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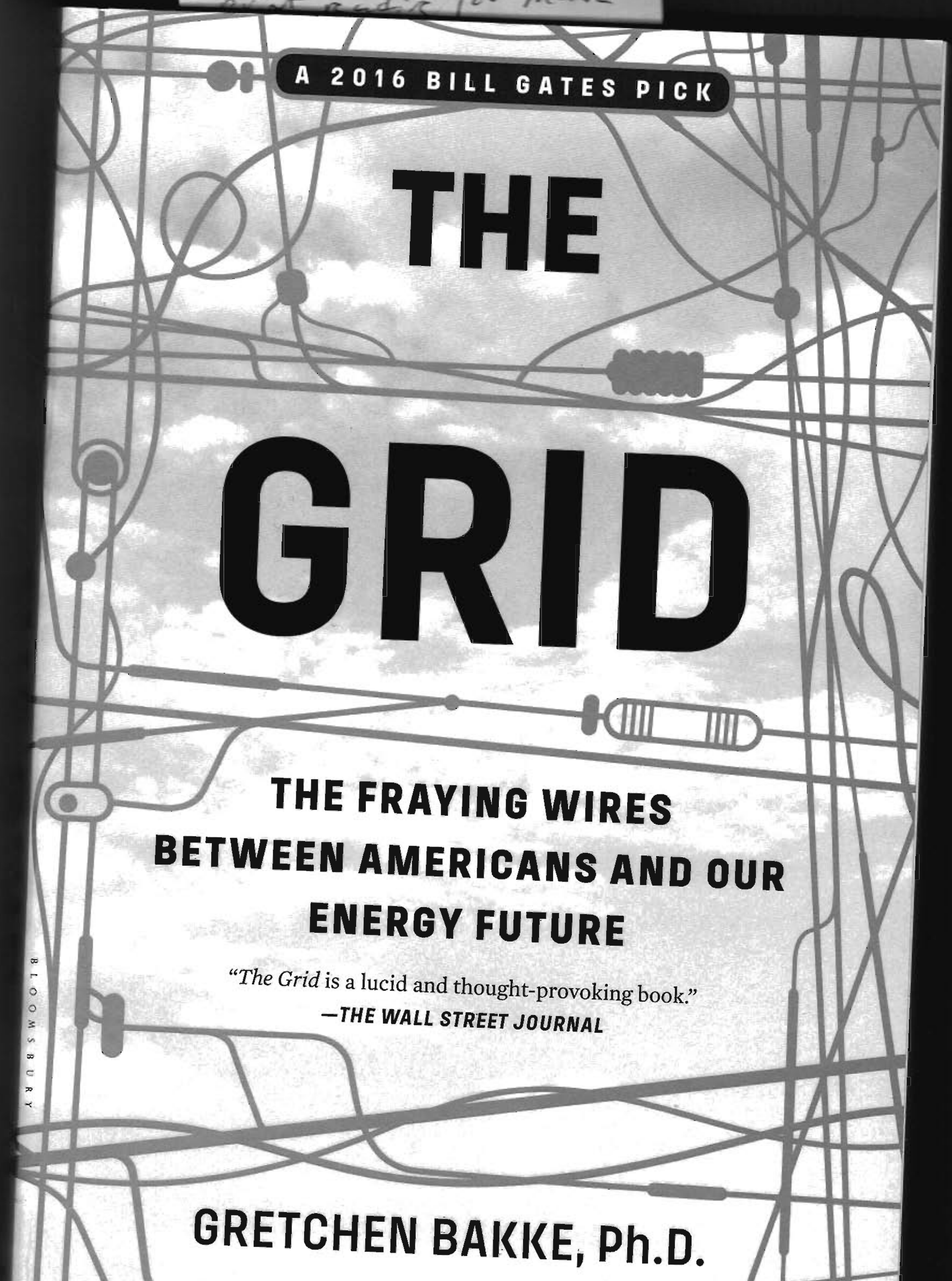

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THE GRID

THE FRAYING WIRES BETWEEN AMERICANS AND OUR ENERGY FUTURE

"*The Grid* is a lucid and thought-provoking book."
—THE WALL STREET JOURNAL

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BLOOMSBURY

witness new logics emerging: small systems and solutions are gaining in currency over big ones, flexible or variable ways of doing things are overwhelming more rigid ones, mobility and portability are more appealing than the static and the fixed, and wirelessness is championed whenever and wherever possible. Initially it will seem chaotic, and it will be chaotic, as a thousand interested actors grab for a piece of what has long been a proprietary infrastructure. But within this mess, certain unspoken cultural attitudes will proliferate, and from these, patterns will emerge.

This book brings all of this into focus—the ruins and the dreams, together with the incomparable complexity of our grid's technology; its history, replete with absurdities and brilliances, together with the people, laws, and logics that brought it into being—so that as historical and technological exigencies press down upon us, we, the users of the grid, might understand the stakes and implications of our choices a little better. The grid might look stable, its presence as steadfast as it ever was; it might feel known, its electrical power almost as reliable as it ever was. But we would do well to wise up to the fact that both impressions belie an intense seething change in the very structure of the power machine that keeps us all warm, lit, and, relatively speaking, well off.

CHAPTER 1

The Way of the Wind

Day one. It's a bright autumn morning in Washington, D.C. I and about four thousand other people, most in business suits, have already made it through four tight rings of security, descending at each stop-and-check farther underground until we pass the final metal detector and emerge into a startlingly well-appointed, underground bunker of a conference center, the Ronald Reagan Building and International Trade Center. The lighting is subtle, the decor an elegant symphony of beige. For the next five days this venue will play host to the (mostly) men who spend their lives making, regulating and transporting electricity to American homes and businesses. Welcome to Grid Week.

This is the human side of the grid, not its wires and poles, substations and power plants, but industry executives, electrical engineers, and utility-company representatives, some of whom are newly in the business of smartening the electric grid; some even are small-tech entrepreneurs. All of them play a part in making it work. We are here this early-autumn morning to hear the conference's first keynote address, to be given by Stephen Chu, a Nobel Prize–winning physicist and also for a time the U.S. secretary of energy. As we settle into our seats, Dr. Chu steps up to his place at the podium and the auditorium falls respectfully still. He, too, has a quietness to him, a demeanor that with his delicate frame and slight baldness make him look more like a monk than a bureaucrat. In an odd way, I think, perhaps he is both. This keynote will be both a sermon and a policy speech.

What Dr. Chu is going to tell them, the men who keep our grid up and running, is to integrate more renewable power generation—more wind, more sun, more waves and tides, more geothermal, more of everything that is hot without being heated and that moves without being pushed—but first he is going to tell them some horror stories.

Sure enough, by about slide 5 (after we have learned many great things about our energy future and how America will soon be rocketing back to unprecedented international success), things start to look really bad.

"On September fourth, 2008," says Secretary Chu, gesturing with his laser pointer at a massive PowerPoint display, "at just before five P.M. in Alamosa County, Colorado, a thick layer of clouds swept across the sky." He pauses to glance down at his audience.

No one is coughing or shifting in their seat, nothing beeps or buzzes. We are attentive.

In fact, given how the room feels, I imagine myself in a cluster of ten-year-old boys with ratty sneakers listening to ghost stories around a late-summer campfire instead of with several thousand middle-aged industry men in well-pressed pants. The other difference is that rather than the play of shadows at the edges of a fire's circle of light, we are given statistics and sharp lines on graphs. This one, the one Chu is pointing at now, plummets precipitously downward.

