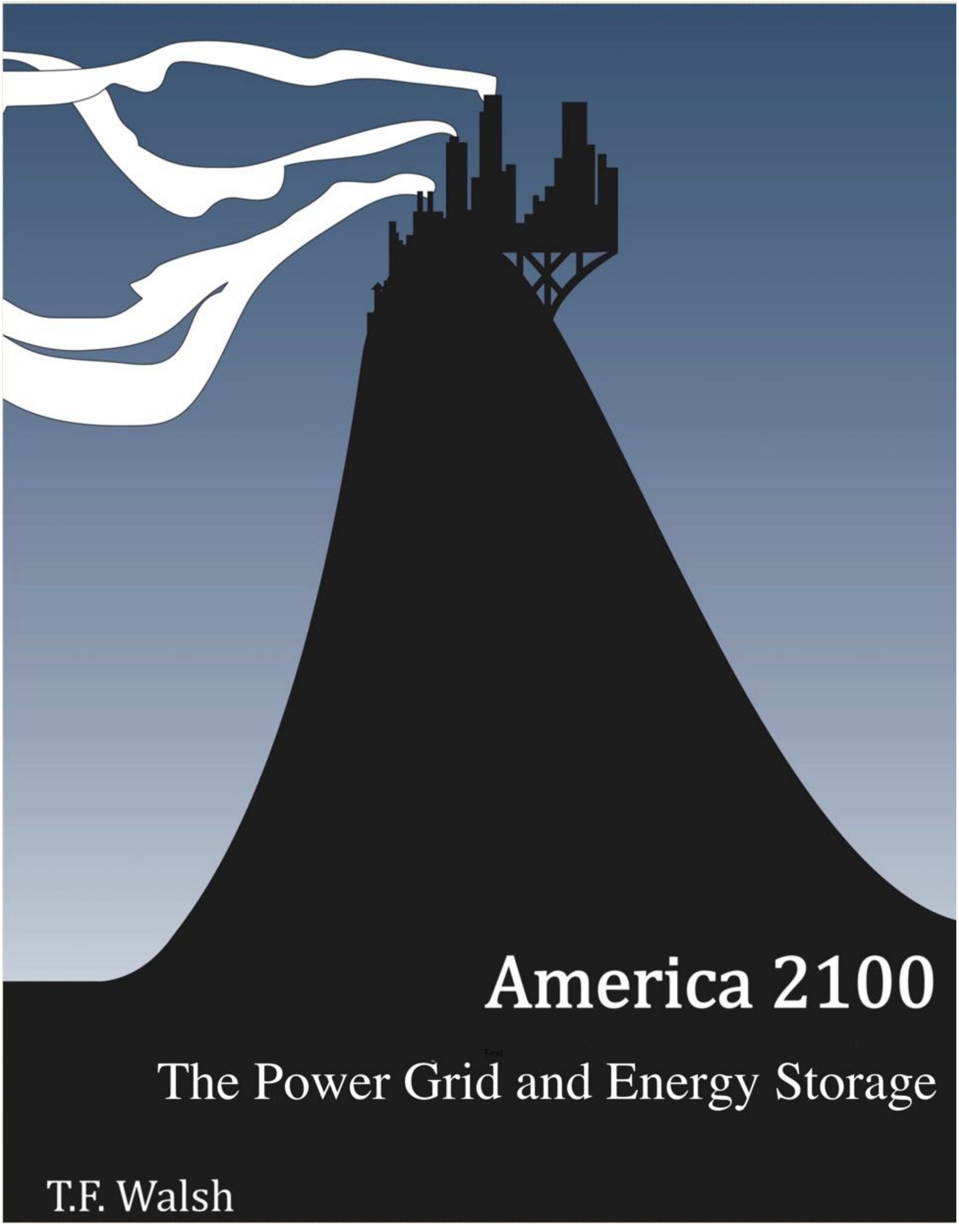


# America 2100

## The Power Grid and Energy Storage

T.F. Walsh

# Preface

Already a century ago, electricity was becoming common - as lighting for homes, power for machines and streetcars. Even our now familiar alternating current electricity was already widely used by 1910. It enabled long distance power lines (lines only tens of miles long at that time) that carried electricity at high voltage from remote hydroelectric stations to nearby cities. A century ago most of these electric power systems were still for cities and states, not the country at large. They were local. Very gradually both the system sophistication and its extent grew.

It was only in the later 1960's and thru the 1970's that the present grid system evolved. Now we have three grids in the continental (lower 48) United States -- Eastern, Western, and Texas. Each has alternating current, synchronized exactly at 60 Hertz frequency. A clock with its timing running off a grid in each of these grids would show the same exact time everywhere. But the clock time would differ in different grids unless adjusted by hand. Even then, clock times from the alternating current would drift apart due to slight differences in frequency. This system allows power from anywhere inside one grid to be moved, and sold, anywhere else in that same grid, a tremendous advantage. Power is produced in large power plants and moved around as needed. Daily generation and use is smooth and predictable. So the individual grids hardly need to store energy--almost all power made is used instantly on a grid scale.

This feature of our system--power used as it is created--will lead to a potential future problem. If our new power sources are seriously erratic rather than steady, the concept of smooth production and use will be lost. It is part of the nature of

solar and wind power to be erratic. Electrical energy will no longer be used exactly when it is created. So energy storage will be a central problem of any future grid or collection of grids. Any future grid system will also have to cope with new challenges to the overall stability of the system. The present grid relies on the modern evolution of nineteenth century technology. A future grid will have to cope with erratic power that cannot mimic the intrinsic stability of our present grid.

Besides the erratic nature of some future electric power, much of it will be produced far from where it is used. The problem of storing energy will be mixed up with the need to transmit it possibly long distances.

We do not and even cannot know how the future grid or grids system will evolve. The grid and its energy resources, storage and interconnections are just too complicated. This book is at best a small introduction to some ideas where our electrical energy distribution may be headed.

# Introduction

The generation of electric power for commerce began in the 1880's with two projects a day apart in September 1881--Edison's coal fired generator station in New York and a hydroelectric plant in Minneapolis. Both supplied electricity for lighting to nearby businesses. Both were small in scale, power to a few dozen installations, at about a hundred volts of direct current electricity. After this start, events moved fast, but very locally because of the short range of direct (one way) DC current provision. This changed by around 1900 with the adoption of alternating electric current. This was based on the new AC electric transformer and its ability to change voltages and electric current. This new industry was the child of discoveries by Michael Faraday and Joseph Henry over sixty years earlier.

Alternating electric current was naturally produced by generators--rotating coils of wire in magnetic fields. The source of power for these generators was usually water turbines or steam turbines driven by the heat of burning coal. This variation of electric potential or voltage in generators made it possible to change both voltage and electric current at will thru the transformer of the 1880's. By 1900 or thereabouts it became possible to produce electric power at a hydroelectric plant and transmit it at high voltage--the first of our transmission lines--to a city some tens of miles away. The use of AC electric power exploded, with about a third of households electrified by 1920.

By our current standards, these original generator stations were small--tens of megawatts of power--and localized in cities or nearby hydroelectric plants. Originally for lighting, the spread of electric motors, led to electric power usable in industry. Electric motors were a sixty year old idea at the start as well and DC motors were used very early (and still are) in electric streetcars. It was the combi-

nation of AC electric generators and AC induction motors--mainly due to Nikolai Tesla--that revolutionized industry.

Conceptually, the revolution was complete with Tesla's ideas. Power could be produced by coal steam plants or hydroelectric plants, transmitted at high voltage, and distributed at lower voltage, thanks to transformers, for lighting and motors anywhere in a city. The growth of electric power became exponential. Developments from Michael Faraday to Tesla took about sixty years; from then another sixty years led to the modern era after World War II.

The basic idea was just a generator coupled to a transformer to raise the voltage to a high level, a transmission line ended by another transformer to reduce the voltage an then an electric light or a motor at the end. [1] Today large generators of electric power for distribution number many thousands and just motors in the home number in the hundreds of millions, not to mention those in industry. (Think of a clothes washer, a dishwasher, a home heating system pump and many other devices with motors in a hundred million households.) Transmission lines carrying over a hundred thousand volts each amount to over a hundred thousand miles of line. Single transmission lines can be hundreds to a thousand miles long.

The early electric power systems were in cities, then small regions and later states and larger regions. But there was a problem with all such alternating current systems. Everywhere in the system the voltages had to match exactly. The maximum voltage at some time in a city might be plus170 Volts and 1/120th of a second later it would be -170 Volts and then after a full 1/60th of a second it would be back to plus 170 Volts. (The nominal "voltage" would then be 120 Volts, clearly less than the maximum of the alternating voltage. The alternation is then 60 full cycles per second from maximum to maximum or 60 "Hertz".) [2]An entire system would reach its maximum voltage at the very same instant everywhere. Another electrical system not connected to the first would have a quite different voltage at that instant. The two systems could not be connected if the instant voltages differed. The solution, of course, was to make the systems "synchronized" if they were to be connected. Two systems run by different companies had to agree to

synchronize. The voltage everywhere had to be exactly the same at every instant of time. This process of expanding synchronized grids went on for quite a while.

By 1964 we were down to eight separate grids in continental North America and now there are three--the Eastern Grid, the Western Grid, and the Texas Grid for the continental U.S. (Plus a Quebec grid and grids for Hawaii and Alaska.) The timing of the 60 Hertz voltage in each of our continental grids is different. It is quite amazing that at the exact instant when the voltage in Maine is a maximum it is also a maximum 1400 miles away in Florida. At that instant, the voltage in California will *not* be a maximum. California is on a separate grid.

But why three continental U.S. grids and not one? This is a bit of a historical accident. The central eastern part of the country was a unified grid quite early; in the 1960's most of the grid fragmentation was in the west. When that was combined, it led to a western grid. Texas is, of course, Texas.

It is interesting that there may be lessons for us today in the existence of a separate Texas grid--it is not really obvious that today we need large synchronized grids. [3] Historically, large grids such as the Eastern and Western grids were created for a good reason. Excess power generated in one area can be easily transferred, usually over multiple transmission lines, a thousand or more miles away if the demand is larger there. You just have to synchronize voltages everywhere. If there were separate grids, this transfer of power would not be so easy. Interrupting this easy transfer of power with specialized stations to connect grids with separate timing of their alternating current would have been both difficult and expensive. With modern advances in the conversion of direct to alternating current, and the reverse, the situation has changed. It was for a long time also expensive to transmit power long distances using direct current transmission lines rather that alternating current lines. Now it is possible to connect two alternating current grids with converters between them--essentially AC on one grid to DC to AC on another grid. Long distance transmission of DC power also leads to no synchronization problem. The once compelling reasons for large synchronized grids have become weaker.

Early on in the consolidation of the AC power grids in the continental U.S. it was thought that a larger grid could be made more stable than smaller grids. This movement to combining grids was mainly the result of a huge blackout in the Northeast due to grid failure in 1965. But we have had blackouts since, originating in what seemed to be out of the way places. Ironically, the big blackout in 2003 also affected the Northeast. Grid stability remains an issue. It is not obvious that larger grids are much more stable than smaller ones.

Another issue with our present grid is the presence of multiple overlapping industry groups coordinating grid operation. This works amazingly well, but this administrative complexity is a bit odd. [4] As fossil carbon energy gets replaced with electrical energy, the grid or grids will become the center of our concerns.

This book, and the others in the series, deals with the effects of the decline in available fossil carbon over this century. Most of our electricity (about 80%) is generated by burning fossil carbon. Without nuclear power, the fraction of electricity from fossil carbon would rise to nearly 100%. [5] But this is not all. Replacing other uses of fossil carbon in our economy with distributed electric power would probably more than double our present use of electricity. This might be reduced by more careful use of energy, but we will still have a very large demand for electric power and the grid or grids that distribute it.

Almost none of our electricity will be from fossil carbon by 2100. How will this affect the evolution of the U.S. grid (or grids) is murky. A nation dependent almost entirely for its energy on distributed electric power is obviously vulnerable to any disturbances.[6] A longer term breakdown of one of the three present grids is already a very scary possible risk to the country. The danger to the nation from disruptions in the future will be truly alarming. There will be no other energy sources to use as stopgap measures. We need to think very carefully about the future of our electric power system.

The problems we will face are similar to those of other nations or regions. These grids are of staggering complexity, certainly one of the great engineering efforts of

the last hundred and twenty years. Ours is now three individually synchronous continental grids serving over 300 million people. A single synchronous European grid covers about 400 million people (most, but not all, of Europe). The Russian grid supplies power to almost 300 million people. When grid integration is complete in China it will dwarf these. But our concern here is our own grid.

In the following chapters I want to present my own tentative view of what our national grid system looks like now and what its near term future might be like with less fossil carbon energy. There is already a vast literature on this. [7] I cannot summarize all of it. My view here will be sketchy but, I hope, helpful to concerned but nontechnical citizens.

# Chapter 1-Some Physics and an Overview

It is impossible to get a useful idea of how our grid works without some basic physics and a great deal of simplification. The ideas behind the grid are only a bit difficult, but over a hundred years of elaboration have made the system mind bendingly complex. But understanding the basic concepts is a good place to start. [1]

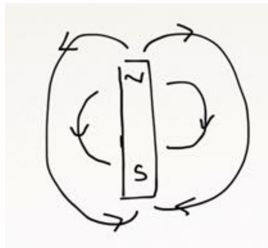
(You may want to skip this, which is, in any case, a very simplified description and overview. But it is central to how the grid works.)

