Chapter 16
The Electric Grid Trembles When Wind and Solar Join the High Wire Act

If we are to have electric transportation—I'm not talking about golf carts here—we are going to have to grow the grid. To use electricity as a transportation fuel, we'll need more electricity, and perhaps a national grid. While sustaining current uses, how much supplemental transportation energy would it be possible for such a grid to support?

The grid of the future will be very different from today. Currently, 87 % of U.S. electricity generation comes from nonrenewables: 67 % fossil (natural gas and coal) and 20 % nuclear. How would that evolve to an 80–100 % renewable electric grid?

Electricity is an amazing all-you-can-eat buffet available at the flip a switch, but a wasteful one, with two-thirds of the power lost as heat from the nonrenewable thermal plants that provide 86.2 % of our electricity (Table 16.1), and another 6–10 % is lost at the power plant (other than heat loss) and over transmission lines. In the end, only 24–28 % of the power makes it to the banquet.

As you can see in Table 16.1, coal generation declined from nearly half of electricity generation in 2005 to 38.7 %, and natural gas increased from 19 to 28 %.

Where Will Tomorrow's Power Come from?

Not nuclear. U.S. nuclear power plants are old and in decline. By 2030, U.S. nuclear power generation might be the source of just 10 % of electricity, half of production now, because 38 reactors producing a third of nuclear power are past their 40-year life span, and another 33 reactors producing a third of nuclear power are over 30 years old. Although some will have their licenses extended, 37 reactors that produce half of nuclear power are at risk of closing because of economics, breakdowns, unreliability, long outages, safety, and expensive post-Fukushima retrofits (Cooper 2013).

New reactors are not being built because it takes years to get permits and $8.5–$20 billion in capital must be raised for a new 3400 MW nuclear power plant (O'Grady 2008). This is almost impossible since a safer 3400 MW gas plant can be built for $2.5 billion in half the time. What utility wants to spend billions of dollars and wait a decade before a penny of revenue and a watt of electricity is generated?

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Table 16.1 Percent of total electricity generation 2005, 2014, and 2030 (frozen at 2014 total of 4092 TWh). EIA Table 7.2a Electricity Net Generation Total 2005 and 2014. 2030 is my estimate

	Coal	Gas	Nuclear	Hydropower	Wind	Biomass	Oil	Geothermal	Solar
2005 % of generation	49.6	19	19.3	6.7	0.4	1.3	3	0.4	0.01
2014 % of generation	38.7	28	19.5	6.3	4.4	1.6	0.7	0.4	0.5
2030 % of generation (my estimate)	26	40.3	9.8	6.5	13.2	1.6	0.7	0.4	1.5

Source http://www.eia.gov/totalenergy/data/monthly/pdf/sec7_5.pdf

Opposition to new nuclear plants is strong because of the risk of proliferation of nuclear weapons, lack of permanent waste storage (Alley et al. 2013), and safety, especially after Fukushima and Chernobyl. If a major accident happens, more likely every year after a plant is 20 years old (Hirsch et al. 2005), opposition might grow strong enough to delay, or even stop new projects. Generation IV reactors are decades from being commercial. For new nuclear power in California to happen, costs need to go down, the Price Anderson Act needs to be extended beyond 2026 to indemnify operators against accidents exceeding $10 billion, and by law, a licensed national nuclear waste repository needs to exist before reactors can be built (CCST 2011). In addition, uranium production may peak as soon as 2015 (Dittmar 2013) or 2020–2035 (EWG 2013).

Not coal. Many think king coal is at retirement age, with its best days behind it in the U.S. Production here has possibly peaked both in tons and coal energy content. Of the remaining roughly 325 GW coal generation capacity, 58 GW is expected to retire. If the EPA Clean Power Plan is executed, up to 101 GW will be retired, and that would reduce coal-generated electricity from 38.7 to 26.6 % of the nation’s total by 2030 (EIA 2015b). This is because new coal plants won’t be permitted to be built without carbon capture and storage (CCS), which is at least 10 years away from being commercial, and likely to be too expensive if it ever becomes commercial (House 113-12 2013). Coal power advocates blame government and environmentalists for the decline. But cost is a larger problem for coal. Right now, coal can’t compete with natural gas. Coal is over the hill.

