot); PXIL (Spot); PPAs	New energy tenders for PPAs and reserve energy tenders	ADME (Spot); PPAs
vRE support scheme	Feed-in tariff and market option; pilot tender scheme	Guaranteed return; formerly feed-in tariff and market option	Partly Renewable Portfolio Standards; net metering	Tenders; export credit tariff for roof-top PV-installations envisaged	Renewable Purchase Obligation with states having tenders or feed-in tariffs	Technology neutral or technology specific tenders; net metering	Tenders; micro-generation surplus purchase
Transmission Grid	TenneT, 50 Hertz, Amprion, TransnetBW	Red Eléctrica	MISO	Eskom	Power Grid India	45 transmission concessions (2012)	UTE
Must-run of vRE	Yes	Not anymore	No	Is envisaged	Yes	No	No
Required vRE forecast types	Trading forecast; grid node forecast; real-time estimation	Trading forecast; grid node forecast; real-time estimation	Production forecast for (re)dispatch or curtailment; grid node forecast	Production forecast for (re)dispatch or curtailment	Production forecast for (re)dispatch or curtailment	Production forecast for (re)dispatch or curtailment	Production forecast for (re)dispatch or curtailment
Forecast clients	Traders (balancing responsible), TSOs (balancing responsible), DSOs, speculators	Traders (balancing responsible), TSOs (balancing responsible), DSOs (balancing responsible), speculators	Midcontinent ISO (balancing responsible)	Eskom (balancing responsible)	National and regional Load Dispatch Centers (balancing responsible); envisaged: Renewable Energy Management Centers	ONS (balancing responsible)	UTE (balancing responsible)
Similar market designs	Denmark, Austria, France, Switzerland	Portugal	New York ISO	Tunisia, Mexico			

4 Generic concept and recommendations to implement vRE forecasts

The aim of this chapter is to provide an overview of the universal aspects and recommendations of beneficially integrating forecasts of the power output vRE units into the operation of electrical grids and energy markets.

In order to provide a background, the following scheme (Figure 17) sketches some of the basic steps to introduce vRE units into the energy system. For each step it is pointed out which aspects have to be considered to allow for accurate vRE forecasting at the end of the day. Experience shows that it makes sense to include requirements due to forecasting right in the beginning of the process, even though the specific step does not seem to be related to forecasting. One example is the national register for vRE units where it is extremely helpful if parameters, such as hub height of wind turbines or inclination angle of solar modules, are required by law. It is very difficult to add these requirements afterwards.

In the following sections details regarding the forecast related requirements are given.

