Chapter 12

Electricity

The future of energy is electricity. It intermediates the two key sources of clean energy, solar and wind power. This chapter explains how electricity works today and how its scale can be increased.

1 Why Electricity?

Electricity is the most versatile form of power. It is the jack-of-all-trades. It can heat and light homes, power cars, drive industrial processes, and power all our gadgets. It can be easily, cheaply, and efficiently converted into other forms of power. Table 1 shows conversion efficiencies. For example, the electric motor in a Tesla has an efficiency of about 90% (compared to only about 25% for a gasoline motor). Even refrigeration, a difficult thermal conversion, can be accomplished at greater than 50% efficiency.

In contrast, fossil fuels are one-trick ponies. They can only generate heat efficiently. For anything else (such as kinetic or electric power), fossil fuels require further, rather inefficient, conversions, typically reaching no better than 30–40%. (If power comes in electric rather than fossil-fuel form so that conversions can be avoided, humanity may need only half as much primary power as it does today.) In addition, electricity can be routed with a transmission grid to the place where energy is needed at the speed of light, although there are losses in the transmission process.

Best of all, the basic technology required to transition from a fossil-fuel to a clean electrical economy is already available today. Transportation was the

Table 1. Energy Conversion Efficiency

	Energy Type				
	Cool	Heat	Kinetic	Light	Chemical
Conversion From Electrical	Refrig 50%	Heater 100%	Motor 90%	LED 50%	Electrolysis 70%
Conversion To Electrical	… Turbine … 50-90%		Generator 90%	Solar Cell 20%	Fuel Cell 60%

Note: Chemical means either fossil or hydrogen. Basic Source: Wikipedia

largest remaining undisputed domain of fossil fuels, but Tesla jump-started the electric car industry in 2012 with its Model S. All major car makers have announced that they will stop making combustion-based cars and light trucks within a decade. Governments are following, too. California will only allow clean cars and trucks to be sold by 2035.

Although technological breakthroughs are always welcome (and indeed likely), the green electric transition will require no moonshots with uncertain probabilities of success. There are just engineering, economic, and business challenges, and we already know that they are solvable. It remains only a matter of research, development, deployment, implementation, coordination, and scale.

Unfortunately, the world is also not yet fully ready for 100% clean energy or even just 100% clean electricity. Our chapter will explain why. The world will be ready soon, though, and there is already a lot that can be done today.

2 Not All Electricity Is the Same

Electricity is always just electrons, but from an economic standpoint, not all electricity is the same. For instance, electricity in the Sahara, where it is inexpensive to generate from solar energy, is not as valuable as electricity in Germany, where it is needed for industry. (It is too expensive and lossy to string power cables from the Sahara to Germany.) Almost everywhere, electricity at 6–8 pm (when demand typically peaks) is more valuable than electricity at 4–6 am (when demand typically troughs). Furthermore, the cost of electricity at the generation plant is only about half of the cost of delivered retail electricity. Someone needs to be paid to build and manage the plants, store power, maintain the grid and transmission infrastructure, handle billing and collections, and so on.

Different technology mixes will also dominate in different locations. Geothermal power can work in California or Iceland. Wind power can work in Chicago and Great Britain. Solar power can work in Phoenix and Mexico. Hydroelectric dam power works in Oregon and Norway. But these technologies may not work elsewhere. In contrast, other technologies, like nuclear power or batteries, can work everywhere.

Suppliers and customers also need to consider that both electricity supply and demand are constantly changing. The allocation problems are so complex that not even the smartest and most benevolent government could plan them perfectly. It's a patchwork of educated guesses.

Shortest-term, there is predictable daily demand variation. Electricity demand usually peaks around 8pm. But weather patterns (and with it both supply of and demand for power) can change, some predictably, some unpredictably. A heat-wave can increase the demand for air-conditioning services. A cold-wave may reduce the available wind capacity. Medium-term, there are seasonal differences in supply and demand — summer and/or winter usually require more power than spring and fall. Long-term, plants have to be built today with lifespans of thirty years or more. Better technology may arrive and obsolete the plant. People may move to different locales. Bitcoin mining demand may increase or decrease. Investing in large power plants involves large, risky decisions and is not for the faint of heart.

3 Basic Electricity Provision

Let's explain how power works today. The United States has approximately 1.2 TW of generation capacity. The largest power sources are natural gas (45%), coal (20%), wind (10%), nuclear (10%), hydro (10%), and solar power (5%). (We will explore these numbers in greater detail in Table 11, where we also provide numbers for China, the world, and predictions for 2050.) Plants don't run all the time, so the power mix is not representative of the energy mix. Instead, of the 4 PWh we consume per year, gas covers 40%, coal 20%, nuclear 20%, wind 9%, hydro 7%, and solar 2%.

U.S.	NatGas	Coal	Wind	Nuclear	Hydro	Solar
Power	45%	20%	10%	10%	10%	5%
Energy	40%	20%	9%	20%	7%	2%

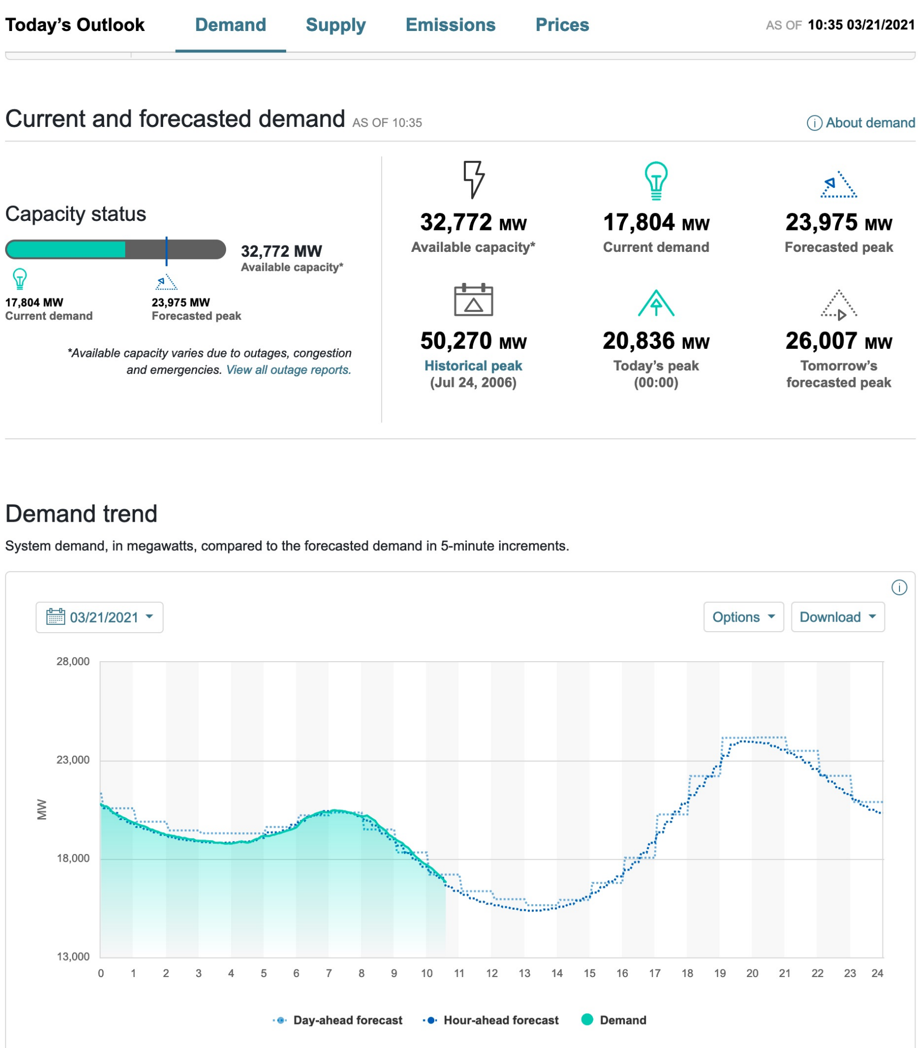
In the last decades, no new coal and nuclear plants have been built in noteworthy amounts; only gas, wind, and solar plants.

It is beyond fascinating how electricity actually manages to arrive at your house. There are thousands of electricity suppliers — some public, some private — with all sorts of different technologies, each with its own generation costs and location relative to the electric grid and local regulations; and of course, there are hundreds of millions of customers. The electricity generators synchronize their power into an irregular interconnected grid, and the consumers tap it whenever they want it. The grid operators are the intermediaries. They route electricity over transmission lines, some over half the distance of the United States. However, transmission lines have limited capacity and are very expensive to build and maintain (and they lose some power in the process of transmission, too), so there are never enough transmission lines. Keeping electricity supply close to electricity demand saves a lot of money.

The most important aspect of electricity relates to daily use patterns, followed by seasonal patterns. Let us explain the system in more detail by describing the daily patterns first in California and then in the United States.

California

Figure 2. Demand on March 21, 2021 in California



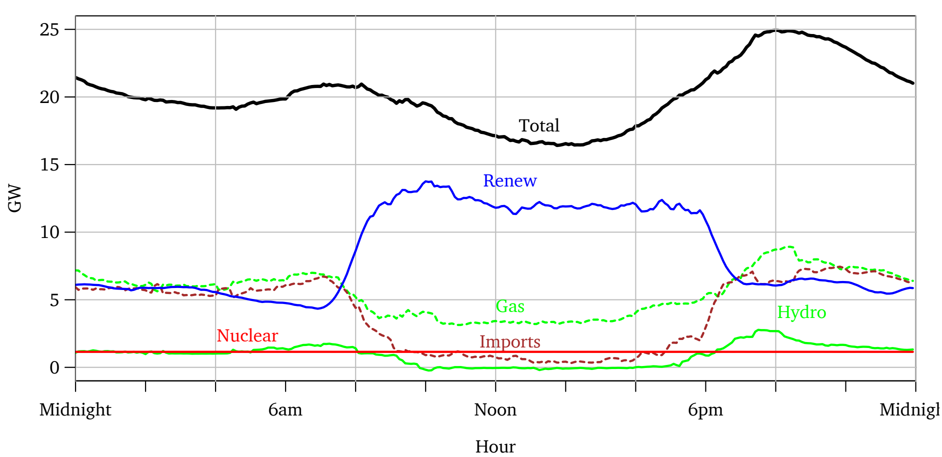
Source: Today's Outlook from CAISO.

The California Independent Systems Operator (CAISO) is the independent non-profit company that operates the grid. Every day, CAISO publishes its anticipated demand on its public computer system, OASIS. CAISO then buys power via both one-day-ahead and real-time auctions from a large number of providers, who all compete to provide power for the lowest price.

Figure 2 shows the demand in California on a random day (March 21, 2021). California typically has nice mid-day weather in Spring, so demand around noon in Spring is modest, between 15 GW and 25 GW. (California also needs to be prepared for days when it needs more than 50 GW of power, such as on hot summer days when a lot of air conditioning and cooling are required.) Demand is highest in the early evening, around 8pm, when people are at home and doing chores. There is also healthy demand all night long, including but not limited to lighting, refrigeration, electric cars charging, and some industrial plants. California's use pattern is similar to that observed in many places around the world.

On this particular Sunday, California expected peak power needs of about 24 GW. This demand was covered by available capacity of 33 GW, of which about 10 GW would never be switched on. The graph also shows discrete time slots when plants were scheduled to start up or shut down (according to forecast demand). Not shown in the figure, on weekdays of the same week, demand was typically about 3 GW higher, with similar day/night use patterns.

Figure 3. California Generation Mix, March 21, 2021



Source: CAISO Oasis.