Coal and nuclear plants have other problems too. Both need to run flat-out to pay back their high capital, operation, and maintenance costs. They’re built to run steadily around the clock, since it takes 4 to 8 hours for them to warm up, synchronize their turbines with the grid, and heat large volumes of water to raise steam for turbines. They are built to provide baseload power and not built to quickly ramp up and down to balance wind and solar power. When forced to do so because wind and solar have first rights of generation, or to avoid negative prices, they not only earn less revenue to pay back their high capital and maintenance costs, their equipment can be damaged, shortening the plant’s life span (CEC 2008; IEA 2011; Wald 2014).

Not Natural Gas. I calculated that if a third of coal and half of nuclear generation need to be replaced with natural gas, then this finite fossil would provide 40.3 % of electricity generation in 2030. In 2014, 8149 billion cubic feet (bcf) of natural gas was used to provide electricity, which would rise to 11,860 bcf, or 44 % of all natural gas consumed in the U.S. in 2014. Production may rise, but this is not a certainty. If tax credits, cash grants, and aggressive depreciation for wind and solar aren't available, then the tripling of wind and solar generation in 2030 will be less than predicted, increasing the share of natural gas for power generation even more. That's not good news for the many other sectors that use natural gas.

There Is No Free Lunch

Nuclear plant construction was greatly restricted in the 1980s and since then because of environmental concerns. Because electrical demand has been growing, most of the increased demand has been met by coal. But now the concern is CO_2 emissions, and coal is the unwanted king. Under new environmental pressures, electricity is shifting to natural gas, which may or may not release fewer greenhouse gases. This will lead, in time, to depletion of natural gas. So our children or grandchildren may one day castigate us for a depletion of the premium feedstock for their much needed nitrogen fertilizer and other important chemicals. Unquestionably, this leaves less natural gas for fertilizer, plastic, heating, and industrial uses. Or, of principle interest here, for transportation.

Drought and sea-level rise will reduce fossil and nuclear power generation. When our needs are projected into a future that will presumably be characterized by climate change, we will have additional challenges. Hurricanes shut down oil extraction facilities in the Gulf of Mexico, and sometimes destroy or damage rigs, as happened to the very expensive Thunder horse rig. Thermal generation depends on tremendous amounts of water for cooling. Both drought and floods reduce nuclear, coal, and natural gas power generation.

Not hydropower. America the beautiful and powerful has 2540 U.S. hydropower dams. There are no places left in the continental U.S. to put very large hydropower dams. Run-of-river and retrofitted small dams could contribute 22 GW beyond the current 77 GW capacity, which has not increased much since 2000 (NETL 2012a, House 113-12 2013). Hydropower is limited. Let us count the ways: By season, rainfall and snowmelt, reservoir size, drought, evaporation, flood control, drinking and agricultural water, ecosystem health, and fisheries. Hydropower has a great virtue in being able to be turned up or down quickly, but operating in this way generates very large stresses on the fish, insect and other ecosystem components below. Water may run as long as time itself, but hydropower plants have an average life span of 60–80 years, failing when the reservoir fills with sediment, concrete settles, cracks or erodes, and with extreme floods.

Not marine hydro-kinetic (MHK) power. Hydro-kinetic almost seems like it's up against an immutable law: You can't fight Mother Nature. Variable MHK power, such as wave, tidal, and ocean currents is not commercial due to too frequent destruction by tides, storms, hurricanes, lightning, icing/ice floes, large waves, marine growth, and corrosion. To transform MHK from pipe-dream into kilowatts, other forces need to be overcome: Very high capital and maintenance costs, low efficiency, locations too far from urban centers and the grid, and conflicts with fishing, ship navigation, aquaculture, marine sanctuaries, and nearby ports. Hydro-kinetic also needs a lot of space. To generate 1000 MW of wave power in the rough North Sea, the Wave Dragon Energy Converter would need to be 124 miles long (NRC 2013).

