andlinger center
for energy+the environment

Scope: This article emphasizes the limitations on grid performance created by unpredictable resources. For the full set of articles as well as information about the contributing authors, please visit http://acee.princeton.edu/distillates.

Article 5: Storage for grid reliability under variability and uncertainty

The purpose of storage is to manage the mismatch between supply and demand. Systems today exhibit demand that varies predictably with time of day and temperature. When a generation system can be adjusted to meet these variations, we say that it is *dispatchable*. Generation from natural gas (and, to a lesser extent, from coal and hydroelectric sources) is dispatchable, while generation from wind and solar is not.

The transition to higher penetrations of wind and solar energy introduces the need to work with generation that cannot be controlled. However, it is particularly important to distinguish between *predictable variability* and *uncertainty*.

Predictable variability includes hour-of-day patterns, forecastable weather patterns, planned generator outages, and human-driven events such as the behavior at half time of those watching the Superbowl on TV.

Uncertainty comes in several forms, including unexpected weather events that differ from the forecast, rare or infrequent events such as equipment failures or storm-related outages, spikes in real-time electricity prices, and erratic behavior by consumers. Quantitatively, unexpectedly high or low outdoor temperatures can produce variations in electricity consumption of around five percent relative to the demand that the utility had planned for the day before. Grid operators have learned to deal with these uncertainties, which are today the dominant effect of normal weather on the supply-demand balance. But where wind and solar energy contribute as much as 20 percent of total electricity supply, another effect will become more important than the effect of poorly predicted temperature, namely an unexpectedly windy or calm day, or an unexpectedly sunny or cloudy day. The contribution of wind energy, in particular, can drop all the way to zero in a broad geographical region on days when a full contribution had been expected, forcing the grid operator to replace the wind with other forms of generation.

A very common error in studies of renewable generation is the mistake of assuming you can predict the future. These studies recall the famous line from Will Rogers: *Don't gamble; take all your savings and buy some good stock and hold it till it goes up, then sell it. If it don't go up, don't buy it.* While we recognize that we can't buy stocks that are guaranteed to go up, this is a surprisingly common error in energy systems modeling.

Variability versus uncertainty

Figure 5.1 illustrates the difference between predictable variation and uncertainty. It shows five days of energy collection from a large solar array at Princeton University. Output on Thursday and Friday (very sunny) and on Monday and Tuesday (very cloudy) is easy to predict. Much more difficult are mixed cloudy days like Wednesday, where patches of clouds dramatically reduce energy generation for short periods of time. Such variations represent a challenge to the stable and reliable operation of the electricity grid.

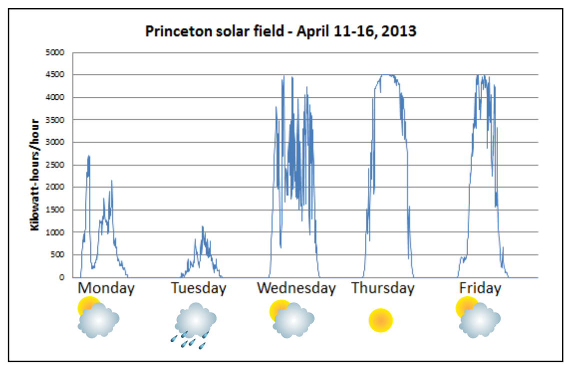

Figure 5.1 Energy from the Princeton solar field.

Figure 5.2 shows the electricity generated during one week of July, 2013, by all the wind farms on the PJM grid at that time, The Figure shows both the forecasted wind (in black) and the actual wind (in pink). Neither the strongest nor the weakest winds were forecasted accurately. If the forecast were to come true exactly, we could use virtually all of the wind, despite the variability. Day-ahead forecast errors limit our ability to use less-expensive energy from steam, but even hour-ahead errors are significant, forcing us to schedule reserve capacity that can respond quickly to variations.

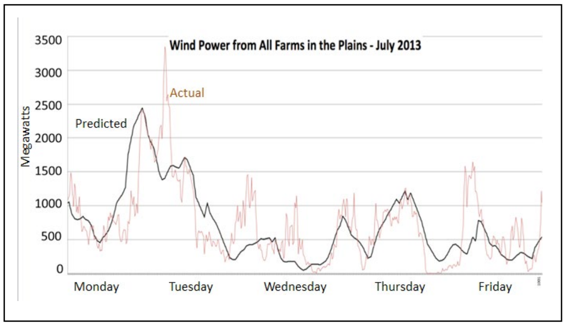

Figure 5.2 shows the total electricity generated in one week of July 2013 by all the wind farms that were on the PJM grid at that time – actual (pink) and forecasted (black).