Figure 3 was recorded the following day. It shows when and how the electricity was ultimately generated. The 10:35am forecast for the rest of the day proved pretty accurate (as CAISO forecasts usually are). Energy provision was lowest at about 17 GW in the early afternoon around 2 pm, coming down from a smaller high of 22 GW at about 8am and peaking at 25 GW around 8pm. Wind and solar covered most of the demand during daylight hours, with wind covering about 5 GW during the night and solar covering about 10 GW during the day. Gas and electricity imports from other states (many from coal plants elsewhere) covered about 5 GW during the night, but not during the day. Nuclear was small but steady throughout the day. Hydro-electric dams began releasing water in the late afternoon.

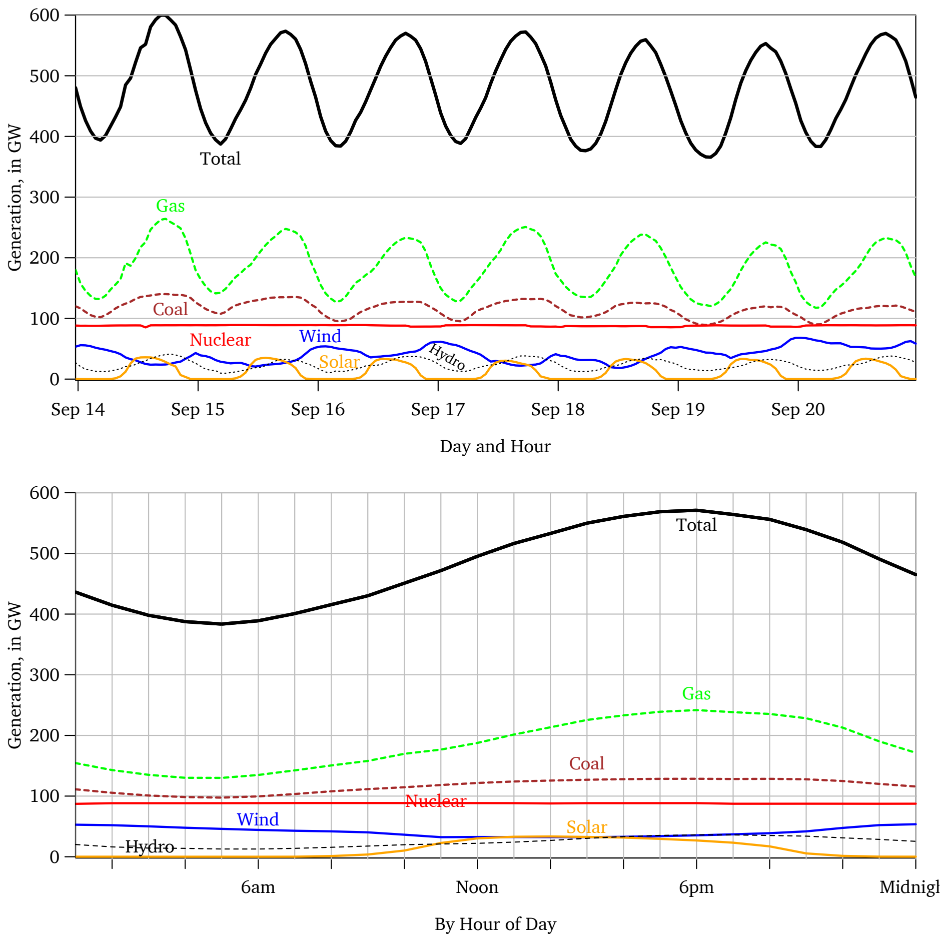
United States

Each state and country has not only its own energy mix but also its own daily and seasonal demand peculiarities. For example, Florida has a lot more demand in the summer, Alaska in the winter. So let's expand our perspective to broader regions.

	Baseload			Base/Dispatch	Intermittent			
Year	Nuclear	GeoT	Coal	Gas	Hydro	Wind	Solar	Other
California 2019	9%	5%	3%	34%	18%	10%	12%	9%
USA 2018	20%	1%	19%	40%	7%	9%	2%	2%
World 2020	10%	0%	37%	24%	16%	5%	3%	5%

California is naturally blessed with a lot of clean energy — not just nuclear and geothermal energy ("GeoT"), but also hydro, wind, and solar. However, the table is a bit misleading, because California sources between 20 and 40% of its electric power at night from out-of-state imports, presumably generated by fossil fuel sources elsewhere. (Another 35% of power at night is natural gas.) In contrast to California, where coal is expensive, coal is cheaper in China. Hydropower is more plentiful in Northern California and China, but not in Australia. And so on. Yet not everything is determined by locales and economics. Plant construction costs tend to be more or less similar everywhere. Nuclear power costs are particularly similar worldwide, because few localized resources are required to build and run one. Worldwide, countries and states also create their own specific issues when they go their own ways on subsidies, regulation, politics, etc..

Figure 4. United States Electric Power Generation, Sep 2021



Source: EIA Dashboard. Fossil fuels are dashed. Hydro consists of about 80 GW of conventional hydropower and 20 GW of pumped storage.

Figure 4 shows the daily electricity generation for the entire United States on a fairly ordinary week in September 2021. U.S. power generation peaks around 6pm (EDT) and troughs around 5am. (This is also roughly the case in local time, too, because relatively more people live on the East Coast — a fact that is then reflected in the national patterns.)

Covering a larger area than California, the U.S. supply and demand seems even more (boringly) predictable. However, this is a little misleading, because it is not economical or possible to transmit large amounts of power across long distances. Thus, solar power in Los Angeles is not useful in Seattle. This means that grid operators must forecast a lot more than just this overall U.S. demand pattern. In particular, wind is nowhere near as steady as the graph suggests. It is true that wind blows relatively steadily during the day *somewhere*, but this somewhere changes around, often unpredictably so.

As in California, nuclear is always steady; solar is always daytime only. Coal, wind and hydro are more steady. Natural gas is the most important single source at any time of the day.

4 Base, Intermittent, Dispatch Power

The two energy mix figures illustrate that not all power is used in the same way: nuclear power is steady, gas power goes up and down, and solar power is day-time only. For this reason, power is sometimes classified into one of three different kinds (admittedly with some overlap):

1. **Baseload power** is from sources that are basically always running. Nuclear power plants are the ideal example. Once built (and staffed), they can supply power at very low marginal cost. They are also expensive to shut down and restart. It makes no sense to turn them off, other than for very rare maintenance.

   Coal plants were also primarily developed as a source of baseload power. However, because the fuel has become relatively more expensive, operators no longer run all the plants all the time but ramp them up or down with on demand. Coal was used to supply <u>almost</u> all electricity in the early 20th century.

2. **Intermittent power** is primarily wind and solar. In large scale, it is the newest and still least important kind of electric power on the grid, but

it will eventually become the most important one. Intermittent power sources operate only when nature cooperates. Not only are there times of the day when they (predictably) cannot generate power, but they may also be (unpredictably) off for entire days or weeks. This variability makes intermittent power the least valuable form.

Solar power is the ultimate intermittent source. The sun does not shine at night, and it's moody even during the day (except in California). In the Northern Hemisphere, there is also less sun in the winter than in summer, when days are longer.

We already mentioned that wind looks more steady in the aggregated U.S. graph in Figure 4 than it should. In real life, from the perspective of where it is needed, wind is quite intermittent, too. However, unlike solar power, wind often blows at night. It is thus more regularly available, but often also less predictable.

Both solar and wind have modest fixed installation costs. However, their marginal post-installation costs are unbeatable — they do not even require fuel. The United States now can obtain up to about 100 GW of peak power each from wind and solar farms, about 1/10 of its installed total generation power. This is about the same magnitude as nuclear power and not far off from coal power. However, given its intermittent nature, wind and solar cannot be replacements for those two. Their power is less available and far less valuable. By 2050, wind is forecast to offer peak capacity of about 400 GW, solar a whopping 1,000 GW.

3. **Dispatchable power** could also be called "stored power." It is electricity that can be delivered on (short) notice at the operator's discretion. Dispatchable power was always needed for handling above-average demand, as in the evening. However, with the arrival of large amounts of intermittent power, dispatchable power is now becoming far more important.

   Its flexibility makes dispatchable power the most valuable and most expensive form of electricity. The big economic problem with all dispatchable power plants is that they sit idle much of the time and ramping up/down reduces their lifespans. Thus, the ideal dispatchable power would have low fixed costs and high capacity, but it could tolerate higher marginal (fuel) costs. We will cover storage in greater detail in Section 6.

If electricity demand were constant over time, we would only need to compare baseload power on the one hand against combined intermittent-plus-dispatchable power on the other hand. That is, it would make no sense to team up baseload power with intermittent power. But with varying demand, the two typically have to work in combination. Furthermore, when it comes to seasonal storage rather than diurnal storage, dispatchable storage capacity may run out. In such cases, base power can become more important, too. Moreover, the distinction between the two need not be as clear over the long run. Even base power plants can be turned into dispatchable plants by adding a heat reservoir. For example, instead of converting the thermal heat from a nuclear plant immediately into steam and hence into electricity, the plant could heat up a molten-salt reservoir that could then be tapped on demand — of course, with an efficiency loss.

5 Technologies For Generation

The fixed construction costs of plants are often the biggest cost component of electricity generation. Once built, the fixed cost is sunk and becomes largely irrelevant. Thus, the single-biggest cost difference among electricity plants is not what type they are, but whether they have already been built or not. With the exception of coal, the cost of fuel ranges from modest to trivial.

Ergo, in the United States, it still makes economic (not environmental) sense to run an already-built coal plant, even if no sane investor today would build a new coal plant. A coal plant can cost $1 billion and has to be profitable for 30 to 50 years. Who wants to build a new coal plant when it is clear that wind and solar plants plus battery storage will be cheaper within about a decade or two, even in the absence of a fossil-fuel tax? Existing coal plants are now just finishing off their 50-year design life.

When we think about electrification of the economy, we have to think in terms of decades. Thus, it is more important to take the perspective of building the next generation of plants rather than worrying about what plants are running and aging out at the moment. Consequently, it is the economics of new plants that matters for determining whether the world will move to clean energy or not.

The Levelized Cost of Electricity (LCOE)

The standard measure for the cost of a new plant is the "levelized cost of electricity" (LCOE). This calculation seeks to include everything — from capital construction costs, to the time-value of money, to operating costs,[1] to fuel costs, and so on. In economic terms, the LCOE calculation is based on the present value of all known and projected cash flows (i.e., appropriately discounted by interest rates and summed up).

Beyond the limitation that the LCOE does not matter after plants have been built, it has a second problem: The LCOE relies heavily on projections of the future. For example, if someone were to invent a newer and better technology, one's own plant may suddenly become obsolete. In this case, the construction cost can no longer be amortized over many years, which means that the true LCOE will turn out to be much higher. Unplanned obsolescence is riskier when both the investment cost and budgeted life-spans are high. Many older coal plants have become functionally obsolete much earlier than anticipated – a fact that has made their realized LCOE skyrocket relative to their planned LCOE.

Table 5 is our best attempt to piece together reasonable cost estimates from many sources (especially the National Renewable Energy Laboratory (NREL), the U.S. Energy Information Administration (EIA), the OECD/IEA, Lazard) and others **as of 2021**. The table provides both current (very near-term) and projected future LCOE estimates. The cost figures are broadly representative for many places around the globe. Of course, this statement is not to be taken too literally. Solar power is cheaper in the Sahara, wind power in England, and geothermal power in Iceland.[2]

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[1](Operating costs could further be divided between quasi-fixed costs [what it costs to staff the system] and variable costs [what it costs in fuel, wear, and tear to generate another MWh].)

[2]For example, regional US Variation (Table 3) suggests a range of $30-$40 per MWh for nuclear power, $70-$100 per MWh for battery power, etc. The summary comparisons in the OECD/IEA report across countries are interesting, too.

