WIND AND SOLAR INTEGRATION ISSUES

Wind and solar power plants, like all new generation facilities, will need to be integrated into the electrical power system. This fact sheet addresses concerns about how power system adequacy, security, efficiency, and the ability to balance the generation (supply) and consumption (demand) are affected by wind and solar power production.

How is wind and solar power different from other generation?

The main characteristics that differentiate wind and solar power from other forms of generation are their variability, uncertainty, and the technical differences in grid connection. Depending on resource, the location may also be constrained to sites far from demand centres.

- Unlike many conventional power plants—which can be turned on and off, as well as up and down as needed—wind and solar generation varies based on wind and sunlight. However, variations in output smooth out when many wind and solar power plants are aggregated over a wide area (Figure 1).
- To deal with uncertainty, wind and solar generation can be forecast minutes to even days ahead, with short-term forecasts obviously being more accurate. Aggregating power plants over a larger area improves forecast accuracy at all time frames.
- Wind and solar power plants are typically connected to the grid through power converters, which changes the dynamic behaviour of power systems.

See Fact Sheet: Variability and Predictability of Large-Scale Wind Power

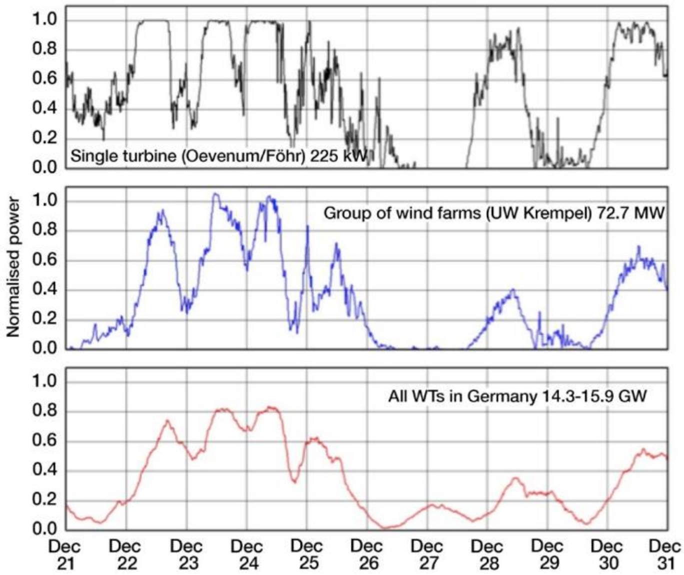


Figure 1. *Short-term power output variations of a single turbine (top) smooth out when aggregated with a group of wind power plants (middle), and even more when aggregated over a country (bottom). Wind generation in a small area can sometimes exceed the installed capacity, as seen in the middle plot. (Source: Holttinen et al., 2021).*

How is wind and solar plant output balanced?

Power systems experience varying electricity consumption, varying wind and solar power output, as well as failures that cause power plants to go off line. All these need to be balanced, and they are balanced together.

- To balance the variations in demand and supply, the output of some power plants and some demand can be adjusted (Figure 2).
- To manage expected changes in system demand and wind and solar output, power plants are scheduled in advance to meet forecasts of demand, wind and solar, reserving capacity for unexpected real-time changes.
- Power plants are fine-tuned closer to real-time, and operating reserves—from generation or demand response—are finally used to maintain system balance.
- System operators manage imbalances at the system level, with all imbalances between supply and demand aggregated, rather than focusing on individual sources.

See Fact Sheet: Balancing Power Systems with Large Shares of Wind and Solar Energy

Which technologies can provide flexibility and thus help manage variability?

The ability of a power system to manage the variability and uncertainty of demand and supply across all relevant timescales is called flexibility.

- Flexibility can be provided from many grid elements, including smaller and larger power plants, storage systems, and demand side resources.
- Through sector coupling, flexibility can be provided from the heating, transport and industry sectors.
- Flexibility can also be shared between neighbouring areas or countries via interconnectors.
- In today's power systems the available flexibility is often (much) higher than what is actually required. However, increased flexibility is important for power systems anticipating large wind and solar shares. Modified operational practices can achieve more flexibility from existing assets (Figure 3).