"Five minutes later," he continues, "there was a jagged but rapid eighty-one-percent drop in the electricity output from the solar farm that served the community."

Eighty-one percent. Five o'clock P.M. A nicely drawn downward-plunging line.

Everyone in the room knows exactly what is going on; what they don't know is how to deal with it. An all but instantaneous 81 percent drop in generation at five in the evening when everyone is coming home from work, switching on their air-conditioning, TV sets, and computers is the kind of story that sets the hearts of electrical engineers palpitating. Electricity consumption on this, the world's largest machine, must at every moment be balanced with electricity production. The more solar there is in any given mix of "fuels" used to generate electricity, the harder it is to cope with the sudden arrival of a cloud, especially at five in the afternoon when things on the demand side have just shot through the roof. On the graph, the black line labeled GENERATION is pointing straight downward while the red line labeled CONSUMPTION is angling up and up toward the sky. When solar is how you generate your electricity, no sun means no power. It puts these very men, in their workaday lives, into a ferocious scramble to avoid a blackout.

"Four months later," says Secretary Chu, continuing blithely on to the next slide, "on January fifth, 2009, in the Columbia River Gorge, the wind stopped blowing quite suddenly and didn't start again for three weeks." He pauses again. He lets the ramification of this massive and long-term stoppage wend its way through his audience. Three weeks. *Three full weeks.* You could have heard a pin drop.

"Meanwhile, all twenty-five of the Gorge's wind farms lay still."

No wind means no generation, and no generation means no power. Yet all the people that live downline from these farms, many of them lefty Northwesterners who believe strongly in the integration of renewable resources like wind and solar into electricity production, aren't just going to sit around happily for three weeks without any electricity. Even the greenest of consumers aren't going to just wait for the wind to pick up again before checking their e-mail or making some toast. Even if just a portion of their electricity comes from wind power, someone somewhere is having to make up for this calm, an adjustment that still, in most cases, involves firing up some other massive power-making machine. It's not impossible, but it's a struggle: it's hard to do well, harder to do fast, and almost impossible to do cleanly. Many of America's backup power plants are the oldest and dirtiest in the fleet. They should have been decommissioned and torn down decades ago. Instead we use them as a last-ditch resource when power supplies fall short. We use them a lot.

It's not just that machines have to respond to the variability of renewables. It's also that the culture of electricity making has to be transformed. The power plants forced to take up the slack when renewables fall still are matched pretty well in age with the people in charge of running them. As a later speaker in the day's proceedings would point out, 60 percent of men who run our electricity system are within five years of retirement. A quick glance around and I would have to agree. The people in this very room are at the end of their careers. They, together with the institutions they work for, have long had one way of doing things, and now they are scrambling to adapt to a changed landscape. Before grid-scale wind and solar power came online, slow and steady always won the race. There was no competition in the electricity business, a protection enshrined in law that made each utility the unique master of its realm. They made our power and they always knew how much of it there would be, where it would come from, and where it would be used. Plans were made seasonally, collegially, as every four months utility men would sit down in a room and talk about how the winter might go, or the spring, or the summer; these men made sure there were enough power plants chugging along to provide what they estimated to be the right amount of electricity. Except for the occasional panic of a too-hot day or too-cold one—when demand for electricity jumps precipitously—their plans pretty much worked.

Nothing in the system they grew up in, and now run, prepared them for a means of power generation that not only varies from minute to minute, but which they do not own, cannot control, and have no plan for. The new world of privately or corporately owned variable generation, strewn about every which where, demands that they be very light on their feet. But the utilities, the utility men, and 2,500-megawatt (MW) coal-burning power plants don't dance much. It's an industry that plods along and likes it that way.

Their balletic capacities to the side, the utility companies do find themselves trapped in an increasingly tight spot between a rock (variable generation) and a hard place (keeping the lights on). If in 2009, when Chu gave this presentation, there were twenty-five wind farms in the Columbia River Gorge; today there are four times that many, most containing hundreds of turbines, each turbine producing well over a thousand kilowatts of power. Some of the largest wind developments in the nation sit nestled into this single slash of land. All that power, currently estimated at 6,000 megawatts (or enough electricity to power 4.5 million households), depends solely on the way the wind blows.

And when the wind, ever fickle, stops its blowing all the electrons these vast machines have been built to harvest out of thin air disappear. It's that simple. The grid must be balanced; consumption must always match production, for there is as of yet no real means of storing electricity for later use. If power is not being made right now, somewhere, somehow, we simply don't have it to use.

As impossible as it may seem grid-scale electricity storage hardly exists. There are some artificial lakes pump-filled with water that folks in mountain states can call on in a pinch, but that's about as far as it goes. For now, no household has a cookie jar full of watts secreted away for later use; no nation has a strategic electricity reserve. As a result the electricity we use, day in and day out, is always fresh. So fresh, that less than a minute ago, if you live in wind farm territory, that electricity was a fast-moving gust of air. And if you live in coal country, it was a blast of pulverized coal dust being blown into a "firebox"—a huge, industrial, flash-combusting furnace. If you live in hydro country it was a waiting rush of water dammed up by a massive concrete wall. Picture it. The electricity you are using right now was, about a second ago, a drop of water.

But it's not water anymore. We like to talk about electricity as "flowing" from one place to another, as if we could predict where it might go once we've released it onto the wires. But we can't. It doesn't flow downhill, it doesn't take the shortest path, nor will it follow one route at the expense of another. The wires we use to transport electric current from where it is made to where it is used aren't much like pipes, or mains (as they are often called). Nor can electricity really even be said to "flow" through them. Wires are conductors, which is to say that they are metal, and to the extent that something electric happens because of them, it seems to happen as much outside as inside the lines. Power lines are there to channel or direct broad halos of electromagnetism in a direction determined by something as simple as someone depressing the lever on their toaster. Suddenly a pathway opens up, one that wasn't there an instant before, and electricity follows it, moving into and through the toaster, where it is slowed down as it passes. This slowing down, or resistance, produced by the device causes electrons to release heat, which toasts the bread. After a certain number of seconds the lever pops back up, ejecting the toast and closing off the toaster channel, and electricity must find another way.

It's not a system that needs to be planned. No one decides which electrons will go to Los Angeles to make doughnuts and which to Walla Walla to make toast; all of the electrons are going everywhere at once. As long as there is a "sink" all the electricity on the grid will move toward it by whatever means possible. The reason your toaster doesn't explode every time you turn it on is because there are thousands, indeed millions, of other sinks on our grid where other devices are making the same kind of "hey, no resistance over here" calls to the

available electric current. There are also a million little devices on the grid, and some big ones, to standardize the voltage, or push, of that electricity, so that the power available to your toaster in the first place is substantially less than that traveling along high-voltage lines from the dam to the nearest substation. Your average outlet is already offering the toaster access to one of the mildest intensities of electricity available. You still don't want to pry a burnt nub of bread out of there with a butter knife—a nasty shock greets that activity—but were you to so much as touch a low-voltage downed residential wire, it would kill you. The system, in its current form, is designed not only to protect the toaster, but to protect us from the potential force that even the modest voltage of domestic electric current delivers.

Toasters don't explode, wires function well, lightbulbs go on when the wall switch is flipped, all because the grid is kept in balance: there is enough electricity available to run our machines, but there is not so much that it rips through and destroys them.