Table 5. Cost Estimates For Electricity Generation as of 2020 for 2026 in 2020$/MWh

		EIA Estimates for 2026 (in 2020$s)				2050
	Plant type	Runs	Capital	Operation	**LCOE**	Frcst
Intermittent		Average Residential Solar Panels:			**$100**	$30
	Solar Panels	30%	$25	$10	**$35**	$15
	Wind, onshore	40%	$25	$10	**$35**	$20
Baseload						
(Scarce)	Geothermal	90%	$20	$18	**$35**	
	Nuclear	90%	$50	$20	**$70**	$60
(0.5 tCO_2/MWh)	Natural Gas CC	90%	$10	$30	**$40**	$45
(1 tCO_2/MWh)	Coal	85%	$45	$30	**$75**	$65
	Biomass	85%	$35	$55	**$90**	$85
Dispatchable, Limited Capacity						
(Scarce)	Hydropower	60%	$40	$15	**$55**	
Dispatchable, Unlimited Capacity						
	Natural Gas (more below)	10(–50)%	$50	$150	**$200**	

Note: These estimates are our heuristic summaries of information published by the U.S. Energy Information Administration (EIA), the National Renewable Energy Laboratory (NREL), and the OECD/IEA, all quoted in real dollars. Solar panel costs are photovoltaic (i.e., based on the cells that you also see mounted on rooftops and that convert light directly to electricity) in utility-scale farms. CC are combined-cycle plants. Hydropower is partly base, partly intermittent, depending on water availability. The levelized cost of energy (LCOE) summarizes all capital and operation costs, as well as transmission costs. (Transmission costs today [usually in near proximity] typically run about $1/MWh for base 24/7 electricity, $3/MWh for intermittent electricity, and $10/MWh for batteries.) In favorable locations, solar can already be installed at an LCOE $20/MWh as of 2022.

Wind and Solar

Table 5 shows that utility-scale solar cells and on-shore wind power in utility-scale installations are already the cheapest sources of electricity, at about \$35/MWh. (This price already reflects the fact that solar equipment is idle more than half the day when no power can be generated.) Better yet, their costs are still falling. And it seems almost unreal, but the price for utility solar power is expected to fall to \$20/MWh as early as 2030 (and less in Western states). When the sun is shining, electricity will cost only a third of what most generated electricity costs today and a sixth of what retail customers are paying today and still make good money for the builders! By mid-century, daytime power could become almost free, perhaps to be sold at a flat service fee to retail customers, similar to how landline telephone service is sold today. This scenario has been called "energy too cheap to meter." And this future is almost here, too. In Western U.S. states, the LCOE has already been quoted as low as \$20/MWh as of 2022! It is often cheaper to build and run solar than to buy NatGas fuel for an existing power plant.

Residential solar panels are much more expensive (at \$100/MWh) than utility-scale solar (\$35/MWh), partly because installation is more expensive, partly because each house needs some additional equipment (such as an inverter to feed unused power back into the grid). However, rooftop solar avoids many other non-generation costs (long-distance transmission, administration, etc.). This is partly why retail electricity costs about \$120/MWh at your house today — but it also works at night! In a fairer apples-to-apples comparison, residential solar is probably about 30% more expensive than utility-scale solar, not more than twice as expensive. The future will also be a race — will roof-top solar (with local batteries) or industrial-scale solar become cheaper faster? The answer may well depend on the location.

Just as Germany jump-started the wind-turbine sector, with strong subsidies and at great cost to its consumers, California is now trying to jump-start roof-solar generation. Besides forcing the grid to accept electricity from roof solar at high prices, California will require rooftop solar on all new construction. Economists remain skeptical whether economies of scale could bring down the rooftop price of solar so significantly that it will become a predominant technology. It is not impossible. The future will tell. If the experiment succeeds, the most important beneficiaries of Californian competition, scale, and learning about rooftop solar will almost surely not be California alone but the wider world as well.

Natural Gas

The cost of natural gas is low enough that it can be used almost all the time in many places around the world. It is often the cheapest source of *baseload* electric power today. The best 24/7 generators are "**combined-cycle (CC)**" natural gas turbines, which use exhaust heat for a second pass at power generation. They can run 24 hours a day and are designed to take advantage of this 24/7 mode of operation. The cost is \$40/MWh. A fossil-fuel tax could change some of the economics of gas plants. A good rule of thumb would be to add about half the proposed tax on CO_2/tonne — perhaps more if the tax is smart enough to penalize methane leaks at the well rather than just at the generator. With a \$50/tCO_2 tax, the gas price would thus be between \$65/MWh and \$90/MWh.[3] Still, gas would remain competitive for quite a while. Gas supplies about 40% today and will supply 50% of the electric power in the United States around 2050.

There is also a second form of gas-powered generation that is more like dispatchable power. To cover electricity demand during off-times, intermittent sources can be combined with gas turbines. This is often done in regions where natural gas is more expensive. Moreover, plants that do not operate 24/7 are more expensive per MWh generated. The last line in Table 5 shows that dispatched power from such "**peaker plants**" is a lot higher. It is somewhere between \$150/MWh to \$200/MWh. We will come back to dispatched power in the next section.

Geothermal Power

The cheapest *clean* baseload power can be geothermal (\$35/MWh) — heat that comes from the sub-surface of the earth. It is produced from mile-deep wells that tap into the radioactive heat coming from the center of the planet. Unfortunately, drilling these wells and creating the infrastructure to extract energy from them (primarily sending water down the hole and retrieving steam from it) is cheap only in a few limited locations. Otherwise, geothermal energy is rare and expensive. California is blessed because it sits on the Pacific Ring of Fire, where geothermal power is viable and cheap. This is also the case in some other countries, like Iceland, the Philippines,

[3]The \$25/MWh add-on estimate is also in line with the cost of Carbon Capture Sequestration.

and Indonesia. However, geothermal power is currently too expensive for utility-scale electricity generation in most locations.[4]

Technology may or may not cure this sometime soon. Quaise Energy, an MIT spin-off, is investigating a new method of drilling super-deep holes which could make reaching 500°C temperatures viable in almost any location on earth. If you have ever seen a volcano, you understand what awesome power is available for the tapping!

Tidal Power

Earth has yet another untapped energy source: the flow of water due to tides. The easiest way to tap this *very large* power source will probably be in tidal inlets. The New York Times reports that Nova Scotia is very close to installing the first clean multi-GW power plant in the Minas Passage — the "Everest of Tidal Energy in the World." Although tidal power is not base-power or dispatchable power, it is also not synchronous with other clean power and thus more valuable. It is too early to say how much tidal power will be able to contribute to humanity's energy needs.

Nuclear Power

The next-cheapest clean baseload source is nuclear power. It is more expensive at "maybe" \$70/MWh. Yet, this is guesswork because few, if any, new nuclear power plants have been designed and built in the United States and Europe for many decades.

One advantage of nuclear plants is that they can be constructed almost everywhere in the world. They are also often the *only* viable clean alternative where there is not enough wind or solar power. After a nuclear reactor has been built, it provides moderately priced base electricity at about \$40-\$50/MWh. (The fuel itself is dirt-cheap; most of the operational costs stem from staffing and other regular expenses regardless of operation.)

We have already discussed nuclear power in the previous chapter. There are many problems: safety concerns, disposal of used radioactive fuel, potential for nuclear weapons proliferation, political and popular opposition, regulatory

[4]Home builders can also often install geothermal heat pumps in houses that extract heating in winter and cooling in summer from coils that are laid just a few meters below ground.

costs, slow and expensive construction, and so on. But the killer problem is economics. It makes no sense to construct a new nuclear power plant in many places (such as the United States) when natural gas can provide base power for \$40/MWh. Even at a \$50/tCO_2 fossil fuel tax, nuclear power would have a tough time competing. The niche of nuclear power has thus been mostly in locales where natural gas is not available in abundance, such as in France.

Even if natural gas were taxed severely, the economic problem of nuclear energy would still not be solved. There is still the fact that a new type of energy storage could also quickly make wind and solar power dominate nuclear power in terms of cost.

Coal

Coal plants used to produce most electricity just a few decades ago. Today, they produce only about as much power as nuclear plants, about 10% of the U.S. power supply. In China, it is close to 65%!

Table 5 shows that new coal plants are not only unpopular in the United States but also already obsolete at "maybe" \$75/MWh. No one has built coal plants in the United States for at least a decade. If someone did, they would almost surely not operate for the 30 years that coal plants have operated in the past. Even the fuel is too expensive, as it needs to be mined and transported in many locations. Already-built coal plants still remain running at \$30/MWh (although even they are already idling much of the time). Coal plants will disappear from the U.S. grid within a few years — but unfortunately, not from grids worldwide. China and developing countries are still building them in large scale.

Of course, the true social cost of coal electricity is much higher than the generation cost in Table 9.2. The left-most column in the table shows that each MWh of coal produces about 1 tCO_2. With a \$50/tCO2 fossil-fuel tax, the economics would kill American coal even for most plants already built.

There are many ironies here. The free market helped coal dominate, at first because it was cheaper than alternatives, later because coal pollution was not taxed appropriately. Nowadays, the free market has abandoned it. Even ignoring environmental concerns, there are simply better and cheaper alternatives in most locations today — if not natural gas, then nuclear power. Coal plants were essential to humanity's past. They are now the enemy of the future.

Coal's survival in much of the world now depends on the opposite of a free market, wherein governments maintain obsolete regulations and/or are catering to coal mining lobbies and employees. (Worse yet, coal has become an irrational rallying point for some nationalist parties.) It is no longer enough for clean technology to be cheaper than coal. Clean tech also has to overcome the vested and legitimate interests of people whose livelihoods depend on coal.

In the United States, Donald Trump won the swing state of Pennsylvania with 48.2% over Clinton's 47.5% in 2016, partly because he supported coal miners — even though there were only 20,000 left (among 6 million voters). Politicians ignore fossil-fuel lobbies (and farmers) at their own risk.

Unfortunately, as for other countries, many are still building coal plants. As already mentioned, China is by far the worst problem. Its coal plants produce about 30% of the global CO_2 emissions, because about 60% of its electricity comes from coal. In total, China is currently planning or constructing about 250 GW of new coal plants (equal to about one quarter of the *total* U.S. generating capacity). These plants will lock in decades of emissions — a globally devastating plan. Why? After all, by the time the plants will be ready to open, solar power with storage should be cheaper in China than coal. The best explanation is that China now has about 2.5 million coal workers. This is down from about 5 million just a decade ago, but still enough to scare the party.

In terms of coal electricity generation, India is about to overtake the United States and become the world's second problem. Other strong builders include Turkey, Indonesia, Vietnam, and Bangladesh, constructing 20-30 GW, each.

If anyone has a good idea about how to stop or throttle coal plant construction in China (and India), this is the time to speak up. The impotence of global institutions and climate negotiations to meaningfully reduce coal-plant construction activities of these countries only reaffirms our views. Much cheaper and better green technology is still our only hope. We even believe that it could be in the self-interest of the United States and Europe now (though not necessarily for the inventors) to share their best nuclear-plant designs with

Figure 6. Coal Power Plant Status, in GW

	Operating	Construction	Permitted	Announced
OECD	501.0	16.0	5.0	3.9
USA	232.8	-	-	-
EU27	117.8	12.2	-	-
China	1,046.9	96.7	43.0	72.1
India	233.1	34.4	11.7	11.7
All others	≈280	≈37	≈20	≈24
World	2,067.7	184.5	78.9	111.8

Source: Global Energy Monitor Global Coal Plant Tracker, February 2022. The tracker excludes Costa Rica, Estonia, Iceland, Lithuania, Luxembourg, Norway, and Switzerland for OECD; and Cyprus, Estonia, Lithuania, Luxembourg, and Malta for EU27.

all countries for free — taking proper nuclear proliferation precautions, of course.