The concepts behind the electric power system go back to Michael Faraday and the concept of induction -- the creation of voltages and electric current by changing magnetism. [2]

The simplest way to think about voltage and current is by analogy to water flow in pipes. The water pressure in a pipe or hose is the analog of voltage and water flow the analog of the flow of electrons that make up electric current. Very high water pressure can be dangerous, as in a water jet cutting machine. Lower water pressure can lead to familiar flows, as in a garden hose. In a single hose or pipe, higher water pressure leads to more water flow. This is not unlike the case of electric current in a wire: higher voltage leads to larger electric current. Other cases are trickier and the analogy works less well. But this is good enough for orientation.

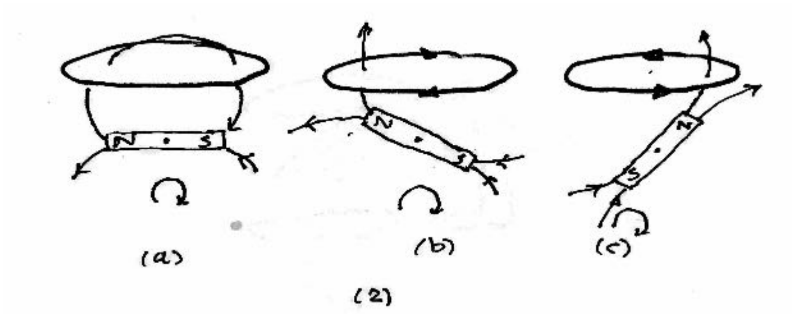
The key physics idea behind electricity and magnetism is the concept of an electric or magnetic "field". Electric fields can directly drive electric currents. [3] Magnetic fields can do this as well--changing magnetic fields "induce" electric fields that lead to current flows. We are familiar with static electricity and also with magnetism from bar magnets or electromagnets.

The idea works something like this, a specific example that will be useful soon. Imagine a bar magnet. Faraday envisioned "lines of magnetic field" emerging from the north end and looping around to the south end, so:

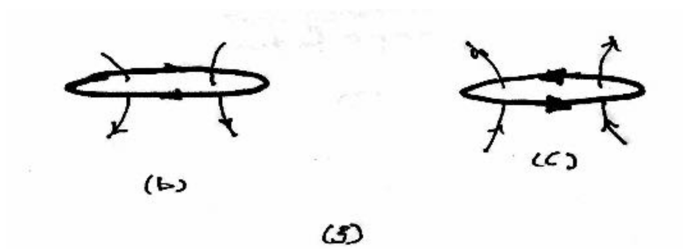



The lines shown are just representative, you have to imagine a lot of them. You may recall that if the magnet shown can move, a second magnet held near it will cause it to move--like poles (N and N or S and S) repel and unlike poles attract. So one magnet can push or pull on another.

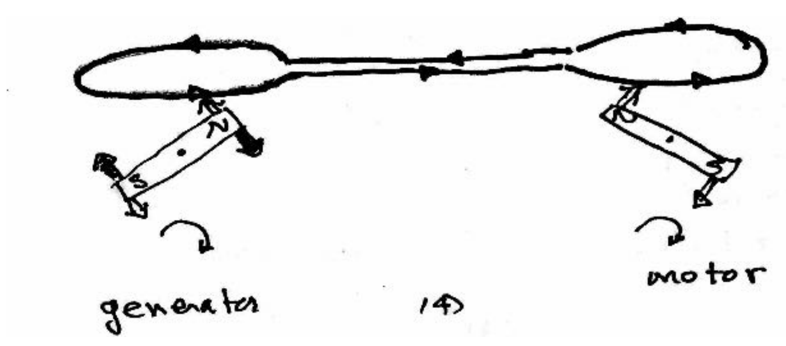
Now imagine this single bar magnet below a wire circle loop, with the magnet rotating step by step smoothly in a clockwise direction. The image below shows just three steps in the rotation. In the first step (or snapshot of the motion), the lines go thru the loop and back out inside the loop. No *net* lines go thru the loop. In the second, some lines go entirely thru the loop and do not return inside the loop. Instead they return *outside* the loop. There is a *net* crowd of lines thru the loop. Imagining the bar magnet to be smoothly rotating, more and more lines pass entirely thru the loop as it rotates. In the third picture below, fewer and fewer lines pass thru the loop; eventually there will be no net lines thru the loop again, as in the first picture. In steps two and three *there is an electric current around the wire loop*. The electric current is caused by the changing net number of magnetic field lines thru the loop. This is Faraday's discovery: the *changing* number of lines thru the loop (the changing magnetic field thru the loop) causes a current to flow in the loop of wire. The direction of the current flow is as shown: one way as the field thru the loop increases; then the other way as it decreases. When the net number of lines of magnetic field is not changing there is no current flow. *The direction of the current flow in the loop changes*.




These current flows in the loop of wire produce their own magnetic field. (This field is not shown in the first diagram, to keep it simple.) This magnetic field is not unlike that of a bar magnet. The interesting part is that the magnetic field of the loop in the second picture above is *opposite* to the increasing field of the magnet. In the third, the reverse happens. The field created by the current in the wire *reinforces* the now decreasing flow of magnetic field thru the loop. This change from the second to the third picture is a key physics fact. The magnetic field from the current in the loop is shown in the next figure.



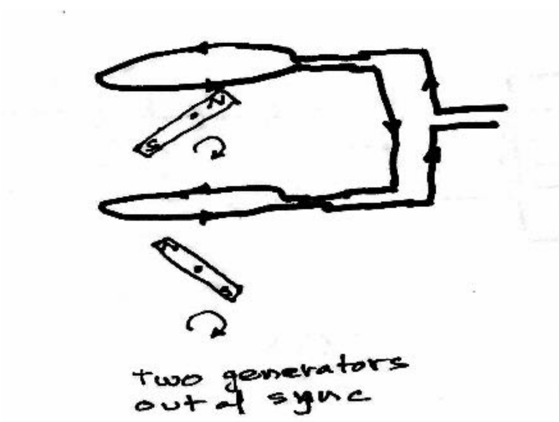

Now we come to the real magic part for us--a generator driving a remote motor over wires between the two. It looks like this




What happens is this. The rotating magnet in the generator causes a current in the

wire shown. The field due to the rotating magnet is like that of a bar magnet and it pulls on the rotating bar magnet, trying to slow it down. This magnetic field caused by the current flow in the generator *opposes* the motion of the magnet that creates the current. A source of power (like a steam turbine) has to pump energy into the generator magnet to force rotation. In the motor, the reverse happens. The flowing current *pulls* the magnet around. This can do work at the motor end. But notice that it only happens if the magnet in the motor *lags behind* the magnet in the generator. So the rotating generator magnet drags the motor magnet around, given enough energy input to the generator. This is all thanks to Faraday's ideas. The forces are shown by the open arrows--slowing the generator magnet down, requiring input energy and speeding the motor magnet up, releasing the energy from the generator.

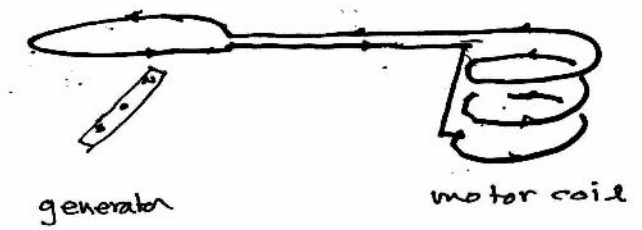
The same principle can be used if there are two generators, but not quite in lockstep motion. If one lags behind the other, putting more energy into one generator speeds up the other. This is the principle behind synchronizing generators on a grid. (The current flow from the generator with more power input is shown.)




The generators I have shown are only illustrations of the idea. The bar magnet is outside the coil to make it easier to visualize the magnetic field through the coil. In a real generator the coil of wire or coils -- there are usually many -- would be around what is shown here as a bar magnet rather than above as in my simple picture. The bar magnet shown here would also be replaced by iron wound with wire. Currents from outside would flow through this winding, producing a magnetic field that would look like that from the bar magnet. So a real generator would be pretty complicated: windings around a rotating core to make a magnetic field and

windings on the outside for the current caused by the rotating magnet (now an electromagnet rather than a bar magnet). But the physics principle would be the same a that I have described here. Notice that the arrangement here has a disadvantage, because part of the time no current is flowing (when the magnet lies along or perpendicular to the plane of the coil above). In a real large generator there are, conceptually, three coils 120 degrees apart. Then there is no time when current is not flowing in at least two of the coils. If the wires from the coils are arranged properly, current is always flowing out or into the generator. This "three phase" system was invented by Tesla and is now the rule. If you look on large streets, you will often see power poles with three wires, one for each phase of the current. Residential power poles often have only *one* wire - one of the three phases. That one wire, at several thousand volts, is connected to a transformer to supply houses with lower voltage power. That one high voltage wire is enough, the return current flowing through the ground.

So far, both generators and motors have been far oversimplified as a bar magnet and a single loop of wire, as I mentioned. In reality, as already mentioned, the bar magnets are iron wound with many loops of wire (they do act like bar magnets) and the motor winding also has many loops of wire but still acts like a bar magnet. [4] The generator and motor windings--idealized here as one loop--also really consist of many windings of wire. The physics depicted here is correct, just simplified. But now imagine that there are many loops of wire at the "motor end" but no magnet to rotate. No work can be done by this arrangement, of course. But the current from the generator still has to create a magnetic field at the end, and the current and the direction of this field both change. What is a quite subtle part of this flow of power, the magnetic field *also* absorbs energy from the generator--but in the next cycle it gives it back. Energy flows not just from generator to motor, but back and forth. This is a crude description of what engineers call "reactive power". Here is a rough diagram of current when there is no work being done at the motor end. In a real generator and motor set, the magnetic fields in the motor create this same "reactive power" flow. The image here is just to emphasize that it is the coils that do this.[5]

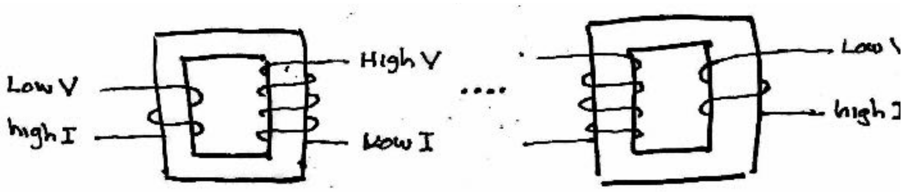



(6)

Why go into this physics detail? It is because motors and generators are so closely related to one another. Our entire electric power system is built around this similarity. Real power flows from a generator to a motor, doing useful work at the remote motor. Reactive power flows back and forth, doing no work, but still a vital part of the energetics of our system.

If you imagine a future, really imaginary, where there are motors everywhere in the economy but *no* actual generators and their rotating machinery--how is that supposed to work? You have eliminated half of the physics that is responsible for the grid power flow and, more important, stability. I will have to come back to this. It is the main problem with radically changing our existing power system.

The last part of the grid today is the ability to transmit power very long distances. This is possible because of the transformer. (The first transformers came long before the power system I have been describing.) Long distance transmission of power needs very small current, because it is the current in the transmission lines that is responsible for power loss (and it was originally the reason why DC power lost out to AC power). Transformers can accomplish this. Here is a rough picture of the lower voltage and higher current at a generator station being converted into higher voltage and lower current for long distance transmission. Transformers also use Faraday's ideas: changing current flow in one side of a transformer creates a changing magnetic field that causes a current to flow in the windings on the other side of the transformer. This only works for alternating current (and thus alternating magnetic fields). It does not work for direct current, the direction of flow of which never changes. Changing the voltage of direct currents or DC is difficult, but it can be done.




(7)

These elements: generator, motor, transformer are the pieces of our present grid. But, of course, there are many details that make up the real grid of today.

Now I want to connect this physics description with our experience of the grid. Then we will get to a more detailed picture of the electric power grid.

**The Grid of Generators and Transmission**

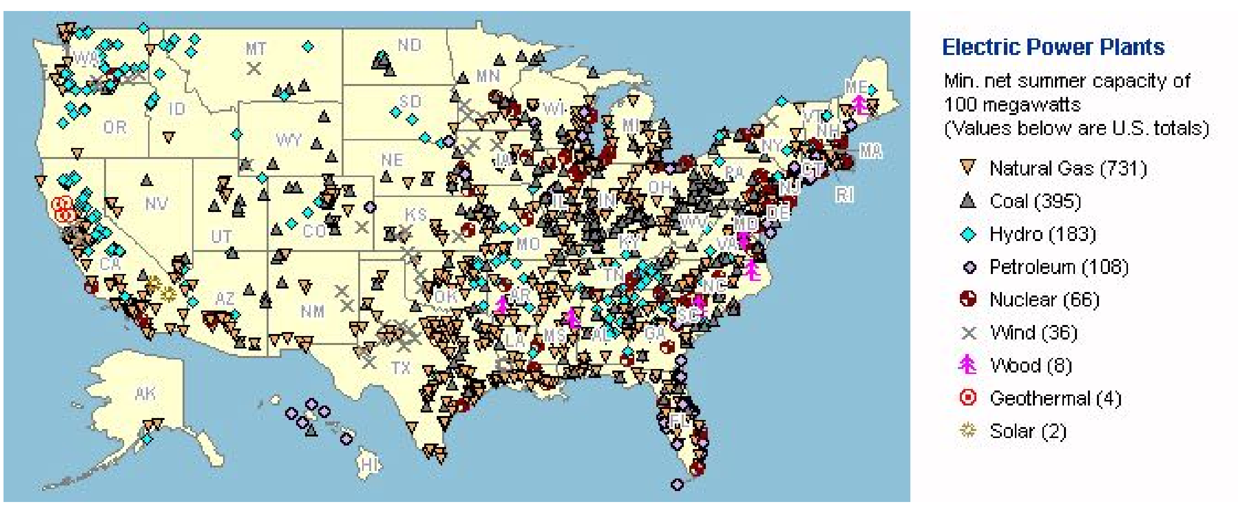
An actual electric power grid consists of many generators producing current at around ten thousand volts. At the power station with the generators there are also transformers leading to long transmission lines at hundreds of thousands of volts with transformers at the remote ends. There the power is used to do useful work. The places where power is used are normally on the customer side of special substations where the high voltage of transmission lines is reduced to a lower value. The long distance power lines might have a hundred thousand or more volts and the reduced voltage, intended to go a shorter distance, might be ten thousand or so volts. The voltage might even be reduced further to a thousand or so volts for distribution to residential areas. All of this has to be perfectly synchronized, with the voltage at one instant *exactly the same everywhere on the grid*--no matter how many generators, motors, transformers or transmission lines there are. This is still so far pretty simple, but it allows us to imagine roughly how the grid looks. These simplified parts are the generators, the high voltage distribution lines, and the stations at the end of these lines.

