LIGHTS ON!

THE SCIENCE OF POWER GENERATION

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INTRODUCTION

This book is about energy and power—the kind that we need to heat our houses and light our streets, to get us from *A* to *B*, and to drive our industries. Power generation is a relatively recent problem historically because the human need for power was minimal until the Industrial Revolution. Nowaday it is, and is rightly seen to be, a formidable and perhaps overwhelming problem that we need to address, for the benefit of future generations as well as ourselves. In this book, I look into the differe ways in which it is possible to generate power—to tap into one or another source of energy that is locked up somewhere, releasing it in a controlled and usable manner.

My approach is that of a scientist and engineer, not a politician or businessman. I am not inclined to excited hyperbole, though it seems to me that some people on the committed environmentalist win of the current debate about energy sources do lean that way. Some folks at the other end of the spectrum are equally irrational, inclined toward equal exaggeration though usually less shrill. The result has been a heated debate (almost a pun—sorry) that spreads confusion and perhaps contributes to a regrettable apathy among the general public.

My aim in writing this book is to provide a readable exposition of the science and engineering of power generation, without raising your blood pressure too much. That is to say, I would be happy if you become engaged with the subject and (dare I say) energized as you digest the meat of this book, but I will not be expounding extreme or one-sided political views, or telling you what to do or think. will be providing brain fodder for you to ruminate upon by presenting you with the story of our searc for energy sources, the science behind each of the power generation technologies, and the facts of historical development. No politics—or, more realistically, no political agenda. (It is difficult to mak a statement about our energy future without being political.)

Before saying more about our subject, let me provide you with a flavor of the approach to it that is adopted throughout this book. Here is a scientist-cum-engineer's quick glance at a much-discussed, promising and benign source of power, and its potential for solving the needs of humankind.

Humanity currently consumes a total annual average of 14–20 terawatts (TW) of power.[1] A terawatt 1,000 gigawatts (GW); a gigawatt is 1,000 megawatts (MW); a megawatt is 1,000 kilowatts (kW). Switching on an electric kettle consumes a couple of kilowatts, and your electricity bill is likely expressed in kilowatts, or in kilowatt-hours (kWh), the energy equivalent of this ubiquitous power unit.

Here is a quick, back-of-the-envelope calculation to put into perspective a few conceptions that yo might entertain concerning power generation. Most of our power and heat, and all of our light, come from a single giant thermonuclear power plant (a fusion reactor) in the sky. Our sun bathes the earth with electromagnetic waves, mostly in the form of visible light or invisible infrared radiation (heat). The amount of solar power that reaches our upper atmosphere is 1.35 kW/m^2; multiplying up by the cross-sectional area of the earth gives us about 172,000 TW. That is, the total amount of solar radiation that bathes the upper atmosphere of our planet exceeds our total power consumption by a factor of 8,600 (assuming the upper figure of 20 TW for current world consumption). Given this elementary fact, isn't it obvious that all our power source problems will go away if only we build up massive infrastructure of solar power plants?

Not at all—although, as we will see in chapter 8, solar power plays an increasing role in our budge First, only about 10% of the solar power that impinges upon the upper atmosphere actually makes it down to ground level. The rest is absorbed by the atmosphere or reflected off clouds. Also, half the time the power source is effectively switched off—we call such times “night” —and for only a few ~~hours a day is the sun near its zenith. Many countries are too far north for efficient solar power~~ generation; sunlight slants in at an angle and is rarely directly overhead—never so, for regions outsid the tropics (north of the Tropic of Cancer or south of the Tropic of Capricorn). Thus, the usable amount of solar power that reaches the surface is, in round numbers, “only” about 860 times the total power needs of our species.[2]

Let’s keep going with this rough-and-ready look at solar power potential. The efficiency of a solar power plant is less than 1%. (Only a small percentage of the land area of a power plant is covered by solar panels, and the solar panels convert only a small fraction of the sunlight they receive into electricity. Interestingly, 1% is also about the efficiency of a photosynthesizing biological plant, converting solar energy into chemical energy.) This figure was gleaned from two of the world’s largest solar power plants, both of which are in regions of very high *insolation*, or ambient sunlight levels. Let us agree on an average efficiency, for solar power plants all over the world, of 1%. Thus, our factor of 860 is reduced to 8.6. This figure shows (doesn’t it?) that we don’t need to bother with other, dirtier sources of power such as biofuels or nuclear plants: covering the world with solar powe plants will provide us with more than eight times our annual power requirement.[3]

Not so fast. We cannot give over the whole surface of our planet to solar power plants. Most of th surface is ocean, and we need most of the land for other things, like cities and roads and agriculture and forests. We cannot realistically expect more than, say, 1% of our planet to be festooned with sola power plants, no matter how desperate we become for electrical power. Consequently, we obtain a value of about 8%—give or take—for the maximum possible contribution to our power needs from the sun. Further, the 20 TW figure for the power needs of our species is likely to rise significantly in the future, as the population rises and as Third World nations industrialize (see the chart). More people means more pressure for land, which is likely to depress my optimistic guess that 1% of the earth’s surface (i.e., 3% of the land surface—about 1.7 million square miles) could be taken up by solar power plants.[4] However we cut and dice the numbers, if we are thinking realistically and not indulging in fantasy, then there is only one conclusion: solar power cannot form more than a small fraction of the total power requirements of humanity.[5]