Finally, if you think the world climate meetings in Scotland in November 2021, marked the beginning of the end for coal, think again. In December 2021, the Wall Street Journal reported that despite efforts to slash carbon emissions, global coal-fired generation is expected to rise 9% and hit a record by the end of 2021. The main drivers of the growth are China and India which together account for roughly two-thirds. As we have said throughout this book, when energy provision is at stake, countries will do whatever is in their own economic interests. That is why continued work to make clean energy cheaper and more reliable is critical.

2023 Update

Estimates are always moving. (Not all our data sources are, however; and we could not rewrite our book every month even if they all did update all the time!) By 2023, both the 2021 estimates and 2050 forecasts in Table 5 were already mildly outdated. The relative LCOEs of clean vs. dirty electricity had changed notably because of higher cost estimates for fossil fuels in the wake of the Ukraine war. Clean energy costs had continued to fall. Shortages of raw material (silicon, lithium, etc.) had not (yet) materialized.

By April 2023, Lazard quoted unsubsidized solar *including storage* LCOEs as \$46-\$102/MWh, wind *including storage* as \$42-\$114/MWh, and NatGas (combined-cyle) as \$39-\$101/MWh. Like the 2021 numbers, these are estimates, not firm quotes. Don't trust them to have great accuracy.

Nevertheless, a clear picture is emerging. For daily electricity, these three cheapest technologies are now neck-in-neck, with local conditions determining which one is cheapest. This local variation is still enough not to render clean energy the least expensive in all locations, but it is getting pretty close. If clean subsidies in the U.S. are also added (or if pollution costs are also incorporated), then even NatGas is barely competitive with wind and solar in most places. The age of clean electricity is arriving quickly. It is only because of the costs of much longer-duration storage and provision that fossil fuels still carry an advantage.

6 Tech for Storing Electric Energy

Dispatchable power is stored energy in a form that is ready for quick release as electricity. The first shoe to a clean future has already dropped. Wind and solar are the cheapest source of electricity today—and they are still getting cheaper. Storage is the second shoe that has to drop.

We have already discussed the most important dispatchable power source in the United States — natural gas. In addition to providing base power, some gas plants function primarily as peaker plants — plants that run only when there is a high demand. Today, natural gas is still marketed to the public as the cleanest fossil-fuel form of electricity (ignoring methane leakage in the transmission). In the future, we expect gas to be marketed as the fossil fuel that makes wind and solar power possible.

If you are like us, when you first hear “electric storage,” your brain probably starts to blink “batteries.” This turns out to be wrong when it comes to utility-scale storage on the grid. Instead, dispatchable power comes in different forms and fulfills different purposes. Most of it is pumped water (hydroelectric dams). It covers about 95% of the world’s storage, which is roughly 170 GW of power and 9,500 GWh of storage. Batteries are less than 5% of this. Roughly speaking, currently all of humanity’s electric storage could power the world for only about 30 seconds, and batteries for a measly 3 seconds. But batteries are the most exciting new technology, so we start with them.

Lithium Batteries

All of today’s best batteries are based on the element lithium. Unfortunately, upon contact with the humidity in the air, lithium catches fire. Lithium batteries also tend to heat up a lot in operation. These two problems make lithium batteries hazardous and finicky, and prevents manufacturing large lithium batteries in giant pools. Instead, lithium batteries need to be manufactured into many small packages, which are expensive to make and need good care, feeding, and cooling. On the plus side, they are highly efficient in the sense that almost no energy is lost in the charge-discharge round trip and remarkably lightweight. Not too long ago, it was a sensation when Tesla bet the farm on a Gigafactory capable of producing more than 1 GWh of batteries per year. (They are now at more than 35 GWh/year.) In 2021, nobody bats an eye when Koch industry, a fossil-fuel giant, announces plans to build a 50 GWh/year factory.

The cost for a utility-sized battery storage farm can be summarized by the following rough dollar figures:

Acquisition Costs of Battery Packs	$120,000/MWh
Costs of Battery Packs, incl. Wear&Tear	$250,000/MWh
Installation and Integration	$250,000/MWh
Rough Farm Cost	$600,000/MWh

After they are installed, the batteries are charged and discharged many times, which is why these figures are three orders of magnitude larger than the LCOE figures in Table 5.

The first figure of $120,000 is based on the cost of the physical chemical Lithium battery cells. On average a battery pack cost about $120/KWh in 2020, with some quotes already down to $100/KWh, others still at $150/KWh. The price of Li-Ion battery packs has been falling by about 10% per annum. It was about $1,000/KWh ten years ago. It will be solidly under $100/KWh before 2023, and potentially will reach $50/KWh by 2030 — and this is without any technological quantum leap discoveries.

The second figure takes into account that batteries don't last for very long. They wear out. We have seen lifetime estimates of 500 to 2,000 cycles. The most common operating pattern of battery farms is to charge every day and discharge once fully at peak time (8pm). Thus the battery packs need to be replaced every 2-4 years. Do basic math and it follows that if a battery farm can work for three years (about 1,000 days) and can charge/discharge fully once a day, then the LCOE from pure battery decay is indeed roughly on the order of $100/MWh. Over the full lifetime of a battery farm, it is not the $120,000 but the $250,000 that is more meaningful, because it includes not only batteries bought today but also in the future, over many generations of batteries.

The third figure is based on the cost of a battery farm. Integrating cells into the electric grid requires planning, housing, integration, inverters (devices that synchronize electricity to allow it to be connected to the grid), maintenance, operators, safety equipment, insurance, taxes, land, capital costs, the strategic know-how to buy electricity when it is cheap and sell it when it is expensive, etc.[5]

Roughly speaking, the true cost of a battery farm with 1 MWh capacity is about $600,000. It will run for about 10–30 years. This is a guesstimate. Even government estimates of LCOEs for lithium-battery provided energy can vary wildly, ranging from $150/MWh (at the EIA) to $350/MWh (at the PNNL) today. Recall that battery wear alone can account for about $100/MWh. The reason for the differences in the EIA and PNNL estimates is that they assume different expected lifetimes of battery farms as a whole (and thus different durations to amortize the non-battery costs). The EIA assumes 30 years, the PNNL only 10 years.

If the PNNL is right, the farm price is high today because storage technology will improve even faster, thus rendering today's batteries obsolete sooner. This means that technological progress in energy storage (including batteries) lowers today's expected price for tomorrow. In this case, the best response is to delay the aggressive installation of batteries. The low installed base in the United States (only about 1.7 GW of batteries at the end of 2019, with perhaps an average capacity of 10 GWh, for a grid of 450 GW and 4,000,000 GWh) and the slow installation pace may seem depressing, but this is because the true situation may actually be quite the opposite.

◇

There are already important lithium-ion battery breakthrough technologies on the near horizon. The biggest cost problem today is the wear and tear. As already noted, current lithium batteries can only charge about 1,000 cycles. More cycles are not important for your $1,000 cell phone, for which extra cycles would be nice but not crucial. Many cell phones break before their batteries do (around 3-4 years in typical use), and the battery replacement cost is only one tenth that of the cell-phone itself. But the economics of battery farms is all about expected battery lifespan. The wear-and-tear cost component looms large.

[5] Storing more energy requires more batteries (think $1 million per 10 MWh); providing more power just requires a bigger inverter (think $40,000 per MW).

The most important progress for battery farms will be batteries that can last for many more cycles. Graphene electrodes allow batteries to charge faster and last 2,500 cycles, but they are expensive. Tesla has already announced that its next generation lithium chemistry will charge 5,000 to 10,000 times. There is no law of nature that limits this number, either. Future engineering could push it to 20,000 or even 50,000 cycles. At this point, the fixed battery costs would become less important, because most people could use their car batteries not only for driving, but also for home grid storage.

However, it seems unlikely that the battery-farm based price will ever go much below an LCOE of $50/MWh. This is because of the integration cost of battery farms. They, too, will come down when storage farms are mass-produced (estimates suggest reductions from $250,000 to $200,000), but this is not as fast as the battery pack prices themselves. This situation mirrors the one for solar farms, where the prices of the solar cells are becoming less and less important, leaving most of the cost to installation and operations.

Bringing down utility battery costs will require a lot of mundane fine-tuning on each cost aspect. If batteries and wind/solar are co-located, the fixed costs can be shared. It makes a lot of economic sense to combine solar, wind, and batteries on the same farm to reduce overall cost. A DC rather than AC based transmission system could further reduce cost. And so on.

Other Batteries

If lithium batteries sound exciting, wait until you hear this. There are altogether different battery technologies that could obsolete lithium-ion batteries for utility-scale storage. Some of these batteries weigh a lot more (and are thus unsuitable for a car), but weight matters little for utility-scale storage. For example, a flow battery is akin to a giant pool of electrolyte with anode and cathode sticks inside. Increasing the battery capacity means increasing the size of the pool and sticks. The potential energy capacity of such batteries kept in large ponds could go far beyond those of racks of finicky lithium-ion batteries. VFlowTech is already scaling up manufacturing of a Vanadium redox flow battery with claimed LCOE of $100/MWh. Honeywell is building a 400 KWh flow battery pilot plant for 12-hour usage (with secret chemical composition) and plans to scale to a 60 MWh plant in 2023.

There are probably another dozen different battery architectures in advanced research stages. Corporations are investing $12 billion into battery storage in 2021 alone. Some technologies seem like magic — such as Aluminum-Ion batteries, which can charge in seconds and store multiple times what a Lithium-Ion battery can provide. One publicly-traded startup claims to have a battery that charges by converting rust into iron and discharges by converting it back. It claims that this could bring down the cost per KWh by a factor of three relative to lithium-ion batteries before the decade is out.

Our previous chapter advised caution. It is wise to remain skeptical about any one particular technology. Technology that works in the lab is a far cry from technology that works in the real world. However, there is no scientific reason why any one of these new technologies could not make a giant leap over current lithium battery technology. As we wrote, a good way to think about the new battery technologies that claim to have solved the problem is that each has a probability of success of less than 10%. It is only because there are dozens of potential breakthroughs that we are optimistic. Yes, there is a chance that none of them will work out, but the smart money bets on odds. In our minds, the odds are that within 10-20 years, either lithium-ion batteries will cycle more than 10,000 times or another battery technology will replace lithium as a utility-scale storage solution.

We close with another irony. Battery farms are relatively small and scalable investments, but battery R&D is not. The biggest risk today to spending billions on developing better batteries are batteries themselves. Any one new promising battery technology could be made instantly obsolete if another battery technology turned out even better and thereby stranded one's own R&D investment! We wouldn't put our money betting on any one technology, but we would put our money betting on at least one of them getting us there.

Hydro

Batteries are far from the only dispatchable storage. In fact, they currently work well only in niche applications.[6] Batteries are simply not economical yet compared to most storage alternatives. They are a long way from being able to supply a full night's worth of electric power almost everywhere.

[6]Batteries can take over many niche tasks. In particular, they can come online within 10 seconds to smooth out quick spikes of energy and thereby stabilize a wobbly grid. This allows operators not to have to over-provision as much electricity. They can also supplement other dispatchable power at peak times or when there is not enough transmission capability.

Their most important shortcoming is capacity scaling — and this is the primary consideration for energy storage. Think of the upper reservoir of a hydro-electric dam. Its energy is determined by the amount of water in the reservoir; its power is determined by the number of turbines. Increase the reservoir basin and you have more water and thus more energy capacity. For natural gas, the power is also limited by the turbine size, but its energy is practically unlimited as long as it is connected into the U.S. gas pipeline system.

