Article 8: Managing a Grid when Variable Wind is Prominent

As wind becomes a more prominent contributor to electricity supply, its variability complicates grid operation on ranges of timescales, from seconds to days to months. The duration of the mismatch between supply and demand (the length of the lull) determines the optimal response, which is some mix of flexible power from other sources, access to more distant winds, energy storage, and demand-side management. Prominent wind power also creates requirements for wind turbines to be able to help reduce the consequences of unforeseen grid disruptions; wind turbines are becoming increasingly helpful.

8.1 The Grid Before Wind

An electricity grid consists of many individual generators of electricity, connected via power lines to consumers. Most of the power is generated by large units (coal and gas plants, hydroelectric power plants, and nuclear power plants), most of them having typical installed capacities in the hundreds of megawatts or larger. These unit capacities are hundreds of times larger than our reference three-megawatt wind turbine, but comparable in capacity to the larger wind farms.

All present-day electricity systems share a common requirement: at every instant, electricity demand from consumers must be met with an equal supply from generators. Very little electricity is stored from one instant to the next. Electricity demand is inherently variable. The time of day, the weather, and the season all impact the quantity of electricity that consumers demand. A century of experience has shown that grids can be operated successfully, even though there is significant demand variability at every time scale.

The introduction of wind power (and solar power) into the grid complicates the supply-demand balancing. Now, not only does demand vary, but available supply does too. The same strategies that enable a reliable grid in the face of variable demand become even more important.

The electricity market of the State of Texas presents a helpful example, to which we refer three times in this article. Texas is the only one of the 48 contiguous U.S. states which has its own electricity grid, largely isolated from two much larger grids that connect the other states.[1] As a measure of its isolation, the external interconnection capacity of the Texas grid is equal to just 1.4 percent of the total capacity of its energy generators [1, 2]. Figure 8.1 shows typical patterns of total electricity demand over a late-March week in 2017 and over that entire year. Hourly consumption during that week (and probably all weeks) is greater during the day than at night. The variation in demand over a year shows the expected summer peak in warm climates due to high demand from air conditioners. Much of this variability

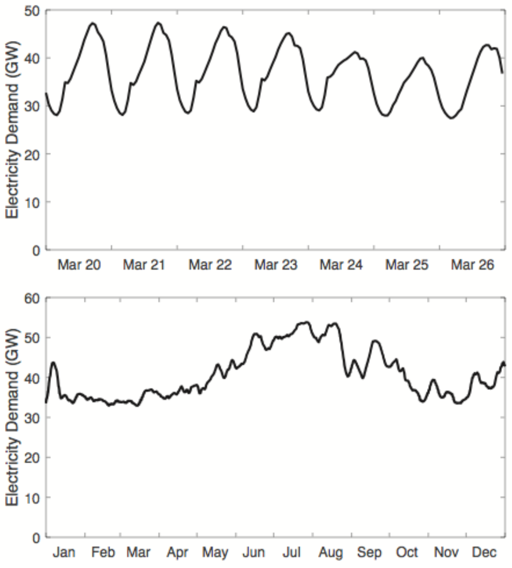

Figure 8.1: Electricity demand in Texas on two different time scales. 1 GW is 1,000 megawatts. *Top:* Hourly demand during one week, from March 20-26, 2017. *Bottom:* Demand for all of 2017, shown as a 168-hour (one-week) running average of hourly data. Data source: [3].

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[1] For simplification, we refer frequently in this article to Texas data, when the data are actually from the service area of the Electric Reliability Council of Texas (ERCOT), which includes nearly all of Texas. ERCOT manages about 90 percent of the Texas electricity market.

can be accurately predicted based on a combination of historical data and weather forecasting. The annual data also show two weather-driven features: 1) a short period of high demand associated with a cold snap in January 2017, and 2) an abrupt drop in demand in August 2017 associated with Hurricane Harvey, which knocked out much of the electricity grid along the Gulf Coast.