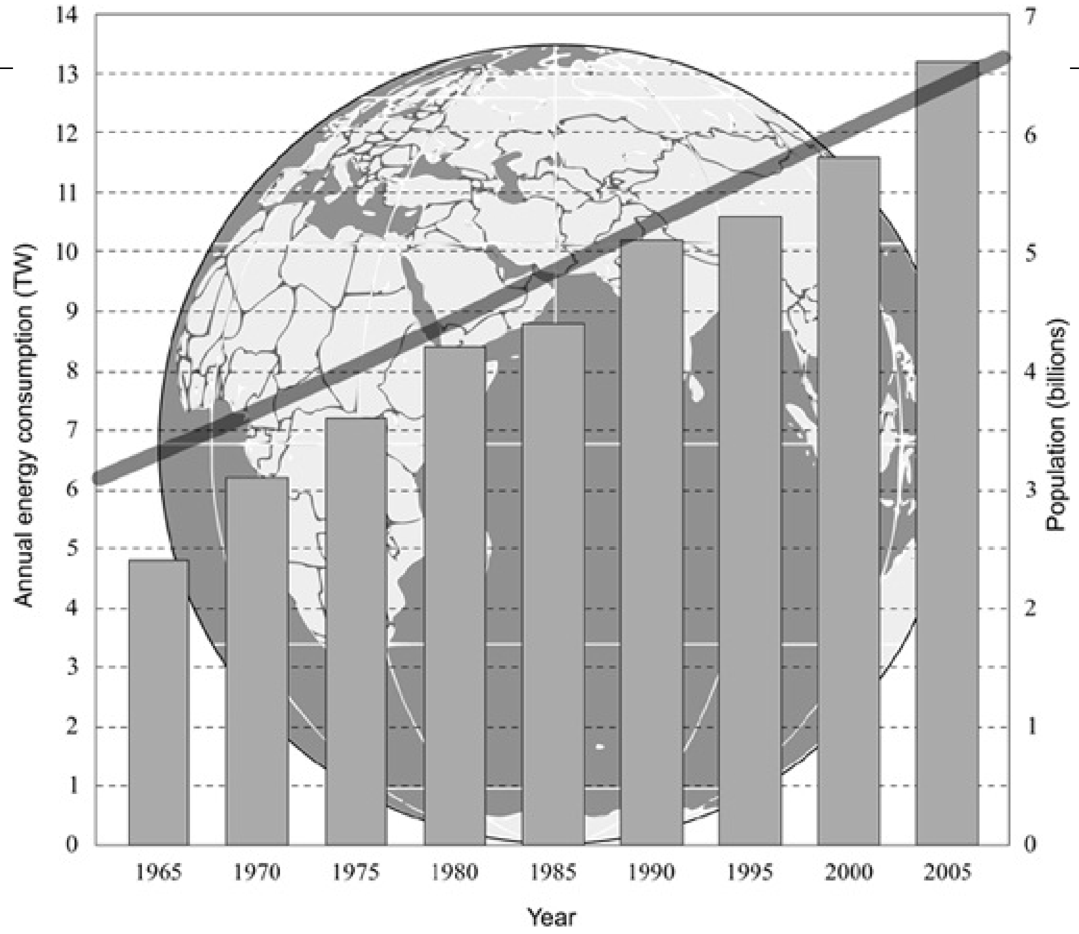


FIG. I.1. Annual world power consumption in terawatts (*bars*, *left scale*) and world population in billions (*line*, *right scale*), over a 40-year period from 1965. Note that energy production increases faster than population, as Third World countries industrialize and First World countries splurge. *Dat from BP (2010)*.

In the above reckoning I used only elementary math, please note, and a broad-brush approximate approach that simplifies a complex subject and yet is scientifically valid and incontestable. For example, the physical area of the earth provides an upper limit to the solar energy that it receives. Th type of estimation (I hesitate to call it a calculation) was the hallmark of that well-known Italian American physicist and Nobel laureate Enrico Fermi, who once famously used it to estimate the number of piano tuners in New York City. The result is only a very approximate estimate, but to put loosely, it is approximately right and not exactly wrong. It would be all too easy in this book to blind you with science; many of the matters we will look at are, in detail, very technical and complicated. Fermi's approach seems to be the wisest here—and apposite, given his significant contribution to on of our most important sources of power, as we will see.

In the first chapter I set the table with some clarifying observations on what we mean by energy and power, as well as set out the limitations imposed by physics and technology on how we convert between different forms of these. I will summarize the different ways in which we currently generate power and show how it is distributed. The rest of the book takes each of the power generation technologies (one or two per chapter) and explains how they work, with the aid of diagrams. Each technology will be subjected to Fermi-like analyses to test the claims made of them—for example, t test their potential for satisfying our growing need for affordable power, or to examine their environmental impact. To begin, I will summarize the history of energy and power generation to plac the subject into context. For example, we will learn about the considerable efforts made by our predecessors to obtain coal and oil and to understand electricity and nuclear forces.

The existing literature on the subject of energy and power generation (its cost, sustainability, and envi~~ronmental consequences) is truly enormous. Some of these books are excellent reads, while~~ othe would be better used as biofuel. Many are highly technical; many others have a political agenda or an environmental or business bias. Apart from academic texts, few of the existing books explain the science that underlies energy and power generation. Very few books explain this broad and complex subject in a manner that is accessible to the interested lay person. The book that you hold in your hands will fill this gap.

NEWTON'S LEGACY

"Energy is not a material thing," a physicist of the late nineteenth century might have said. Einstein would demur at this statement, and because of him, the physicists of later times think differently. Material or not, energy is a property of objects—a characteristic with a well-defined meaning. Our nineteenth-century physicist was not wholly ignorant about the subject, however; he knew that energ was conserved, that it could take on different forms, and that, like a genie or a spirit, it could change from one form to another. Sir Isaac Newton, who thought and calculated and wrote and sat under app trees in the late seventeenth and early eighteenth centuries, knew nothing of energy. The exact, mathematical science that he bequeathed to us was expressed in the language of forces, not energy. After his death, Newton's laws of motion and of gravity would be elegantly reinterpreted in terms of energy by succeeding generations of gifted men.[1]

Yet the title of this chapter—which is about energy in its various forms, the transformation between them, and the distribution and storage of it—suggests a significant contribution by this grea though difficult and unpleasant man. Why? Because modern engineers are taught the physics that wa given to us by Newton, as well as that which emerged in later centuries. Newton's way of looking at the world is easier to convey to nonspecialists because it connects with things we have an intuitive feeling for, like force and momentum. Consequently, his methods are still used, particularly in the world of practical engineering, where Newtonian concepts are readily applied. For these reasons, in this book I will use Newtonian ideas—plus energy—to explain the physics of our subject. Please bea in mind, however, that the knowledge of modern-day engineers who design and build power plants, energy storage devices, and distribution networks comes from Joule, Carnot, Poncelet, von Helmholt Rankine, Einstein, and a thousand other physicists and engineers, as well as from Sir Isaac.