In contrast, batteries have hard energy capacity limits. If all that is needed is 1 hour of 1 MW of backup power, batteries are already cheaper than natural gas. The farm needs just a few batteries. If 10 or 100 hours of 1 MW of backup power is needed, the farm needs 10 or 100 times the number of batteries. The price of gas dispatch power per MWh at a rate of 1 MW is the same for 1 MWh, 10 MWh, or 100 MWh of energy. Right now, it appears that batteries and gas are about equally expensive for 4 hours. This is not enough to cover a night's worth of electricity. Batteries have similar installation costs as dams per MW of power, but again fall short in terms of energy when the upper basin can hold a lot of water.

Thus, it is hydropower and not batteries that is the most important clean energy store today—by far. There are different kinds of hydropower. To be dispatchable, there has to be a dam. Conventional dams hold back water from a river in an upper reservoir and release it when needed. Pumped-storage hydropower (commonly called pumped hydro) means that a pump can push the water back up above the dam when electricity is cheap. This is not very efficient for each round trip, but it is easy to do at large scale. The United States has about twice as much conventional storage as it has pumped storage.

Hydropower is the largest source of storage today, with about 20–30 GW in the United States and 130 GW in the world. It accounts for about 2.5% of U.S. generation capacity. In terms of energy capacity, think roughly half an hour's worth of U.S. needed energy (compared to all grid-scale batteries, which could muster a few seconds). Thus, hydroelectric dams sit somewhere between batteries and gas. Reservoirs can hold enormous amounts of water. However, the water is not infinite. Once the water has been released, the upper reservoir needs to recharge, either by pumping water back up or by waiting until the rivers naturally refill it.

Unfortunately, hydro-electric power is not only expensive but also in very limited supply. Sites are limited by terrain, geology, and water availability.

Figure 7. Hydro Power and Energy

	Pumped	Dammed
USA	30 GW / 250 GWh	100 GW
World	180 GW / 1,600 GWh	900 GW

Source: Wikipedia and Wikipedia. Beside the fact that it provides on-demand energy, the world generated about 17% of electricity from hydro, which is about 4,000 TWh per year. (The third category, flowing hydro-power is not even dispatchable.) Note: Other estimates suggest as much as 550 GWh of U.S. pumped storage.
For perspective, the world is expected to reach battery storage of 135 GW / 450 GWh by 2030 — about one quarter of the world's pumped energy storage. However, unlike pumped water storage, battery installations are suitable for installation almost everywhere and are growing rapidly.

Nevertheless, the world could install more than four times the existing capacity. Getting more power by building out hydro can cost as little as $10/MWh and as much as $250/MWh — and this includes fixed costs. On average, hydro power newly built these days has an LCOE of $50/MWh. And once built, the marginal cost of hydro has been estimated to be as low as one-tenth that of batteries: not $100/MWh in battery wear-and-tear, but $10/MWh. Figure 3 shows that CAISO brought hydro power online around 5pm, throttled back around 9pm, and turned it off around 10am.

There are also other drawbacks. When there is a drought, hydro loses power. In California, this is already a serious threat. And dams can have negative effects on the environment, as well. Many environmentalists are fiercely opposed to them. They have a point because dams often have a significant impact on the natural environment. Nothing comes for free. As we economists would argue, one needs to weigh the costs against the benefits in each case.

Other Solutions

There are also other ways to store electricity that are not (yet?) in wide use. There are mechanical solutions, such as one that involves driving a train up a slope, and another that uses a crane to lift and lower blocks. The two most interesting large-scale options are, however, geothermal storage and compressed-air storage. Both take advantage of underground caverns, many created by century-long oil and gas extraction.

Geothermal storage could warm a substance like molten salt and extract the heat energy (as steam) on demand. (Earth further donates some extra energy in the form of radioactive heat coming from the planet's interior. It could even make sense to augment this heat further with a human reactor deep underground.)

Compressed air is similar to pumped hydro but more experimental. Air is compressed into underground caverns when electricity is cheap, and let out (like a balloon) when it is expensive. As with hydro dams, air-storage caverns and plants are expensive to construct and require suitable underground rocks and caverns.

The round-trip energy leakage is much higher for hydro, geothermal, and compressed air than it is for batteries, but their energy capacity potential is also much larger. And again, ironically, the biggest problems with all large-scale storage schemes are their high fixed costs and the risk of batteries. Who wants to build out energy storage at a cost of many billion of dollars when it could become obsolete if a better battery were to be invented?

A smaller-scale solution is chemical storage. Hydrogen could be electrolyzed when electricity is cheap and stored. The previous chapter explained why this is particularly useful for off-grid needs, such as in airplanes or ships. In stationary applications, hydrolysis is not (yet) economically viable. The round-trip efficiency of about 35% remains too low. It may become viable when solar and wind power cost $20/MWh and chemical engineers find better catalysts. We will return to hydrogen in the next chapter.

Table 8 shows rough estimates for the cost of storing large amounts of electric energy today. All technologies can store energy for somewhere between $100/MWh and $200/MWh. It is much cheaper to capture 1 MWh from the sun at noon at $25/MWh than it is to store and retrieve the same MWh.

Table 8. Electricity Storage Choices, LCOE per MWh, ca 2020

		2020		2030		Efficiency
	Facility Size:	100 MWh	1 GWh	100 MWh	1 GWh	
Battery	Li-Ion (EIA)	............$120............				
	(PNNL)	\$350	\$340	\$250	<\$240	85%
	Redox Flow (PNNL)	\$220	\$180	\$210	<\$210	
Hydro	(Pumped)		\$130		\$130	80%
	Natural Gas	Peaker Plant: \$80–\$200, including fuel.				
Other	Compressed Air (CAES)		\$105		\$100	50%
	Hydrogen		\$200		\$150	

Explanations: These are energy storage devices where both input and output are electricity. If the end use is heat, heat storage is likely to be cheaper. The energy cost to charge is not included. Figures assume one full charge-discharge cycle of once per day. Efficiency is the fraction of energy that is regained from input to output. The PNNL \$350/GWh cost reflects Lithium battery prices of about \$140/KWh in 2020, expected to fall to about \$50/KWh by 2030; and a 10-year lifetime.

Source: PNNL 2020 Report and EIA 2021 Outlook.

Beyond Daily Storage

Most of the previous discussion centered around the provision of regular night-time electricity. However, wind and solar power may fail not only at night, but for days at a time.

For example, in January/February 2019, a polar vortex over the East Coast for about one week took out about 10 GW wind-power from the grid's 30 GW load. The electricity price shot up from its usual \$50/MWh to \$200/MWh and more. On some days, conventional generation had to step up from its typical 60% to 99% coverage (with record profitability for generators in the process).

Energy storage for polar-vortex-like events would need neither the immediate response of batteries nor their near-perfect input/output efficiency. The power provision could come on line more slowly and have higher variable cost (as long as fixed costs are really low). The grid would hopefully not have to resort to vortex-emergency power very often.

The economics of cell-based battery capacity for rare but long-time power provision is brutal. Recall that capacity expansion is not just a matter of enlarging a reservoir or pool, but a matter of purchasing more expensive cells. It is unlikely that batteries will become economically sensible for this purpose within a few generations. It also makes little sense to build other high-fixed cost installations (underground caverns, dams, etc.) for such unusual events.

Because of such rare cases, a litmus test requiring 100% green energy makes no economic sense. It would be so expensive that it could wipe out public support for the transition. We therefore believe that it is enough when 95–99% green energy provision can be sensibly achieved. The only viable economically sensible "last-resort" alternative for long-term storage (and for decades to come) is natural gas or hydrogen with their near infinite capacity and run-time. Even otherwise crazily expensive and dirty Diesel generators (at \$100-\$200/MWh) could have a very rare role to play.

But the message of our book is to stop arguing about whether decarbonization should be 80% or 100% — the world is so far from 80% that the arguments are currently irrelevant. The world should instead focus on *moving the needle* to 80% asap and worry about the final 20% later.

Many other interesting developments are coming out of left field, often seemingly mundane improvements over existing designs. Standard radial flux alternators (generating electricity from turbine engines) have efficiencies of 90%. Axial alternators can push energy losses down to 2–3%. This can improve the economics of round-trip converting mechanical power to energy and make all sorts of alternative energy storage viable. A new way of drilling non-mechanically may just have opened up access to very deep holes to tap the power of magma.

Speculating for fun as in science fiction, what will ultimately be feasible in terms of storage cost? The world will probably need many types of energy storage. It could be that the best storage method has not even been invented yet. If some storage technology could solve the problem of large-scale provision when there is a run of low intermittent power days (i.e., offering long-term storage at high capacity), this technology could also solve another related problem: long-term seasonal storage. Electricity demand is highest in winter, then summer, then spring and autumn. If there was such a viable technology to store energy in spring and autumn, the economy would need less generation capacity in the first place. Builders could tolerate even more energy losses as long as fixed installation costs were cheap enough and if the new technology could hold sufficient amounts of energy. This scenario may eventually become feasible with some aforementioned underground solutions, such as molten salt. A cost of $50/MWh in a few decades seems achievable. At this cost, wind and solar power could compete economically with all but natural gas. Push it to $30/MWh, and wind and solar would become dominant.

We admit much of this remains a dream. Molten salt storage as well as many other potential energy storage solutions all call for more research and development. Put the brightest minds on the biggest problem of the world today and give them enough money to experiment and come up with better potential solutions. Let's create the conditions that could allow us to get lucky!

No Electricity Out

The above solutions discussed the storage from the perspective of electricity in, electricity out. For many applications, this is not necessary.

The cheapest and best solution to the problem of energy storage is to avoid having to store electricity in the first place. This is not a crazy idea, and it does not require either more base power or a return to the stone age. Instead, it mostly requires passing the right incentives on to electricity consumers. We will come back to this theme a few times in the rest of the book.

Much electricity ends up being converted into heat or cold. In such cases, it is usually cheaper to transport electricity to the destination first, where it is used to heat or cool a substance (often water or oil) in an insulated container. This heat/cold can be released later when it is needed. It even has a fancy technical term, "sensible heat storage."

There are sensible heat storage solutions both on industrial and small scales. Industrially, underground caverns and insulated furnaces can hold large amounts of heat. In homes, most of today's water heaters already work this way. Sensible thermal storage (together with heat pumps) could take over much of both residential heating and cooling; and do so both for water and air heating and cooling. This will work well *if* electricity is extremely cheap when wind and solar generation is at a maximum mid-day. With the right incentives, electricity consumers will no longer want to buy as much energy at night.

7 Transmitting Electricity

The transmission grid is a fascinating topic to study. Let's carry you away for a few moments.

The National Academy of Engineering ranks the U.S. electricity grid as the greatest engineering achievement of the 20th century. It is the greatest machine humans have ever built. And it was not as much designed as it grew over time — almost organically.

Remember the 2019 East-Coast polar vortex? Or the 2021 Texas outage? Why did the rest of the United States not simply send more power from elsewhere to the East Coast? It's because there was insufficient transmission infrastructure. It had been too expensive to build a line that could shuttle enough electricity over such large distances (and do so just a few times a year).

Today, of the \$120-\$150/MWh that retail customers pay for electricity ca. 2020, only about \$1-\$3/MWh is due to transmission costs. (The U.S. Department of Energy cites a wholesale price range from \$0.19 to \$5.29/MWh.) This is because lines are short. Most electricity is generated locally. To make the grid capable of carrying a lot more intermittent power over longer distances and be smarter, customers would have to pay a lot more for transmission.

A good rule-of-thumb is that it costs about \$1,000 to build 1 km of 1 MW of power transmission. (Let's ignore that transmission further loses about 1% of power every 500 miles; costs another \$5,000/km/year in maintenance; and lasts only for about 30-50 years.) If a transmission line is well used, say 5,000 hours per year, its building cost would be \$0.20/MWh/km. The capital cost of this construction at a 10% rate, would be about \$0.02/MWh/km/year. This implies that every 50 km adds about \$1 to the per-MWh delivery cost. 500 km adds about \$10/MWh. With electricity costing between \$50 and \$100 to generate in most locales, long-distance "arbitrage-by-cable" between two different locations becomes economically challenging.