See Fact Sheet: Flexibility for Power Systems

See Fact Sheet: Flexibility Through Electrification

Do wind and solar power need dedicated back-up or storage?

Since power systems are balanced at system level, dedicated back-up or storage should not be allocated to any single source of variability.

- Introducing back-up or storage, only for wind or solar, would be inefficient, and an unnecessarily costly utilisation of installed resources.
- Storage is most economical when operated to maximise the economic benefit of an entire system.
- The most economical size and duration of storage varies depending on wind, solar and demand patterns. In summer-peaking systems, solar pairs well with 4-hour storage. During extended low-wind and low-solar periods, longer-duration storage helps maintain energy supply.

See Fact Sheet: Storage for Power Systems

Does it make sense to curtail wind power production?

Curtailment of wind and solar may occur when there is excess energy and low demand or when there are network constraints. While it may seem inefficient, curtailment can actually make wind and solar more flexible, enabling larger shares of them in the energy mix.

- Alternatives for curtailment include reducing conventional power output, exporting energy, activating demand response and utilising storage. If these options are costly or have been exhausted, curtailment helps manage surplus energy.
- Curtailment also allows wind and solar to provide upward reserves, using curtailed energy for valuable system services.

See Fact Sheet: Wind and Solar Energy Curtailment

How do we ensure that there is enough supply to meet firm demand when wind and solar output is low?

Power systems need to plan for resource adequacy, that is, being able to meet firm demand during stressful periods.

- All power plants have a possibility of failure and may face limitations due to extreme weather or fuel supply, for example.
- Wind and solar power plants are not likely to fail all at once. However, there is risk of very low wind and sun during high demand, even with aggregated supply from many wind and solar power plants dispersed over a large region.
- Resource adequacy can be provided by generation and storage, but also by reducing demand and through transmission to neighbouring regions.

See Fact Sheet: How Do We Ensure Long-Term Reliability of Future Power Systems?

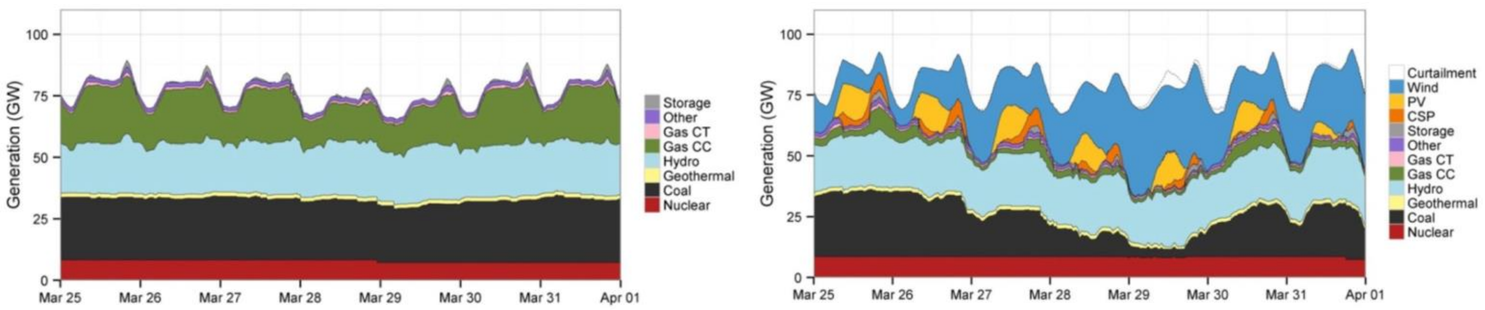
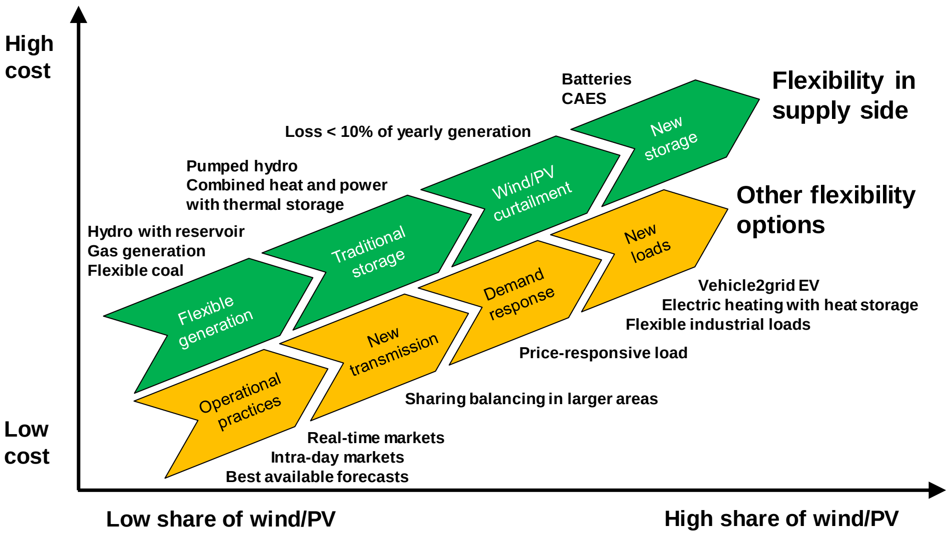