In this chapter I lay out our modern understanding of energy and power. This groundwork is necessary for a meaningful discussion of power generation, by various technologies and in the language of Newton, in later chapters. I avoid technical analyses but paint an accurate picture of the concepts and processes that we need later on.

Energy

One catchall definition of energy is "the ability to do work." Water flowing in a river can do work by turning a millstone; burning gasoline can do work moving an automobile. In the first case we have energy of motion—flowing water—and in the second case chemical energy, stored inside the molecules of gas. Through their ingenuity, engineers produce mechanical devices to convert these different forms of energy into useful work:[2] a waterwheel converts the energy of motion of a flowing river into the rotational energy of a millstone; an internal combustion engine and a crankshaft conver the chemical energy of gasoline into the energy of motion of an automobile.

Energy is related to force (which is why we can use the language of Newton to describe the subject). The work done in moving a mass is just the energy expended on the task: it is the force applied to the mass multiplied by the distance it moves. For example, the energy you expend in dragging a heavy trunk across an attic floor is the force you apply to the trunk multiplied by the distance you drag it across the floor. Increase the force, or increase the distance, and you increase the energy that you expend, and so the work that you do.

There are many types of energy, and the connection between them is well understood by physicist who can write down formulas that tell us, for example, how to convert mechanical energy into heat. A moving mass possesses mechanical energy; the mass may be moving along a straight line, or it may be stationary and rotating about an axle. Both freight trains and flywheels posses such *kinetic energy* or mechanical energy of motion. *Potential energy* is the energy possessed by a mass by virtue of its position. Thus, a compressed spring and a rock raised up from the ground both possess potential energy. We can see that this is so by considering what happens when the spring and the rock are released. The spring will jump in the air or cause a mechanical toy to move; the rock will fall to the ground (thus gaining kinetic energy) with a thud (acoustic energy). Here we have another example of energy being converted from one type to another. Again, physicists can write down equations that tel us exactly how to convert potential energy into kinetic energy. For example, they know how fast a rock will hit the ground if it is released from a specified height above the surface. Kinetic and potential energy, and the conversion from one to the other, is illustrated in figure 1.1.

A LIGHT WORKOUT

To shed some light on the common units of energy, let's consider a light bulb. This little exercise wi give us a feeling for the magnitude of energy in its different forms. The energy consumed by a 100-watt (W) light bulb that is switched on for one hour is 0.1 kilowatt-hour (kWh). Here are some equivalents: The same amount of energy would enable an adult man to climb about 300 feet up a ladder (assuming he weighs 180 pounds and converts only 20% of the energy into useful mechanical work). The same energy expenditure would bring a stationary half-ton truck up to a speed of 13 mph (assuming 15% fuel-to-wheel efficiency). The same energy could bring a little less than 5 ounces of water up from room temperature and cause it to boil. The same energy could power stereo speakers t play music loudly in a moderate-sized room for 8 hours.

Our estimation of energy consumption is somewhat biased by our sensory perceptions. The quiete sound we can hear contains much less energy than the dimmest light we can see. The energy needed t raise water to 100°C is much less than the energy needed to cause it to boil at 100°C.

Thus, energy falls into one of two categories: the kinetic energy of motion and the potential energ of position. Chemical energy is a kind of potential energy.[3] It takes a lot of energy to create the molecules of, say, gasoline, and this stored energy is released when the gasoline is burned. Gunpowder, nitroglycerine, firewood, and a myriad of other materials possess internal chemical energy that can be released in a useful manner: they can do work. Heat is a form of kinetic energy,[4] sometimes called the lowest form. Heat is like money—a common currency in which we trade different commodities (in this case, forms of energy) and compare their values. All other forms of energy can turn directly into heat. Thus, a meteorite falling to earth converts kinetic energy and gravitational potential energy into heat: it arrives at the surface hot and has heated up the air it passe through. The chemical energy stored in gasoline is converted into thermal energy, which in turn is converted into the mechanical energy of moving pistons. The laws of thermodynamics and mechanic and the detailed engine design characteristics, tell us how much horsepower we can extract from a liter of gas. In a nuclear power plant, nuclear energy is converted into heat, which is then in turn converted by turbines into electrical energy.[5] Two simple examples of energy conversion are shown i figure 1.2.

FIG. 1.1. A space shuttle launch: chemical potential energy (liquid hydrogen and liquid oxygen fuel) i converted into the kinetic energy of the speeding rocket, in order to overcome the gravitational potential energy of the Earth. *Photo courtesy of NASA.*

In our power generating plants, of whatever type, energy is converted from one form to another several times before emerging as electrical energy. Consider, for example, a dam. Historically built t contain water,[6] most dams today serve another purpose—providing hydroelectric power. First, water levels build up in front of the dam, and the water acquires gravitational potential energy. This potential energy is converted into kinetic energy when the water flows down into the hydroelectric turbines, which are usually positioned inside the dam near its base. The flowing water gives up most of its energy to the turbines, causing the large turbine rotors to spin fast—rotational kinetic energy. The clever design of such turbines leads to high efficiency, but no energy conversion can be perfectly efficient, and some of the water energy is wasted as heat. Finally rotor energy is converted into electrical energy; we will see how in a later chapter.