Not offshore wind, which has the same issues as hydro-kinetic. In the U.S., 90 % of the optimal offshore wind sites—where the winds blow regularly and with gusto!—are in water too deep for current technology. Offshore turbines are too big to travel on land and must be launched from new $1.3 billion port facilities with $100–250 million vessels capable of lifting 757 ton turbines (Navigant 2013; NREL 2010b).

Not geothermal. There is not a lot of steam near the surface that can be readily tapped outside of Iceland. Geothermal relies on rare, near-surface geologic formations, needs lots of water and nearby power lines and roads. It provides only 0.4 % of U.S. power, most of it in California and Nevada. Untapped remaining sites are usually too small to justify transmission lines, too expensive, or lack water (CEC 2014; CCST 2011; NREL 2012a, 2013).

Not biomass. As discussed earlier in this book, biomass doesn't scale up enough and transportation has higher priority, more valuable freight to haul than biomass for electricity. Wood, the fuel of preindustrial societies (Perlin 2005), is half of renewable power in the European Union now, much of it imported from North America since Europe has little timber to burn (Economist 2013).

That leaves onshore wind and solar PV to save the day… with a little help from their fossil and nuclear friends, while they're still around. It will take time, since renewables are likely to grow slowly from 2018–2030 (DOE/EIA 2015) because tax incentives might go away once current renewable portfolio standards are met. There has been considerable discussion about whether the EROI of wind and solar are sufficient to support modern society, especially if backup systems are included (see Weissbach et al. 2013, 2014; Prieto and Hall 2013; Palmer 2013; Raugei 2013; Raugei et al. 2015). Charles Hall and other scientists believe this issue is not resolved yet, especially if the high costs of batteries or other backups are factored in.

Wind turbines come in many shapes and sizes, and their numbers are growing. Yet, they provide only 4.4 % of U.S. electricity, 181,791,000 MWh. That's equivalent to the power generated by 32,428 2-MW wind turbines (a). To supply half of America's power with wind, another 332,600 2-MW turbines are needed (b).

(a) 32,428 wind turbines: 181,791,000 MWh/5606 MWh power/year per turbine = 2-MW wind turbines × 0.32 average U.S. wind capacity × 24 h × 365 days).
(b) 365,000 wind turbines: 4,092,935,000 MWh U.S. electricity 2014/2 = 2,046,467,500 MWh/181,791,000 MWh provided by wind = 11.26 × 32,428.

Wind and solar are intermittent. The wind blows free—but about 70 % of the time, not at all, or enough to turn the blades, or blows with too much gusto. The sun can be depended on to set in the evening and rise in the morning, but clouds are more whimsical, creating crescendos and lulls of solar output.

All the while, the grid must remain in balance.

Intermittency

A big problem with electricity is that you have to use it when you produce it. If you dump too much electricity into a grid, you get load imbalance, blackouts, and can even melt equipment. Storing energy seems easy to those of us who do not use much in flashlights and car batteries, which are well-developed technology.

The problem is scale: All the batteries in the world can store less than 10 min of world electrical production (Gates 2010).

In the 11 states of the Western grid, if 35 % wind and solar were integrated, their intermittency would require 100 % backup from conventional sources such as natural gas and large hydro to maintain system reliability (NREL 2010a).

So to get 100 % of electricity generation from wind, which is only blowing a third of the time on average (the capacity factor) requires building three times more reliable capacity to keep the system stable and backup wind when it isn't blowing (CCST 2011). Right now that is mainly done with fossil and nuclear power. But in a 100 % renewable system with little or no natural gas, you'd need to build massive amounts of energy storage and three times as many wind turbines to charge the backup energy storage batteries.

So our 365,000 wind turbines need to be multiplied by at least three (plus energy storage) for a grand total of 1,095,000 wind turbines in a mostly renewable grid, and somehow connect even the most distant wind turbines in the remote regions of the Great Plains. That seems like the game is stacked against wind and solar, and that someone is moving the goalposts. Why three times more capacity? Read on.

The capacity factor is how much power is actually generated, which is always a fraction of the theoretical maximum amount of power that could be obtained if the wind always blew at the optimum speed or every day was the sunniest day of the year.

