VARIABILITY AND PREDICTABILITY OF LARGE-SCALE WIND POWER

Wind power generation fluctuates because of continually changing wind speeds. Accurate forecasting models are required for successfully integrating such fluctuating generation into the grid and market. Aggregating many wind power plants will smooth variability to a certain extent, which will also improve predictability. Wind power forecasting has already achieved a high level of accuracy, and further improvements are becoming increasingly smaller. However, there is promising research focused on integrating forecast uncertainty into operational planning processes.

How much variability is there in wind power?

A single wind turbine may shut down from full power in seconds and start up very quickly during high winds. However, the aggregated output from a wind farm (which could comprise tens to hundreds wind turbines), or from tens to hundreds of wind farms will fluctuate more smoothly (Figure 1). Especially high-resolution variability, such as changes within an hour, is smoothed out. Lower resolution variability, such as daily changes, remains significant even over larger areas.

The variability of large-scale wind power depends on the wind resource variability and the dispersion of wind power plants within the area. Generally, the hourly step changes from large-scale wind power are usually within ±10% of the installed capacity—in larger areas, even within ±5%. This means that with 50 GW of wind power, the changes could be about 5 GW in one hour. This should be compared with changes in electricity consumption. For a power system that has a peak load of 45 GW (such as in Spain), consumption can change by more than 3 GW in an hour, typically once a day. However, consumption variation is usually more predictable than wind power variation.

In extreme situations, the change from one hour to another can be more than 30% of installed wind power. This is particularly relevant for offshore wind energy, where a lot of wind power is installed in a relatively small area. The most extreme case is a storm, where wind speeds cause wind turbines to shut down from full power to protect their structures. Modern turbines can manage wind speeds up to around 30–32 m/s and have controlled shutdowns to mitigate ramps.

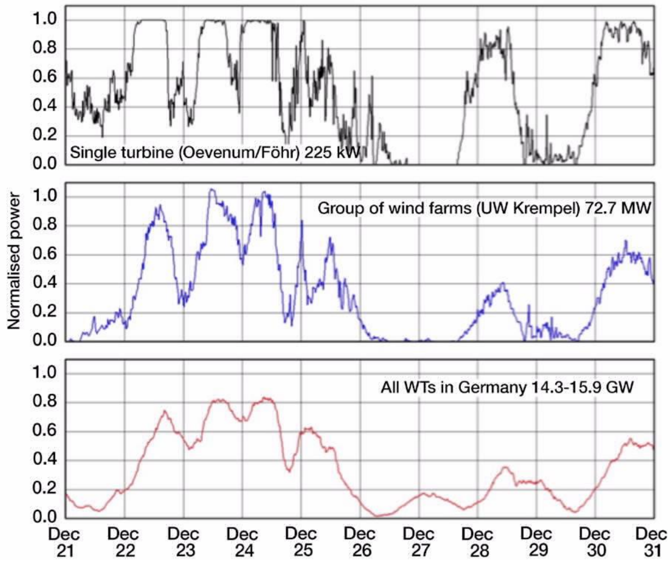

Figure 1. *Aggregated generation from multiple wind power plants is a smoother curve than that of a single turbine. As seen in the middle plot, wind power generation in a small area can sometimes exceed the installed capacity. (Holttinen et al., 2021).*

On the other hand, storm fronts usually take several hours to pass through a region covering several hundreds of kilometers. For large-scale wind power, this will result in a decrease in total power output lasting for 2–6 hours. Such severe storms do not occur every year in all countries, but in storm-prone areas, there can be several storms in one year.

A suitable grid congestion management system and adequate transmission capacity are required to benefit from the spatial smoothing of wind power variability.

How accurately can wind power generation be forecasted?

Wind energy forecasting has been evolving since the 1990s. For shorter forecast horizons, the accuracy improves due to the use of current observation data. To predict wind power for more than a few hours ahead, wind speed forecasts from weather prediction models are used. The use of accurate data in combination with artificial intelligence methods has led to significant progress, achieving a high level of accuracy. Significant errors can still occur occasionally in the output level and timing of wind squalls—for example, predicting that winds will start blowing at 10 am when they actually start at noon. Low pressure areas often lead to major errors due to their difficult predictability.

There is a strong aggregation benefit for wind forecasting. Aggregation of many wind power plants over a 500-km radius reduces forecasting error by about half (Figure 2).

In recent years, forecast accuracy improvements have become smaller, and a future expansion of wind and solar power could lead to an increase in the absolute forecast error. Figure 3 shows the error of wind and solar power forecast in Germany, both for the wind and solar installations in 2019–2023, up to about 160 GW, and for a 2030 scenario with wind and solar installations amounting to 360 GW. Even assuming a further 15% improvement in forecast accuracy, the absolute error will more than double in 2030.