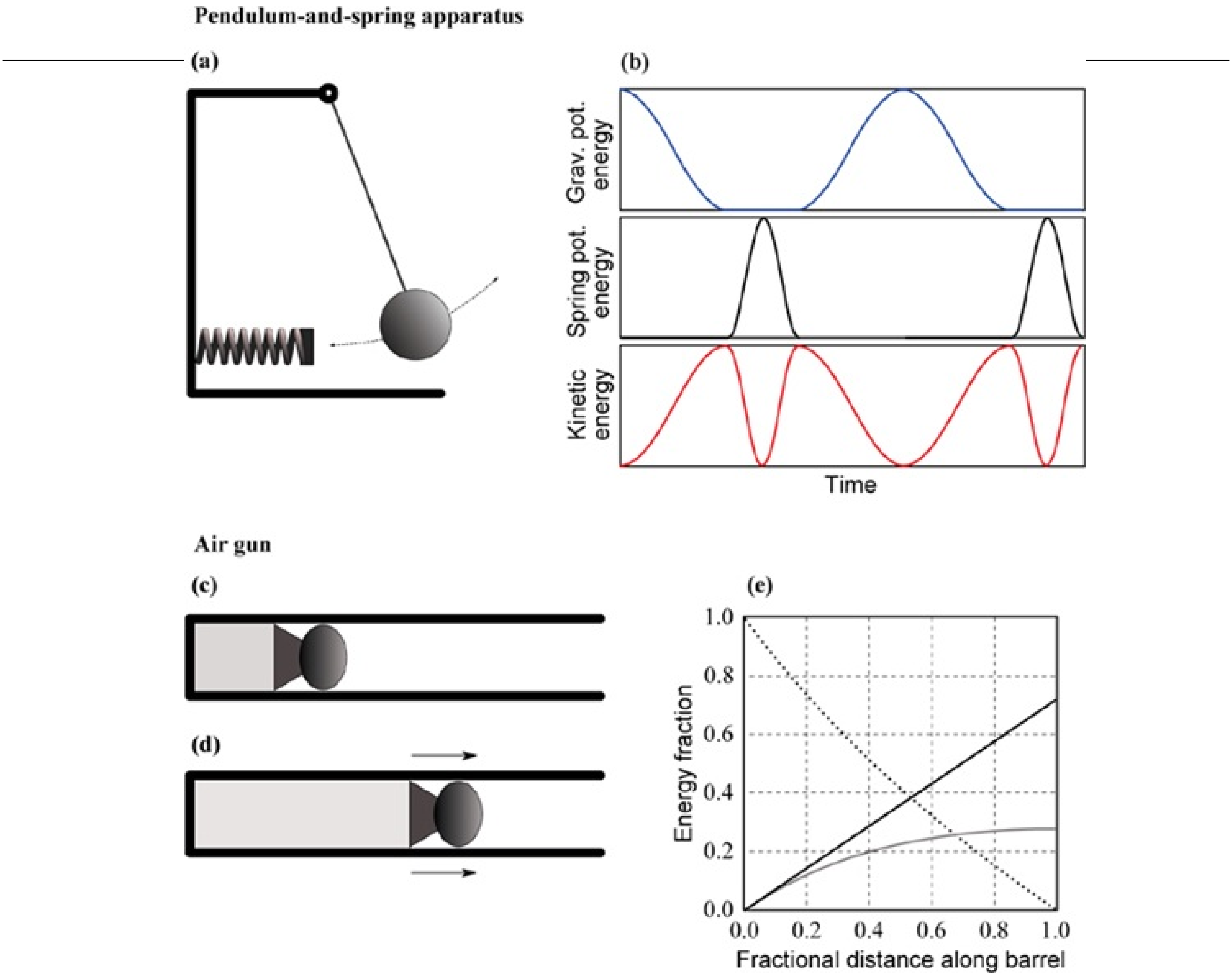


FIG. 1.2. Two examples of energy conversion—a pendulum and spring and an air gun. (a) This pendulum-and-spring apparatus stores potential energy in a spring and gravitational potential energy in the pendulum bob. The bob also exhibits kinetic energy of motion. (b) Analysis shows how the energy of this apparatus is divided up and how the division changes with time. In this hypothetical case, with no energy dissipated by friction, the sum of all three forms of energy is a constant. (c) Another example of energy conversion, an air gun, showing a pellet at rest in the barrel before the trigger is pulled. Behind the pellet is compressed air, which has a lot of potential energy. (d) After th trigger is pulled, the compressed air is released, and the pellet accelerates along the barrel; potential energy is converted into kinetic energy. (e) A graph of energy fraction vs. pellet position along the barrel: *dotted line*, the potential energy of compressed air; *black line*, energy lost to friction, mostly a heat ; and *gray line*, the pellet's kinetic energy. This air gun is about 30% efficient because 30% of th initial potential energy is transferred to the pellet.

Power

Power is the flow of energy—the rate of change of energy. If you expend 100 J of energy dragging th trunk across that attic floor, for every second that you drag it, then you are expending energy at the rate of 100 J/s, which means that you are exerting 100 W (0.1 kW) of power.[7]

In some cases, energy is easy to store but difficult to release in a controlled manner, as a steady power supply. Thus, nuclear energy is stored compactly as mass, but a carefully designed nuclear power plant is necessary to release this energy in a steady flow. In other cases, energy is difficult to store~~, but the flow of that energy—its power—is readily achieved. Electricity is *the* important~~ example of this type. It is the most efficient means of distributing energy, yet electrical energy is ver difficult to store. We will see that electrical energy that is not needed immediately is converted into different types of energy (potential or kinetic) before being stored. Other forms of energy can be stored easily and also can be made to flow easily, providing steady power. Water, by virtue of its weight and movement, has historically been our most important source of power for this very reason.