This is our grid in a nutshell: it is a complex just-in-time system for making, and almost instantaneously delivering, a standardized electrical current everywhere at once. And though schematas of the grid tend to make it seem like there is a line out of a power plant that ends in the toaster, the whole thing is actually a giant loop that both starts and ends at the power plant, or generating station. These factories make an electric current by tearing electrons out of their atomic orbit and then give them no real choice but to power the whole system as they make their way, rather quickly all things considered, back into these orbits again. The power plants that accomplish this electron-ripping task can be made to run on wind, or natural gas, or coal, or uranium hexafluoride, or dried cow dung; any fuel will do. Strung into this loop are the manufactories, businesses, farms, and toasters that use the power electrons release as they pass by. Whatever power needs these consumers and their things have at any given instant in time has to be balanced pretty much perfectly with the amount of power being produced at that same instant way on down the line. This is as true of a customer who turns on their porch light as it is of one who brings a new server farm online. This is why peak load—when customers suddenly use a lot more electricity than they were using just five minutes before—is a startling kind of problem for utilities. It's also why figuring out ways to design our world to use power when it is made, rather than whenever we feel like it, is a brain-twisting, but fundamentally smart, idea.

Variable generation—the technical term for power plants that make electricity out of unpredictable fuel sources like the wind, sun, or waves—is a problem. It doesn't matter which end of the system escapes control. It can be us, using too much power all of a sudden (like when we all come home after a long day's work and simultaneously turn up our air-conditioning just as the wind slackens), or it can be cloud cover, stripping the generative capacity from solar panels. Regardless, the utilities and other balancing authorities have to act very quickly to set things right again. Otherwise there just isn't enough power in the lines to keep the lights on. Lots of blackouts start this way.

The rub is that, with the exception of hydroelectric dams, the output of all existing, comfortable-to-utilities, means for generating electricity take significant time to turn up or down. The wind can stop instantaneously. A cloud can blow over the sun just as quickly. Or, ten thousand customers can turn on their air conditioners. When this happens a controller sitting in front of a wall of flat screen monitors in a control room somewhere sees it: *bam*, an 81 percent drop in output or an 81 percent increase in demand. It's a precipitous curve graphed on a screen; it's a red warning light blinking in mechanical panic; it's a buzzer irritating in its insistence; it's a nerve-jangling phone ringing and ringing and ringing. Someone on the other end needs a fix and he needs it now.

I sat in the control room one day for the company that runs 54 of America's wind farms scattered from the Gorge to the Arizona desert to northern New York State and I saw how it worked. Response time is limited by human and mechanical capabilities, but wind speed and lightning storms are not. There are predictive mechanisms in place. The man in front of those screens sees lightning strikes move their way across a map drawing closer and closer to repair crews until he picks up the phone and makes the call: "Get out of there, shut it down." The same is true of the wind, usually. The weather is predicted to be blustery or calm. The spinning of the turbines is closely monitored, and electricity is priced for sale based upon expected output.

But sometimes a lull comes, like the one Chu has pointed to, and it's total, stable, and unexpected. At this instant there is nothing the controller can do, there is no dial at his right hand that he can just turn to increase the output of some other generating plant on the same lines. Not so quickly at least. He will turn dials and push buttons and make calls. He'll do whatever he can, but the physics of electrical generation from "stock" or man-made resources such as coal, natural gas, or uranium are against him. And though they are getting faster, they are just not very adjustable. Coal-burning plants, which can ramp up to 50 percent in five minutes, are one of the fastest; natural gas (from a cold start) takes about ten minutes to get up to speed; while nuclear takes a full twenty-four hours to turn up, though it can be shut down in seconds.

In human time, five minutes might seem pretty quick, given that we are talking about moving a mechanical system as massive and complicated as a coal-burning power plant, which pulverizes and combusts, on average, 125 tons of coal every five minutes.

But in electricity time, which is what matters to grid stability, five minutes might as well be infinity. In five minutes, electrical current generated by a power plant outside Muncie, Indiana, can go to Mars. Even in the decidedly imperfect conditions of electrical transmission more characteristic of life on Earth, the wind power generated in the Columbia River Gorge that is not used by the relatively sparsely populated states of Oregon, Washington, and Idaho can be easily transported along a long DC (direct current) line to the good people of Los Angeles County, where it is gobbled up by air conditioners well before its sixty seconds are up. This is one of the reasons the grid is big. Big means that power plants can be built in places with not too many people but still provide electricity to large population centers as distant from one another as Seattle is from San Diego.

At times, however, even the grid's remarkable span is insufficient to absorb all the power produced in the Gorge. For this river valley is not only a phenomenal source of wind power, as Secretary Chu pointed out, but it has an extensive hydroelectric infrastructure left over from the heady days of big government investment in public works that helped to pull America out of the Great Depression. These New Deal dams (Grand Coulee and Bonneville most especially) and their smaller, more recent brethren were providing 98 percent of the Pacific Northwest's electricity needs before the first industrial wind turbine went up; now there is all that hydro and all that wind power all in one place.

Washington, Oregon, and Idaho, they could live bright, warm, electric lives without the wind. The rain, snow, and meltwater are more than sufficient. In fact, of all the power produced in the Gorge, from whatever source, only about 15 percent is used locally. The rest is shipped on down the lines to whomever will buy it. This is why it is a big deal when the wind stops blowing for three weeks. It's not just some widely scattered Left Coast ranchers that lose power, it's also city people and townsfolk all over the Western United States and certain choice bits of Canada as well.

The fact that we don't yet have a good means of storing electricity doesn't just mean that we have little backup power on hand to deal with shortages; it also means that it is difficult to dispose of surplus power when it's produced in excess. While our dependence on oil may have taught us to think about and prepare for interruptions in supply, it has never happened that instead of a carefully measured tank of gas, what you get at the filling station is a giant splash of the stuff tumbling down and over and utterly inundating you and your car. But solar and wind power see to it that the energetic equivalent of this great messy slosh is happening to the grid all the time. Anywhere in the nation with a high concentration of wind turbines or a high concentration of photovoltaics always runs the risk of generating more electricity than can be easily consumed. This is the part of the renewable energy horror story that Secretary Chu left out.

You can't just turn the wind down. When it blows hard, those turbines spin and spin and the output is tremendous. The young control room operator with whom I sat watching the weather as it approached and moved through widely scattered wind farms told me with a note of awe in his voice that you can actually see a gust of wind as it tops the Rockies and then hits one set of turbines after another all the way to the coast. You can see it in the power spikes—*bang, bang, bang*—of wind farm after wind farm shooting electricity into the system. It floods the grid; it crashes through the infrastructure much like a wave crashing against a sea wall on a stormy day. Even Los Angeles can't absorb all the electricity made on a seriously blustery day in the Pacific Northwest. Even the Western Doughnut, as the high-voltage DC line that carries electricity from the Gorge to the people of Southern California is called, with its 3,100 megawatts of transmission capacity (or half of L.A.'s peak capacity), cannot carry it all.

When there is too much power on the wires they overload, or circuits break to protect them, and in so doing they close, rather than open, available paths for excess power to take. It's hyperbole that your toaster will explode; the system will self-protectively black itself out long before your toaster turns into a bomb of flame on your kitchen counter. In this way, blackouts should be seen as source of grace as much as a bane and a burden.

Imagine, then, that Secretary Chu's story does not stop with the wind's unpredictable calms, but rather continues to include its more impetuous, tempestuous side. Imagine that instead of moving on to a discussion of solutions he follows his harrowing tales of what unexpected cloud cover means for solar output and what a lengthy calm means for wind power with a third story of the relationship between renewable energy and our electric grid, for this story is also true.