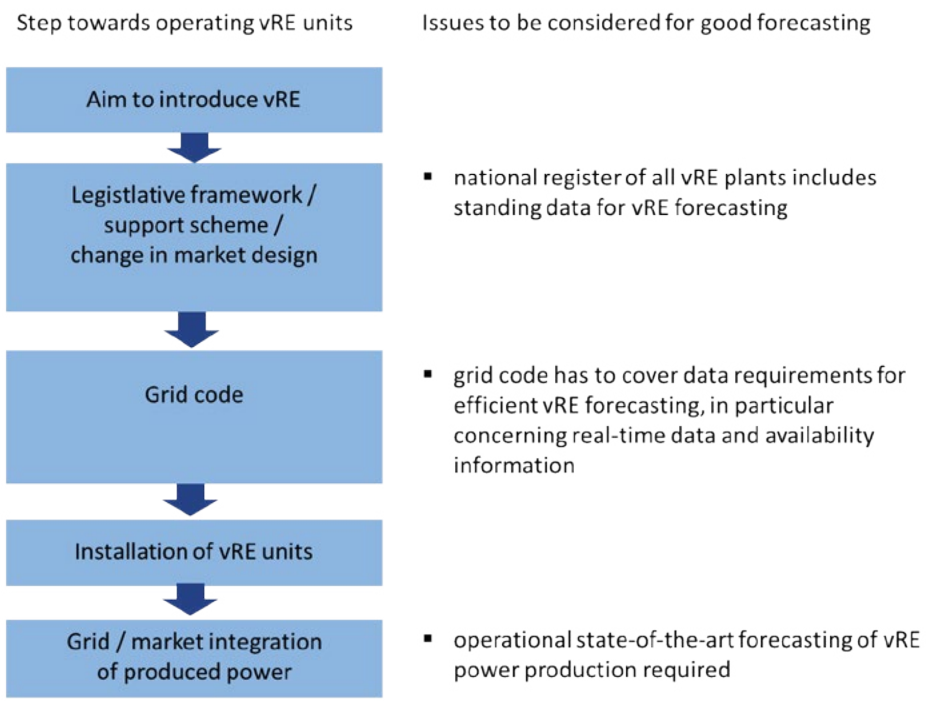


Figure 17: Basic steps for introducing vRE units into the power system with related issues due to vRE forecasting

4.1 National register of standing data for vRE units in legislative framework

Legislative framework refers to the laws and regulations that are introduced or amended due to the introduction of renewable energies. Classical examples would be the support schemes to promote the installation of vRE units. These regulations often do not refer directly to vRE forecasting, but contain aspects which are very relevant for an efficient forecasting process such as the register for standing data, i.e. the information that describes the geographical locations and the technical specifications of the vRE units.

The standing data of all decentralized production units, in particular vRE units, should be compulsory collected in a national database which is publicly available. Standing data are very important to set up a forecast and a real-time estimation. Therefore, this register should at least capture the following standing data of new installations for every vRE unit:

- unique identifier for each unit
- technology of the generator (i.e. wind, solar)
- installed capacity of each generator
- geographical location of each generator according to the World Geodetic System 1984 as a degree in decimals
- associated grid connection point
- for wind turbines: hub height and rotor diameter
- for PV modules: inclination angle and orientation
- date of initial operation and date of decommissioning
- if the generated power is used on location or only fed in to the grid

4.2 Grid code requirements due to variable Renewable Energy forecasts

In general, wind and solar power forecasting systems, no matter if they are based on a physical or statistical approach, require real-time information from the vRE units to calculate precise forecasts. The experience in countries that have just started with large shares of vRE installations is that these requirements can easily be integrated into the grid code. This seems to be the best solution to guarantee a standardized and reliable data supply for grid operators and market participants. The important point is to define the data requirements as precise as possible in terms of the contents, the format and the quality of the data.

As pointed out in the previous chapters, modern power prediction systems can consider all scheduled information that is relevant for the future power output, as far as it is available in time and in an adequate format. In particular, information on availability of turbines, planned outages and curtailment can and should be included in the forecasting process. These pieces of information are, of course, very crucial for the forecasting quality because unscheduled events like curtailments lead to deviations between forecasts and actual power output.

In the following, the complete wish list from the forecasting perspective is provided in decreasing order of importance:

- Power output (real power output)
- Available active power (power output due to meteorological conditions)
- Information on scheduled availability of wind farms and solar plants in terms of effective installed power to cover e.g. scheduled maintenance, known outages of machines
- Information on current availability of vRE units
- Information on scheduled curtailment, i.e. limits to power output

TECHNOLOGY

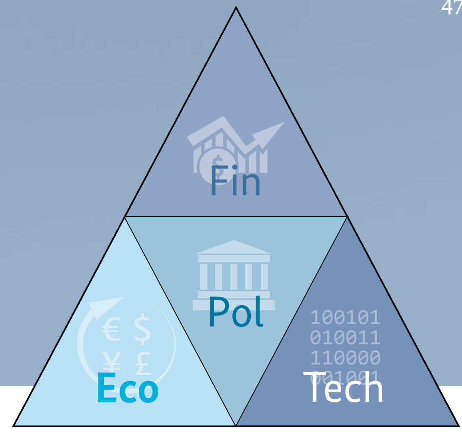
- Information on currently activated curtailment by grid operators or dispatch centres
- Meteorological data that measure the available resource
- Wind farms: wind speed and direction close to hub height
- Solar plants: solar irradiation (direct and diffuse separately if possible)

In general, a time resolution of five minutes is sufficient for most forecasting applications. The timely and reliable retrieval of the real-time data is, of course, an important issue. It is highly recommended to collect this data centrally and make it available to the DSO.