Two examples of natural energy flow—of power—are shown in figure 1.3. These examples illustrate the potential for, and the problems of, human power generation. Niagara Falls (fig. 1.3a) expends power at an average rate of about 1.3 GW. We can readily estimate this value from knowledge of the flow rate and the drop in height of the water. Because of seasonal variations in the flow rate as well as human intervention in allowing the river to flow freely, the power of the falls varies. Falling water is a key component of human power generation because it is readily exploited. Indeed, the Niagara River is diverted from the falls, on both the American and Canadian sides of the border, for the purposes of hydroelectric power generation. Up to 75% of the flow is removed above the falls and returned to the river below the falls.[8]

POWER UNITS

Consider a half-ton truck with a 230 horsepower (hp) engine. Such an engine can power 1,715 incandescent light bulbs (each of 100 W). A horizontal stream or a water channel with a cross-sectional area of 5 m^2 (say it is 1 m deep and 5 m wide) flowing at 12 mph may generate the same amount of power, assuming an efficiency of 50% for the waterwheel or turbine that converts the wate power into mechanical or electrical power. If the water is falling through the same water channel, as a waterfall or inside a hydroelectric dam, instead of flowing through it horizontally, then it can generate the same power by falling only 0.9 m—about 3 feet. (I am mixing up English and metric units here—horsepower and watts, feet and meters. This practice reflects the real world. As a scientis I would prefer to consistently use metric, but the engineer in me knows that people like some of the older units.)

The second example of natural energy flow is that of lightning (fig. 1.3b). A typical lightning bolt transfers about 140 kWh of energy from a cloud to the ground in a fraction of a millisecond and so represents a prodigious—albeit brief—rate of power: typically 4 TW. We do not use lightning as a source of power for a number of obvious reasons, but we do choose to transfer our energy from one place to another via electricity. The distance covered by a lightning bolt may be only a few hundred meters; the controlled flow of electricity along uninsulated conductors can be over hundreds of kilometers.[9]

Energy Conversion

In engineering, *transducer* is the generic name given to a device that converts energy from one form to another. No transducer is perfectly efficient; there is always wastage to a greater or lesser degree. some practical cases the efficiency of transducers can approach 100% as technology improves—for example, with design improvements, friction reduction, or size reduction (to reduce the energy absorbed by moving parts). In many cases, however, it is impossible even theoretically to convert energy perfectly. An important class of transducer that fits into this latter category is the *heat engine*

Heat engines can be considered abstractly (physicists will recognize the *Carnot engine* here, an early ther~~modynamic theoretical tool that demonstrates the second law of thermodynamics). However~~, many real engines fall under the same umbrella: steam, diesel, and gasoline engines are all heat engines, and so they are limited in efficiency by the laws of physics, not just by practical engineering considerations.

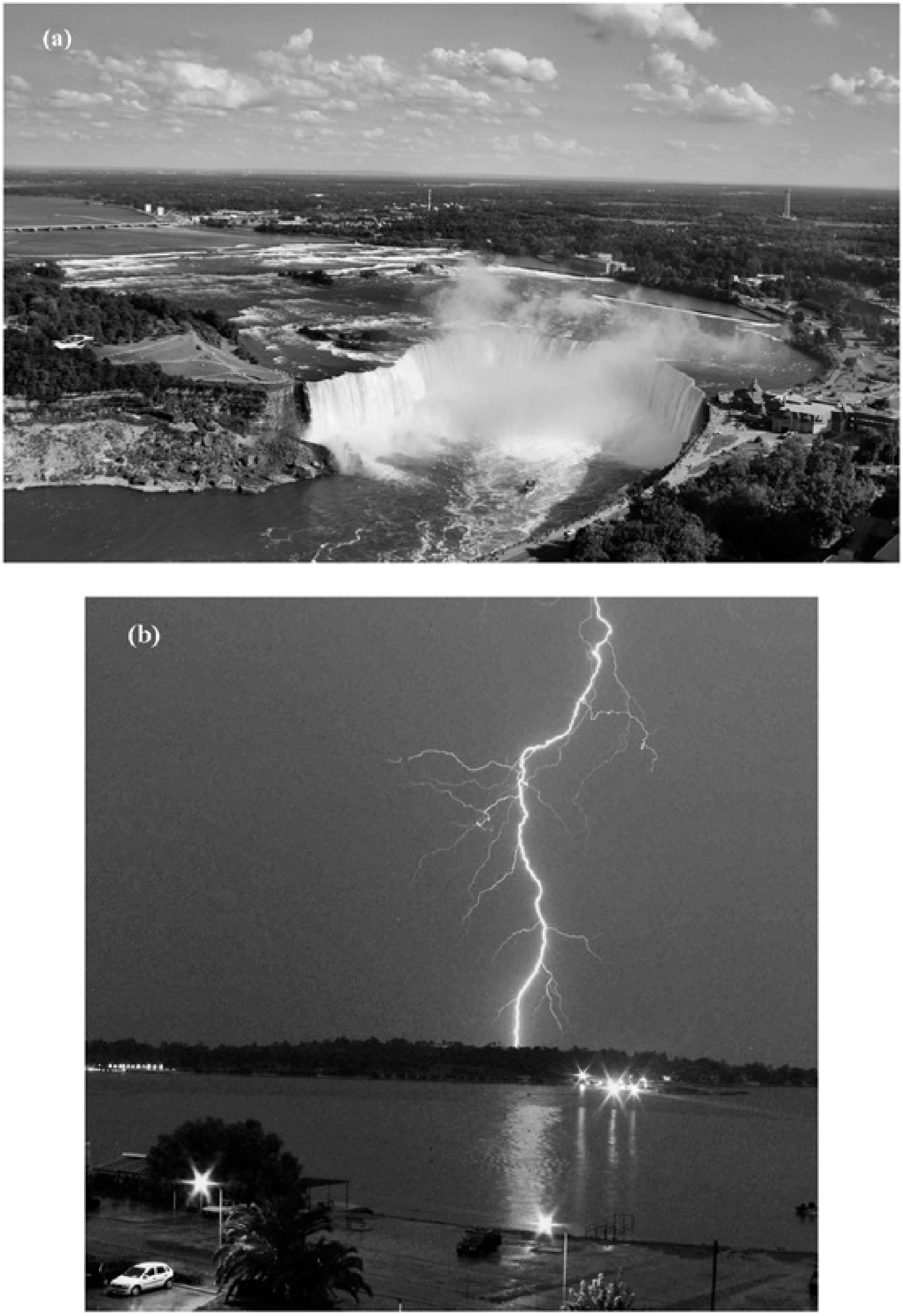


FIG. 1.3. Two examples of natural power. (a) Horseshoe Falls, the largest of the three Niagara waterfalls. This image illustrates the power of falling water. Except during peak tourist visiting hours much of the Niagara water is diverted to hydro power stations. (b) Electrical potential energy that builds up in clouds discharges to the ground. A typical lightning bolt represents about a quarter of the power used by humanity—but only for a tenth of a millisecond. *Photos by (a) Ujjwal Kumar and (b)*