Figure 2. *High wind and solar power generation will alter the contribution of more stable generation of conventional power plants, especially coal (in black) and gas-fired generation (in green), when compared to a case of no wind and solar. The example here is for the US Western Interconnect over one week for no wind or solar (left) and for high wind and solar (right). (Source: WWSIS2, 2013, https://www.nrel.gov/docs/fy13osti/55588.pdf)*

Figure 3. *Methods to increase flexibility in power systems. (The relative order of options is illustrative only).*



Do wind and solar power cause extra emissions?

The primary value of wind and solar energy is to offset fuel consumption and the resulting emissions, including carbon dioxide (CO_2).

- Each megawatt-hour (MWh) generated by wind and solar reduces the required operation of fuel-consuming power plants, and thus, their emissions.
- At high wind and solar shares, fuel-consuming power plants will experience more start-ups and shut-downs, steeper ramps and more operation below full load to balance variations in wind and solar generation and demand. This reduces their efficiency and leads to potentially higher CO_2 and other emissions from fossil fuel plants.
- However, these extra emissions from balancing wind and solar energy with fuel-consuming power plants are very small, estimated to be less than 2% of the overall emission reductions achieved by lowering fossil fuel power generation. (Figure 4).

See Fact Sheet: Emission Impacts of Wind Power

How do wind and solar change prices in electricity markets?

Wind and solar plants have near-zero marginal costs since they are weather driven without inherent energy storage. Due to this, they will be dispatched first.

- This pushes more expensive generators out of the market, lowering electricity prices on average. If there is more wind and solar generation available than needed by the consumers, prices will momentarily drop to near zero or below, as generation needs to be curtailed.
- Over time, lower prices encourage increased demand, and high price variations encourage investment in energy storage and flexible demand solutions. More demand will push prices up and flexible demand will decrease price variability.

See Fact Sheet: Electricity Market Impacts of Wind and Solar

How much new transmission investment is needed for wind and solar?

The need for new grid investment for wind and solar depends on the location of the power plants and the strength and characteristics of the existing grid.

- Any new power plant and larger demand usually requires a new line to connect it to the existing power grid. Moreover, both distributed and centralised power plants can increase transmission upgrade needs.
- Recent studies estimate a doubling or even tripling of the transmission system to support the clean energy transition and electrification. Transmission is essential to connect distant electricity sources and demand centres and to harvest differences in weather patterns.
- The upgraded network will benefit the entire power system. Hence, transmission cost is not normally allocated to a single power plant or technology.
- Overall, transmission is only a small fraction of the total energy price for consumers.