Since the average wind capacity factor over a year is around 33 %, you need to build three times as much wind to provide power to the electric grid, and somehow connect them, if the goal is to replace nuclear and fossil generation, which theoretically could have 100 % capacity factors if grid operators chose to run them around the clock and needed no down time for maintenance. But that's just an average, and there will be days when 300 % of what is needed would be generated and the excess would need to be stored or curtailed, and other days when less than 33 % was generated. The triple overkill is for reliability, to compensate for transmission losses, and make it more likely to have half of electricity power generation when needed.

The record year for the most wind generation ever built in the U.S. was 2012, equivalent to 4819 2-MW turbines. If we tilted towards windmills and built that many a year starting in 2016, it would take 220 years to build 1,095,000 of them to generate half of our electricity. Since their life span is 20 years, even more time and windmills would actually be needed for construction (Davidsson et al. 2014).

The word "wind" belies the fact that these machines are not light and airy. Nor easily popped up. Each 2-MW wind turbine weighs 3,375,000 pounds (Guezuraga 2012; USGS 2011), equal to 102 18-wheeler trucks. The wind may be free, but wind turbines surely are not.

Solar photovoltaic (PV) and concentrated solar power (CSP) provides only 0.45 % of U.S. electricity in 2015. The most solar built occurred in 2013, 9285 GWh. If this amount of solar is built every year starting in 2016, solar would reach half of 2014 electricity generation of (2,046,468 GWh) in 220 years.

The EIA has been providing statistics on solar PV and thermal capacity factors since August of 2014 (Table 16.2). For the last year, the average capacity factor of solar PV has been 28.3 %, Concentrated Solar Power (CSP) 22.2 %, and wind 31.5 %. So at least 3.5 to five times more solar capacity needs to be built to make up for the low 28.3 and 22.2 % capacities, and to make up for a solar PV panel degradation rate of 0.8 % (mean 0.5 %) per year. That would take 1100 years, plus PV panels will need to be replaced every 25 years, the average length of their warranty (Jordan et al. 2013). Also, a great deal of energy storage will be needed for times when the sun isn't shining.

Table 16.2 Capacity factor percent for U.S. Solar Photovoltaic, Solar thermal (concentrated solar power), and wind from August 2014 through June 2015

Year	2014					2015						
Month	8	9	10	11	12	1	2	3	4	5	6	7
Solar PV %	31.9	32	26.7	23.4	15.6	18.9	25.9	29.4	33.9	33.9	34.2	33.8
Solar CSP %	25	25.9	20.8	13.4	5.5	4.6	15.5	23.6	31.8	31.1	34.5	35.1
Wind %	22.5	26	31.5	42.2	30.4	31.3	34.2	31.5	37.6	35	28.2	27.6

Source (EIA 2015a)

The Electric Grid Trembles When Wind & Solar Join the High Wire Act

Grid operators are ringmasters. They have had to cope with the mismatch between demand and supply, and over decades have learned what the patterns are, and how to turn power plants up and down, on and off, accordingly. But wind goes from a whisper to a roar when storms arrive (Halper 2015), a bucking bronco that gets increasingly hard to manage and control the more wind and solar penetrate as a percentage of overall power (IEA 2013).

So far, wind and solar power penetration is so small that operators can balance it with natural gas peaker plants, dispersing excess generation across a larger region, more frequent scheduling (15 min or less), (pumped) hydropower, or curtailment.

A National "Super-Grid"?

America has three grids that cover the lower 48 states. They are only loosely connected, and have minimal ability to transfer power between them. A national U.S. super-grid is thought by many to be needed because the Eastern states, where most of the population resides, have very little renewable power. Also, renewable resources are concentrated in different areas of the U.S., with Western states having the most hydro and geothermal power, Southwestern states the most solar PV and solar thermal (CSP), and Midwestern states the most biomass and wind (NREL 2012b).