For example, consider the economics of a coast-to-coast transmission line. A cable that could transmit about 1 GW of power — capable of carrying about 0.1% of the U.S. power generated — would cost about \$1 million per km to build and install. At about 5,000 km from Los Angeles to New York City, the cost would be about \$5 billion (before payment for the electricity generation itself). Constructing a local nuclear power plant capable of delivering about

1 GW would also cost about $5 billion. Clearly, local electricity generation is typically a lot cheaper than coast-to-coast transmission.

Design and Capacity

Today's U.S. electric transmission grid remains both primitive and chaotic, but also sophisticated in the many patching mechanisms that make it work. This is because our grid was never truly designed. Grids began as private efforts in the 19th century and grew organically during the 20th century to handle primarily connections that ubiquitous and relatively local coal plants needed to provide power to customers.

Thus, the U.S. grid has never been operated by one centrally coordinated agency, but by many private operators within different states and regions, with strong links to their local providers, customers, and politicians. This arrangement worked well when local supply and local demand were tightly paired. However, the problems today are changing.

With intermittent wind and solar power, a lot of extra energy may need to be shuttled around. This alone could double the necessary wires. Moreover, wind and solar power also require greater coordination, because the grid will have to be ready to transmit when these generators want to send power, not when the operators and customers want power. The grid will also have to be ready to allow connections to newly built wind and solar plants. Too much power and the wires could fry.

In some situations, transmission could be a substitute for storage. Instead of storing electricity in Los Angeles when afternoon demand is low and supply is high, it could be transmitted to New York City where the opposite (with its 3-hour time difference) is the case. Wind power is almost always available somewhere in the United States, but not always where it is needed. It needs to be shifted around. For another wrinkle, AC transmission lines are great when power comes from rotating engines (like windmills) and when there are many on-ramps and off-ramps, but it is not efficient for DC power-based generation (like solar) and not over very long distances. The United States may thus want to build a new DC network. The DC power line from Washington state to California proves that this can be economically viable at least in some cases.

Smarts

Operators have only modest real-time intelligence. They know how much electricity was needed in the past and they can learn a little from how stable the frequency and voltage are at a few sensor points. However, by the time they learn of problems, e.g., a plant that goes offline, customers may already have suffered consequences. Because the operators' guesses are inaccurate, their best option is to provide too much electric power, so that the grid will not brown out.

A better solution would be a "smart grid" that could entail all sorts of real-time measuring meters and switches that allow grid operators to improve their routing of electricity to meet demand. Even more importantly, smart meters could allow customers to signal how much power they will need in the future. With better intelligence, operators could waste less electricity.

With price signals, customers could balance their demand throughout the day. The grid could let consumers know when the price is lowest so they could charge their cars or do their laundries — or, more likely, let their cars and laundries know. The ability of devices to adjust their demand and signal it back to the utilities would reduce the volatility of electricity demand, the volatility of price, and the total price itself. A smart grid would reduce the need for storage and backup power.

Linked Grid and Technology Coordination Problems

A large expansion of the U.S. grid is a necessary precursor to a clean energy future. If the economy is to electrify activities that are not electricity-based today, then the grid needs to have a capacity of at least twice its current capacity. (The U.S. Department of Energy suggests a short-term 50% increase.) More distant regions need to be interconnected with fatter wires. Some estimates suggest that a region-by-region clean solution without dramatic changes in long-distance transmission capabilities would cost $135/MWh (about three times today's price), while a grid-supported national solution could reduce the cost to only $90/MWh (about two times today's price).

For many other issues we discuss in the book (e.g., generation and storage), we can worry about this decade — about "moving the needle now" — rather than about future decades. However, this is not the case for the grid. The grid has to be planned and upgraded asap in its transmission capability, its coordination, and its smarts in order to be ready for the subsequent construction of more intermittent generation and storage.

The upgrading process will be difficult, because it will involve hundreds of interest groups — generators, customers, storage, politicians, regulators, lawyers, environmentalists, and so on. Today's grid operators are already pretty good and quick when it comes to sending power on to neighboring regions' operators on a daily basis. They are not so good and quick when it comes to planning and approving large new transmission infrastructure over years and decades, especially across larger distances. It is not clear whether private and regional operators will be capable of engineering the large and rapid changes that are in the public interest and not necessarily just their own.

And if all this was not difficult enough, the changes must also not jeopardize what the fossil-fuel grid largely already delivers today — though with terrible consequences for the environment and public health. Most of the time, despite its mechanical nature prone to breakdowns, fossil-fuel generators have delivered reliable electrical energy that is critical for the operation of a modern economy. Interruptions, such as those recently in Texas, are costly. But upgrading the grid while maintaining its reliability is a delicate and tall order – it's like upgrading an airplane in flight.

In the United States of 2023, interconnecting to the grid has become a serious bottleneck. Many systems operators take years to allow new renewable generation onto their grids, on top of other approvals. Other operators no longer even take applications — stating only that they hope to reopen their application systems again in a few years. These are problems that even the best renewable technology inventors cannot overcome. (Fortunately, there are still markets elsewhere in the world.)

8 Earth's Electricity Problem

In the 20th century, almost all electric power came from baseload power in the form of coal, and almost all transportation power came in the form of oil. The future belongs to wind and solar power, supported by a better grid with dispatchable energy storage. Wind and solar power are ready. They are already the cheapest sources of energy *ever*. They are so cheap that further improvements are no longer of first-order importance. The grid and storage are not ready. The grid "just" needs some grit to improve it. It can be made ready, though at a non-negligible cost.

The key remaining real problem is storage. It remains an order of magnitude too expensive. It is not an overstatement to characterize humanity's energy problem as little more than an energy storage problem. Solving it will mean solving the world's dirty energy problem. With cheap storage, wind and solar technologies will rapidly eliminate the need for fossil fuels worldwide without the need for much further intervention.

Perhaps the storage problem has not already been solved because it was not so important, so urgent, and so potentially profitable in the past. We hope that some people will get very rich solving the problem — capitalism at its best.

Base or Intermittent/Dispatch Power?

To understand at least the outlines of the tradeoff today vs. where it has to be, we want to compare how much it would cost to supply all of the United States with natural gas electricity on the one hand vs. with solar/wind/stored power on the other hand.

Our goal is not to be exact. We are not grid operators. The actual operation of the grid is beyond human comprehension. In real life, the grid operators model, simulate, and predict the grid on large computers. When it looks as if power will fall short soon, they offer to pay more, thereby inducing higher-cost providers to come on-line. Over longer time horizons, with technological and construction uncertainty, the operators' allocation tasks become even more difficult. If they get it wrong, a few years later, woe is us. (China is seriously afraid of running out of power, which is why they are building so many new coal plants.)

Instead, our goal is to present back-of-the-envelope calculations and only for daily provision needs. We will round aggressively, because our calculations are far from exact and make many simplifying assumptions — such as assuming that electricity on the West Coast is the same as on the East Coast (even though the United States cannot transmit a lot of power across the continent) or assuming that storage incurs no losses. We will not allow wind to blow at night or allow the sun not to shine during the day. We will assume that intermittent wind and solar power will always be working like clockwork from 10am to 6pm, i.e., for 8 hours a day, and not a minute more or less. You have been warned.

The United States needs about 520 GW of power during those 8 working hours, i.e., $520\ GW \times 8\ h \approx 4\ TWh$ of energy. It also needs a further 450 GW during the remaining 16 hours, i.e., $450\ GWh \times 16\ h \approx 7\ TWh$. Ergo, these 7 TWh need to be generated and pushed into storage during working hours and pulled from storage when needed. To charge storage of 7 TWh in 8 hours plus deliver 4 TWh immediately requires about 11 TWh of generation during the time when wind/solar are available. Dividing 11 TWh by 8 hours suggests that 1.4 TW of wind/solar power generation can satisfy immediate power needs and charge the storage reservoir.

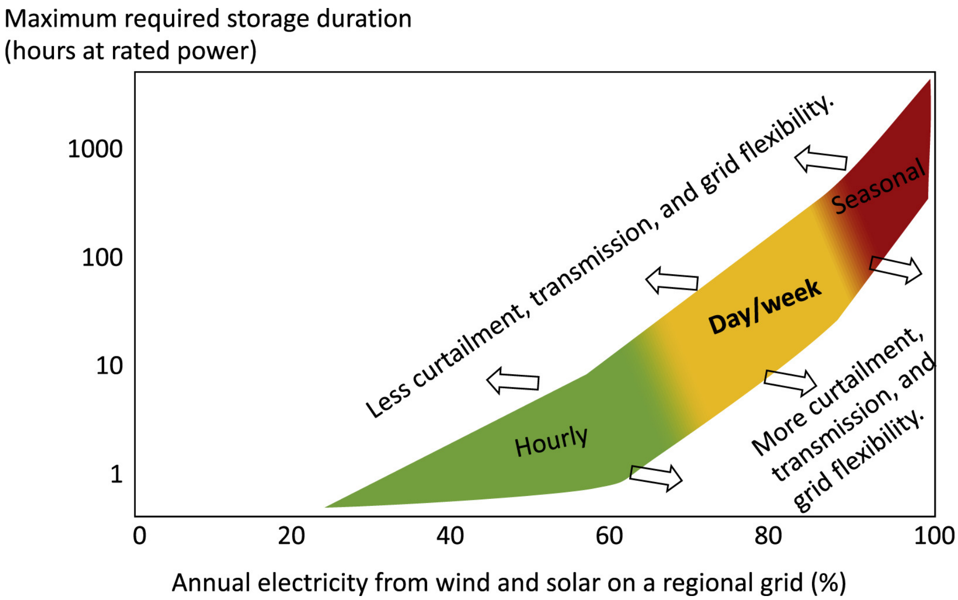
The example's first rule of thumb is thus that the United States would require a nameplate (peak) capacity of wind and solar output of about 1.5 TW. which is about two to three times the immediate retail customer daytime power requirement of about 0.5 TW. A second rule of thumb is that it would require energy storage for about 20 hours.

Figure 9 shows a more realistic assessment. The law of diminishing returns (from Chapter 5) is at work: About 80% of the grid could be covered with solar and electricity storage of about 10 to 20 hours of electricity. To reach 90% would require about 100 hours. To reach 100% could require 1,000 hours or more — the equivalent of "murder" from an economic perspective.

Let's move on to cost. Ignoring storage cost, generating 11 TWh for a price of, say, \$33/MWh from wind and solar would cost about \$350 million. The same 11 TWh from natural gas at a price of, say, \$50/MWh, would cost about $11\ TWh \times \$50/MWh \approx \$550$ million in generation costs. The difference of \$200 million is our clean energy-storage budget.

If scientists and engineers can find a way to store 7 TWh for less than \$200 million, it's curtains for natural gas on ordinary days. This suggests that

Figure 9. Required Energy Provision



Source: Albertus, et al., 2020, Joule. Recall from the introduction to Section 6 that the world today has only about 30 seconds worth of storage, 95% of which is pumped hydro.

technology would need to bring down storage cost to $\$200$ million$/7$ TWh $\approx$ $\$30/$MWh. Ziegler at al. estimate that storage costs would have to drop to \$20/MWh to allow a 100% clean system — but \$150/MWh could be enough to make it to 95%. *We are already there!*

Now look back at Table 8 for today's storage technologies. Unfortunately, current technologies can't make it down to \$30/MWh. It costs more like \$100–\$200/MWh today for storage at scale. Existing hydroelectric storage could do it at \$30/MWh, but only if construction costs are ignored and only if magic created an unlimited supply of hydro-electric storage dams.