Working with predictable variability

If we could remove all forms of uncertainty, powerful optimization algorithms (used by most grid operators) could match almost any load pattern with a large number of dispatchable generators (nuclear, steam, gas turbines), even in the presence of variable wind and solar energy sources. The problem is not unlike creating a wall from a pile of stones of many sizes (Figure 5.3).

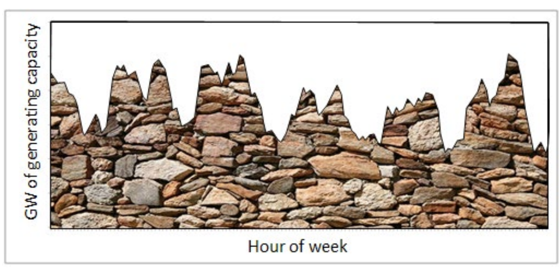

Figure 5.3 If we can perfectly forecast loads, we can plan a set of generators to meet demand just like building a wall from a set of stones.

However, the capacity to manage uncertainty in today's grids is limited by the realities of advance notification requirements, which range from instantaneous to a year or more. The examples below have a very wide range of time horizons:

> An alternating current (AC) power grid will react instantaneously to small, unexpected deviations (several percent) much as an air-filled tire will absorb small variations in a road surface. An AC grid will stretch to cover voltage deviations of a few percent, which can amount to several gigawatts on PJM Interconnection, a regional transmission organization serving the mid-Atlantic states out to Chicago.
>
> Automatic generator controllers (AGC) will tune different types of generators (including steam turbines) up or down based on signals that arrive every two to four seconds.
>
> Economic dispatch procedures will adjust generators up or down once every five to 15 minutes (without turning anything on or off).
>
> PJM's intermediate scheduling process will turn gas turbines on and off. It is run every 30 minutes with a horizon of approximately 45 minutes.
>
> Customers that have signed up to adjust their loads on demand typically require two to four hours of notice. Some demand response systems are much faster, but these are less popular.
>
> In anticipation of a peak load that the grid cannot meet (say, at 3 p.m. on a summer day), the grid operator needs to plan eight to 16 hours ahead to assure that storage or other resources are located where they can be used to meet this peak.
>
> Operation of steam generators is typically planned 12 to 36 hours into the future.
>
> Scheduled maintenance of a nuclear power plant is planned at least a year in advance.
>
> New generation capacity is planned with a two- to 10-year horizon.

Both the variation in notification times and the range of lags between when a decision is made and when it goes into effect create complex interactions that play a major role in the ability of a grid operator to deal with uncertainty. One value of storage is that it does not require advance notification, but the marginal value of storage has to be compared against the ability of the system to handle variability without storage.

Managing a portfolio

It is essential to recognize that electricity generation and storage must be managed as a portfolio. The value of each type of storage has to be measured in terms of how it interacts with all the other types of generation. This is particularly important on a larger grid, which emphasizes the value of a network. Microgrids, where a building or campus operates independently, limit the ability to coordinate different types of generation. A residence trying to run entirely off a solar array requires a very large storage device to accommodate the lack of sun at night and during cloudy days. These variations are easier to manage when the residence is part of a larger grid.

Access to the grid, with its ability to tap an array of generators, usually reduces total system costs, and moderate penetration of distributed generation can be handled using existing mechanisms for managing variability, including storage. However, high penetration of distributed generation introduces formidable challenges related to impact on power quality, the ability of grid operators to meet loads, and the economic viability of the traditional electric utility.

But they can do it, so why can't we?

It is common to hear people talk about how a particular country (such as Denmark or Spain), or a particular state (such as Iowa or South Dakota) is generating a high percentage of its energy from wind. Wind (and solar) are variable ("intermittent") resources and inevitably require backup generation to handle periods when the intermittent resource is not available. Denmark, which is roughly the size of northern New Jersey, draws power from Norway and Sweden, with their large hydroelectric resources whose output can be varied. Maine and South Dakota are small regions in a larger grid that can easily export excess wind to the rest of the grid, and import energy when the renewable resource is not available. New England has access to energy from Hydro-Québec, which manages generous hydroelectric resources. PJM's limited access to hydroelectric power will complicate its ability to manage high penetrations of wind and solar power.