High wind penetration especially depends on a large balancing area, so a calm cloudy Nebraska can be balanced by a windy Wyoming and sunny Arizona. Unfortunately, most good to superb wind (class 4+) is stranded because these sites tend to be in states with low population density and usually far from cities. It's not just coincidence. Cities arose near flat farmland, usually far from the best wind resources on hills, mountain ridges, and other high ground where wind speeds are highest. Flat areas can be good too, the smoother the better to reduce friction and keep the wind moving. That's why eastern Iowa can capture some of the powerful winds blowing across the Great Plains—the corn crops don't stop it (IEC 2015).

Because of this stranding far from transmission lines, very little of the potential power that could be harvested from wind will actually be realized. Even if we built legions of wind mills, they wouldn't contribute as much power as existing fossil and nuclear generation. The National Renewable Energy Laboratory added up the undeveloped prime and non-prime renewable power potential in one of the country's three major grids, the 11 Western interconnection states (WECC). Don't think you can read this report and get in first on the wind rush. The best, low-cost areas *have already been fully developed* in California, Oregon, Utah, and Washington. The remaining non-prime resources will cost more and be less productive. Total potential future renewable generation was 378 TWh (148 TWh prime, 230 TWh non-prime)

(NREL 2013). This is less than the current 481 TWh of fossil and nuclear power production in these states (EIA 2013).

Despite the need for a larger balancing area, a national grid in America is unlikely. There are downsides: the potential of a national blackout from instability, cyber-attack, terrorism, and aging equipment (NRC 2012). A national grid would continue to require a long-term stable economic and political environment.

Although a national grid can increase stability, this isn't always the case. Operators have fine-tuned data and familiarity with their own regions, but can't see adjoining systems well enough to reliably detect impending extreme events and take countermeasures quickly (CEC 2008). Size doesn't always increase reliability. Greater size provides more pathways for local disturbances to propagate, which can lead to complex chains of cascading failures (Morgan et al. 2011). In addition, increased loading of transmission lines and transformers without increasing investment to expand this infrastructure (Clark 2004), and poorly planned generation and transmission capacity (Blumsack 2006) has the potential to cause additional widespread blackouts.

Think of what it would take for wind to provide half of America's electricity. Think of what it would mean for the American landscape, and what it would mean for the grid. You'd need 1.1 million 2-MW wind turbines. Each would require 170 acres of wind to harvest (NREL 2009). Together, they would cover 290,860 square miles, the equivalent land mass of Illinois, New York, Florida, Pennsylvania, Virginia, and Kentucky. This would require at least 50,000 miles of new transmission lines, with many up to 1500-mile-long underground, multi-gigawatt links from the Great Plains to the coasts (Smil 2010) costing millions of dollars per mile. It can take 14 years to build transmission lines to distant renewable sites, due to lawsuits and negotiations with land owners and political jurisdictions (DOE 2002; Wald 2008). Are the windmills of your mind spinning?

Wind and Solar Don't Replace Conventional Power, They just Add to the Blaze

Wind and solar add logs to the fire. But they cannot replace conventional plants, because they can't be counted on. It would be like expecting 3-year-olds to harvest strawberries. Adults are going to end up doing most of the work.

In the IEA world energy outlook 2012, New Policies scenario, it was calculated that 450 GW installed capacity of wind in 2035 would only produce 112 GW of power, given the ebb and throb of wind. Even that is of little use to the grid. When the grid needs power, it must have it immediately, *now*. Wind (and solar) cannot always be counted on like fossil and nuclear power on peak demand days and at peak demand hours. The IEA New Policies scenario calculated that wind could be counted on only 5 % of the time (*the capacity credit*) for just 22.5 GW at peak demand times. That means an additional 89.5 GW (112–22.5 GW) of reliable fossil, nuclear, or biomass power is needed to back up wind power. The concept of capacity credit for wind is not intuitive, and hard to get your head around. But it this simple: The more you replace conventional power plants with wind, the more you depend on wind. And, the more you depend on the wind, the less you can depend on it.