Under realistic current storage costs, say \$150/MWh, the cost of a clean-energy U.S. system would balloon the electricity cost to $\$350$ million, which comes to a cost of about \$1,400 million in total. This is roughly three times the cost of a natural-gas electricity system — think 5–10% instead of 3% of GDP. (Double this if you want to electrify the transport and heating sector.) Nuclear power would be much cheaper — but, like wind/solar/storage, its economics cannot compete with natural gas.

Simply put, completely clean energy is still too expensive, despite the low price of wind/solar power. Even if generation were free, it would not be enough. The storage-cost problem still kills the universal clean-energy solution on an economic basis. A fossil-fuel tax could help somewhat, but even \$50/tCO_2 wouldn't be enough to completely wipe out natural gas.

Today, there is really only one way to transition to a clean energy economy — shifting energy demand towards day-time hours. When no storage is needed, no one needs to pay for it. As mentioned, we will come back to plans to shift energy use below. In the very long-term, storage technology breakthroughs will hopefully change the arithmetic.

Now look back at Figure 4. The United States is still ramping up natural gas generation even when wind and solar are still working. That is, expensive peak gas generators are still being dispatched due to demand increases, not due to supply decreases. Not all but a lot of this extra mid-day power could be replaced by wind and solar energy almost immediately. Instead of 100 GWh generated by wind and solar today, it could probably be 200-300 GWh. *Moving the needle* could get us to 200 GW in short order. Market forces are already working. In 2021, new installations added 30 GW of wind and solar power.

Now or Later?

Economically, it is too soon to transition *all* of the grid by installing 7 TWh of battery storage. The public is unlikely to stomach electricity prices 2–3 times what they are paying now. Moreover, the clean energy cost is getting cheaper by the year, so waiting just a few more years makes sense. And many other storage technologies also look promising at utility-scale needs, perhaps reducing the cost to \$60/MWh within a decade or two. At this point, countries can contemplate whether the full clean-energy sacrifice is worth it. More importantly, for the world' sake, it has to be not just the United States and Western Europe that make sacrifices. A clean-energy solution will also have to become feasible all over the world. Remember if only the West were to move away from fossil fuels that would not be enough to reduce CO_2 in the atmosphere .

If there ever was a role for governments to subsidize R&D in the social interest, clean-energy storage research is it! This is where collective clean-energy sacrifices should be directed.

9 The Business Perspective

Let's look at the decision of an entrepreneur today. She is not concerned about how to migrate all of California, the United States, or the world to clean energy. She is more concerned about the economics today — how she can make money by selling electricity or building new plants. She need not install many hours' worth of batteries to cover all 12 hours of nighttime demand. All she needs to do is to work out whether she can make a profit from buying electricity at the lowest day price and selling it at the highest day price — say, buying 1 hour's worth at 1pm and selling it at 8pm. In an ideal free market, competition between entrepreneurs is such that the rest of us are getting them to sell electricity to us almost at what it costs them. This is the socially positive aspect of capitalism at work.

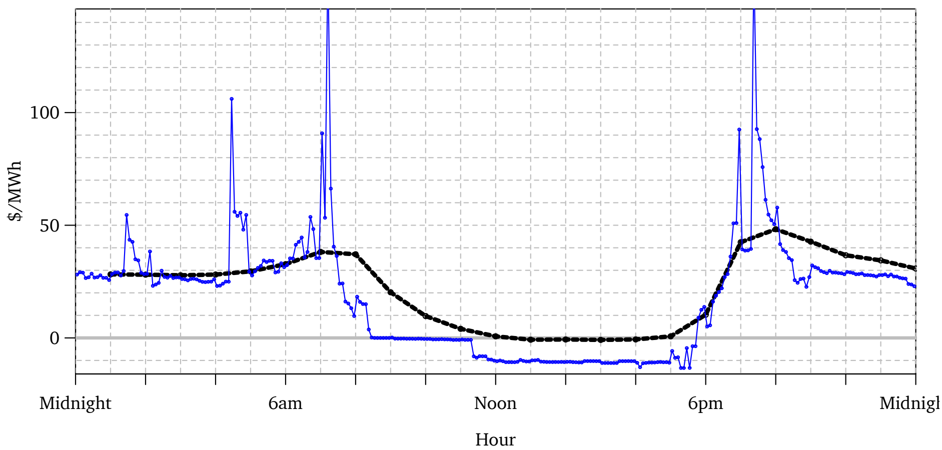
The decision entrepreneurs face regarding what type of new plant to build depends not only on the demand pattern but also on all the other plants on the grid. If there is a lot of intermittent power, it makes more sense for her to build dispatchable power, and vice-versa. If there already is a lot of base power, then building solar power only makes sense if there is excess demand during daylight hours. How can the grid operator direct what plants entrepreneurs should build? Or how can the entrepreneur decide?

Fortunately, for the most part, this is not a decision that regulators need to make. It's a decision that they can leave mostly to market forces. And all the entrepreneur needs to do is to look at the price of electricity. If it is usually high during the day, she can build a new solar plant. If the price varies too much, she can build electricity storage (and thereby make the prices more similar).

Let's look at the business case from the perspective of a California entrepreneur. (Of course, entrepreneurs elsewhere have different problems. For example, gas is more expensive in many other parts of the world.) Figure 10 shows the electricity price on the same day for which we graphed the provision in Figure 3. Our entrepreneur could have sold her electricity at those prices, which came from multiple auctions conducted by CAISO. The smooth black curve shows prices auctioned one day ahead. The electricity price ranged from zero from about 10am to about 6pm, all the way to $45/MWh around 8am and 8pm, with most of the night around $30/MWh.

The operator can never perfectly predict demand and supply, and so leaves some electricity to be purchased in real-time. This is seen in the more spiky

Figure 10. California Price, March 21, 2021



Source: CAISO Oasis. The black line is the 1-day ahead prices, averaged for Southern and Northern California. The blue line is the 5-minute auctions. Note that the day-ahead price of electricity was $0 from noon to 5pm in Southern California.

blue graph. Brief spikes on this day could be as high as $200/MWh. If you had owned a battery farm, you would have jumped in to sell power — which is also why the spikes did not last long. Real-time electricity also had a negative price from 5pm to 6pm, because the transmission grid was overloaded. If you had no way to spill power, you would have had to pay the grid to take it. At this point, if you had owned a battery farm near the hubs, you would have tried to jump in and buy it for this negative price. If you were close to the spilling generators, they would have happily paid you and not the other way around.

With conventional technologies, it seems there is not much money to be made in California on ordinary days by installing new plants and storage — the market seems to provide electricity at very competitive prices, at least on this day in spring. (In summer, there is more power demand during the afternoon for air conditioning, allowing generators to earn more. And not every day is as boring as this March 21. Moreover, California also runs an auction every three years paying utilities to install more capacity.) Some plants are still being built to earn money when demand is high and supply is low. Moreover, some plants in California are ready to be retired, opening up opportunities to build new ones. And, of course, you could make a killing if you could invent cheaper generation power to beat the prevailing price of \$30/MWh at night or a cheaper storage technology to take advantage of the short spikes and variability.

Let us harp yet again on a final point. In the short term, the grid must take customer demand as given and cover it as effectively as possible. In the long term, market forces are more dynamic and responsive. Low electricity prices are not only caused by but also put a damper on the installation of more solar energy generation. Over time, however, economic forces will induce more consumers to use more power during the day if they can take advantage of cheap electricity. The prime potential consumers would be battery farms that would effectively "arbitrage" the electricity price and thereby even it out! That is, they will compete around noon for purchasing electricity and thereby drive up the price; and they will sell in the evening and thereby lower the price.

10 The Role of The Market

If the grid and related decision problems seem impossibly complex, it's because they are. The only planning device known to humankind capable of coordinating a system as complex as an electricity grid is to rely, at least in part, on market prices. Market prices induce competitive electricity suppliers to do the right thing. If there is not enough electricity supply, the electricity price rises; the price rise induces entrepreneurs to bring more power online, both short-term and long-term. Attempts to coordinate electricity provision without healthy market competition among companies – or, worse yet, attempts to fight economics – are bound to fail, as they always have. However, solutions without any regulation are also impossible. There is a need for regulators to coordinate the system and make sure that there is healthy competition among generators. Countries with good governments and the trust of their public will find it much easier to transition their energy systems.

Laissez Faire and Price Controls

Of course, no consumer likes power companies when power prices are high. Everyone wants safe, reliable, and affordable power.

Who wants to wait for new plants to be built and come online (and then bring down power costs) when their power bills have just tripled today? Thus, the public often clamors for price controls — and they do work quite remarkably at first. After power plants have been installed, they can continue to produce electricity profitably on the margin, although they cannot recoup their investment. If regulations are lax, generators can also neglect upkeep to lower prices and make consumer happier. (In the case of natural gas operator, they can provide cheaper electricity by neglecting pipeline leakage and proper capping at the end of life of the wells.)

Unfortunately, price controls also mean that not enough generators will want to build more plants thereafter in the future. It is the expectation of recouping investment at higher market prices that makes it worthwhile to build more plants. Take away high prices, and companies will become less eager to build more plants.[7] Similarly, it is the high price variability that makes it worthwhile to install more electricity storage. Take away price variability (the "arbitrage" of buying low-priced electricity and selling high-priced electricity), and companies will become less eager to build more storage.

Price controls and fear of them have ruined electricity sectors in many third-world countries, in which competitive entrepreneurs without political connections no longer want to sink the large amounts of capital required for building out power. They don't trust governments not to turn around in the future and expropriate their capital investments. Would you like to volunteer to invest your own savings on such terms?

Electricity markets require both competitive companies to build plants and sell electricity and regulators that coordinate and limit the power of these companies. Central planners influenced by political considerations or nepotism and not subject to true competitive pressure or negative consequences when they fail — whether in Washington DC, Moscow, Beijing, Kinshasa, or Brazzaville — cannot do the job. But neither can the free market alone. It's a vexing problem.

[7] To keep companies building new plants and stand-by power ready to provide more electricity, many U.S. grid operators hold capacity auctions, which pay generators not for energy but for power provision.

Role of Regulation

However, some caveats are in order. Leaving everything to the free market is also not the best way. Regulators still need to make sure that utilities follow stringent safety and upkeep requirements; that the grid has the reliability that is more in the social than in the private interest; that competitive entrant plant builders can easily connect to the grid; and that builders do not collude with one another to keep the price artificially high or merge to reduce competition. Mergers would raise their profits by creating electricity scarcity. With fewer plants (or "maintenance" at the worst of times in a few key plants), the electricity price will be much higher than it would be in a competitive market. It is also well known that incumbents try to take advantage of the system. They will push for ever more difficult reviews and regulations for newcomers. Given the large capital requirements (and long process requirements), they will make it harder for smaller, cheaper, and better entrants to come in and compete away fat profit margins.

Thus, it is the regulatory agencies of the government that must watch the competitive market on behalf of the ultimate customers (industry and households). Without guard, the competitive system would quickly deteriorate. But guarding is itself difficult to do even for the best of governments. The regulators have no choice but to depend on information that is fed to them by power generators. If the regulators turn too adversarial, they will have to regulate in the dark (perhaps quite literally). Worse yet, power generators operate in political systems in which campaign donations and bribes often speak louder than words and lower prices. Even in the United States, the average regulator today is a former or subsequent industry lawyer or executive for a power-generation company, appointed by politicians. (Who else would know the ins and outs?) In other countries, it is often the nephews of the rulers.

Even in the United States, many economists believe that government regulation itself often becomes not a guarantor but a barrier to entry — creating a system that is abused by incumbents. Among the two evils (no regulation vs. biased regulation), it is not clear which is better in any one particular case. Maintaining impartial regulation is a never-ending and never-perfect difficult balancing act. Naïve environmentalists who instinctively prefer government regulation over capitalism may be well-meaning but often fail to appreciate the real-world dilemmas.