"On the afternoon of May nineteenth, 2010," he might have said, "in a single chaotic hour, more than a thousand wind turbines in the Columbia River Gorge went from spinning lazily in the breeze to full throttle as a storm rolled out of the East." Here he would pause, to see if his audience understood what was about to happen, what all of this wind was about to do to all those turbines. "Suddenly, almost two nuclear plants' worth of extra power was sizzling down the line—the largest hourly spike in wind power the Northwest has ever experienced."

A massive uncontrollable, unmanageable, unstorable, undumpable electricity surplus. Chaos on the lines. And what is worse: it's May.

In Oregon in May it's still raining. It's been raining since November, and it will continue to rain for another month or so before things begin to lighten up. In the Cascades, the mountain range that bifurcates the state, all that rain is snow, and in May all that snow is meltwater—pure, chill runoff. The rivers are very full, and they are sloshing their way down the sides of mountains and hills into the man-made lakes that sit behind, and feed, each and every dam on the mighty Columbia. In May these reservoirs can't hold another drop. They are full up. And the turbines on every dam up and down that mighty river chug along at a fearsome rate, because if they don't there are only two options. Either the reservoirs flood up over the homesteads, highways, and towns that dot the river's edge, or the dam operators let the water out through spillways.

Though the second might sound like a good option, sadly for them, it also happens to be illegal. Because, in May, the fishlings are running, tiny silver slivers that will, in two to three years, grow into beautiful, fleshy oceanic salmon. If the dams flood their spillways, these fingerlings will be ravaged. Their numbers will be decimated year by year, and not only will the commercial salmon industry be threatened, but the species itself will slip slowly from plentiful to endangered, from dinner plates to Grandma's memory bin.

So, spilling the water isn't an option, at least not in May.

The only option is to let the dams operate at close to maximum capacity. And if the dams are going to make all the power they can, they are going to need all available transmission lines to move that power out of Oregon to anyone and everyone who looks like a market. It can't be stored, it must be transported and used immediately, or the land will flood, or the grid will crash. This is every day in May. There is water, there are fish, there are laws, there are power lines with a finite capacity to transport electricity, and there is a market that just might not be big enough to use all the power they are being fed.

Power production isn't just an industry, it's an ecology. And renewable resources are not just about the planetary good kept from public offer by corporations with other visions for their own profitable futures. Making American power is about how technological, biological, and cultural systems work in concert to keep our lights on, our basements and roadways clear of flood water, and fresh fish on our tables. It's delicate in all sorts of ways. Though I will concentrate largely on infrastructural delicacy in this book, it does the reader well to remember that the vulnerability of the grid as a technological system is intimately linked to the fragility of biological systems (like salmon runs), the intractability of legal and bureaucratic systems (like the endangered species act), and the unpredictability of meteorological systems (like wind storms).

The wide-scale integration of variable forms of power generation didn't create this situation. The grid's entanglements with culture and law and natural systems were always there. Renewables have just made these entanglements impossible to ignore; they stress the existing system just enough that all the delicate balances reached over the passage of a century are thrown off-kilter. As all of these diverse bits of what make our grid work interlock and entangle, there just isn't a lot of room for quick action. Once people with politics and profit motives get their fingers into the briar patch, it seems at times like there is no room to act at all.

This was the situation into which the equivalent output of two nuclear power plants was suddenly poured that mid-May day back in 2010. The only real option was to shut down the wind turbines. Switch the beasts off. Still their spinning. Clear the lines. Let the storm blow itself out. Leave all those electrons unreaped.

At the time, that's exactly what the local balancing authority—the Bonneville Power Administration (BPA)—mandated be done. They called up the corporation that developed, built, and still manages most of the wind farms in the Gorge, the Spanish-owned conglomerate Iberdrola, and asked them to pretty please, and yes, immediately, turn off their many hundreds of wind machines, whipping around just then at absolutely ferocious speeds in the onslaught of wild air.

But what does Iberdrola care for the grid? They are in the business of making electricity, not of moving it to market. Transmission is the utilities' problem and balancing is the balancing authorities' problem, regulation is the regulators' problem, interregional cooperation is the ISO's problem. Iberdrola's problem, as the second-largest wind company in the world, is maintaining a profitable bottom line. Turning off their turbines at a moment of maximal productivity? Well, it's just not a sensible course of action. Most especially because the federal subsidies that have helped them to build and maintain their almost three thousand American-sited turbines only accrue if those machines are turned on and running. It's not just that they only make money from these beasts' ceaseless rotation, it's also that they have to *pay back* money if their turbines are ever off. Even the agency that Chu headed didn't imagine as it wrote up its guidelines for subsidies that sometimes the best thing anyone could do with a wind turbine is turn it off; that sometimes, in America, we can have too much of a good thing. If Iberdrola switches off even one turbine just to be nice, this has very real ramifications for their profitability. From their point of view, if the grid isn't up to the task of moving to market the power they make, then the grid needs to be better.

In this they are right. Every man at Grid Week knows it. That is part of why they have come.

Over and over, investments in renewable sources of power generation are failing or falling very short because America's electric grid just isn't robust enough or managed well enough to deal with the electricity these machines make. And not just in the Columbia River Gorge.

In West Texas, the largest wind farm ever planned on American soil was abandoned in 2008 because the utility refused to build a high-voltage line out to the site. And the developer, the local oilman T. Boone Pickens, thought it was a travesty given how much he was investing to build the farm itself that he would be expected to also build the transmission infrastructure. He shelved the project after having installed just a thousand turbines, a fraction of the total.

Add to this a second outrage. Pickens had already been obliged to use turbines that were small by international standards, just as was every other wind farm developer in America at the time. The grid's fragility demanded it. If a wind storm can turn a field of "small" wind machines into the equivalent of a nuclear power plant in a period of minutes, you can only imagine what would happen to a field of the really big ones. Germany's Enercon makes a 7.5 MW model (only slightly smaller than the largest offshore turbines, which come in at 8 MW), whereas in the United States the most common turbines remain the 1.5 MW GE model and the slightly bigger 2 MW Gamesa. This has nothing to do with how fast the wind blows across American plains versus German ones; it has everything to do with the wires these massive machines feed into. It is the system that stands between the point of generation and point of consumption that delimits productivity. The grid is the weakest link. It isn't made for modern power.

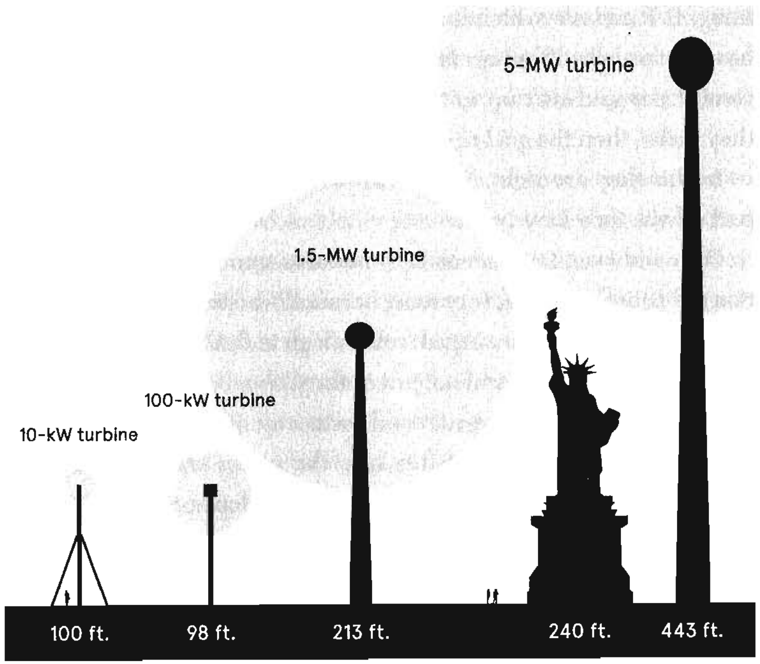

FIG 1 The height, swept area, and power rating of common wind turbines

So this one windy May day in the Gorge may have been exceptional as regards the quantity of electricity suddenly surging through the wires, but the problem of too much unpredictable electricity is all too ordinary, in the American West and Plains states especially.