There are many familiar examples of transducers. The light bulb is a common transducer that converts electrical energy into light, a form of electromagnetic (EM) radiation. The reverse process i achieved with a photovoltaic solar panel. We have seen already how inefficient solar panels are; ligh bulbs are almost as bad. The old incandescent bulbs convert about 5% of the input electrical power into EM power; fluorescent lights are better, at about 20%. Metal halide lamps are better again, around 25%, while LEDs can be up to 35% efficient and low-pressure sodium lamps 40%. An electri heater converts over 95% of the input electrical energy into heat, another form of EM energy. The heater is so efficient because heat is the desired output, whereas it is an unwanted by-product of most conversion processes. A home gas furnace is another example of a transducer, this time turning store chemical energy into heat. Again, heat is the desired output, and so heat production is not a source of inefficiency—quite the opposite. Such furnaces are about 95% efficient. Oil furnaces are not quite so good, at 65%. The steam turbine is an example of the reverse transducer, turning heat into electricity turbine efficiency is usually between 45% and 60%.

A crankshaft converts one type of mechanical kinetic energy into another: it turns reciprocating linear motion into rotary motion, and vice versa. It is not a heat engine; thus, its efficiency is not theoretically limited. Gear trains are another example of mechanical transducers that can convert one type of mechanical energy into another. Because such devices are not heat engines and are not limite theoretically in their efficiency, good design and good manufacture can result in very efficient conversion.

An automobile engine is a transducer for converting chemical energy into rotational mechanical energy, which it does at about 25% efficiency. (The lower efficiency of the whole automobile, 15%, i due mostly to drive train inefficiency.) Electricity generators convert chemical energy into electricity we will look at the different types of generators in chapter 3. Dynamos convert rotational mechanical energy into electricity, while electric motors do the reverse. The little hub dynamos that power bicyc lights vary in their efficiency, depending upon speed, but peak at about 65%; automotive alternators get up to 90% efficiency—that is, they turn up to 90% of their input mechanical energy into electricity, which is used to charge up the automobile battery. Electric motors vary in efficiency between about 40% and 90%; larger motors are more efficient than smaller ones.[10]

Figure 1.4 shows a transducer loop—which is impractical, of course, because of the waste from th inefficiencies of our technology and of heat engines.

There are many other types of transducers. A microphone converts acoustic energy into electricity a speaker does the reverse. Windmills and water-wheels convert the kinetic energy of wind and running water (traditionally) into the rotational kinetic energy of a moving millstone. Antennas are transducers; they are like electric lights or heaters, in that they convert electrical energy into EM radiation, except that antennas can also work in reverse, converting microwave or radio signals into electrical signals. Muscles convert chemical energy into mechanical energy, as do internal combustic engines. Hydroelectric dams convert the gravitational potential energy of water into electricity, and batteries convert chemical energy into electricity.

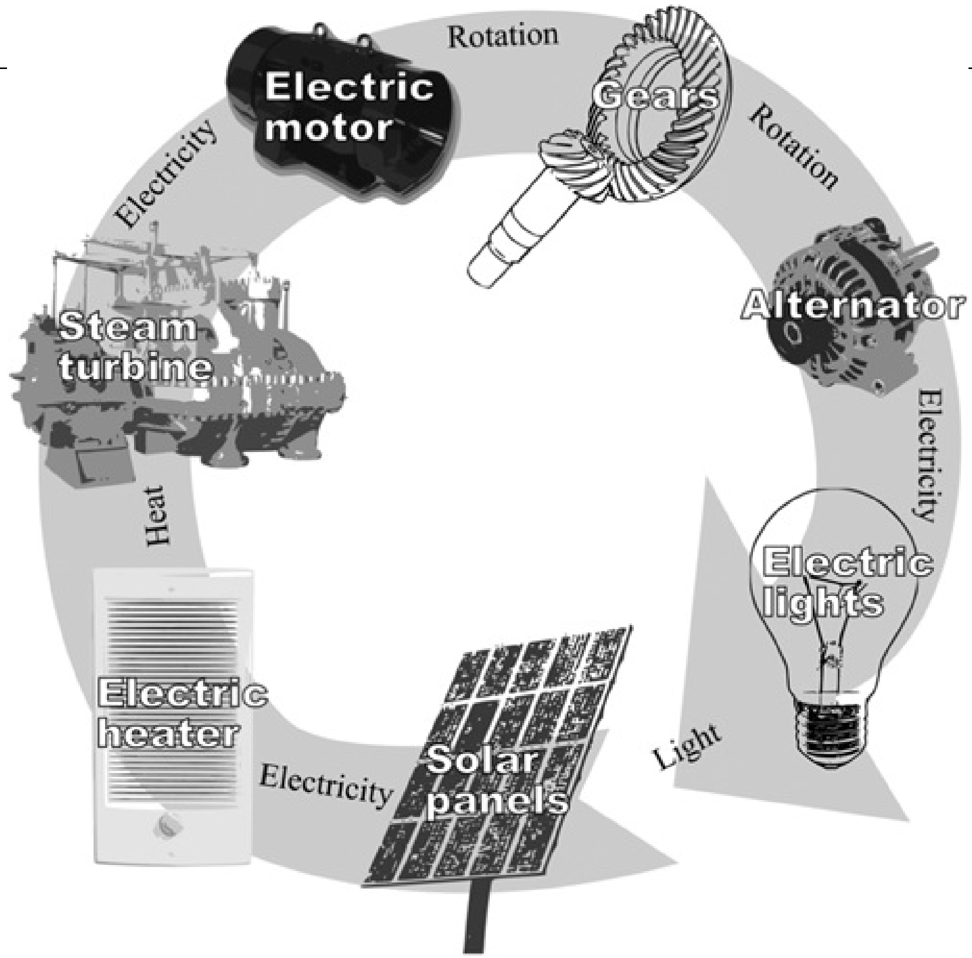


FIG. 1.4. Energy transformation. If all these transducers were perfectly efficient, energy would circulate around this loop endlessly, without loss. In practice, because of the efficiency values of eac component, 99.8% of the energy would be lost after just one cycle.