See Fact Sheet: Impact of Wind and Solar on Transmission Upgrade Needs

Compound Emitted	Emission Reduction Due to Renewables	Cycling Impact
CO_2	260 – 300 million lbs 29%–34%	Negligible Impact
NO_x	170 – 230 million lbs 16%–22%	3–4 million lbs
SO_2	80 – 140 million lbs 14%–24%	3–4 million lbs

Figure 4. *The increase in fuel consuming plant emissions from cycling to accommodate variable renewables is very low compared to the overall reduction in CO_2, NO_x, and SO_2 due to adding renewables. (Source: WWSIS2, 2013, https://www.nrel.gov/docs/fy13osti/57874.pdf) (1 million lbs = .45 million kg).*

How do wind and solar impact the dynamics of a power system?

The dynamic behaviour of a power system is dependent on the dynamic performance of its components, including generators, loads and transmission devices. The dynamic behaviour can be stable or unstable as more wind and solar is added.

- Power systems must stay stable in different power flow situations as well as during and after faults or sudden disconnection of generation or demand. An unstable system can lead to a costly blackout.
- Wind and solar power are not a likely cause of system disturbances, but their hardware and control software can complicate situations caused by faults.
- Stability is generally easier to maintain in larger, interconnected systems, though weaker areas can still face challenges. Stability concerns become more pronounced when wind and solar supply over 50% of the system demand instantaneously.
- Wind and solar power plants can help support system voltage and frequency during power system disturbances with control capabilities that are important and still evolving.
- Models and tools are continually evolving to manage periods when wind and solar dominate the supply.

See Fact Sheet: Impacts of Wind and Solar Power on Power System Stability

Is there a limit to how much wind and solar capacity can be accommodated by the grid?

By 2022, several countries have already seen wind power contribution exceeding 20% of electricity consumption annually, with Denmark reaching even a 58% share. Ambitious targets for wind and solar are seen in many countries.

- High instantaneous wind and solar contributions are technically and economically feasible. Countries like Ireland, Denmark and Portugal sometimes see over 100% contribution from wind generation—and manage this through exports. While Denmark and Portugal are part of larger synchronous systems, Ireland is a small-sized system where all changes occur more quickly, making system operation more challenging.
- With current technology, there is a limit on how much generation can come from wind, solar and batteries at any instant, as systems require some part of the generation to be from synchronously connected generators. As systems move towards net-zero carbon emissions, achieving 100% renewable operation will require some wind and solar plants to have "grid-forming" and blackstart capabilities, traditionally provided by conventional generators.

See also ESIG Guide on Grid Reliability Under High Levels of Renewables https://www.esig.energy/esig-101/

Can lessons learned in countries using wind and solar power be transferred to power systems in other countries?

The short answer is “somewhat.”

- Power systems worldwide differ in their generation mix, demand variability, grid strength, and the rules and strategies practiced in daily operations.
- Experience and studies conducted so far conclude that for smaller wind and solar shares, some basic measures are relevant:
  - Accurate forecasting of wind and solar power is important for power plant operational decisions.
  - System operators should monitor the generation of wind and solar plants in control rooms.
  - Grid connection rules for wind and solar power plants should require sufficient system support.
- For larger shares of wind and solar, grid studies should be conducted to understand relevant technical issues. For most systems, integrating more than a 20% share of annual demand from wind and solar will require new tools for planning and operational practices.

Associated publications

- 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
- **Greening the Grid Fact sheets** available at: https://greeningthegrid.org/Grid-Integration-Toolkit
- Milligan, M., et al. (2009) “**Wind power myths debunked**.” IEEE Power & Energy Magazine, vol. 7, 6, ss. 89–99. DOI: 10.1109/MPE.2009.934268. https://www.researchgate.net/publication/38289316_Preface_Wind_Power_Myths_Debunked
- International Energy Agency (2017) **Getting wind and sun onto the grid**. IEA, Paris, https://www.iea.org/reports/getting-wind-and-solar-onto-the-grid
- International Energy Agency (2024) **Integrating Solar and Wind: Global experience and emerging challenges**. IEA, Paris. https://www.iea.org/reports/integrating-solar-and-wind
- **WWSIS Western Wind and Solar Integration Study 1-3**. https://www.nrel.gov/grid/wwsis.html

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/