In the spring of 2011, when I interviewed Elliot Mainzer, then BPA's director of strategic planning and now its acting director, the balancing authority had once again just paid the wind farms in the Gorge to shut down. This time not because of a storm, but because of an exceptionally robust runoff. The dams needed all the space on the wires. Mainzer, who is both a realist and an optimist (a rarely seen combination of traits), predicted then that "at the current rate of wind development the region's system of dams and power lines will start running into consistent operational problems around 2013, when wind in the agency's territory reaches a total capacity of some 6,000 megawatts."

In other words, we've already passed the point of no return. If they were shutting down the wind farms with some regularity in 2010 and 2011, right now, with 6,000 MW of power rolling out of thin air and into our grid, at precisely this point, Mainzer predicted that the grid "will require major structural changes"—adding, after a pause, "If it's done right it's a huge opportunity."

This, then, was the substance of the fear felt in the soles of the feet of every well-shod industry man sitting in the Washington, D.C., auditorium that lovely September day listening to the secretary of energy speak about the problems of integrating renewables into the existing grid. They knew, to a man, that it would be better for them and for the reliability of the technology they are charged with shepherding into the twenty-first century if we could just stick with coal and natural gas, nuclear and hydro. The complexity of the rest, with its now-you-see-it, now-you-don't volubility, with its fiefdoms and awkward economics, with its ties to knotty physical systems, and with its unpredictability across domains—it's all a terrible headache to an industry whose job is to keep the lights on no matter the social, technological, fiduciary, meteorological, or political circumstances.

And then, after all of this, Secretary Chu smiles. He looks down upon them from his podium and drops the bomb they all knew would come.

"The Obama administration," he said, "has set a goal of 25 percent renewable energy use by power producers by 2025; ten percent by 2012." And before the men in attendance could leap to their feet and demand with one unmodulated voice: "Yes, but HOW!?" Secretary Chu continued unperturbed through the rest of his PowerPoint presentation, which amounted to a tidy list of solutions to the grid's known woes: use smart grid technologies, curb customer demand, end peak demand, develop grid-scale storage, add a nationwide extra-high-voltage DC/AC transmission network, reduce line congestion, encourage interregional cooperation, develop interoperability standards, increase government investment, train a new generation of grid operators, and integrate large numbers of electric vehicles.

This is the "solutions" laundry list, and a pretty thorough one, especially if we add deployable energy efficiency to the mix. Almost all of it lands squarely in the laps of the utilities and their regulators—sometimes friends, sometimes enemies, always themselves trying to balance investments with profits while maintaining infrastructural integrity. Because if they don't there is no state entity that can just step in and make the grid work if the utilities have to declare bankruptcy or otherwise fail at their appointed task. There is no backup system to the grid. If we can't make it work, then it doesn't. It's as simple as that.

If you listen carefully you will notice that Chu's laundry list is the same set of solutions, in part or in whole, that have become the talking points of anyone interested in reforming the grid for most of the last decade. But rattling off the list is not the same thing as getting the state of California, balky after the deregulation debacle of the late 1990s, to talk to anybody about cross-border transmission. Pointing out a series of best practices is not the same as persuading consumers to let their obtuse utility company take remote control of their home air-conditioning. And throwing money at the problem is not the same as figuring out how to get Vermonters (or anyone else) to allow high-voltage lines to be built in their backyards.

The complexity of the situation is way beyond anything actually captured by the talking points or anything resolvable by a repeated return to stated goals.

We know, with the benefit of hindsight, that the interim goals of the Obama administration's 2009 renewable energy plan have not exactly been met. Though the numbers do look surprisingly good on first glance. According to NREL (the National Renewable Energy Laboratory—a thirty-five-year-old federal institution that is something like the NASA of renewable energy), 12.4 percent of America's electricity was made from renewable resources in 2012. Read the small print, however, and it immediately becomes clear that slightly more than half (55 percent) of the total still comes from hydroelectric power.

Drought years to the side, the dams are steady. In 2000 they were generating about 78,000 megawatts, and in 2012 they were generating about 78,000 megawatts, though this should rise somewhat in the near future as the big old dams are "returbined"—their efficiency raised by the integration of newer technology. In most cases, however, when a "renewable energy" goal is issued by an administration, or anyone else, it is usually cast in terms of "nonhydro" renewables. And that number, for the United States as a whole in 2014, was 6.76 percent—though, because electrical production is still largely a local affair, it's much more than that in certain pockets, such as the Columbia River Gorge, California's Altamont Pass, Arizona's deserts, Hawaii, the Dakotas, Iowa, and West Texas.

This 6.76 percent renewable generation within our nation's still largely fossil-fuel-driven electrical economy might make wind and solar seem negligible in absolute terms. However, a closer look at the numbers reveals something remarkable, something that grid engineers already know: the recent growth in these two domains has been nothing short of explosive. In 2012, wind power installations accounted for 75 percent of all new generation in the United States, while installed solar, still a tiny piece of the electricity pie—only 0.3 percent of the on-grid electricity in the country—was nevertheless up by 83 percent over 2011 (and in 2011 it was up 86 percent over 2010). If in 2012, a banner year for American solar, only 30 MW of new concentrating solar power was brought online, then 2013 is nothing short of meteoric—with 900 MW planned. That's a 3,000 percent increase in a single year.

In 2015, the Obama administration virtually promised that these trends will continue upward for at least the next fifteen years, by legislating a 30 percent cut to 2005 CO_2 levels by 2030. The largest producers of CO_2 in the United States are coal-burning plants for making electricity, and the only way to meet these goals is to close hosts of them: "The ambitious rules hope to remake the nation's electricity system by closing hundreds of heavily polluting coal plants while rapidly expanding the use of natural gas plants, wind and solar power." In response to which, Nick Akins of American Electric Power, a Midwestern utility, responded with a simple threat: "If the proposed rule stands, there will be blackouts."

Nor do these "national trend" numbers include home installation of solar panels, which are contributing in their own way to the mounting crisis of infrastructural management. Though there are issues of excess and shortage tied into "net-metering"—when electric companies pay homeowners for the power their solar panels feed back into the common system—this crisis for utility companies is as much one of cash as it is of current. In certain expensive markets, like Hawaii and Southern California, and in certain sunny ones, like Arizona and, recently, New Mexico, homemade solar power now costs about the same or even slightly less than grid-made power. Why, then, pay a utility company for something you can make for yourself? No good reason at all. Quite suddenly, the utilities aren't earning enough money to perform basic upkeep on the grid, though all of their customers are still using it. Solar-panel owners feed power into the grid during the day, but they draw electricity exclusively from the grid in the evening and at night. To cover basic infrastructural costs utilities in regions with a lot of rooftop solar are charging those customers without solar panels, the ones still getting all their power from the grid, higher rates. This of course leads these folks to switch to solar as well. The situation has gotten so bad in Hawaii that in 2015 the state's utility refused to enroll any more customers into net-metering programs. People can still put solar up on their garage roofs in Hawaii, but the utility won't connect to them, won't pay for the electricity they generate, and won't offer any kind of deal to homeowners on power consumed after dark. This cycle hadn't yet reached crisis level in 2009, when Chu was listing the known woes of power companies. It's at crisis level now.