Note that many of my transducer examples involve electricity. This reflects our real-world dependence on this form of energy and, particularly, power. It turns out that

- electrical energy is difficult to store, and
- electrical power can be transported from *A* to *B* readily.

I alluded to these phenomena earlier; they are important and are discussed in depth in chapter 3. For now, we need only know that they apply in the real world and that we must live with the consequence which is this: no matter how we generate energy on a large scale (at the level of big utility companie and of nations), we must find efficient ways to convert it into electricity because that is the most economical way to distribute energy over long distances.

Power Distribution

The large-scale distribution of power—across municipal boundaries, across nations, across continent —varies in efficiency depending upon its form. Such large scales make the distribution of most sources of power expensive or impractical. For example, flowing water can be moved tens of kilometers via aqueducts—but no farther than this, and only if the topography is right. The Romans were very skillful at distributing water in this way, though in their case the water was usually for drinking or irrigation, not for generating power. (We will encounter an impressive exception in chapter 2.) Moving water over longer distances for power generation would prove to be wasteful (water flows only downhill, thus depleting its potential energy) and expensive in terms of infrastructure.

Oil contains chemical energy, and today there are enormous pipelines and supertankers that transport this fuel across the globe. (We can regard such transportation as power distribution as well as energy distribution; the energy is flowing.) But oil, coal, firewood, food, and all the other sources of stored chemical energy that we need in order to live our lives and power our industries are expensive to move because they are heavy, like water. Because they are heavy (and, in some cases, toxic), we do not transport such chemical energy sources over long distances unless we have to, as with oil and coal. What about heat? Heat weighs little,[11] but it is difficult to transport more than a fe tens of meters (as in a power plant) because it leaks. I am unaware of any heat pipelines or “calorie cables” snaking their way across the countryside or throughout cities.

We are obliged to transport oil and coal over large distances because it is more economical to do s than to burn the oil or coal at the source and then transport the power it generates as electricity. (It is not always possible to place power plants at the oil wells or coal fields: for example, many oil fields are under the sea.) And we move oil and coal because of limitations in our technology: our automobiles are powered by oil derivatives, and our power plants rely upon oil or coal as fuel.

In general, though, the weight of most sources of chemical energy makes them too expensive to transport. Even if we could reduce the transportation costs, there are other reasons why electricity is the favored means of distributing power. First and foremost, it is fast. Electrical power is carried via cable at about the speed of light.[12] Second, it is compact and can be squeezed into thin cables. These cables can be distributed widely, then split and redistributed, throughout a city and throughout a house. These properties make electricity the favored form of power distribution; it is far more convenient than any other form.

Speed of distribution matters to the companies that generate power for a city or a nation because o the economics and technology of power generation. We will see that most of our power plants work best—most efficiently—when they are producing power at a constant rate. Yet the demand for power is far from constant. We heat our homes more in winter than summer. We work during the day and sleep at night, so power needs are reduced at night. We get up in the morning and switch on the toast or coffee maker, causing demand to surge. Power demand thus varies over many timescales: annually daily, and from minute to minute. There are spikes in local power consumption for any number of reasons: during the Super Bowl in America, at half-time during televised soccer games in Europe and South America, after a popular soap opera when millions of teakettles get switched on in Britain.

All these myriad sources of transient demand for electrical power present themselves as a random fluctuation in the output that is required from a nation’s power grid. A single generating plant might be required to supply electrical power at a rate that fluctuates slowly with the seasons, fluctuates mor quickly with the hours of daylight, and also fluctuates randomly from one minute to the next. Figure 1.5a provides an illustration of the demand from a power plant. This fluctuating demand causes problems because the grid of power plants supplying a region or nation works best when generating constant power. If a generating plant produces power to meet *peak* demand, then much power is wasted. If, on the other hand, a generating plant produces enough power to meet *average* demand, the waste is reduced, but there will be times when demand is not met unless power is held back during low-demand periods and then supplied during high-demand periods. This option is the one usually adopted, because it is more economical and more practical than attempting to meet peak demand for power.