8.2 Integrating Variable Wind

To illustrate the potential for mismatches between variable supply and variable demand, we return to Texas. The Texas grid has the highest installed wind capacity of any state: at the end of 2017, 21,000 megawatts were installed [3]. Wind turbines produced 17 percent of the state's electricity, and natural gas power plants produced 39 percent [4].

Figure 8.2, top panel, repeats the curve in the top panel of Figure 8.1 that shows Texas electricity demand during a week in March 2017. The same panel shows, as well, wind power production during that week. Wind power supplied about one quarter (28 percent) of total electricity generation that week [4]; production was well below total demand all week, and wind output did not align with detailed consumption very well.

The bottom panel of Figure 8.2 shows a counterfactual case where Texas experiences the same pattern of wind power production across the week, but the amount of power is multiplied uniformly by a number (a little less than 4), chosen so that the week's total wind power equals the week's total demand. The week contains four periods of extra wind that alternate with four periods where wind power is insufficient.

Imagine that all of the excess wind power in the idealized energy system were stored and then used during the times of under-supply. The wind power input would meet demand exactly throughout the week. To be sure, this result requires the storage system to operate with no energy losses; in fact, there are always energy losses whenever a storage system acquires or discharges energy. For an energy system that even slightly resembles the one shown in Figure 8.2 in its prospective periods of excess and shortfall in energy supply, energy storage would be only one of many strategies to rebalance the system.

Two countries where wind power already accounts for a large fraction of annual electricity production are Ireland (21 percent in 2016 [5]) and Denmark (44 percent in 2017 [6]). Like Texas, the Ireland grid is relatively isolated, with only a 9 percent interconnection capacity [7]. Also like Texas, Ireland achieves wind integration primarily with natural gas, which accounts for about 44 percent of Ireland's electricity [8]. Denmark, by contrast, has relatively little gas generation to balance its high penetration of wind; its second largest electricity source is coal, which provides 25 percent of its electricity [9].

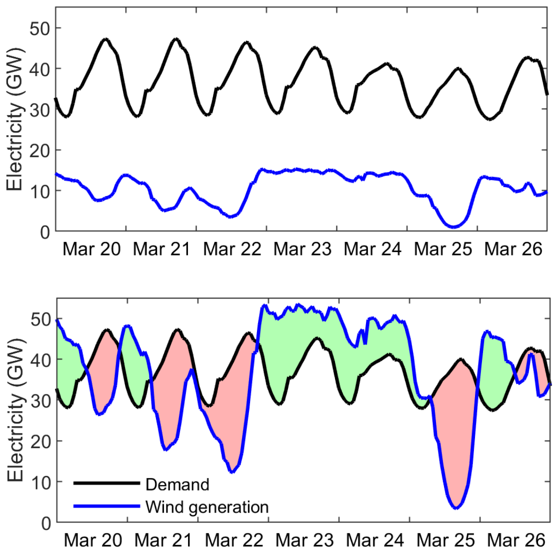

Figure 8.2: ***Top:*** **Actual electricity demand and wind generation in Texas, March 20-26, 2017 [3].** ***Bottom:*** **Wind capacity, rescaled to create the counterfactual situation where the total wind generation that week equals the total electricity demand, and no other changes are made. Green and red shaded areas represent excess wind and a deficit of wind, respectively.**

Denmark's principal strategy for handling its lows and highs in wind-powered electricity is to use its strong interconnections with the electricity grids of surrounding countries, including the much larger German grid to the south and the flexible hydropower assets of Norway to the north. Its total interconnection capacity is 44 percent of the country's total installed electric capacity [7]. Wind generation in Denmark can exceed 100 percent of its total in-country demand during high-wind periods without creating problems for its grid.