What we are bearing witness to are the early days of a variable and distributed generation revolution. Electricity is being made everywhere, by power producers of all sorts and sizes, and increasingly from uncontrollable and largely unpredictable means. And because of an awkward piece of legislation called the Energy Policy Act (1992), which laid the foundation for the deregulation of the electricity industry, in many places not only have the utilities lost control of who makes power and how and where they make it, but they have also lost the right to own power plants themselves.

The Energy Policy Act separated electricity generation by law from electricity transmission and distribution (a divorce formalized by the Federal Energy Regulatory Commission's Order 888 issued in 1996). In effect this means that private companies can build condensed solar power plants wherever the sun shines hottest, individual home owners can mount solar panels on anything that doesn't move, and multinational conglomerates, or farmers, can install wind farms wherever the wind blows most ferociously—as well they should, for these are the sites that are most efficient when it come to the generation of electricity.

What is new with the Energy Policy Act is that these investors in electrical generation, large and small, don't need to give much thought as to how the grid, in often very out-of-the-way places, might deal with the influx of unpredictable power. Nor do they need to care for how utility companies will manage the task of keeping people's lights on when they are faced with the problem of too much power one instant, and too little the next. And even where the utilities do have a modicum of control over the stability of generation, they are losing control of their revenue streams, through rooftop solar, through the loss of big power plants, through the advent of real-time electricity markets, and through interventionist rate making by regulatory agencies that control how much customers will be charged for their electricity. It begins to seem that in the not too distant future the companies we now call "utilities" will become stewards of the wires and little more. But the wires, of course, are the only piece of the whole system that generates no revenue save a small rental fee to those who use them to pass electricity from one cash cow power plant to a thousand or a million paying customers.

For the moment this is mostly a problem in the West, on the part of the grid known as the Western Interconnection, and in Texas, which has its own grid. With numerous offshore wind farms planned in Lake Erie and in the Atlantic, off the Eastern Seaboard, the renewable power problem besting grid managers on the Western Interconnection is about to become an onus on everybody.

Renewables and their scattershot siting are not what make America's electricity difficult to manage in the second decade of the twenty-first century. They just brings to light a problem that has been characteristic of our grid for more than half a century: it was made to be managed according to a command and control structure. There was to be total monopolistic control on the supply side of great electric loop—which included generation, transmission, and distribution networks—and ever-increasing yet always-predictable consumption on the customer side of things. Electricity would move from one to the other, while cash would move in equal measure in the opposite direction.

This system was always partly fantasy, but it also mostly worked for a long time. Even the early big blackouts, like the one that took down much of the Eastern Interconnection in 1965, were to be blamed more on systems complexity than on flaws in the logic undergirding the grid as a whole. Today it's a different story.

Every time America changes, whether a little bit or a lot, infrastructure lags behind. The things we build, especially the big things, and the institutions we invent to support these are far more permanent than the ways we choose to live. The 1950s were not the 1970s. People lived in different parts of the county, they bought different products in different quantities, they consumed different amounts of power at different times of the day, they lived in different-sized houses, pursued different professions, and raised their children with different values. Yet the grid of the 1950s was in many ways the grid of the 1970s. And the grid of the 1970s was in many ways that of the 1990s. For the most part it is still our grid today.

When it comes to our electrical grid, decades pass, half centuries pass, and the logical structures that underlie its mass, most of its machinery, and many of the people educated to work on it age, are patched up but are rarely replaced. And then something happens to disturb the balance like the Energy Policy Act or the mass deployment of some really good wind turbines, or a 50 percent drop in the price of solar panels and the whole system reels. The grid, its values, and its base technologies have been out of true for decades, but renewable and distributed forms of power generation have pushed the whole system over the edge of the easily recoupable.

The grid will have to be reimagined, it will have to be reinvented, and parts of it will have to be rebuilt. This would have happened without the mass introduction of wind and solar power, but these have hastened the realization of the necessity of change. Or, to borrow the words of a recent article in the *Los Angeles Times*: "The problem is that renewable energy adds unprecedented levels of stress to a grid designed for the previous century."

It's worth considering in more detail what this previous century's grid actually is, where it came from, and why we have so long retained its most basic premises and components.

* * *

Our grid might have long been an inflexible, brittle, monopoly-managed monolith, but that is not how its story started out. In the beginning, electricity was a highly local affair. At times, in fact, it seemed we might not end up with a national grid at all, but rather a system of household-sized generation plants with no wires at all between buildings. Then for a while we also had a bunch of "microgrids" with a generation plant or two and a system of wires for a relatively speaking tiny "community" of users. Nowadays this is how quite a few college campuses, prisons, and military bases make their power, but back in the early days of electricity, unlike today, these designated grids all ran different voltages of electricity. They all also overlapped geographically. There was one voltage for streetcars, one for the lights, one for industrial concerns, and each of these had its own private system of wires. There were so many wires; the sky was a black spaghetti tangle of wires. In the late 1800s electrical infrastructure was an absolute mess.

From these inauspicious beginnings we got a national grid with power plants far from view, long loping lines between us and them and, nearer at hand, distribution networks strung through neighborhoods, that link individual houses by means of pole-top transformers to the system as a whole. That this is how electricity works in America is not the logical outcome of physics, it's the product of cultural values, historical exigencies, governmental biases, and the big money dreams of financiers.

In order to understand why we have a grid at all—and why we have this one in particular—we need to jump back a bit, to the earliest days of electrification, and watch how the grid was invented and built into a brittle, inflexible machine of massive scope and unimaginable complexity that is nevertheless remarkably egalitarian. Our grid delivers electricity as easily to the poor as it does to the rich, and it blacks out privilege almost as often as poverty.

CHAPTER 2

How the Grid Got Its Wires

Electricity is not like anything else. It's not a solid, or a liquid, or a gas. It isn't quite like light or heat. It doesn't move like the wind or the tides. It doesn't combust like oil or burn like wood. If it resembles anything at all from the world we know, it is in some way like gravity. Which is to say, it is a force to be reckoned with.

Unlike gravity, electricity is lethal, most especially in its wild form—lightning—though the threat of electricity's killing side is always there, even when it's been most thoroughly domesticated. This is why we don't touch downed wires, don't do much home electrical repair ourselves, and discourage children from sticking bobby pins into outlets. In the early days of the grid, people didn't even change their own bulbs for fear of electrocution. Instead, a trained bulb replacer was dispatched on a bicycle balancing a giant sack of hand-blown vacuum-filled ampules on his back to replace all the bulbs that had burned out during the previous weeks.

Although we now know that electricity is a force and we understand in nuanced ways how it works—much of which will be explained in this chapter—what is curious about the grid's earliest days is that then we did not. Nobody knew what electricity was until long after Edison's first grid was built and had burned down. A circus elephant

.net/article/show/single/en/6228-Nuclear-not-fracking-is-the-answer-to-China-s-future-energy-needs-.

nuclear power development: Wei Wei (2013).