**The Generators**

Generators come in many sizes. At major power stations, generators range from

those producing around a hundred million watts of power to a billion watts (a hundred or so megawatts to a gigawatt). There may even be several generators at one plant. The energy input of the plant that is turned into electricity is varied. It might be burning coal making steam that runs through a steam turbine attached to the generator. It might be a natural gas turbine attached to the generator. Or a nuclear power plant, also producing steam for a turbine attached to the generator. A dam might have several water turbines. And so on. Too high a voltage would damage a generator, so a typical output voltage of a generator might be 10,000 volts or 10 kilovolts. [6] For comparison, a typical household averages a use of about a thousand watts or one kilowatt at 240 volts (split into two 120 volt lines). So one 100 megawatt generator (a hundred thousand kilowatts) can supply an average of 100,000 households or fewer industrial plants. Large industrial plants can require tens of megawatts of power, usually at the somewhat reduced distribution voltage of ten thousand volts or so.

There are plots of the U.S. showing where the larger power generation plants are located. Here is one of these plots, from NDSU in North Dakota for 2009,




There are about 1400 power plants, 100 megawatts and up, on this graphic. [7]All together they produce on average about 400 gigawatts of power -- about 4 kilo-watts per household. [8] Households actually use only about a kilowatt on average; most of the power is used for industry and city infrastructure.

It is amazing that the vast number of generators in the plants are able to spin at exactly the same speed with their voltages synchronized perfectly in order for the system to work. (Of course, there are three grids in the U.S. that are separately synchronized.)

Large generators and the turbines that drive them are immense machines. A generator and its steam turbine can easily weigh several hundred tons.

## The Transformers

After the electric power is produced at a voltage that the generators windings can withstand without damage, typically about ten thousand volts, the voltage has to be boosted for long distance transmission.[9] Transmission voltages can be ten to thirty times the generator voltage. The transformers to do this are as large as the turbine and generator themselves.[10] A large transformer can weigh several hundred tons.

Usually we just see the transmission lines, but the important parts are the transformers at each end of the transmission line. How many transformers are there in the U.S.? The number of power plants depends on size; often quoted numbers are 3000-6000 without the size being mentioned. (See an earlier note.) Since there can be several transmission lines for a power plant, and some independent ones, an exact count of the number of transmission lines, and thus of transformers, is unclear to me. The National Academies quotes 15,000 electric power substations, each of which must have at least one transformer. [11] So there are a *lot* of large transformers in the U.S.

## The Long Distance Transmission Wiring

Between the vital end transformers we commonly see just the wiring, the actual transmission lines. These are towers with three or more large conductors strung between them for the three phases of the voltage (and current). The transmission

system wiring is, for the high voltages above 115,000, about 180,000 miles in total length. Including lower voltage lines, the total is probably several times this. There is at least enough wire length in the U.S. to run well beyond the moon. [12]

**The Motors**

Counting the total number of electric motors in the U.S. is probably hopeless. Common household device motors-clothes machines, dishwashers, pumps and the like--are mostly a tenth of a watt to perhaps a few hundred watts. (Less than a horsepower or 750 watts.)  Each household in the U.S. must have a few of these for a total number of motors in the hundreds of millions. Some substantial part of our energy use that goes into households must be to drive motors, not just lighting and heat.

In industry the total number of motors must be also very large, although the individual motors are larger (up to and beyond a few hundred horsepower or about 100,000 watts or 100 kilowatts). [13]  A total number of industrial motors of some million or so does not seem unreasonable.

Why the concern with motors? We usually ignore them, which is why numbers are often hard to find. Interest in them lies in the fact that motor windings absorb energy in two forms--energy that goes into useful work or heat and energy that is fed back into the power system each of the 60 cycles per second. This is not true of a simple electric heater, like a toaster, which has no windings. It just turns electrical energy into heat energy. So motors are a dynamical part of our grid. Even more, they are at least partly an unpredictable part of the grid because they switch on and off. [14]

Our actual power grid is very complex, but this outlines the underlying physics and the basic components. But we will see that the whole system is much greater than the sum of its parts.

# Chapter 2-The Structure of our Grid now.

Descriptions of the grid usually start off in an abstract way, with a map of power lines going everywhere in a very difficult to understand mesh. I want to go in the reverse direction and start outside my own house with the 240 Volt feeder line to my house(really +120 Volt and -120 Volt AC wires plus a “return” wire at 0 Volts). Then I want to work up to the nearby substation that converts an inner city 115,000 Voltage line to the local neighborhood feeder lines at 13,800 Volts. That 115,000 Volt line comes from a main line to my city (Minneapolis) that brings in power from outside the metropolitan area at 345,000 Volts. That high voltage end then connects to what we usually refer to as “the grid”. The grid we usually think of is mainly outside cities. But if you start locally, it becomes clear that the grid really also runs inside cities such as mine, not just between cities and electric power plants.

**To the Grid from the end**

Why do this inside-to-outside approach to the grid? I think that it makes a very complicated system a bit more concrete. Almost anyone can do what I did, following the power lines up to the main grid connection in a city. If you live in a rural area, you can do the same; some of the interconnections and “substations” may just be far away. Then you will have an idea what the grid looks like, starting small and building up to the main power lines and power generating stations. This can be fun, but it will not work if your power distribution wiring is underground.

To start, the following image is the power pole outside my house. There is, at the top of the power pole, a single wire. This one wire carries a single phase of the 13,800 Volt “feeder line”. In the grid proper there are actually *three* wires, the three phases mentioned in the last chapter. Each of the phases carries power, but its maximum voltage shifted a bit from the other phases. This makes for smoother power distribution at higher voltage. For a house, this is unnecessary and only a single phase wire is needed. But there is a complication. The current flow in the

single wire has to be balanced somehow so that current flow into the houses fed by the transformer is balanced by current flow out. The single phase feeder wire is connected to the transformer in the picture. From the transformer, Three wires run out to the upper right. One of these, the one at 0 Volts, is just a steel cable that supports the insulated + and - 120 Volt wires wrapped around the cable--the 240 Volts total to my house. This trio of wires goes into my backyard where further poles are used to distribute the 240 Volts AC from the transformer to my house and six others. (This is a pretty standard number of houses per transformer.) Notice the three separate wires below the transformer that head off to the lower right. This is the old version of the +-120 and 0 Volt household distribution, common in my neighborhood. The 0 Volt return wire might run on further. Most of these lines are from the late 1920's. They are *very* slowly being replaced by the more modern cable return + two wrapped lines. (The bottom coaxial cable is not for power, it is television plus data.)

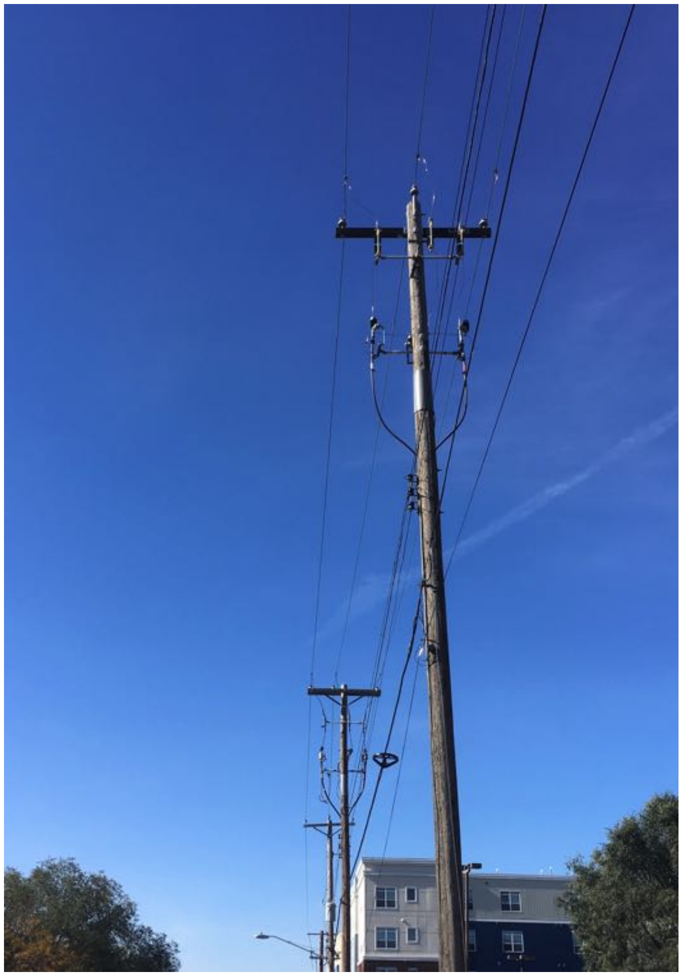
The neutral current return wire, the 0 Volt part of the +120, -120, 0 Volt wiring off the transformer, should be connected to the ground by a bare wire leading down the pole you see. The return wire would carry the return current flow from the transformer to the houses it serves. I assume that this return current flow has the same phase as the high voltage feeder line, so it can cancel out other current flows from other feeders.

This is the end point of the single phase feeder wire in my area. Where does it go from here?

It is not hard to follow this single phase wire through my neighborhood (or yours, if you try this). It wanders past a few dozen houses and a few transformers to this intersection, where the single phase is hooked up to one of two wires, in the following picture. The single phase wire to my house heads off to the right and the two phases of wire off to the upper left. There are also three 240 Volt wires and, lower on the pole, low voltage coaxial cable.

After this hookup, the neighborhood wiring gets complicated, with the next pole having all three phases of wire, split off to a number of houses, apartment and commercial buildings. (Including come coaxial cable and city WiFi.) I will not show that other confusing bunch of connections.

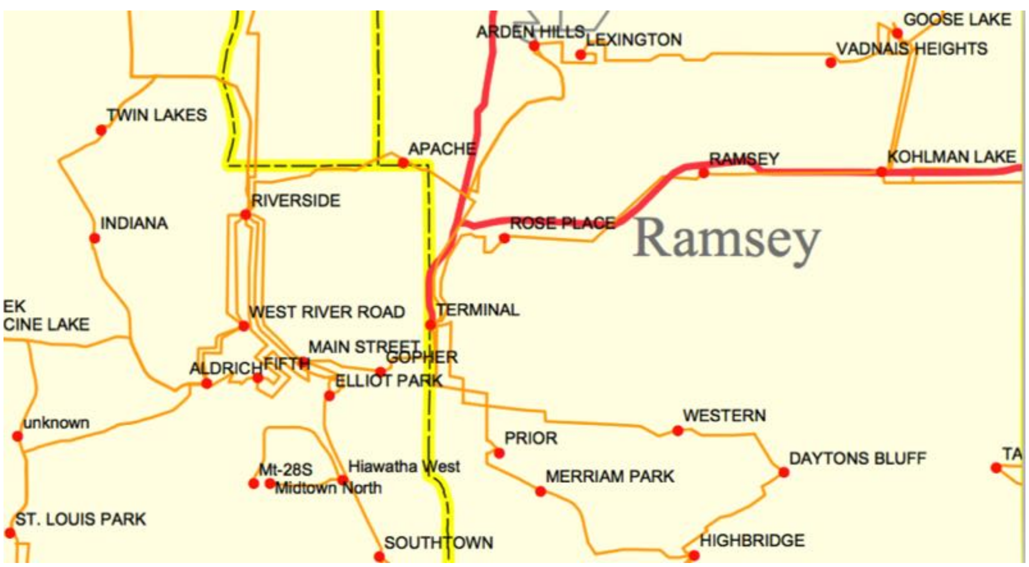
Here, however, is where the three phase lines branch off to my neighborhood from the main three phase feeder lines running down a main street. This feeder line runs up the main street a ways and then branches off to the left to a heavier grade three phase feeder line. Here is a picture of that feeder line with its heavier gauge of wire. This feeder is headed towards the distribution substation.



And here is the substation where a number of the 13,800 Volt three phase feeder lines originate. One of these lines leads very indirectly to my house through quite a few branches. This substation has a wire drop that you can see coming down at the upper right from a major 115,000 Volt line that runs toward downtown Minneapolis. There are several of these wire drops to substations before the 115,000 Volt line ends near downtown. This substations has an emergency disconnect at the 115,000 Volt end and a transformer to 13,800 Volts next. You can see both in this picture. The city is threaded with quite a few of the major 115,000 Volt lines on their massive towers. The substations have names. This one is the “Gopher” substation near the University of Minnesota.

Rather than follow the 115,000 Volt line upwards, I will just show an image of where it ends, at the main switchyard for Minneapolis and Saint Paul. This switchyard is named "Terminal" where a number of incoming 325,000 Volt lines are reduced to 115,000 Volts and then distributed throughout both cities. Terminal is much bigger than this picture shows, with lots of outgoing lines (the lines split as well).