How To Lower Prices

Allow us some pontificating. As we are writing this, the UK is experiencing an energy shortage. A primary reason for this shortage? Price Controls! The UK has a price cap on unit electricity. Unfortunately, the price of gas has recently skyrocketed, making it unprofitable for gas generators to come online. What exactly did the U.K. expect when it instituted price controls? Utilities that would voluntarily sell for a loss?

Here is "the economists' advice" on how to lower consumer prices. This holds whether it is in the context of power or apartment rents. Price controls always backfire in the long run. Instead, the correct economic solution is to encourage as much competitive entry as possible. Prices will come down when incumbent sellers cannot prevent entrants from competing and offering lower prices. If it takes a while for entrants to arrive and solve the cost problem, subsidize the consumers. Do not punish the suppliers.

11 Current Power Plans and Forecasts

Table 11 is among the most important tables in our book. It summarizes the existing electricity energy generation and power capacity of the United States, China, and the world. It shows how the picture has changed in the last 5 years and the reference forecast for 2050. Except for longer-lived hydropower, 30 years is also roughly the lifetime of a power plant. Thus, most of the plants generating electricity in 2050 have not yet been built.

In the United States, coal has been on a steep decline — but it isn't done yet. Even by 2050, about 10% of U.S. electricity is still expected to come from coal. Natural gas generation is continuing to expand. Together, fossil fuels may already have peaked, but the decline will be slow. The U.S. industry has become bearish on new fossil-fuel generation power plants.[8] For now, entrepreneurs are bringing online only new wind and solar plants, whose purpose it is to cover the growth in our energy demand. In sum, the future looks rosier than the past, but it is not all that rosy. There is no "zero-carbon" electricity future on the U.S. drawing board for now.

[8] Much of the 6.6 GW had been in planning stages for many years and is located in fossil-fuel-friendly Texas, Oklahoma, and Pennsylvania, with 3.9 GW for base power and 2.6 GW in peak power.

Table 11. Power and Energy Forecasts

Panel A: Generation, in TWh per year

Region	Year	Coal	NatGas	Nuclear	Hydro	Wind	Solar	(Others)	Total
USA	2015	1,410	1,317	797	249	191	39	(2.2%)	4,092
	e2020	774	1,636	785	283	343	132	(2.7%)	4,061
	e2050	593	1,953	594	294	790	1,071	(3.0%)	5,458
China	2015	3,860	148	161	1,103	186	45	(1.1%)	5,562
	e2020	4,313	267	331	1,117	574	281	(1.5%)	6,893
	e2050	3,556	803	1,002	1,448	1,001	3,379	(0.4%)	11,230
World	2015	9,621	5,585	2,440	3,843	828	263	(2.6%)	23,171
	e2020	8,244	6,458	2,630	4,034	1,741	832	(4.2%)	24,991
	e2050	8,115	7,306	3,025	5,548	6,833	10,152	(2.3%)	41,953

Panel B: Power Capacity, in GW

Region	Year	Coal	NatGas	Nuclear	Hydro	Wind	Solar	(Others)	Total
USA	2015	...758 ...		99	80	73	23	(2.2%)	1,074
	e2020	221	429	97	79	127	84	(2.7%)	1,155
	e2050	106	788	72	80	241	519	(5.9%)	1,919
China	2015	...990...		27	296	129	43	(2.0%)	1,516
	e2020	1,087	88	48	322	184	169	(1.2%)	1,921
	e2050	1,101	316	143	417	333	1,480	(7.8%)	4,108
World	2015	..3,919..		343	1,051	415	227	(4.4%)	6,231
	e2020	2,201	1,839	374	1,120	595	511	(7.4%)	7,172
	e2050	2,273	2,414	427	1,507	2,362	4,640	(7.6%)	14,747
Plant Changes in 2020									
USA	New	+0	+7	+0	+0	+24	+14	(4.5%)	+46
	Retire	–9	–2	–2	–0	–0	–0	(4.7%)	–13

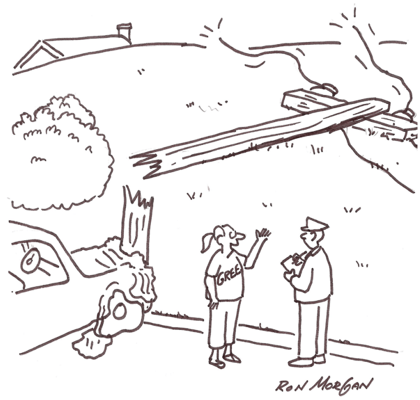
Source: U.S. Energy Information Administration. Panel A: 2015 and e2020 and e2050 generation. Panel B: 2015 and e2020 and e2050 power. (We use estimated 2020 numbers for comparisons with estimated 2050 numbers.)

In contrast, in China, coal remains dominant. It provides the majority of electricity. Worse, it is projected to shrink only slowly. The world's biggest environmental calamity today is China's massive coal-plant building program — driven more by employment in the coal sector than by cost advantages of coal. These new Chinese coal plants will be with the world for another 30 years. If anyone has a good idea how to stop them, this is the time to speak up. In total, fossil fuels in China are forecast to grow, not shrink. Nevertheless, as in the United States, wind and solar plants are expected to cover the lion's share of China's electric energy *growth*.

The world overall is more like China than the United States. Coal will remain steady, and natural gas will grow modestly. Clean energy will grow faster to cover most of humanity's increasing electric energy demand. Thus, fossil fuels are expected to provide about one-third of humanity's energy in thirty years — down from about two-thirds. The planet does not work in percentages, though. In absolute terms, emissions in the electricity sector will no longer increase relative to where they are today, but they will also not decrease. Just holding emissions where they are today in the face of a 66% growth in electric energy consumption is a great accomplishment for clean energy, but it's not enough. This future does not look carbon-free. It would be wise to do everything possible to accelerate the transition.

12 Reliability

A critical aspect of electric power that we have so far neglected is its reliability. The electric power grid must cover both energy and power needs on demand. When consumers demand 1 TW of power (about the average power in the United States), the grid needs it *now at that very moment*. If it is not provided, the grid may "brown out" (delivering insufficient voltage, which can damage some machines) or may collapse altogether. When the grid demands 12 TWh of energy today (approximately the U.S. energy consumption per day), it is not sufficient to deliver the energy tomorrow.



Look on the bright side, Officer. I've reduced the electrical consumption of an entire neighborhood.

Customers in richer countries expect electricity to be available when they need it. Their businesses and their livelihoods depend on it. They thus greatly value reliability and are usually willing to pay for it.[9]

Yet, even in the first world, power has never been perfectly reliable, but it is so near-perfect that we take it for granted. The typical U.S. household suffers only 6 hours of outages out of about 8,800 hours per year. Most outages happen when a local power line is cut — and the utility company will almost immediately dispatch crews to fix it.

The generation itself is even more reliable, because the U.S. electric grid is designed to oversupply electric power at all times. However, it is possible for large parts of the grid to fail, and they have indeed done so recently. For example, California famously had to curtail power delivery in 2001 in order to prevent a collapse of the system. (Nowadays, California electricity utilities also regularly turn off power in certain locations when high winds threaten to topple electricity towers and start wildfires.) The Texas power outage of

[9] Grids tend to be more reliable in countries that are wealthier. The two reinforce one another. On the one hand, it is difficult to run an economy without a reliable grid. On the other hand, many aspects of an economy that promote economic growth and stability also promote a reliable grid.

2021 affected about 5 million people and crippled its economy for about a week. The public outrage was on the news every night. A typical headline read Despite Losing Power for Days, Texans Will Pay Higher Power Bills — Perhaps for Decades to Come.

With less base power and more intermittent power, the variability in power availability could rise. Storage can mitigate some of the daily volatility, but there need to be plans to address once-per-year or once-per-decade situations in which weather conditions are consistently bad and the standard storage will have run dry. What company would want to build a plant that is turned on only once a year or once per decade?

The economists' answer is that if customers value the presence of this once-per-year availability highly enough, they should be willing to pay for it. In the Texas 2021 outage, the retail price of electricity shot up to $9,000/MWh. Many customers saw their service cut off (the equivalent of infinite pricing) — whether intentionally by the grid (because they had to pay suppliers so much that end-use provision was unprofitable), or unintentionally because no further electricity was available.

Interestingly, Texas is unusual. It is its own island on the grid, largely unconnected to the rest of the United States. (This avoids Federal regulations). Indeed, Texas was so deregulated that it had already allowed retail customers to buy electricity at a prevailing grid-tied price, rather than at the more common fixed price. In normal times, the customers who had chosen this option paid electricity bills that were much lower than those of their neighbors who chose the guaranteed price. However, the response by these customers to the spikes in the electricity price was not one of gratitude towards the last-standing providers (at $9,000/MWh), who unlike their peers had not neglected to make their plants resistant to the cold weather.[10] Instead, these customers had a visceral reaction against "vulture providers," who took advantage of the desperate needs of their customers to charge them 100 times what electricity usually costs, and earned them billions of dollars of extra profits. In a true free-market system, such high electricity prices are precisely what is needed to induce better maintenance and more competitive entry in the future. In the real world, it doesn't work with citizens and voters.

[10] Ironically, the costs to weather-proof the plants would have been trivial, but incompetent or colluding electricity plant owners failed to do so. This turned out to be very profitable for the industry.

A fair characterization is that customers want reliability and are willing to pay for it — up to a point where they still want reliability but are no longer willing to pay for it. The problem is finding a good pricing solution to this inconsistency.

Just as the free market is not robust in maintaining competition, it is also not robust for protecting against and handling rare events.[11] The only solution, again, is good but difficult regulation. Regulators could charge customers in order to fund a set of fossil-fuel plants, which will lay idle almost all the time but are ready to jump in under dire circumstances. But how to ensure this? There are a lot of important questions here that lie beyond the scope of our book.

➤ Beyond Rich Countries

In contrast to the first world, electricity in the third world is often intermittent. For example, Beirut residents received only 5 to 20 hours of electricity per day in 2020. Lebanon's generation capacity simply cannot cope with demand, and no one is willing to invest to bring more generation online. Power plants make nice big stationary targets in wars, too, of which Lebanon has had plenty; and (once built), power plants make easy scapegoats that governments can force to provide power below cost. The last standing providers were barges, where operators hoped that they would not be confiscated by a desperate government and citizenry.

In Lebanon and many other poorer countries, establishments like hospitals that require reliable electric power typically run additional, but very inefficient, "mini-grids" based on their own diesel generators. Even in the United States, one of the attractions of roof-top solar with battery backup is its resiliency to wider power outages. Absent power outages or lack of transmission infrastructure, such hyper-local electricity generation is usually less economically efficient than utility-wide generation — though this may change in the future.

[11] The same can be said for relying on for-profit utilities that build traditional nuclear power plants. Once the probability of a blow-up is low enough (say, below 1 in 10,000 years), the day-to-day profitability concerns begin to dominate the low-probability blow-up concerns of most executives.

Conclusion

The point of our chapter was not to convert you, our reader, into an expert on electricity, but to give you a taste of the large real-world complexity of the electric energy problem and its potential solutions — and of the exciting time that we are living in today. If we were still teenagers looking for an appealing profession to pursue, electricity in all forms would be high on our list. Although we understand the outlines of the problems, there are plenty of interesting questions left. Will nuclear power become a lot safer and cheaper? Will someone offer a storage technology that will allow wind and solar to render natural gas and nuclear plants obsolete? Will residential roof solar (with car battery storage) dominate industrial solar (with a better transmission grid)? When should government take a hands-off approach, and when should it be hands-on? How can governments promote clean energy without causing voter riots? Will third-world countries leapfrog over the fossil-fuel stage in their electricity generation? How can China and other countries be induced to abandon coal-based generation of electricity in favor of cleaner technologies? What can we do to nudge decision-makers towards the better solution?

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