Grid Flexibility

The principal way a current grid deals with threatened mismatches between supply and demand, when the mismatch is for short times (from seconds to hours), is to call on sources of electricity that can ramp their power production up and down quickly. Gas turbines (which are much like airplane engines) are suited for this assignment, "load-following," as are hydropower facilities in many cases. Batteries are also helping with load balancing, more and more as their costs fall.

A traditional fossil-fuel power plant experiences substantial extra costs when its output power varies often: its operating lifetime and its efficiency decrease, and it requires increased maintenance. Demands for operational flexibility are harder on older ("legacy") coal and natural gas plants than the new natural gas plants being added to grids, whose designs, to a greater degree, anticipate frequent calls for changes in output [10, 11, 12]. Looking ahead to grids with incentives to lower their carbon dioxide emissions, a successor

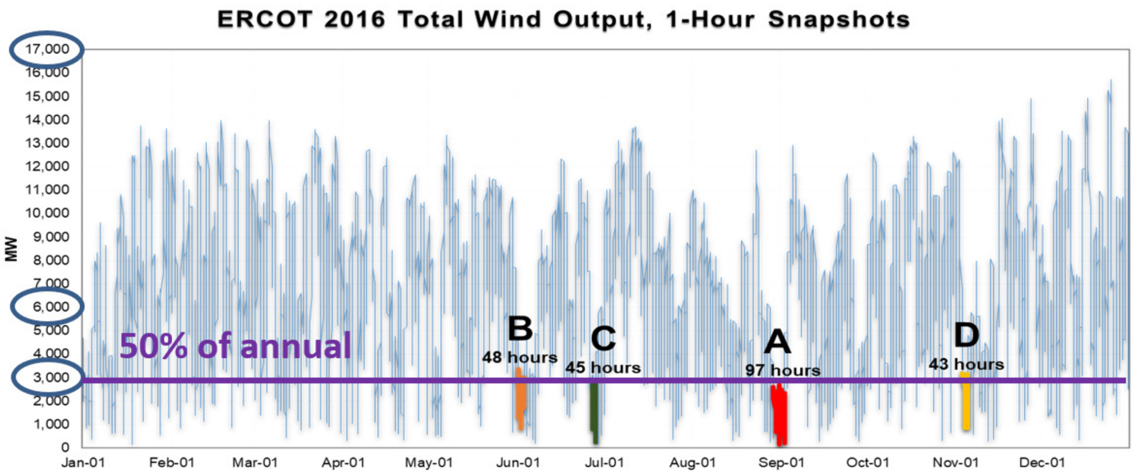

Figure 8.3: Hourly total electricity production from the wind farms in the ERCOT service area in 2016. Three values are identified on the vertical axis: 17,000 megawatts is the total capacity of the wind farms; 6,000 megawatts is the annual average wind power production; and 3,000 megawatts is half of the annual average – the threshold we have chosen for the illustrative analysis here. The four longest lulls are labeled A, B, C, and D. Source: [14].

generation of natural gas plants may arrive that capture the carbon dioxide produced when burning the fuel. The carbon dioxide, which otherwise would be emitted to the atmosphere, could be pumped into deep underground geological storage reservoirs.

When a mismatch is to be avoided and available wind power is in excess, the sale of wind power can be curtailed: the wind turbine operator would be told that not all output can be placed on the grid. The unsold power is said to be "spilled." In addition, some other electricity generators can be told to produce power only at certain hours; for example, a coal plant or a hydroelectric dam would be scheduled to run during the day but not at night.

Another strategy that can be pursued by the electricity generation system is to invest in transmission lines that access distant winds which are strong when local winds are weak, and vice versa, thereby smoothing out wind's contribution to the grid while at the same time creating a larger market. More generally, expanded transmission and distribution capability enables greater diversification across power generators; for example, it may foster the export of excess solar power from one region at midday to a second region where winds have subsided at the same time. The Competitive Renewable Energy Zone in Texas, which connects the state's major cities to sites in western Texas favorable to wind and solar generation, is an example. The costs of financing the transmission lines are borne by the state's electricity consumers; the benefit is greater diversification in electricity generation and a larger presence for wind and solar power [13].