"will need to be replaced by new plants": James E. Rogers, in his foreword to Peter Fox-Penner's *Smart Power Anniversary Edition: Climate Change, the Smart Grid, and the Future of Electric Utilities* (Washington, D.C.: Island Press, 2014), xv.

twenty times as much solar: These numbers are from an August 2015 speech by Barack Obama introducing his "Clean Power Plan," the aim of which is to reduce carbon emissions by 2030 to 32 percent lower than they were in 2005. Power plants are responsible for about one third of current carbon emissions nationally, and thus the plan should have a noteworthy impact on plant retirements, upgrades, and choices of replacement technology. Since the plan also addresses methane emissions, a significant portion of which occur during the extraction of natural gas, it will also affect the cost of using natural gas as a replacement for coal or nuclear.

about 7 percent overall: To be precise, nonhydro renewable energy sources amount to 6.76 percent. Wind accounts for 4.42 percent, biomass wood for 1.04 percent, biomass waste for 0.52 percent, geothermal for 0.39 percent, and 0.39 percent is from solar. "How Much U.S. Electricity Is Generated from Renewable Energy?" U.S. Energy Information Administration, June 12, 2015, http://www.eia.gov/energy_in_brief/article/renewable_electricity.cfm.

it's a stunning 30 percent: "U.S. Wind Energy State Facts," American Wind Energy Association, accessed September 15, 2015, http://www.awea.org/resources/statefactsheets.aspx?itemnumber=890.

dropped to negative 64¢: Eric Wieser, "ERCOT Sets Wind Generation Output Record Sunday, Real-Time Power Prices Move Negative," *Platts McGraw Hill Financial*, September 14, 2015, http://www.platts.com/latest-news/electric-power/washington/ercot-sets-wind-generation-output-record-sunday-26208539.

has more than doubled: It was 3 percent in 2009, according to Dr. Stephen Chu, the Nobel Prize–winning physicist and former U.S. secretary of energy who spoke at Grid Week in Washington, D.C. (see chapter 1).

Maine is aiming for 40 percent: Jocelyn Durkay. "State Renewable Portfolio Standards and Goals" *National Conference of State Legislatures*. October 14, 2015, http://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx.

Hawaii is aiming for 100 percent: Ari Phillips, "Hawaii Aims for 100 Percent Renewable Energy by 2040," *Renew Economy*, March 13, 2015, http://reneweconomy.com.au/2015/hawaii-aims-for-100-renewable-energy-by-2040.

"month's worth of purchases": W. Kempton and L. Montgomery, "Folk Quantification of Energy," *Energy* 7(10) 1982: 817–27.

"benefits of their actions": Kathryn Janda, "Buildings Don't Use Energy: People Do," *Architectural Science Review* 54, 2011: 15–22.

would have happily left behind: We can see this history of uneven development in Vermont, where in 1920 only 10 percent of the farms in that state had electricity; by the start of the Great Depression, the percentage had risen to 1 in 3. In the decade after the passage of the Rural Electrification Act (1936), most of the state's rural residents had electrical power, in their milking parlors if not yet in their homes. And in 1963—almost a hundred years after America's first electric light—its final two towns, Granby and Victory, Vermont, got their wires and became a part of our grid. This is just one example, but it's an important one: electrification was not an all-at-once affair; in some spots its history is far thinner than in others. From a radio commentary by Vic Henningsen on Vermont Public Radio, August 27, 2015, http://digital.vpr.net/post/henningsen-statewide-service.

"works in practice, but not in theory": Alexandra von Meier, "Electronic Power Systems," September 17, 2010, Public Lecture 14 Energy Systems, University of California, Berkeley.

America, didn't know how to change: In part, according to Richard Hirsh, utility hiring practices selected for the risk-averse, noncreative, bottom of the engineering barrel. This led to conservative reactions to new problems. Richard Hirsh, *Technology and Transformation in the American Electric Utility Industry* (Cambridge: Cambridge University Press, 1989).

(utility since the Depression): The California blackouts in 2000–2001 were not caused by degraded infrastructure but by a perfect storm of bad legislation, criminal profit-mongering, and poorly designed infrastructure (see chapter 4).

"emissions of greenhouse gasses": "Economic Benefits of Increasing Grid Resilience to Weather Outages" (2013), 3.

constructing eighty-three new microgrids: "Microgrid Deployment Tracker 4Q15," *Navigant Research*, accessed December 15, 2015, https://www.navigantresearch.com/research/microgrid-deployment-tracker-4q15.

CHAPTER 1: The Way of the Wind

power 4.5 million households annually: The Foundation for Water & Energy Education estimates that there is the potential to produce 100,000 MW in the Gorge, though this would require blanketing much of the available space with turbines. "Wind Farms & Northwest Energy Needs," *Foundation for Water & Energy Education*, accessed December 1, 2013, http://fwee.org/nw-hydro-tours/how-wind-turbines-generate-electricity/wind-farms-northwest-energy/.

any fuel will do: Dried cow dung, like oil, is a negligible source of electricity production in the United States.

over the sun just as quickly: The problem with solar power, and to a lesser degree wind power, isn't only these dramatic instances of total cloud cover or breeze-to-stillness, but also that generation is actually very jiggly. Solar panel output shifts five or six times a minute, and a field of solar panels doing this in sync is difficult for the grid's automation to balance.

a full twenty-four hours to turn either up or down: Eric Hittinger, J. F. Whitacre, and Jay Apt, "Compensating for Wind Variability Using Co-Located Natural Gas Generation and Energy Storage," *Carnegie Mellon Electricity Industry Center Working Paper* CEIC-10–01 (December 2010).

can go to Mars: 55.8 million miles in five minutes. Mars's distance varies from Earth; sometimes it's closer than this, sometimes farther away. But it wouldn't be wrong to say that on a good day, under perfect transmission conditions, we could send a current from Indiana to the red planet in about five minutes.

before its sixty seconds are up: The 2003 blackout of the Eastern Seaboard, the third-largest blackout in this history of the planet, essentially happened in thirty of the seconds between 4:11 and 4:12 p.m. There were a lot of problems leading up to these very bad thirty seconds, but the imbalance that tipped over into darkness propagated in about the time it takes to draw in a breath.

meltwater are more than sufficient: On an average blustery day, the wind power in the Gorge produces enough power for three times as many people as live in Oregon.

"Northwest has ever experienced": Ted Sickinger, "Too Much of a Good Thing: Growth in Wind Power Makes Life Difficult for Grid Managers," *Oregonian*, July 17, 2010, http://www.oregonlive.com/business/index.ssf/2010/07/too_much_of_a_good_thing_growt.html.

let the water out through spillways: There is also pumped storage on the Columbia, and excepting years of extreme drought this is all also full in May.

from dinner plates to Grandma's memory bin: Full disclosure: my father, Bill Bakke, did this (made it illegal for the spillways to operate in the spring). He is not well loved by many in the electricity industry, but we as a nation still eat a lot of Pacific salmon, and without this law the palates of a generation would already be otherwise.

ferocious speeds in the onslaught of wild air: Most newer wind turbines can be turned down via adjustments to pitch and yaw, this was not so much the case in 2010. Such a basic technological improvement is one of the many small things under way that make the integration of variable renewables into our national electricity system increasingly plausible.