This is the place where most of the TwinCities is connected to “the grid” or, rather, that part of the grid outside the metropolitan area. These 325,000 Volt wires incoming from the left in the picture extend quite far. Here is a map of the metropolitan grid:




This map includes much of the metropolitan area. It has a network of the 115,000 Volt lines (in yellow) to their numerous distribution substations (the red dots, one of these is my local Gopher Substation). The incoming high voltage lines are in

red. If I were to follow these high voltage lines further out they would branch out, leading to a large coal fired power plant and a nuclear power plant to the Northwest, a smaller coal fired power plant East, a larger nuclear power plant Southwest, the connection to a direct current line from a coal fired power plant West and the connection to a 500,000 Volt line to Manitoba and its hydroelectric power plants North. [1] Some of these lines would lead to other states than Minnesota. The 325,000 Volt lines are mainly in the southern part of the state, themselves branching out via transformers to the rest of the state on 230,000 Volt, 161,000 Volt, 115,000 Volt down to 69,000 Volt lines. I will spare you the details, but there are some important things to realize here . A surprisingly large part of the grid is inside the metropolitan area (I think that this is also true in other states) and outside the metropolitan area there are actually few connections that are directly to large power plants. (There are, of course, many small plants also connected to the grid.) Most of the grid wire interconnections--hundreds of them in Minnesota--are in the countryside. Sometimes they are simply one line with a connection at the same voltage to two or more lines and sometimes there is a connection through transformers and switches.

This may seem boring, but it is the easiest way to develop a mental picture of the grid, from the bottom up. It now becomes easier to imagine just how complex the grid is for just one of the two synchronized AC grids, the Eastern Interconnection and the Western Interconnection. (Texans have it easier with their single separate grid.) Individual wires, or “Transmission Lines”, may be only tens to hundreds of miles long, but there are interconnections that branch out over the whole of one of our grids, over thousands of miles.

**Managing the Grid**

How is all this complexity managed? Again, it is simplest to start locally, in Minnesota. (You can do the same for your region.) In our case, transmission is managed by an organization, called the Midcontinent Independent System Operator, Inc. (MISO). It manages power transmission and power sales (i.e. it sets prices) for 15 U.S. states and Manitoba. It and the other system operators answer to the

federal government agency, the Federal Energy Regulatory Commission (FERC). MISO manages roughly 150 gigawatts of power and has members who own transmission systems or power generation capacity. MISO sets rules for its members, who can complain to the FERC if they dispute something MISO has done. MISO seems to determine which power provider can sell electricity on its part of the grid and at what price. Documents refer to its "control" of power stations' distribution.

Later, I will be interested in the reliability of the grid, not the price of electricity. There exists what seems to be a parallel organization here, the North American Electric Reliability Corporation, NERC. There are eight regional members of NERC, and the one for Minnesota and other nearby states is the Midwest Reliability Organization, MRO. NERC can set reliability standards, but it is not too clear to me what actual authority it has over the system operators, apart from the overall command of FERC. Underlying the intense cooperation of all these management pieces is the fear of a large scale grid failure. Much of what we see now by way of regulation is due to the large 2003 Eastern U.S. grid blackout and the fear that it might happen again

The impression this makes on me is that the regulatory system is all quite fragmented. But it has worked so far.

**The Structure of the Grid Now**

There are, at least in my area, two sorts of grids. The one shown above is that inside the metropolitan area. For the most part it is a feeder grid with power flowing only "downstream" from the high voltage main "Terminal" station to the substations and then to users. This is a picture from vonMeier's book (mentioned in an earlier note; I hope that the author does not object to my using this.), a one way power grid looks like this (the dark short vertical lines are the "busses" in a power plant; the wiggly ones transformers):

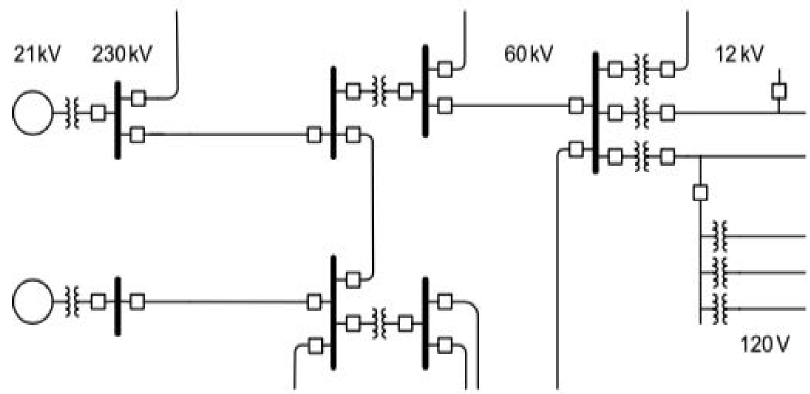


**Figure 6.3** One-line diagram showing basic power system structure.

The "12kV" lines would be to factories and the "120V" lines to houses. The small square boxes are circuit breakers, large versions of the breakers in houses or apartment blocks. They are there to cut power to parts of the downstream grid where dangerous failures happen. Some of the breakers can automatically reconnect if the failure is just momentary (they are "reclosers" and typically restore power in a few seconds). Other breakers do not reclose, so teams have to repair any failure before reconnecting the damaged part of the local grid. Not shown here are switches that can rearrange the power flow if needed. It is a property of this sort of grid that there are no alternate routes for power to flow to a home or business if the lines are interrupted by a fault.

The larger scale grid, with many large generators and transmission lines, is typically outside a metropolitan area. This is where the real complexity arises, because this larger grid has many different routes for power. If a generator or a transmission line fails, the grid can still maintain power flows. Up to a point, users of power may even not know that a failure has happened. Here is a rough sketch, from vonMeier, of such a larger system. The problem with such a large system is that failures at one place can lead to completely unexpected routes for power to flow. The rerouted power can even overload a part of the system, leading to a spreading series of failures. Since the entire U.S. has only three power systems, failures can spread quite far before they stop. A large area can be "blacked out".

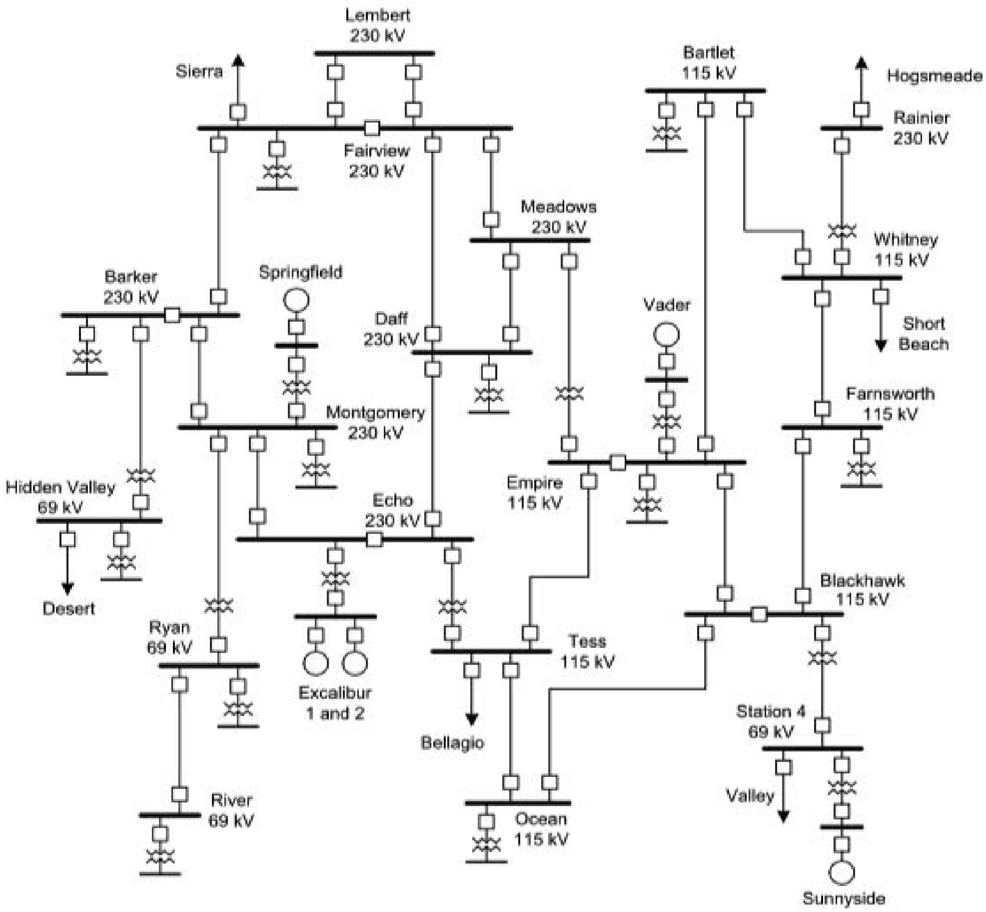



**Figure 7.1** One-line diagram for a power system.

## Grid Control

Controlling local one-way power grids is at least straightforward in concept. If there are no generators or other electric power sources, everything runs nicely at a steady 60 Hertz and timing set by the external grid that feeds the local one. Power flows only one way and if something in the flow breaks, it can be located and fixed. It is almost like repairing a broken water main to restore the flow of water. Electricity is interrupted, but only for a short time. In a worst case-after a storm for example- some areas can be off the grid for days before overloaded crews deal with all the failures. Planning can tell which areas need more power lines or protective devices to minimize failures.

Larger grids--one of the three national ones--are a very different challenge. There are thousands of generators and many tens of thousands of miles of transmission lines, with voltages determined by transformers.

**Grid Failures in the U.S. : 1965**

There is a long history of U.S. "blackouts"; the most significant for us are those in 1965 and 2003. It seems likely that more are to come, despite efforts to prevent blackouts.[2] The 1965 grid failure led to the Northeast, and Ontario Canada, loosing almost all electrical power on November 9, 1965 for a period up to 13 hours in some places. This affected 30 million people. The immediate cause was a circuit breaker that failed, stopping some of the power transmission to the north, into Toronto from a Niagara power station. Only one line failed, but the excess power to Toronto on the other lines to cause them to also (correctly) fail by opening circuit breakers. As a result of this, the entire power flow (of 1700 megawatts) to Ontario stopped, isolating that province. Since power has to go somewhere, it overloaded lines to the Northeast U.S., which failed; the whole process took only four minutes and Ontario and the Northeast U.S. went mostly dark. In fact, that first breaker should not have failed at all, it was incorrectly set to trip at a low power level. The broader reason for the blackout was the inability of the regional grid to absorb the sudden excessive power flows. All over the region, breakers opened and shut off power. During the first few seconds of the failure, many power generating stations in the Northeast became isolated from the larger grid in the region, called "islanding". They could not supply their power demand and failed in turn. Some stations continued operating for several minutes, but had to shut down.

Once power generating stations had shut down, they found it difficult to restart without outside power. This prolonged the blackout.[3]

One lesson of the grid failure in 1965 was the lack of flexibility in the system. The failure of one line into Canada should not have led to the others failing as well. Them having failed, the power surge into the Northeastern U.S. should not have

caused yet more lines to fail. The list goes on, in the report mentioned in the previous endnote.

The 1965 blackout was a major shock to the view that the grid system was reliable; it was not. That grid failure was only the largest of many failures around this time. The response was to improve and expand the grid; the 1967 report to the president of the U.S. contained extensive plans. The Eastern grid got much bigger, with power able to move over large distances, not just from that one large Niagara station to Ontario and the Northeast (with its smaller power stations). The idea was to prevent further large scale power interruptions. These grid changes worked reasonably well for almost forty years.

**Grid Failures in the U.S. : 2003**

The plans developed after the 1965 grid failure worked well. But then even this larger grid failed, in part, in 2003. [4] In all, about 50 million people lost power, some of them in the U.S. for four days and even longer in Canada.

The 2003 blackout developed in a very different way than that in 1965. The blackout began slowly, in Ohio around 1:30 p.m on August 14, 2003. A generator automatically shut down then--not so unusual. But shortly after that, the monitor systems in the area failed as well. As power lines in the area touched overgrown trees, the lines automatically shut off, but the monitor equipment did not register it. This meant that power would flow around in hard to predict ways. By shortly before 4 p.m. still more lines failed and, finally a key power line failed just after 4 p.m.

This was all happening in the Ohio area and had not spread as yet. But by 4:10 p.m. the uncontrolled power flows due to shut off transmission lines led to a large area failure of lines and shutoffs of endangered generators. This “cascade” of failures only took about another three minutes and the entire Northeast and part of Canada went lost all electric power. By then enough power stations were offline

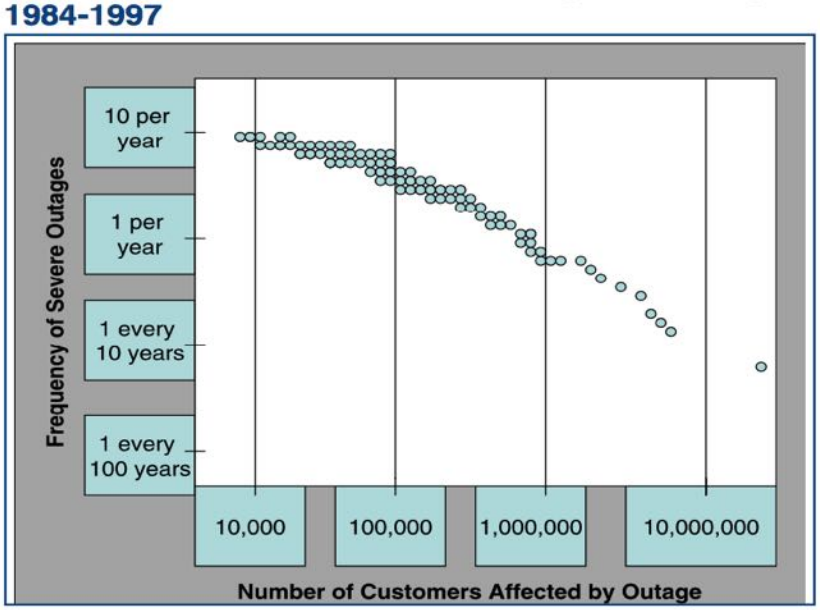
that the cascade stopped. It was days before power was fully restored to the Northeast and Canada.