Still another enabler of high wind penetration is more flexible electricity demand ("demand-side management"). The timing of delivery of electric power to a water heater or electric car battery, for example, can be put under the control of the grid operator. Customer buy-in is fostered when there are time-variable electricity prices and smart appliances that are programmed to benefit from these prices. It becomes profitable for all parties when a washing machine is operated on a windy day rather than a calm day, for example.

8.3 Lull Analysis and Long Lulls

An interesting way to appreciate the variability of the wind is to use "lull analysis" [14]. A lull is a period of definite duration when the wind speed is below some threshold. A lull might last from a few seconds to several days. In Figure 8.3 we return to Texas once more to demonstrate a lull analysis. Hourly wind production is shown for an entire year, 2016. At the end of 2016, the total installed wind capacity of the Texas wind farms was about 17,000 megawatts and during that year the rate of wind-power production averaged 6,000 megawatts. For this analysis, we arbitrarily select the threshold to be half the annual average value, or 3,000 megawatts, shown as a horizontal line in Figure 8.3. A lull begins when wind power output first falls below 3,000 megawatts and ends when it first ascends above that value.

Starting with the first hour of the year, we can note every hour when total wind power falls below the threshold and also note when it first crosses back to a value that exceeds the threshold. It turns out that there were 219 of these lulls in 2016. Their average duration was 9 hours, and 75 percent of them lasted less than 12 hours. Only five percent of lulls (12 lulls) lasted more than a day. (Applying the same methodology but defining a lull using the lower threshold of 1,500 megawatts, which is 25 percent of annual average power, the longest lull lasted only 20 hours.) The four longest lulls are labeled A, B, C, and D, in Figure 8.3. Event A lasted roughly four days, and events B, C, and D lasted roughly two days – a total of ten days for the four events.

Long lulls will elicit very different responses than short lulls. Batteries (as well as other storage strategies whose cost is roughly proportional to the energy they store) may compensate well for short lulls, but not for long lulls. Innovative responses to long lulls will be necessary – notably, generation technologies that are profitable even when alternating between running and not running for months at a time. One can imagine differential consumer behavior during long lulls, the counterpart to behaviors during “snow days,” when schools are closed, but more like “harvest months,” when schools are closed because children participate in bringing in the crops.

The variability of wind is a challenge that cannot be wished away. Even if wind power were free while still as variable, its ability to become a major contributor to power generation for any large region would require many forms of accommodation that are just beginning to be developed.

8.4 Grid Stability and Grid Services

Events that can disrupt the operation of the grid can occur over timescales from seconds (heavy machinery turning on or off, failure of a generator or transmission line) through hours, days, and months (power plant shutdown, routine maintenance). To minimize these vulnerabilities, the operator of a power grid takes account of specific features of each generator, such as its size, its start-up time, the maximum rates at which it can increase and decrease its output (its “ramping” rates), and its costs for electricity production. The grid operator also considers transmission constraints.

Disruptions to the grid appear as frequency or voltage reductions. Frequency reductions are caused by a generator disconnecting from the grid or a new load coming online. Voltage reductions result from electrical circuit faults. Such drops create problems for those electricity consumers requiring high-quality power.

In a minor frequency disruption, the grid frequency remains within its narrow “dead band” of permitted frequencies – departures from the reference frequency limited to roughly 0.02 cycles per second (1 part in 3,000 for a 60 cycle-per-second grid). A larger disruption results in the grid frequency falling below the bottom of the dead band.

The conventional steam and gas power plants on the grid can counter a drop in frequency or voltage in two ways. First, those that are running below maximum power output can be programed to respond automatically with additional power generation over the first few seconds, stabilizing the grid within a few minutes [15]. These power plants have deliberately held some generation capability in reserve to respond to such contingencies. Second, because their generators are all synchronized with the grid, these plants can also add power to the grid by showing down their rotating machinery. This supplementary response is even faster (it occurs over tenths of a second), but it generally has less overall effect [16].