Great Britain's office of science and technology estimated wind could be counted on reliably only 7–9 % of the time if the overall penetration of wind power ever reached 50 % (GBHP 2014). So if 25 GW of wind capacity were built to replace 25 GW of fossil and nuclear plants (life span 35–50 years), and the capacity credit of wind at peak demand was 5 GW, then an additional 20 GW of fossil and nuclear plants would be needed for backup, with nearly double the energy generation as before (45 GW). In regions where peak demand occurs in the winter, the capacity credit of solar power is zero, because peak demand occurs after dark. And thus the stark reality: "Investment in renewable generation capacity will largely be in addition to, *rather than a replacement for power stations*" (GBHL 2007). It hardly seems fair.

Intermittency is the fly in the ointment. Backup fossil and nuclear power plants must be online, burning fuel while waiting to step in when wind or solar power drops, and back off when they increase. Since nuclear and coal run as baseload and can't quickly ramp up or down without damage, natural gas plants and some hydropower are called upon. Areas heavily dependent on coal or nuclear power might need to limit the amount of intermittent generation because of the damage done, slow ramp rates, and lack of stability if too much fossil generation is idled (NETL 2012b).

How Much Intermittent Wind and Solar Penetration Can the Grid Handle?

Claims that Denmark has 32 % wind penetration come with a caveat. They ignore the fact that excess power is dispersed across a large area and stored in Norwegian hydropower reservoirs. Likewise, Iowa may generate 28 % of its power from wind, but because it is shared with 12 other states, wind power penetration is 5 % in all those states collectively.

The more flexible a system, the more variable power can be used. In California, in 2014, 11.8 % of *in-state* power generation was intermittent, 5.3 % solar and 6.5 % wind, easily balanced with the whopping 61.3 % of power from flexible natural gas and 7.1 % large hydropower, and by sharing the power with the ten other states in the Western grid. California in-state renewable power also came from biomass 3.4 %, geothermal 6.1 %, and small hydro 1.2 %, for a grand total of 29.6 % renewables in all. California does not generate as much power as it consumes, and imports an additional 33 % of power from the other ten states in the Western grid (CEC 2015).

Spain has the highest intermittent renewable penetration at 25 % (20 % wind, 4.9 % solar). This is done with a huge excess of installed power, hydropower and natural gas plants, frequent scheduling, a very sophisticated control center, excess electricity exports to France, Morocco, and Portugal, and less demand from customers (due to financial decline in Spain).

Since power supply must match demand at all times, as wind penetration increases, the need for accurate forecasts becomes increasingly important. Kevin Forbes argues wind forecasting errors are much greater than are being acknowledged. If wind penetration increases, more accurate forecasts will be needed to prevent blackouts (Forbes et al. 2012).

Wind and solar penetration may be limited to 55–61 %. Beyond that, the grid can become unstable. This limit was derived from a study of the Western grid (WECC) in the U.S. To reach this level of penetration would require improvements in grid transmission, sharing power between balancing areas, and 400 MW of energy storage (NREL 2014).

Conclusion

How far can we go down this stop-and-go road? Europe, especially Germany, wants to go 100 % renewable electricity. California 50 %. Even though most 100 % renewable scenarios see wind and solar as providing at least 80 % of electricity, their penetration may be limited to less than that. Limits include the stability of the grid, lack of a national grid, inability to scale wind and solar to 80 % of power, a dearth of energy storage, enough biomass to balance power, and inaccurate forecasts.

Wind provides only 4.4 % and solar 0.5 % of U.S. electricity now. Wind is unlikely to scale up to more than 13.2 %, and solar to 1.5 %, by 2030. Development could slow as subsidies end, Renewable Portfolio Standards are met, or another recession hits. Even if we continue building wind and solar at the current record rates, it would take centuries to reach half of our total power generation from wind and solar. Why not a crash program? We need to look before we leap. Accelerating development would be unwise until the maximum penetration level of intermittent power is known. Likewise, eminent domain at all levels of government to build necessary transmission lines should be in place. And we'd want to know whether there is enough natural gas production in the U.S. and/or available import LNG to balance the grid.

So in addition to facing an energy crisis, the potential for an electricity crisis exists as well unless energy storage can come to the rescue. Energy storage—what a dull name for such a heroic role.

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