The report I drew this account from lists major causes of the blackout:

- Inadequate vegetation management
- Failure to ensure operation within secure limits
- Failure to identify emergency conditions and communicate that status to neighboring systems
- Inadequate operator training
- Inadequate regional-scale visibility over the power system
- Inadequate coordination of relays and other protective devices or systems.

It is not clear to me which, if any, of these causes might happen again with similar results. Large scale blackouts smaller than 2003 are not uncommon. Here is a plot of failures from the same report for 1984 to 1997.

**Figure 7.1. North American Power System Outages, 1984-1997**




In the decades ahead, the grid will contain a mix of older conventional power sources and new intermittent power sources. Gradually the old power sources will

be retired, changing the grid in difficult to imagine ways. Old monitoring equipment and procedures adapted to the old grid may not work well. It is likely that new sorts of failures will occur. The more we depend on distributed electric power to replace old fossil carbon power, the more dangerous failures will be.

# Chapter 3 Electrical Energy Storage Now

Electricity cannot be stored in any obvious way. The reason is, in essence, the huge size of the electric force. It is impossible to accumulate significant electric charge in one place for later distribution. The force law of Coulomb prohibits it. (It is possible on a not very useful small scale in devices called "capacitors".) The result is that electric current must flow, it cannot just stop somewhere. For example, the flow of electric charge into your house has to be balanced to enormous precision by the flow out. What current flows in must flow out. Electrical *energy* can, of course, flow into your house and there converted to another form of energy (heat, for example). But not electric current, the flow of charge.

The result of this is that electric power is not stored, it is used exactly when it is generated. Electric power is not like oil, coal or gas that can be stored. Even when we speak of electrical energy being "stored", it is more useful to think of it being "used"--for example, to charge a battery, in the form of stored chemical energy.

So electrical energy can be converted into another form of energy and then later this other form of energy can be converted back into electrical energy. But there is a price to pay--the storage of electrical energy in another form has losses (heat is generated). The conversion back into electrical energy also has losses--more heat. It is very hard to keep these losses below about half of the initial electric energy.At present this is such a disadvantage that there is very little storage of electrical energy in other forms. But I do want to describe this storage here, partly to emphasize just how small it is today in comparison with electrical energy use.

There is a broader problem with storing electrical energy, a problem that is often ignored. The problem is the scale of storage--how much storage mass or money is needed for meaningful storage, when compared to the amount stored or its value. The typical case is that you cannot really store much energy and the storage device is very heavy and costs a lot.

The simplest illustration is the now famous lithium ion battery in automobiles. The storage is usually given in units of kilowatt-hours, an energy unit. I prefer a different unit, the megajoule, often abbreviated MJ. One kilowatt-hour is 3.6 megajoules or 3,600 kilojoules or 3,600,000 Joules, so if you see references to kilowatt-hours, you can easily convert to my preferred units. The power output of a lithium ion battery is usually given directly in units of Watts or kilowatts--thousands of watts. We know already that automobile batteries are heavy and expensive--they weigh hundreds of kilograms and cost a big fraction of the cost of the car. The key question is how heavy and expensive is the battery in an electric automobile? How much energy can it store, and what can we compare that to? A lithium ion battery can store about 0.5 megajoules per kilogram of battery mass. [1] For comparison, the gasoline in an internal combustion engine releases about 43 megajoules per kilogram when it is burned in air. The ratio is

$$(0.5\text{megajoules/kilogram})/(43\text{megajoules/kilogram}) = 1/86$$

(Of course, the battery can be reused, the gasoline not. But both involve a form of chemical energy, so this is a reasonable comparison.). The battery is a very ineffective use of chemical energy. And this is a battery technology that has benefitted from decades of development. Cost is another problem. A lithium ion battery this year (2017) costs about $75 per megajoule; gasoline costs about 2 cents per megajoule, over 3000 times less (although, again, the gasoline cost is for one use).

This is the essential problem with all electrical energy storage concepts. The details vary, but the problem is of the same scale. A survey of the Web will show that many power plants *do* have energy storage on the site. This is for the case when they need a brief extra supply of electric power to help stabilize the grid. A typical battery installation might be able to deliver 5 megawatts to the grid for about ten or twenty minutes. This is useful, but the moderate sized power plant might *continuously* deliver 500 or more megawatts in total. So the battery is short term and only about a percent of the plant capacity. And these installations are expensive and large--over $1 Million and a mass of over 30 tons. Scaling up to a 1000 megawatt (one gigawatt) power plant and expanding the battery power delivery to a more

reasonable 10 hours would get us to a plant with a cost of many billions of dollars and a mass of some tens of thousands of tons!

This does not mean that electrical energy storage is not useful. But it does mean that we have to look carefully at what storage can and cannot be used for. Here are some present options in use.

**Batteries**

This is what I just described for lithium ion. It is hard to believe that batteries will advance by more than a factor two in price or capacity or so over the next decade, so we will live with million dollar installations that can briefly deliver a percent or so of the installed plant capacity. [2]

There are other sorts of batteries--essentially storing electrical energy in other chemical forms. [3] Many are technologically innovative but not much different in their fundamental physics than lithium ion batteries. I will come to them later.

**Flywheels**

Flywheels have been used for a very long time to store electrical energy in the form of kinetic energy of rotation. They have  a great advantage that the frequency is easy to control and they can dump a lot of energy to the grid very quickly. But, yet again, the energy storage capacity of flywheels is not impressive. The latest ones, rotating at high speed with advanced construction, can achieve about the same energy storage per kilogram mass as a lithium ion battery. [4] So no improvement here, except for the ability to quickly deliver power at a convenient frequency.

Flywheel storage at power plants is typically about the same scale as batteries -- 5-10 megawatts for ten to twenty seconds. They are expensive, in the ballpark of $500 per MJ storage. [5]

**Pumped Storage**

The idea of pumped storage is to lift water over some height, which requires energy. The when the water runs downhill through a turbine, much of the energy put into lifting it can be recovered. Pumped water energy storage is unusual because the energy stored per kilogram of water is almost absurdly small, sometimes as little as a kilojoule per kilogram of water lifted a hundred meters. But it is possible to move vast amounts of water. There are today numerous pumped storage plants that can store *tens of gigawatt hours* of electrical energy and deliver the energy back over about ten hours. Present ones can approach an efficiency of 70%, meaning that only about 30% of the electrical energy put in is lost as heat. They are expensive--a modern pumped storage plant with a peak energy output of a gigawatt, or a thousand megawatts might cost a half billion dollars. But they are built anyhow because of their ability to deliver a lot of electric power over a long time of many hours.[6]

At present, total electric power storage in the U.S. can produce peak electric power levels of about 20 gigawatts. About 95% of this is pumped hydro storage.

There are other mechanisms I have not discussed here, but they are minor right now. This might change over the next few decades.

# Chapter 4 Future Energy Storage

Energy storage now is tiny and electric power is almost entirely used as it is generated. A rough number for energy storage now is that the *peak* power that can be produced from all storage, if it were delivered at once, is about 5% of our *average* electric power use. Storage exists just to handle fluctuations in power use and to maintain the stability of the grid, as I mentioned. [1]

Power from conventional fossil carbon and nuclear power plants is quite predictable, and there is a lot of excess capacity. (Average national electric power use is about 40% of the total installed power capacity.) Natural gas fired power plants can even be turned on and off quickly, to cope with sudden demand. This will change in the future, when erratic power sources such as wind and solar are a large part of the grid because fossil carbon availability will go down. Some states now use natural gas plants as part of grid power to cope with the erratic nature of these replacement energy sources. Texas and California are examples of this. But this "escape hatch" will go away as natural gas supplies drop off later in this century. We will face the need for very large and diverse energy storage on the grid. [2]

Unfortunately, we have no coherent idea just how much grid energy storage will be needed. There are many studies. In my view present studies are likely to be captive to apparent and hidden assumptions. We just do not know how much erratic "alternative" energy we can live with, nor how efficiently  we can move energy around the country to mitigate local irregularities in production or demand. [3]

The future of energy storage is sometimes expressed as "grid level storage". There are really multiple levels of grid level energy storage. For me, grid level storage is enough stored energy to balance out any residual fluctuations in erratic energy production. This is a lot of storage capacity, far beyond what is often casually called "grid level storage". The exact amount needed is not very clear at present Just how much storage will be only a bit more clear later on.

My aim here is just to describe some types and the scale of grid energy storage, given a wild guess how much might suffice. The EAC report in an earlier endnote estimates that the storage requirement, with power delivered from storage over hours, might be of the order of the distributed power. For example, if the distributed "renewable" electric power were chosen equal to the present average U.S. use of about 400 gigawatts, then a peak storage capacity of about 400 gigawatts

would be needed. This is about twenty times the present peak storage capacity. [4] Most large storage installations now can deliver this level of power for about 10-20 hours or so, for a total estimated need of about 4000-8000 gigawatt hours.

So the amount of storage needed will be very large. In examining options, the best place to start is with storage technology that exists now and that we know how to use. That is pumped hydro power storage. Then we can move on to other storage methods, big and small. Smaller ones will likely be in the range of 10 to 100 megawatt hours.

**Pumped Hydro Storage**

We met this in the last chapter. U.S. pumped storage simply moves huge amounts of water uphill using electric power for large pumps and then delivering power to the grid later, using the pumps in reverse as generators as the water flows back downhill. A figure of merit for pumped storage might be a peak power equal to that of a large coal fired power plant (1000 megawatts) and a time (to empty the water reservoir) of, say, ten hours. This would then be 10000 megawatt hours or 10 gigawatt hours. [5]

Older pumped storage plants mostly depend on exploiting a hill a hundred or more meters high above an existing large body of water. They can reach efficiencies of about 70% (that is, total output energy divided by input energy as a percent). More modern plants can be built on ground above existing bodies of water, as now, or by building both an upper and lower basin of water. These are called "closed loop" plants. [6] The advantage of these plants is that the basins can be filled and maintained by little more than an irrigation ditch to supply water. They can reach efficiencies above 80%, better than many batteries.

Is it realistic to build very many times the number of existing pumped hydro plants or capacity? Almost all of these would have to be closed loop plants, but there are already permits for a number of such plants submitted to the government. [7] So how many pumped hydro plants at the 10 gigawatt hour scale *could* be built in the U.S.? We would need about twenty times what we have now. The only data I have is old, but the answer appears to be yes, it is possible to reach 400 gigawatts peak power (or 4000-8000 gigawatt hours or 4-8 terawatt hours energy, mentioned earlier). [8]

There is a disadvantage to pumped hydro plants--you have to build them where it

is geologically practical and then you must transmit power to and from the plants. There are places in the U.S. where it is just not realistic to build many of them. But the height restrictions are not too onerous; a plant in Michigan (the Luddington plant) is just above the shore of Lake Michigan.

There are other options for pumped storage than the pretty standard type mentioned here. They can be built near the ocean as a water source. The reservoirs can be underground or elsewhere. There are lots of possibilities. Cost is not a major concern since there are no cheap other energy storage options. [9]

Present pumped storage plants can be ramped up to peak power in less than a half hour. This is enough for most purposes, but not if there is a sudden grid power demand over seconds. For that, other storage--probably smaller in scale-- is essential. Before turning to smaller scale storage, I want to briefly mention another large scale grid storage option.

**Pumped Air Caverns**

This is sometimes called compressed air energy storage (CAES). There are only two in long term operation, one in Germany and the other in the U.S. [10] Unfortunately, neither of these is of much interest to me, as both compress air to use later as input high pressure air to gas turbines. Future small scale plants that do not need natural gas will be quite useful, but in this section I want to focus on large grid scale plants, roughly 1 gigawatt for 10 hours or so. No such plants exist yet. Some fundamental engineering problems need to be solved. The idea of such plants is to compress air, the process of compressing then storing energy in the high pressure air. The energy is then recovered by releasing the compressed air thru a turbine that produces electricity. The problem is that when air is compressed, it is heated. (This is familiar from bicycle pumps, which heat up.) If this heat is lost, the efficiency of the plant is compromised; the released air is cold, the reverse of the heating when it is compressed. Energy is lost. To be efficient, either the heat has to be retained directly as heat of the compressed air, or the heat has to be extracted and then reintroduced into the air as it is released thru the turbine that produces the final electricity.

Compressed air can store energy. Squeezing air at atmospheric pressure to 50 times atmospheric pressure into a final volume of one cubic meter requires about 8.5 megajoules (2.4 kilowatt hours) of work by the compressor. This is the energy that

can be recovered by later expansion if the efficiency is 100%. So the final compressed volume if storing my estimated 10 gigawatt hours of energy is about a few million cubic meters or the volume of a cube about 150 meters on a side. Whatever container holds this has to be able to resist the pressure. [11] Popular ideas are air storage in caverns leached out of a salt formation, tunnels in rock or even underwater balloons or rigid structures.

There is no problem of principle that prevents compressed air storage in the range of the 10 gigawatt hours that interests me.