The first wind turbines that produced grid power played little role in stabilizing the grid during a sudden and significant disruptive event. Typically, the wind turbines on a grid were immediately disconnected from it, as were other smaller, geographically dispersed (“distributed”) energy resources, like solar arrays. But, as distributed generators on the grid became more numerous, a threat to the stability of the grid emerged where all of these generators could simultaneously disconnect during a grid disruption and turn a minor event into an event with cascading impacts, where each turbine shut-down makes the grid anomaly worse. Both grid managers and the wind industry realized that wind turbines needed to be modified so that they could contribute toward minimizing the consequences of any grid disruption. Such modifications become especially important when distributed energy sources are providing a large fraction of total power, such as when winds are strong and the load is light.

Grid operators, starting in Europe, have been issuing new rules that apply to all power sources, including wind turbines. The rules essentially require every wind farm to stay online during grid disruptions and to regulate its output power to keep its characteristics within narrowly specified ranges. These requirements govern the voltage, frequency (cycles per second), and shape of the oscillations of the alternating current (AC) electricity. Wind turbine developers are responding to these new rules by equipping the turbine with new control capabilities and operating procedures [17].

A modern wind turbine counters a wayward fall in frequency with strategies that are similar to those provided by conventional power plants. To be able to provide extra power quickly on demand (the grid may request as much as an additional ten percent of its rated power), it must not already be producing power at its maximum value for that wind speed. Instead, it must deliberately produce less power than it could, thereby creating the “headroom” to respond for a call from the grid for extra power. Such headroom can be achieved by setting the pitch of the blades in normal operation slightly away from optimal or orienting the turbine slightly away from straight into the wind. Since there is a loss of revenue when operating with headroom, the wind farm must be either incentivized or required to operate in this manner [17, 18]. The most recently installed wind turbines can also contribute extra electricity to the grid to compensate for a falling frequency by using power electronics to reduce the rotational speed of the blades and other rotating components [19]. Earlier wind turbines did not have this capability.

A wind turbine with modern power electronics can also help control a grid's voltage deviations. It can support voltage stability even when the turbine is not producing power at all.

Farm-level Grid Services

Wind power can provide grid services at the level of the wind farm, not only at the level of the individual turbine. With the help of power electronics and advanced turbines, the operator of a wind farm can coordinate the outputs of each of the farm's turbines to keep the farm's total output within narrow limits and to control the rate at which total output ramps upward or downward. Consider the two-hour field test reported in Figure 8.4. Prior to the onset of the test, a 30-megawatt wind farm is operating at far below its rated power under nearly constant high winds (just above 15 meters per second) – at only 10 megawatts; this could be the result of some strict curtailment. During the first 90 minutes, the farm output's climbs upward in the same high winds back to 30 megawatts in four five-megawatt steps, each accomplished in approximately three minutes, with output tightly controlled at each step [20].

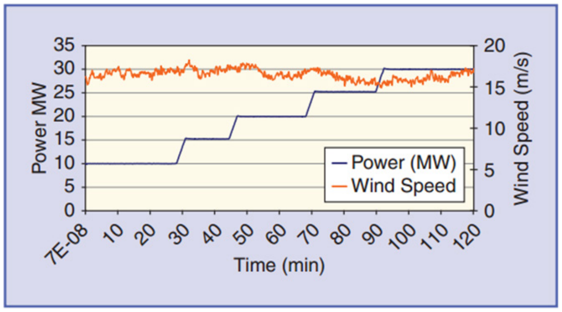

Figure 8.4: Controlled upward ramping of a wind turbine farm's output power. MW: megawatts; m/s: meters per second. Source: [20].

In short, "grid friendly" wind power is becoming the new norm.

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