4.3 Operational state-of-the-art forecasting solution for vRE

According to the current best practices of different stakeholders in different regulatory frameworks or market designs, and according to the practical experiences made with wind and solar power forecasting in different areas of the world, the optimal forecasting solution can be summarized as follows:

- Service solution comes from an experienced forecasting provider (company or institute)
- Power forecasts are based on multiple weather model input, i.e. weighted combination is generated to ensure high accuracy
- Forecast provider has meteorological know-how to tune the forecasting system for different areas in the world, in particular area of interest
- Reliable real-time production data can be supplied to forecast provider to allow for accurate shortest-term forecasting (0 to 6 hours)
- Outage information and grid curtailments can be supplied to forecast provider such that this information can be considered in forecasting process
- Forecast provider has flexibility to match additional requirements such as aggregating forecasts on certain levels (e.g. regions or balancing areas) or provide extra information on expected ramps or forecast uncertainty



5 Conclusion

In many countries around the world, wind and solar energy are seen as major sources for the extension of electricity capacities. However, in the past, policy makers often did not think about the need of forecasts for the production of vRE sources. In many cases, balancing responsible parties only realized the need of forecasts when already a large extension of vRE had been undertaken. Processes often then had to be changed ex post as e.g. a unit register for vRE units was missing. That is why it is e.g. important to set up clear and well-defined grid codes, including standing data registers or actual measurement provisions to the system operators.

A conclusion from the experiences shown in this study is that there are only a handful of different required forecast types, varying by the electricity market design and institutional framework. For markets, where renewable energy is sold in Power Purchase Agreements and the system operator has full dispatch rights, shortest-term forecasts are the most important forecasts, as there is no spot market on which conventional and renewable generators both offer their electricity. In these markets, there is only one client interested in vRE power forecasts, the system operator. In Europe, where the vRE has to be sold at the spot market, the trader is in need of day-ahead and intraday forecasts, whereas the system operator needs grid node forecasts including region forecasts. Moreover, real-time estimations are being used by traders as well as system operators.

There are different approaches in how markets deal with the accuracy of forecasts. Whereas in Europe, the traders have to pay for balance energy in case of imbalances in their balancing groups, India e.g. tries to implement a sharp quality criterion, but this only gives incentives to meet the quality criterion, not to integrate vRE into grids and markets.

Another conclusion is that regional forecasts lead to better results than single plant forecasts because of regional smoothing effects.

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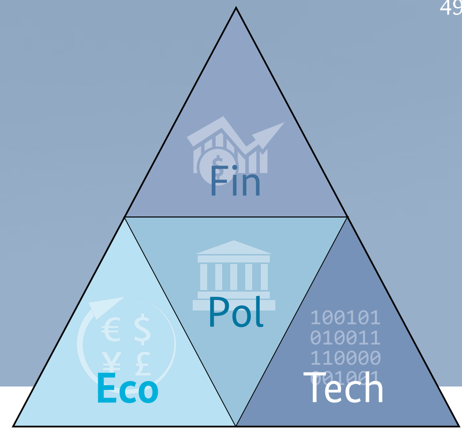

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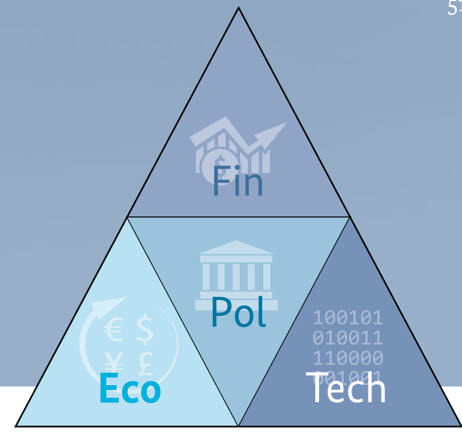

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