There is an older development effort in Germany, the ADELE project, whose aim is to store the heat energy produced in air compression and reintroduce it to the expanding air that has been stored in a cavern in a salt formation. The hope is to reach about 70% overall efficiency. [12] There are other proposals of this sort, usually a few hundred megawatts or even much less. The key idea and difficulty is to avoid the need for outside fossil carbon energy.

Many small scale compressed air storage systems are likely to work in the coming few decades. Most are likely to be in the range of tens to a few hundred megawatt hours stored energy. To reach ten or so gigawatt hours with small hundred megawatt hour plants would require about a hundred of them, not at all unrealistic, but this is only a small part of our future energy storage needs. Really large energy storage using compressed air is probably a long time off.

**Batteries**

As I mentioned in the last chapter, batteries are not really very effective energy stores, despite their popularity. A typical modern lithium ion battery installation at a power plant or electrical switchyard might amount to a few megawatts to around a hundred megawatts. And it might cost almost $300,000 per megawatt hour, so a hundred megawatt hour battery installation might cost $30 million and have a mass of almost ten tons. This is perfectly reasonable for this sort of application; whether or not it is good for other applications is not immediately clear.

Let us investigate a battery storage option--imagine storing the energy produced by a single wind turbine that outputs an average 1.5 megawatts. Storing ten hours of produced energy (15 megawatt-hours) would need a lithium ion battery that would cost over $4 million, even at an unrealistic 100% efficiency. That is as much or

more than the turbine would cost. So this sort of energy storage would at least double the cost of wind energy. The problem is the same if wind turbines and batteries are aggregated into a wind/battery farm. And the real problem with erratic wind energy is that, historically hourly fluctuations are common but loss of wind for about a week is not unknown. (I will come to this problem in a later book.) Ten hours storage will help, but it will not be decisive. And such storage for, say, 200,000 wind turbines will require well over a million tons of batteries, enough for many millions of electric cars. [13] Eventually, the supply of lithium metal will become a problem. [14]

Lithium ion batteries are a good example to use to judge all battery technologies; that is why I am going into a bit of detail here. Lithium ion batteries have a long history of decreasing prices (but not mass). Over the next decade or two their price, per kilowatt-hour, might drop another factor two or so, down to $150 per kilowatt hour. This is approximately the goal set by our Department of Energy for the price of energy storage for *all* battery types, ignoring any problems this scale of production might lead to. [15] In the future, we will likely be looking at many tens of millions of tons of batteries of all types.

I want to briefly comment on other sorts of batteries that have emerged in the last decade. Many of them are more promising than lithium ion batteries, but just how their cost, resource demand and environmental consequences will evolve is not known. The number of novel types of batteries is large. [16] I will mention only one type, to illustrate where developments are headed.

**Flow Batteries as an Example**

There are many types of flow batteries. The common feature is that there are two electrolytes that are separated liquids. They can be flowed together by pumps and the current that is produced is an electron flow through a membrane. A currently popular version is the Vanadium redox flow battery, Vanadium dissolved in Sulfuric and Hydrochloric acid. The Vanadium is in *both* electrolytes, but in a different state in each. [17] This sort of battery can have a lifetime of decades and low maintenance costs. They are expensive and heavy, about 2000 tons per 100 megawatt hours capacity. These batteries do have a higher energy capacity per cubic meter, roughly 60 megajoules. By comparison, a pumped storage plant that raises water 100 meters would store only one megajoule per cubic meter. A very big battery installation with 10 gigawatt hours capacity would weigh some hun-

dreds of thousands of tons, be staggeringly expensive and cover a lot of land. These batteries will probably be limited to around a hundred megawatt-hours--a good use would be in power plants and switchyards. They can be turned on in milliseconds, which is good for grid control and for emergency situations where power is lost for less than an hour or a few hours. [18]

Over the next few decades many newer types of battery will become commercial. Virtually all of them will be limited in some way, mostly to energy densities below about one megajoule per kilogram. The power delivery, in watts, will be a difficult problem for many battery types. [19] It will take a long time for costs to drop below some hundreds of dollars per kilowatt hour. The significant price decline of lithium ion batteries has taken two decades.

**Flywheel Energy Storage**

I have already mentioned flywheels. Energy storage can now reach perhaps one megajoule per kilogram of rotating mass, less if the packaging is included in the overall mass calculation. There is an interesting possibility of storing more energy by increasing the flywheel size. The centripetal forces that limit the rotating mass go up with the square of the speed, but down inversely with size. Present flywheel rotors are small diameter cylinders, but maybe they could be scaled up. Really big flywheels could store enough energy to increase the stability of the grid if their rotation were synchronized to the AC grid 60 Herz frequency. This is what "spinning reserve" generators do now.

**Electromagnetic Field Energy Storage**

Electric fields store energy now, in the form of capacitors. Most of these store tiny amounts of energy--joules rather than megajoules. The only current exception are the "ultracapacitors" that can store several coulombs of electric charge, which is a lot, at quite low voltages of a few volts. A single one might store of order 30 kilojoules per kilogram mass [20] This is not large, but these gadgets can be useful because they last a very long time and can deliver current almost instantly. For grid storage, ultracapacitors will likely remain a small scope method.

Magnetic fields can be very large and store a great deal of energy if modern high temperature superconductors are used to create the magnetic field. Modern high temperature superconductors can carry current at zero resistance up to the boiling

point of liquid nitrogen (about 80 Kelvin). They work better at lower temperatures, around 50 Kelvin for liquid hydrogen cooling. They can reach fields about twice that of conventional superconductors. Just as an example, the huge fusion research device ITER, now under construction, has a magnetic field of 11 Tesla and a stored energy of about 40 gigajoules. At twice the field, stored energy would amount to about 160 gigajoules. Storing 10 gigawatt-hours of energy would need a device with several hundred times the volume of such a high field version of ITER. I doubt that such a device will ever be built, but it is not inconceivable.

Smaller high field magnets could be very useful because they have almost instant response to a demand for energy.

**Hydrogen Gas Storage**[21]

Hydrogen gas at atmospheric pressure has a high energy content, if it is to be burned by combining it with oxygen--about 12 megajoules per cubic meter. This is not as good as a flow battery mentioned above, but this is for a gas. It was once common to store large volumes of coal derived 'syngas' (mostly hydrogen and carbon monoxide) in cities, so hydrogen as an energy store is not very novel. The old name for such storage tanks was 'a gasometer', so an atmospheric pressure gasometer of hydrogen that is 100 meters in radius and 50 meters high could store about 5 gigawatt hours of energy--quite a lot. Smaller ones could also be useful.

A safer way to store hydrogen, but make storage buildable anywhere, might be to mine out an underground spherical cavern with a smaller 50 meter radius and store the hydrogen at 50 atmospheres pressure (this has already been done for pressurized air). Such a cavern could store 90 gigawatt hours of energy, much more than a simpler above ground gasometer. All that would be needed is rock that can be mined out to a cavern whose walls could support the modest pressure. The cavern might have to be lined to prevent hydrogen leakage; for a spherical cavern a simple balloon as a liner might suffice.

The major disadvantage of hydrogen gas as energy storage is that the round trip efficiency is not high. Modern devices, electrolyzers, that can produce hydrogen and oxygen gas from electric power can do so with an efficiency of about 70%. But this gas has to be burned with air in turbine-generators to produce electric power and modern turbines are seldom more than 60% efficient. [22] So the overall end to end efficiency (electricity to hydrogen to electricity) is around 40%--not too good. But it is an advantage that such gasometers or caverns could be put almost any-

where on the grid.

Of course, the disruption and resulting combustion of an above ground gasometer would be spectacular. But hydrogen gas is light and the burning hydrogen would rise rapidly.[23] It would clearly be wise to have plenty of open space around such a device. Even caverns might leak, presenting their own dangers.

It would be unusual to also store the oxygen from an electrolyzer--probably a dangerous idea if a gasometer is used. With caverns this might be possible. Whether turbines could be built that use burning pure hydrogen and oxygen is unclear to me. Conceptually, this is a bit like using a hydrogen and oxygen rocket engine to drive a turbine. Really large fuel cells could accomplish this as well if with less drama. [24] In any case, this sort of energy storage is not likely to be practical in the near future. But this is almost the only energy storage option that reaches the tens of gigawatt-hours number I have been using for true “grid level” storage.

**Ammonia Energy Storage**

It is possible to convert hydrogen from electrolyzers to ammonia ($NH_3$), using atmospheric nitrogen. The chemistry of this is well understood, and plants exist now with an efficiency of about 50% that turn hydrogen from natural gas plus atmospheric nitrogen into ammonia.  Using electrolyzers to produce the hydrogen is an easy step. The problem is, again, the overall efficiency of the process. The efficiency from electricity to ammonia is only going to be about 30% (0.50 times 0.60 as a percent) and this will be reduced further when the ammonia is burned to make electric power. But the energy storage density will be very high, and ammonia can also be used as a vehicle fuel. This use is likely quite far off.

Storing energy as hydrocarbon fuels is possible but also not an option for the near future. Either coal has to be used as a carbon source, with hydrogen from electrolyzers, or the carbon has to be extracted from the air or another source. This latter is possible in principle but problematic on a large scale in the context of my interest in a low carbon future. So I will not discuss storing energy in the form of burnable hydrocarbons.

For several decades, the most likely largest grid scale energy storage is likely to be as closed loop hydro plants. More exotic options will probably evolve in time.

# Chapter 5 The Future Grid

Our present grid, or rather our three grids, grew over about the last century. Most of the system was shaped fifty or sixty years ago. The future grid, out to at least the year 2100, will be constrained by the near or complete absence of most fossil carbon energy sources.

The U.S. has lots of coal that will become increasingly difficult and expensive to mine. Coal use may decline slowly, but it will decline. Oil was never an important grid energy source. Natural gas is becoming an easy way to deal with intermittent wind and solar power. It fills the gaps. Our natural gas will not last. Perhaps fission power will slowly go away. Fusion power may be far off.

Without fossil carbon energy--for industry, as an example[1]--we will need to employ electric power, created in some fashion, to run almost everything. Right now, about a third of all primary energy used is electrical. It is a larger fraction, about 40%, of all "useful energy", disregarding heat losses. [2] That 40% will increase to close to 100 %, in the form of "replacement energy". Even with some energy conservation, we will likely see about a doubling of electric power use. (Most energy conservation measures will really just hold down growth in electric power use.)

The entire concept of the grid we have now is based on heat engines that produce steam to drive rotating machinery--ultimately generators. Generators are well matched to the sixty or so percent of electric power used by motors. Generators, as we have known them, will largely decline with the heat engines that drive them. What then? The time scale of change may be out to the year 2100, but the transition is underway now.

There is, even now, much discussion about replacment energy sources. So far, in practical terms, they do not amount to much--wind, solar and geothermal energy is about 3% of our national primary energy use. (It is a larger fraction, perhaps 6%-8% of useful energy.) As this grows, so will the effects on the grid of replacement energy. The effects will appear first in our states that use the most such

replacment energy; but at present they are buffered by cheap natural gas power and the ability of our grid to export or import power. So we need to think of the nation as a whole.

The existing grid is an amazing engineering accomplishment. But it is also a historical hodgepodge of systems linked together, each of the three grids based on perfectly uniform synchronous alternating current. Often discussions of a future grid assume that replacment power from wind, solar and geothermal sources can simply substitute for the existing fossil carbon stations. That is probably not true because the central problem of our hodgepodge grid is not its total power, but rather its stability against catastrophic failure. The total transformation of our present old fossil carbon grid to to one or two national AC grids based on intermittent power sources and some energy storage is asking for trouble. [3]

Replacement energy sources will be very unlike our centralized power stations. Power sources will be in the form of large numbers of distributed elements--tens or hundreds of thousands. Even the form of the future grid will be affected. (This is usually, to my mind, trivialized by references to “the smart grid” or “smart grids”.)

I think that what we now imagine as “the grid” will take a form by 2100 that we simply cannot now realistically envisage. Remember that as fossil carbon declines and electric power replaces most of it, any instability of the grid will affect everything we do. Now, if our lights go off and factories get no power for days, we can still cope. Gasoline autos still work, we can still heat our houses with natural gas. Hospitals have backup diesel generators. Factories that use oil or gas will continue. And so on. In the future, the danger of grid failure will be that *everything* will stop. Between now and then it is likely that there will be true major power system disasters--not like our recent blackouts, but much worse.

The way forward may be back to the past, when there were very many regional grids, not just three. There is even an example of such a grid at hand: the Texas grid, known as ERCOT.

**The Texas Grid**

The Texas grid serves most of the state of Texas, largely independent of the national grids.

The Texas grid is not small--it serves over 20 million customers and delivers on average about 40 gigawatts of electric power, a tenth of the U.S. total. (Peak power is a bit under twice the average.) It is only connected to the rest of the U.S. continental system with two small “DC interconnects” of hundreds of megawatts each. About 6 gigawatts of the average delivered power is from wind generators--15% of the total. Natural gas and coal produce most of the power with a small 12% fraction from nuclear power stations. The grid is managed by an organization, ERCOT, which does coordinate with the rest of the U.S. grid management system.

The Texas electric power system is particularly interesting for two reasons. One, it is largely disconnected from the rest of the U.S. grid system and so it serves as a useful testbed for future development. Second, Texas has some similarity to the rest of the U.S.--there are large areas with high wind and also high solar irradiation and they are far from the major population centers (if only by a few hundred miles). So it is interesting to speculate about a future with less and maybe no fossil carbon power--and maybe even no nuclear power. That is, to change phrases, replacement energy as “renewable energy” which, today, means wind and solar energy.

