Many studies have demonstrated the technical feasibility of meeting the majority\(^1,2\) or even all\(^3,4\) electricity demand with renewable energy resources. However, renewable energy generators, such as wind turbines and solar photovoltaics, introduce different grid management challenges than power generated with nuclear and fossil fuels. Currently, the grid currently must be sufficiently flexible to respond to unexpected fluctuations in energy demand. Using wind and solar based energy technologies, however, requires that the grid be flexible enough to respond to variability in energy supply because we cannot choose when they generate electricity. Some of this variability is predictable and some more uncertain, as described below.

**Seasonal variability**

Some renewable energy resources have seasonal peaks. Solar, for example, produces the most electricity in the summer, while hydro-electric power peaks with the spring snow melt.\(^5\)

**Daily variability**

Solar photovoltaics produce electricity on a predictable daily cycle during daylight hours. Wind energy often also follows certain daily patterns, but these are much less predictable.

**Short-term variability**

Wind turbine output, based on wind speed, can change rapidly over seconds or more slowly over the course of hours. Solar panel generation can also unpredictably drop in seconds if a cloud passes overhead.

**Solar variability and ramp rates**

Changes in electricity output from variable renewables may result in a need for rapid ramping of dispatchable resources. For example, when the sun sets, generation must ramp up quickly to replace solar power that moves offline. Figure 1 shows the daily net load curve for California - the amount of generation required to meet demand. The plot illustrates the impact of increasing rates of rooftop solar: additional daytime generation requirements drop as rooftop solar increases, and thus, the ramp rate at sunset increases. High levels of solar penetration have resulted in a duck-shaped net load in some areas, nicknamed “the duck curve”.\(^6\)

**Strategies for integration**

In this section we describe a few strategies for ensuring that variable renewables resources can reliably meet demand.

**Energy storage**

Energy storage, like batteries or pumped hydropower, can help to mitigate the variability of renewables by storing electricity when there is too much - such as during the midday peak in solar - and discharging the energy when the demand is greater than electricity generated (Figure 2). Storage can be used to smooth shorter fluctuations in output caused by passing clouds or sudden changes in wind and smooth ramp rates as well.\(^7,8\)
**Integration of many types of renewable resources**

The integration of different types of renewables can help to smooth out the variability from a single source. As an example, Figure 3 shows the different roles played by renewables on a California day in April 2012. Geothermal and biomass resources provide constant baseload generation. Solar and wind each peak at different parts of the day (and year), but hydropower can be dispatched at different rates to compensate for some of these changes in output. Meeting all demand may also require an excess of installed renewable capacity.

![Figure 3: Renewable generation in California on an April day](image)

**Integration across a wide geographic area**

Numerous studies have illustrated that connecting generation distributed across a large geographical area reduces the variability of generation from wind and solar. Demand response programs allow grid operators to control certain types of customer electricity use, like air conditioning, to better match generation and demand. If variability from renewables causes a drop in generation, demand response lets some demand to be lifted until generation increases again.

**The integration of many types of renewable energy resources with energy storage and demand response in a smart grid can provide the flexibility needed to create a reliable low-carbon power supply.**

**References**