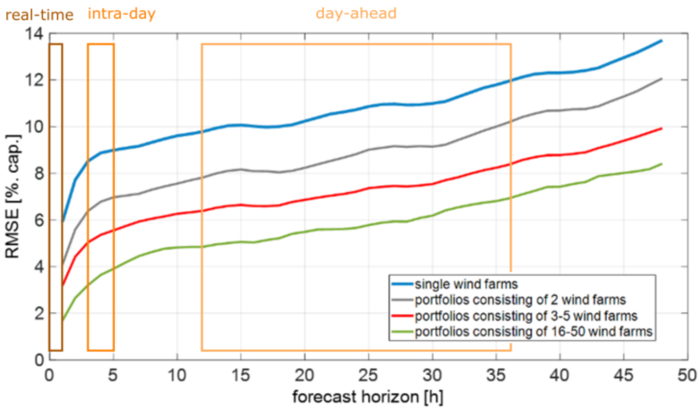

Figure 2. *The average forecast error is increasing as the time horizon increases. When wind power plants from a larger area are aggregated, the errors are smaller, in all time horizons. (Adapted from: Dobschinski, 2014)*

Today, there are already forecast systems that provide additional information about the forecast uncertainty. These forecasts can also warn of the possibility of extreme forecast errors that may impact power system stability.

Associated publications

- Kiviluoma, J. et al. (2016). **Variability in large-scale wind power generation**. Wind Energy, 19(9), 1649–1665. https://doi.org/10.1002/we.1942
- Murcia Leon, J.P. et al. (2021). **Power Fluctuations In High Installation Density Offshore Wind Fleets**. Wind Energy Science, 6, 461–476. https://doi.org/10.5194/wes-6-461-2021
- Holttinen, H. et al. (2021). **Design and operation of energy systems with large amounts of variable generation**. Final summary report, IEA WIND TCP Task 25. https://doi.org/10.32040/2242-122X.2021.T396
- Dobschinski, J. (2014). **How good is my forecast? Comparability of wind power forecast errors**. 13th Wind Integration Workshop, Berlin.
- Siefert, M. et al. (2024). **Forecast errors in wind and PV generation for 2030 – analysis and outlook**. 6th symposium on energy meteorology, Kloster Banz, Germany

More information

This Fact Sheet draws from the work of IEA Wind TCP Task 25, a research collaboration among 17 countries. The vision in the start of this network was to provide information to facilitate the highest economically feasible wind energy share within electricity power systems worldwide. IEA Wind TCP Task 25 has since broadened its focus to analyze and further develop the methodology to assess the impact of wind and solar power on power and energy systems.

See our website at

https://iea-wind.org/task25/

See also other fact sheets

Storage for Power Systems
How Do We Ensure Long-Term Reliability of Future Power Systems?
Balancing Power Systems with Large Shares of Wind and Solar Energy
Wind and Solar Integration Issues
IEA Wind Task 51 Forecasting for the Weather Driven Energy System: https://iea-wind.org/task51/

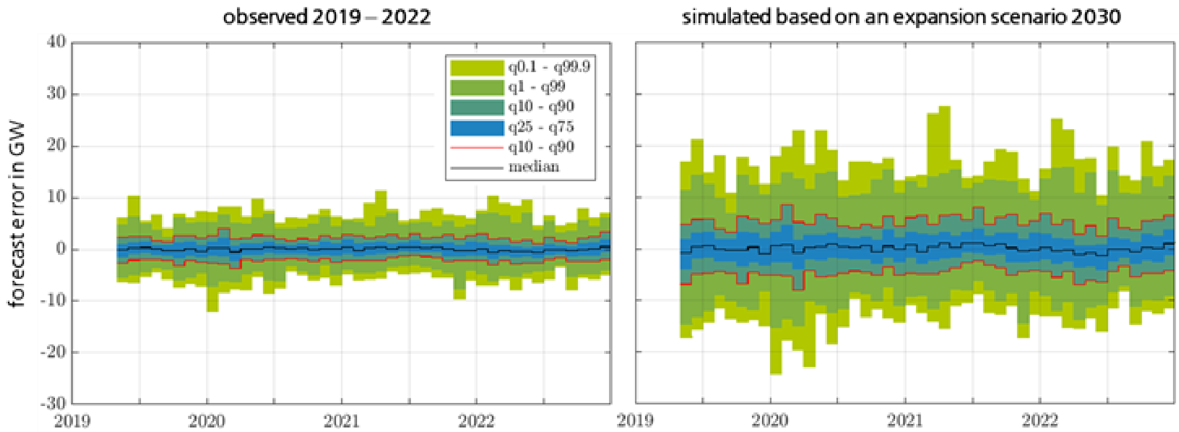

Figure 3. *Absolute forecast errors become larger as wind and solar shares grow. The day-ahead forecast errors for aggregated wind and solar power in Germany are shown in the form of monthly error distributions, represented by quantiles and medians. (Siefert et al., 2024).*