There are two problems with this sort of intermittent energy as a sole source of electric power. Both are connected to the absence of our familiar generators. Generators today do two quite different things: they hold grid voltage constant and they hold grid frequency constant. The first ends up as our customary 120 volt household voltage. The second is our largely unnoticed 60 Herz AC frequency. Maintaining the first is easier than keeping the second constant. Most grid planning keeps about “10 percent spinning reserve”--about ten percent of the current power demand. This does both things: if there is too much demand for power so voltage drops, reserve power keeps the voltage up. But too much demand also causes generators to slow down, lowering the frequency. The first--voltage--can be kept

up even without generators. You can use batteries, switched in when voltage drops. The second, keeping the frequency constant, is harder. It is connected to what is called “reactive power”--that is power that is not consumed, but always surges back and forth in the grid. It is essential because of the dominance of motors in our industrial system. Motors do not just consume real power to do work, they also absorb and then emit power into the grid, sixty times a second. This is an essential part of their construction and their purpose. The ability of the grid to deal with this is expressed as “inertia”--that is, the inertia of rotating generators and turbines. Present Texas wind turbines and also usual photovoltaic systems do not have any of this “intertia”. [4] Batteries, by themselves, do not help. Any battery 10% “spinning reserve” power can keep voltage up, but not frequency--at least not without complex and computer controlled devices. Generators do that job quite simply and almost automatically. It is this that leads to the stability of our existing grid.

Of course, both wind and solar photovoltaic power are intermittent. So additional batteries--or some other source of power--are needed to deal with this. This is what will make the Texas power grid evolution interesting as coal and natural gas energy drops off (and maybe nuclear power as well). [5]

**A Grid of Grids**

I suspect that in time the Texas grid will connect to the rest of the now Eastern Grid. But the problems it will face make me think that a safe development of our future grid system would be to copy the Texas grid--one grid for each 20 or 30 million people, with modern connections to other grids.

It is no longer difficult to connect independent grids. There exist systems to convert AC power at one frequency to DC power and back to AC power a another frequency--meaning that two grids need not be synchronized. Already, the Texas grid is not synchronized with our huge AC Eastern Grid. It need never be synchronized. Modern systems can connect different AC grids with up to about 10 gigawatts power transfer per station. With two or three 10 gigawatt AC-DC-AC connections, the Texas grid could deliver or absorb power from neighboring grids. This is

probably not what Texas would prefer, but they may have to do this anyhow when their natural gas runs out.

I think that it would be a good idea to simply break up the existing two West and East grids into smaller grids--each like the Texas grid, some tens of gigawatts each and connected to several neighboring grids, allowing a flow of power but without the nuisance of synchronizing AC grids.

Why do this?

AC grids are useful for delivering electric power in a region. But it is not clear that they are needed nationally. A single large grid, under the stress of intermittent power sources, and large scale energy storage needs is asking for trouble. Any failure could mean disaster on a new scale. So we should separate the grids. Smaller grids could also move power smoothy from parts of the nation with excess power (wind or solar) to other regions. The AC-DC-AC interconnects would allow this if they were large enough. [6] If not, a few long distance DC transmission lines could mitigate any problems, without the need to build a whole new DC transmission system.

About 10 to 15 grids would be enough. They could be managed thru a consortium of the national government and state governments, like our national freeways.

This would be a "grid of grids". If one grid runs into problems, the problems can be localized and fixed. Outside power can move into the troubled grid in a controlled way. Each local grid system might evolve differently--a grid in an area with a lot of wind power will look different from one in an area with solar power or even nuclear power.

Remember, the promise of more stability of large grids in the U.S. has already not worked out exactly as planned. We still have blackouts. As power generation changes in drastic and uncertain ways, we will need flexibility. A "grid of grids" can accomplish that.

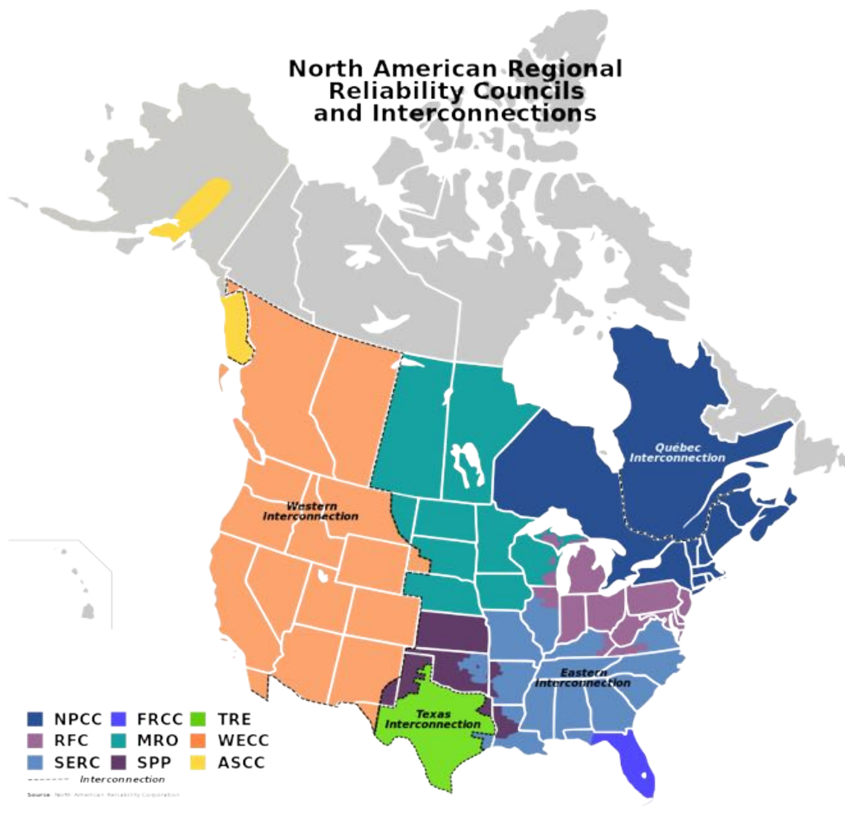
# Introduction

1. The reason for the high voltage transmission line is due to a basic principle of the transformer. The high voltage from a transformer is combined with a low electric current. It is high current that leads to losses of power or energy, so the low current is essential to long distance electric power transmission.

2. Our household voltage, about 120 volts, is the "root mean square" of the maximum or the maximum 170 volts divided by the square root of 2.

3. Much of this story I have from an IEEE book "Power: A History of Electric…" by David Morton. This book is available on the Web (but without the title page!). The three grids are connected at a few points by special stations that convert AC power to DC and back to AC with a different timing. Not a lot of power gets transferred, however.

4. Here is a Wikipedia diagram (check there for the original author) of the industry organizations responsible for control and oversight:




5. Actually 94%--about 6% of our electric power is from dams, hydroelectric.

6. At present, about a third of the useful energy in our country is distributed electricity. (See the Livermore energy flow plots in other books in this series for details.) The nonelectric rest is

energy directly from fossil carbon -- for transportation, heating and industry. While the thought of a massive grid failure leading to a long, maybe month long, loss of electric power is alarming, we would have fallback energy sources. By 2100 there will be no fallback energy sources.

7. Much of the literature on the future of the grid can be found in the MIT study "The Future of the Electric Grid", http://web.mit.edu/mitei/research/studies/the-electric-grid-2011.shtml . Unfortunately, many of the excellent studies are of limited use to most people. They tend to focus either on bureaucratic issues, often being addressed to "policymakers", a species I am not familiar with, or are very technical and deal with only a part of the future grid problem.

# Chapter 1-Some Physics and an Overview

1. The only book I have found that is even moderately approachable for most citizens is "Electric Power Systems, a Conceptual Introduction" by Alexandra von Meier, Wiley Interscience. This book is very good and I have stolen ideas liberally from von Meier's exposition. The book has a good deal of theoretical detail. Another basic book is "Electric Power Systems Basics", IEEE Books, by Steven Blume. A great advantage of Blume's book is the very extensive discussion (with pictures) of system equipment. There is a much more technical useful old textbook "Elements of Power System Analysis" by William Stevenson, Jr, McGraw Hill. This is an undergraduate textbook (!). Glancing thru it gives anyone an idea of just how complicated the subject can become. The full list of books on the subject is almost endless, so I will not try to elaborate.

2. You can find Volume I of Faraday's experiments on the Web, most notably on Gutenberg. He was one of the most remarkable figures in the history of physics. His descriptions of the experiments is entirely verbal and conceptual, not mathematical. Faraday and, later, Tesla proved that it was possible to develop a conceptual understanding of electromagnetic phenomena with little mathematics. Alas, that era is long past.

3. There is such an "electric field" in a current carrying wire, and it drives the current flow. The electric field is not directly related to the voltage; in a wire it is the voltage across the ends of the wire divided by the wire length. So we find voltage to be more convenient.

4. That motors have many loops of wire in them (not just the one in my simplified picture) is very important for the power grid. These many loops of wire develop their *own* magnetic fields and these fields store energy.

5. Later on, we will revisit this in another context--power systems sometimes deliberately use windings, called "inductors", to store and release energy back into the grid as a way of controlling it.

6. Ten thousand volts is a lot, but remember that generators have lots of windings or loops of wire. So the voltage between these windings can be small and still lead to a large overall voltage.

7. There are many more than this 1400 or so plants, 100 megawatts and up, if all power plant sizes are counted-over 7000 with *one* megawatt and up in 2016, according to the U.S. Energy Information Administration (EIA).  The biggest power plants and their generators are huge and expensive. Here is on from GE. The generators themselves are almost all driven by steam from coal, natural gas or nuclear heat.

8. Notice that households use only about a quarter of our total electric power generation. Constant references to "households" can confuse the issue of where most of the power is really used.

9. Power plants are expensive and need to run most of the time, so it makes little sense to built a plant solely for use at one location, or factory. This was done in the past, though--the original Ford auto plants usually had a dedicated power plant that generated their electricity.

10. Here is one, from the Dutch firm SMIT. Notice the three output feeds. I think that this unit is for 765 kilovolts.

11. There is a Department of Energy Study from June, 2012, “Large Power Transformers and the U.S. Electric Grid”, (large meaning larger than 100 megawatts or, in technical jargon, “100 MVA”). According to this source, the number of large power transformers in the U.S. is “in the tens of thousands” and the number at extra high voltage (more than 345,000 volts) perhaps 2000.

12. There is much opposition to the land use by transmission lines, so this might be a good place to mention that wind and solar power sources also use a lot of land. If future transmission lines are needed, land use will become an issue.

13. There is an old DOE sponsored survey that covers about 30,000 industrial motors. This is probably only a small part of the total. The claim is that in 1995 industrial motors used 23% of the distributed electric power in the U.S. If so, and if the average motor was 100 horsepower, the total number of industrial electric motors could easily run to a few million. The largest but uncommon motors on the grid may be those that power the “draglines” at coal strip mines. Multiple motors on a dragline can exceed 1 megawatt each.

14. If you have a large motor in your house, you may have noticed your lights dimming briefly when the motor switches on. Imagine this on a grid scale.

# Chapter 2 The Structure of the Grid Now

1. Minnesota has over 190 power plants above 1 megawatt capacity, of which about 20 have capacity over 100 megawatts. So this list is only of plants near the Twin Cities.

2. There is a very good book on grid failures and blackouts by David Nye, “When the Lights Went Out”, MIT press. It is mostly on the history of blackouts and their social environment and consequences. The book also has useful references, among them the 1967 Federal Power Commission report “Prevention of Power Failures”.

3. There is a short Wikipedia article on the 1965 blackout, with this regional map--power loss is in red.

4. There is a very good Wikipedia article on the 2003 grid failure, with a timeline. There is also a report "Final Report on the August 14, 2003 Blackout" by Canadian and U.S. experts. I have used this report here. A map of the areas affected shows--a much larger area and more people caught up than in 1965:

# Chapter 3 Electrical Energy Storage Now

1. The Tesla Models S 85 kWh battery weighs 540 kg for a ratio of 0.57 MJ/kg -- a bit better than the number in the text; the battery is reported to cost about 1/5 the retail price of the car. The ratio for Tesla's "Powerwall" is less than this 0.57MJ/kg.

2. This is a Tesla battery installation in California

3. A type that is used at present is the “flow battery” that stores energy as the changed states of the two liquids that are used. These batteries at present store considerably less energy per kilogram of mass than Lithium-Ion batteries.

4. The most modern flywheels are geometrically a thin cylinder of composite spinning at a rim speed of about 1000 meters per second about the cylinder axis. So the kinetic energy is then $(1/2)Mv^2$ or 0.5 MJ/kg. It is possible but hard to do much better than this. Flywheels were used already long ago to pulse large electromagnets in particle accelerators. These were slow and large (tens of tons).

5. Here is part of an installation by the flywheel company Beacon Power. The company entered bankruptcy in 2011 but now appears to be operating under new owners. Flywheels are a very small part of power plant energy storage.


6. Here is the image of a small pumped hydro plant on the Elbe near Hamburg. It is only 120 megawatts with three turbines; the layout is easy to see in this image. The largest early pumped hydro plant in the U.S. was in Ludington, MI some 40 years ago and has now reached about 2 gigawatts maximum power for about 13 hours. It has a present efficiency of about 75%.

# Chapter 4: Future Energy Storage

1. The present grid needs about 10% of the power as “spinning reserve”, available to deal with short term changes in voltage or frequency. This reserve is in the form of real spinning generators and turbines. If this were replaced by storage, the 5% figure would have to be increased.