care for the grid: In 2013, 42 percent of Spain's electricity demand was covered by renewables, 21.2 percent wind, 3.1 percent solar photovoltaic, 1.7 percent solar thermoelectric, 2 percent renewable thermal, and 14.2 percent hydroelectric. "Corporate Sustainability Report 2013: 4. Committed to Security of Supply, Efficient Management and Innovation" (Red Eléctrica Corporación, May 7, 2014), http://www.ree.es/sites/default/files/02_NUESTRA_GESTION/Documentos/memoria-2013/English/RC/RC13_07_en.pdf. Despite this centralization, Spain's grid suffers from similar kinds of problems as Iberdrola faces in Oregon. For example, around Easter 2013, Spain saw "extremely low demand, high production of hydroelectricity with dumping in some basins, and a high producible wind power . . . Given this scenario, to ensure system security it was necessary to give orders to reduce production to a level not seen to date. These reductions affected, among others, nuclear production an exceptional fact [*sic*] and unprecedented since 1997." "Corporate Sustainability Report 2013" (2014), 53.

machines are turned on and running: There were 2,760 turbines in 2011, so three thousand in 2014 is an educated guess. Miriam Raftery, "A Walk Through the Wind Farm with Iberdrola," *East County Magazine*, April 2012. http://www.eastcountymagazine.org/walk-through-wind-farm-iberdrola.

electricity these machines make: Some of this has to do with money, but a lot of it has to do with the way the utilities are run and managed. Historically they have been given a form—the so-called "natural monopoly"—that is slow to change, innovate, or cede power to anyone else. This is history and the principal topic of chapters 3 and 4.

line out to the site: The largest wind farm in Texas as of 2015 was the Roscoe Wind Farm, owned and operated by E.ON Climate and Renewables, which began operating in 2009. Eileen O'Grady, "E.ON Completes World's Largest Wind Farm in Texas," *Reuters*, October 1, 2009, http://www.reuters.com/article/2009/10/01/wind-texas-idUSN3023624320091001#1Oc6qUxRCSELa3Zr.97.

"The turbines installed at the farm range in between 350ft and 415ft tall, and stand 900ft apart. Out of the total number of turbines employed, 209 were the Mitsubishi 1000A model, with a rated output of 1.0MW." From "Roscoe Wind Farm," *Power Technology*, accessed November 8, 2015, http://www.power-technology.com/projects/roscoe-wind-farm/.

1.5 MW GE model: "The widely used GE 1.5-megawatt model, for example, consists of 116-ft blades atop a 212-ft tower for a total height of 328 feet. The blades sweep a vertical airspace of just under an acre. The 1.8-megawatt Vestas V90 from Denmark is also common. Its 148-ft blades (sweeping more than 1.5 acres) are on a 262-ft tower, totaling 410 feet. Another model becoming more common in the U.S. is the 2-megawatt Gamesa G87 from Spain, which sports 143-ft blades (just under 1.5 acres) on a 256-ft tower, totaling 399 feet." "FAQ:

Output from Industrial Wind Power," *National Wind Watch*, accessed November 8, 2015, https://www.wind-watch.org/faq-output.php.

"The average nameplate capacity of newly installed wind turbines in the United States in 2014 was 1.9 MW, up 172 percent since 1998–1999." From "2014 Wind Technologies Market Report" (U.S. Department of Energy, August2015),http://energy.gov/sites/prod/files/2015/08/f25/2014-Wind-Technologies-Market-Report-8.7.pdf.

"done right it's a huge opportunity": These quotes are from the Sickinger (2010) article. Manizer and I mostly talked about domestic hot water heaters and how to make interregional power swaps like the Western Doughnut the norm. These issues are addressed in chapters 8 and 9.

from renewable resources in 2012: A negligibly higher 13 percent in 2014. "How Much U.S. Electricity Is Generated from Renewable Energy?" (2015).

as a whole in 2014 was 6.76 percent: "How Much U.S. Electricity Is Generated from Renewable Energy?" (2015).

Dakotas, Iowa, and West Texas: Thomas P. Hughes, *Networks of Power: Electrification in Western Society* (Baltimore: Johns Hopkins University Press, 1983).

75 percent of all: "U.S. Wind Energy State Facts," American Wind Energy Association, accessed September 15, 2015, http://www.awea.org/resources/statefactsheets.aspx?itemnumber=890.

a 3,000 percent increase in a single year: These numbers are from the *2012 Renewable Energy Data Book* (National Renewable Energy Laboratory of the U.S. Department of Energy, October 2013), http://www.nrel.gov/docs/fy14osti/60197.pdf.

"there will be blackouts": Coral Davenport, "A Challenge from Climate Change Regulations," *New York Times*, April 22, 2015, http://www.nytimes.com/2015/04/23/business/energy-environment/a-challenge-from-climate-change-regulations.html.

"grid designed for the previous century": Evan Halper, "Power Struggle: Green Energy versus a Grid That's Not Ready," *Los Angeles Times*, December 2, 2013, http://articles.latimes.com/2013/dec/02/nation/la-na-grid-renewables-20131203.

CHAPTER 2: How the Grid Got Its Wires

during the previous weeks: I use the term "electrocution" here, but in the early days of electricity. "No standard words had yet been adopted for killing or death by electricity. Ones pondered by the *New York Times* included electromort, thanelectrize, celectricise, electricide, electropoenize, fulmen, voltacus, and electrocution." Nicholas Rudduck, "Life and Death by Electricity in 1890: The Transfiguration of William Kemmler," *Journal of American Culture* 21, no. 4 (1998): 86, note 8.

without being properly understood: On August 1, 1890, William Kemmler, a convicted murderer and inveterate drunk, was put to the chair and slowly roasted to death over a period of about eight minutes. Despite Edison's assurances (for he had designed and built the chair) that Kemmler's would be a swift, humane, and painless death, and despite the fact that the chair had been tested and retested and electricity of varying voltages had been used to efficiently kill all manner of things, from stray dogs to a retired circus elephant, Kemmler did not go out as planned. It was not his size that was the problem; Kemmler was a thin man, petite by today's standards. Nor was it a lack of sufficient voltage on the coal-fed, steam-powered 1,680-volt dynamo used to power the chair. The problem was that the wire connecting the chair in the Auburn prison to the dynamo in its basement was also being used that day to light thirty-six bulbs strung in parallel, which collectively siphoned off about a thousand volts, leaving a mere trickle of electrical capacity for the chair. What remained was enough to kill Kemmler eventually, but certainly not enough to kill him fast. It was a highly publicized horror that effectively ended Thomas Edison's career.

its ineffable physics: Gérard Borvon, *Histoire de L'électricité: De L'ambre à L'électron* (Paris: Vuibert, 2009), 1.

something like an instant: The first working telegraphs appeared in the 1830s, while the 1850s to 1870s saw the advent of intermittently functional transatlantic telegraphy.

displaced a less effective technology: Or as Isaac Asimov once said, "No steam engine or internal combustion engine, however powerful or however perfect, could run a television set (in the absence of electricity) with the direct simplicity electricity makes available to us." From a funny little pamphlet published by the U.S. Atomic Energy Commission: Isaac Asimov, "Electricity and Man" (United States Atomic Energy Commission Office of Information Services, 1972), http://www.osti.gov/includes/opennet/includes/Understanding%20the%20Atom/Electricity%20and%20Man.pdf, 19.

with it remotely fueled electric lighting: The power plant built at Niagara Falls was turned on in 1895, though it did not begin to transmit power to Buffalo until 1896.

always secondary to the story: The first "modern" dynamo for use in industry was invented independently by three different men in 1866; though Faraday gets the true credit in the early 1830s for a machine that makes electricity, his design was not a precursor of the next-generation machines, even though his ideas were essential to these.

by incandescent bulbs: Here Richard Moran was quoting a reporter from the *New York Times* in his book *Executioner's Current: Thomas Edison, George*