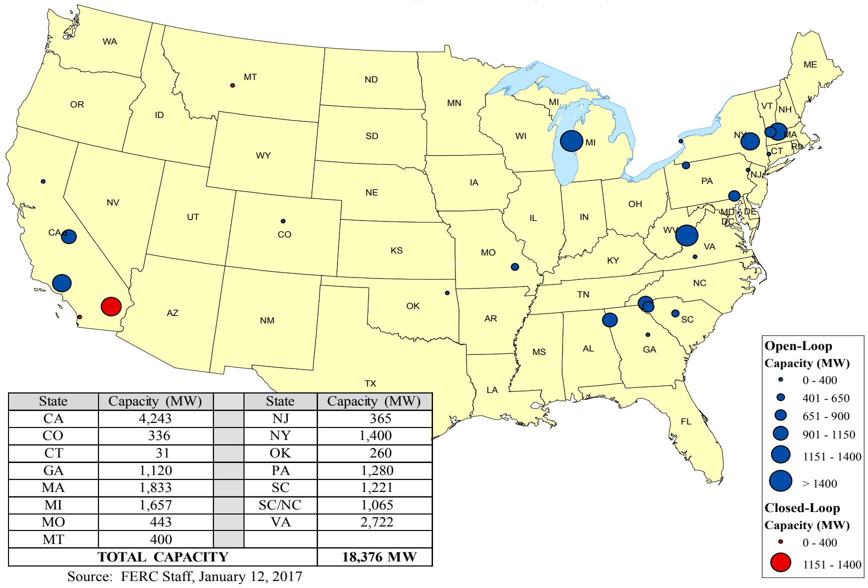
2. I have found a useful source of general information on energy storage, with a view to the future, in the Electric Advisory Committee’s “Bottling Electricity” (2008). Check energy.gov, although the EAC link no longer exists. Another general source is the DOE report “Grid Energy Storage”, 2013.

3. A good source of skepticism on storage of “renewable energy” is by Euan Mearns at euan-mearns.com He focusses on the UK, a small country compared to the U.S., but many of the criticisms are more generally useful.

4. I suspect that this estimate is very low,  but it is hard to produce a better number than this. A satisfactory number would depend on the ability to use the grid, or parts of it, to average out the irregularities in wind and solar power production. In addition, the present grid has a total generating capacity over twice the actual average power use of 400 gigawatts. If erratic sources also had a larger capacity than the average use, this also has to be taken into account. It would reduce the need for storage. Then the need would be less, compared to “brute” storage that has to cope with all irregularities over part of the nation. This, in turn, would depend on the ability of the future grid to transfer very large amounts of power from, say, the Southwest U.S. to Chicago. For the purposes here, I will stick with a need for about 400 gigawatts peak production from storage, or twenty times the value now.

5. The Federal Energy Regulatory Commission (FERC) has a number of maps that are useful here. This one shows the existing plants.

**Licensed Pumped Storage Projects**

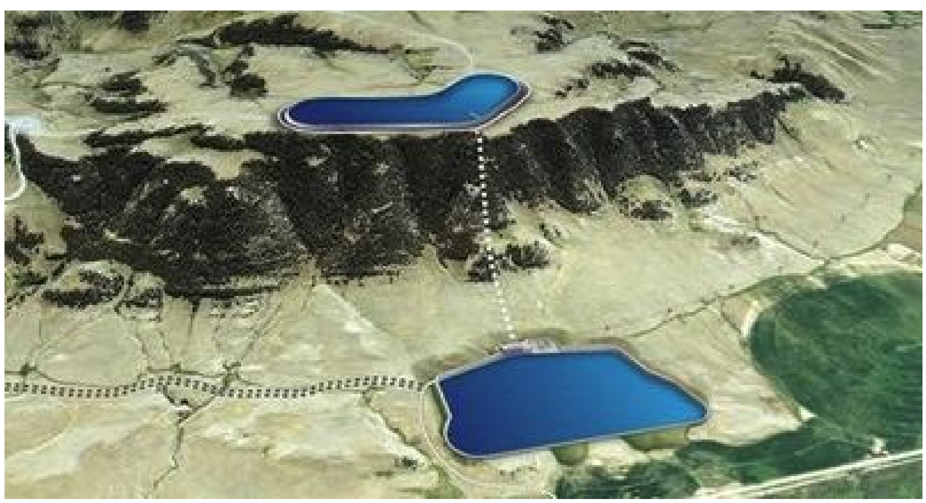



| State | Capacity (MW) | | State | Capacity (MW) |
|---|---|---|---|---|
| CA | 4,243 | | NJ | 365 |
| CO | 336 | | NY | 1,400 |
| CT | 31 | | OK | 260 |
| GA | 1,120 | | PA | 1,280 |
| MA | 1,833 | | SC | 1,221 |
| MI | 1,657 | | SC/NC | 1,065 |
| MO | 443 | | VA | 2,722 |
| MT | 400 | | | |
| **TOTAL CAPACITY** | | | | **18,376 MW** |

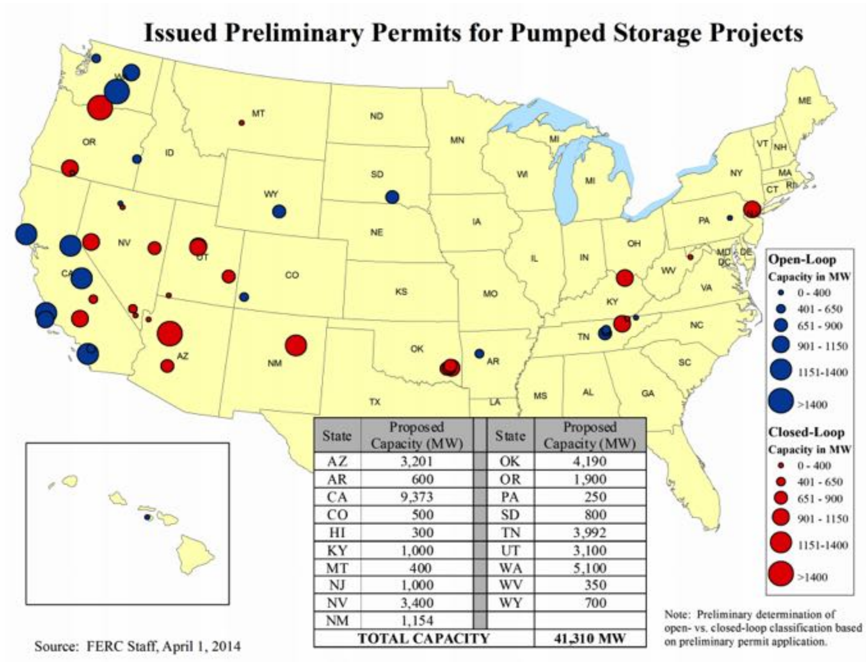
Source: FERC Staff, January 12, 2017

The total is near 20 gigawatts peak, but few plants are very large (over 1000 megawatts peak power delivered).

6. This is an image of a planned closed loop plant in Montana.



7. Here is a FERC map of preliminary permits from a few years ago. Many of the planned plants are big and of the closed loop type and the total, if built, would double U.S. capacity.




8. This is a real antique, from the Army Corps of Engineers in 1981.

| Region | Operating (MW) | Projected (MW) | Federal or Licensing Status (MW) | Identified Potential (MW) |
|---|---|---|---|---|
| 1 | 4,430 | 2,000 | 1,400 | 49,400[a] |
| 2 | -- | -- | -- | -- |
| 3 | 3,186 | 3,775 | -- | 1,405[d] |
| 4 | 2,622 | 1,216 | 3,000 | 8,589[d] |
| 5 | 299 | -- | 730 | -- |
| 6 | 623 | 200 | 5,020 | 650,000[b] |
| 7 | 1,612 | 2,155 | -- | 341,100[c] |

**Note:** Not all regions have been studied for potential sites. Region 2 is probably the only region where there are no potential sites.

**Sources:** [a]Public Service Electric and Gas Company, 1976.
[b]U.S. Army Corps of Engineers, 1972.
[c]Federal Power Commission, 1975.
[d]U.S. Army Corps of Engineers, personal communication.

(You have to check the original for the regions.) This is for 1980's conventional pumped storage and is likely a lower bound on possible potential capacity using closed loop storage. Think of this as a proof of concept for pumped storage.

9. A Department of Energy (DOE) goal for energy storage cost is about $150 per kilowatt-hour or, scaled up, about $150 Million per gigawatt hour or $1.5 billion for a 10 gigawatt hour plant. Most proposals cost less than this.

10. The German plant is 290 MW and the one in the U.S. is 110 MW.

11. If no heat is lost in compressing air to this pressure, then the final air must heat up. In this case it heats up to over 600 degrees C. Most proposals to use compressed air energy storage require caverns that have been dissolved out of large salt volumes. So heat will be lost to the walls of the cavern after some time. If this heat is extracted beforehand and stored, it can be reintroduced to the expanding air. There are proposals how to do this, but the technology is only at its beginning now.

12. The web site is at rwe.com and there is a project description there, which can also be found by a Web search. The project description is useful, although nothing has been heard of the ADELE project for several years.

13. This number leads to a staggering total of 3000 gigawatt-hours storage in batteries. This has led to the frequent suggestion to use the batteries in electric cars as a grid storage, so long as the cars are not being driven.

14. Lithium for batteries will eventually be a serious problem. Lithium *can* be recovered by evaporating seawater (which is how some of the existing mined deposits were formed). But then the price will go up. I am not sure that existing battery price estimates properly include future resources. (See the next note.)

15. Tens of millions of tons of batteries are going to create at least some resource and environmental problems, beyond price, that almost everyone ignores. I have seen estimates of 100-200 grams of lithium per kilowatt-hour battery (from an Argonne lab study). For ten million batteries that becomes well over a hundred thousand tons of lithium metal. From USGS data, this amounts to about a hundred times present U.S. production or ten times world production (these are "ballpark" numbers)

16. Rechargeable batteries can be solid or liquid; the number of types is very large. There are several good Wikipedia articles on them. There are very few battery types that store even one megajoule per kilogram of battery cell mass. When packaged, the mass goes up, sometimes quite a bit. This reduces the real, usable number of megajoules per kilogram packaged battery mass.

17. A new design Vanadium redox battery using a mix of sulfuric and hydrochloric acid  is sold by UniEnergy (uetechnology.com). They are not particularly energy dense, at about 60 megajoules per cubic meter and an installed mass of about 2000 tons per megawatt hour. Prices are unclear to me but probably quite a bit more than $500 per kilowatt-hour. Many older versions of this battery exist, using sulfuric acid in the electrolyte.

18. It is likely that, in time, large batteries will become common. An interesting question is: where in the grid do you put them? At the power source, such as a wind farm, is one possibility. As another example, a typical electrical substation might supply power to ten thousand homes using an average of a kilowatt each. This is ten megawatts, so a ten megawatt hour battery could supply emergency power for about an hour, if power delivery upstream of the substation is lost.

19. To illustrate, a battery pack for an automobile that can deliver, say, 200 kilowatts at 80% efficiency will also generate 40 kilowatts of heat. If the packaging is a metal, the heat capacity of the package will ensure that it heats up fast, requiring effective cooling.

20. A typical ultracapacitor available now might store 3000 Coulombs of electric charge at 2.7 Volts or about 10 kilojoules, roughly 30 kilojoules per kilogram (from commercial spec sheets).

21. A general source on hydrogen is at energy.gov/eere/fuelcells/hydrogenstorage. I owe some of the details of hydrogen storage here to the students in a freshman seminar on this topic many years ago.

22. There has been much research on power turbines fueled by 100% hydrogen gas. It is now known how to do this in almost conventional turbines without unacceptable generation of nitrogen oxides. (You need to dilute the hydrogen gas with water or nitrogen.) But the real interest is in more advanced turbines that burn straight hydrogen; that fancier technology is not now commercial.

23. As the burning hydrogen did in the famous Hindenburg disaster. It is now common knowledge that the visible flames were from the flammable shell of the zeppelin and that many of the passengers survived by waiting for the shell and frame to reach ground level. (They were in a gondola below the burning shell material.)

24. The largest fuel cells I know of are 120 kilowatts at an efficiency over 60%; such cells ten to a hundred times larger, with good efficiency (and quite a few of them), would be needed to convert tens of gigawatt hours of stored hydrogen energy to electricity. Present large fuel cells from Siemens seem mainly to be used in submarines, converting stored oxygen and hydrogen to electricity.

# Chapter 5-The Future Grid

1. Industry now uses about a quarter of all primary energy, mostly as petroleum and natural gas.

2. The relationship of “primary energy” to “useful energy” is mentioned in earlier books. Useful energy is what actually does useful work after heat and other losses.

3. This is why I am very skeptical of calls for “100% renewable electric power”. I think that we need to continue development of both fission and fusion power that is not dependent on a climate that will become increasingly erratic during this century.

4. “Inertia” is expressed in funny units. It is the time that a generator can deliver its normal 100% power if there is no power from the steam turbine it is connected to. If the turbine fails but is still connected, this is the time the generator can still do its job of delivering power to the grid. This time is basically how long it takes the kinetic energy of rotation of the generator-turbine system to decay as its energy is used up producing electricity. A common value of this “inertia” for a generator (or the whole generator grid system) is about 5 seconds, more or less. This is vital, because it allows time to connect additional generators to the system in case of a failure. These newly connected generators must, of course, be producing the needed 60 Hertz power. If they do not, having “intertia” in the system does no good.

5. After writing this, I discovered a fascinating study by Peter Davies that, among other things, models a Texas grid that uses only wind power and photovoltaic solar power plus storage. Check https://judithcurry.com/2017/05/14/electricity-in-texas-is-100-renewables-feasible-part-i/

6. With roughly 10 gigawatt grid-to-grid connections, the AC transmission systems on both sides would have to be built up, probably to high voltage lines. But the right of way for these mostly exists now, in the form of lower voltage transmission lines. An interesting option might be to back up these grid-to-grid connections with local large scale energy storage. This storage would buffer the energy transfer between grids.