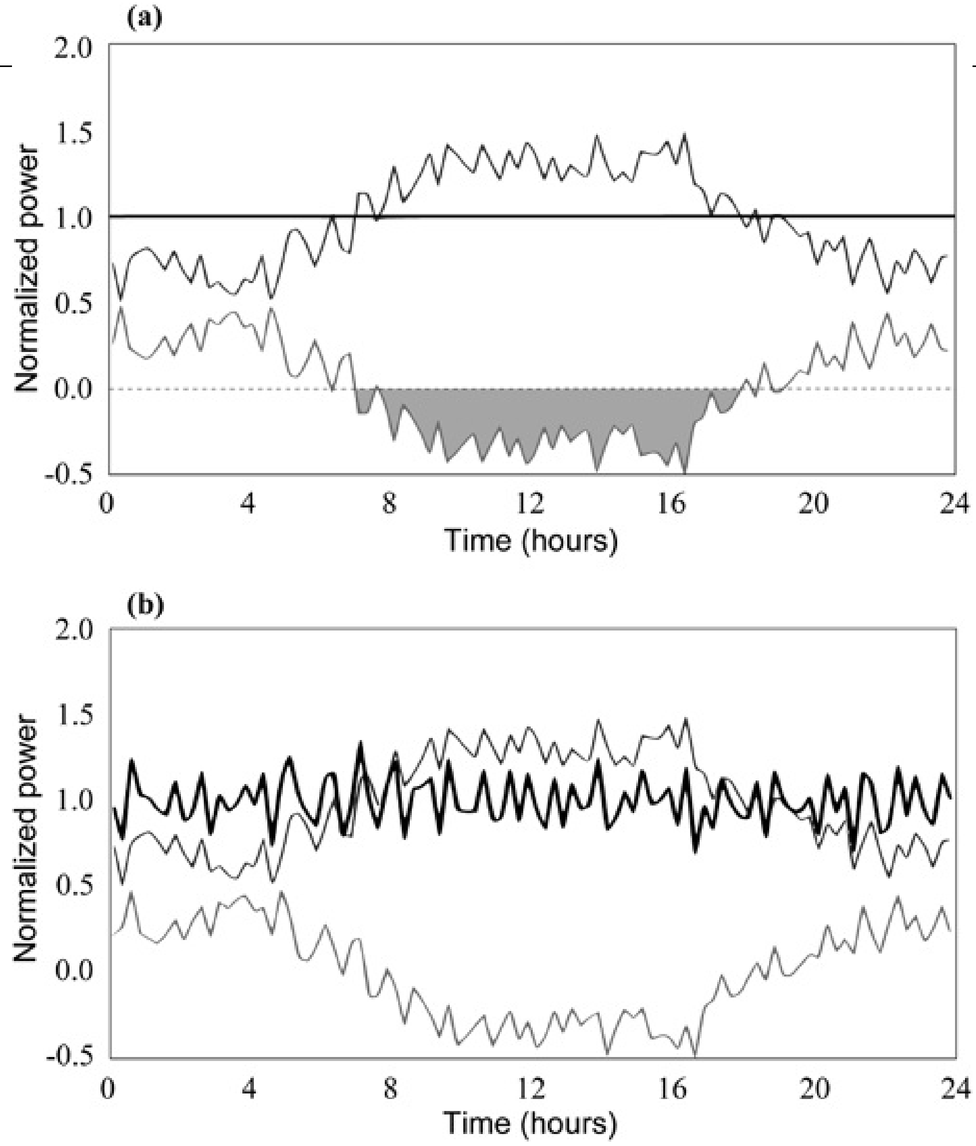


FIG. 1.5. An idealized power management system. (a) A power station supplies a city; the demand (*upper jagged line*) varies not only daily but also randomly from minute to minute. This demand is met by the basic power supply only up to a certain level (here shown as 1.0). To this basic supply is added a varying supplementary supply (*lower jagged line*) by storing and releasing energy as required so that the total power supply (*bold horizontal line*) is constant. The shaded area shows when stored energy is being expended to meet high demand; at other times stored energy is being increased. For this simulation, the day has been divided into 15-minute intervals, and the response to changing demand is idealized as instantaneous. (b) A slightly more realistic case in which there is a 15-minute response time between demand and supply. Note that there is now a fluctuation in total supply (*bold line*), which a utility company would want to minimize, for reasons discussed in the text.

In figure 1.5a we see also the manner in which a power plant must respond to local demand so that it is able to maintain a constant supply. The plant manages its power by using surplus to store energy. (Exactly how this storage is achieved will be the subject matter of the next section.) When needed, this extra stored energy is then converted into electrical power and distributed as required. The result, idealized in figure 1.5a, is a generating plant that produces a steady supply of electrical power—just enough to meet the average demand of its customers.

More realistically, a power plant cannot respond instantaneously to changes in demand although, as we will soon see, it can respond quite quickly. Assuming a 15-minute response time, the required supply for our hypothetical generating plant is shown in figure 1.5b. Now the demand for power is no reduced to a perfectly constant level; the managed power supply fluctuates randomly but much less than ~~it would without power supply management via energy storage. In order to ensure that it is~~ able to meet its customers' power demand requirements, the generating plant would have to increase its level of power production (assumed to be constant) to match the peak of these reduced fluctuations. Clearly, it is in the economic interest of the power supplier to minimize the level of these residual fluctuations.

This minimization can be achieved by pooling the resources of many generating plants. Let us extend our hypothetical example to 10 generating plants supplying 10 cities. We will assume that the average demand of each city is the same and the daily variations in demand are the same; only the minute-to-minute fluctuations change from one city to the next. Each generating plant supplies the same average amount of power. By pooling resources, the generators limit the statistical fluctuation i demand, to about 30% of the fluctuations shown in figure 1.5b.

This simplified simulation of the power demand-and-supply situation for a large power producer demonstrates that power management requires some considerable sophistication. It is wasteful to simply supply the peak power demand, and yet producing a lesser amount requires a careful and quic response to minute-by-minute changes in the amount of stored energy, and its release back into the power grid, in order to meet the ever-fluctuating demand of customers.

The economics of power generation has led to a considerable maturing of generation and distribution strategy and technology, as you might imagine. In fact, it is an ongoing process; the lates ideas and capabilities go under the name of *smart grid*, and they represent the contribution of digital technology to the current power management schemes. The idea is to further improve efficiency and increase the resilience of an electricity grid to fast-changing circumstances. For example, as customers develop their own solar power supplies, they will be able to sell excess power back to the grid, with bi-directional metering managing the process automatically. Variability of power—likely t increase in the future, as solar and wind power become more significant—will be smoothed out faste by local energy storage and also perhaps by *local control switching*.

Local control switching involves the power supplier's checking domestic usage—for example, by monitoring and restricting the times at which high-power household equipment (washing machines, air conditioners, water heaters) is used. Half the power used in average American households goes to consumer electronic goods, such as TVs and computers; local control switching would monitor usage and automatically hibernate equipment that is not in use. These ideas are implementable; the civil liberties issues remain to be sorted out. The idea is to reduce consumption during peak times and move it off-peak, thus reducing the likelihood of widespread brownouts.

An example of smart-grid thinking is the vehicle-to-grid (V2G) idea, whereby electric and hybrid plug-in cars charge up off-peak and sell excess power back to the supplier at peak times. V2G will help smooth out the demand placed on a utility—and it is easier than it sounds because most vehicles studies show, spend 95% of their time sitting in the garage.[13]

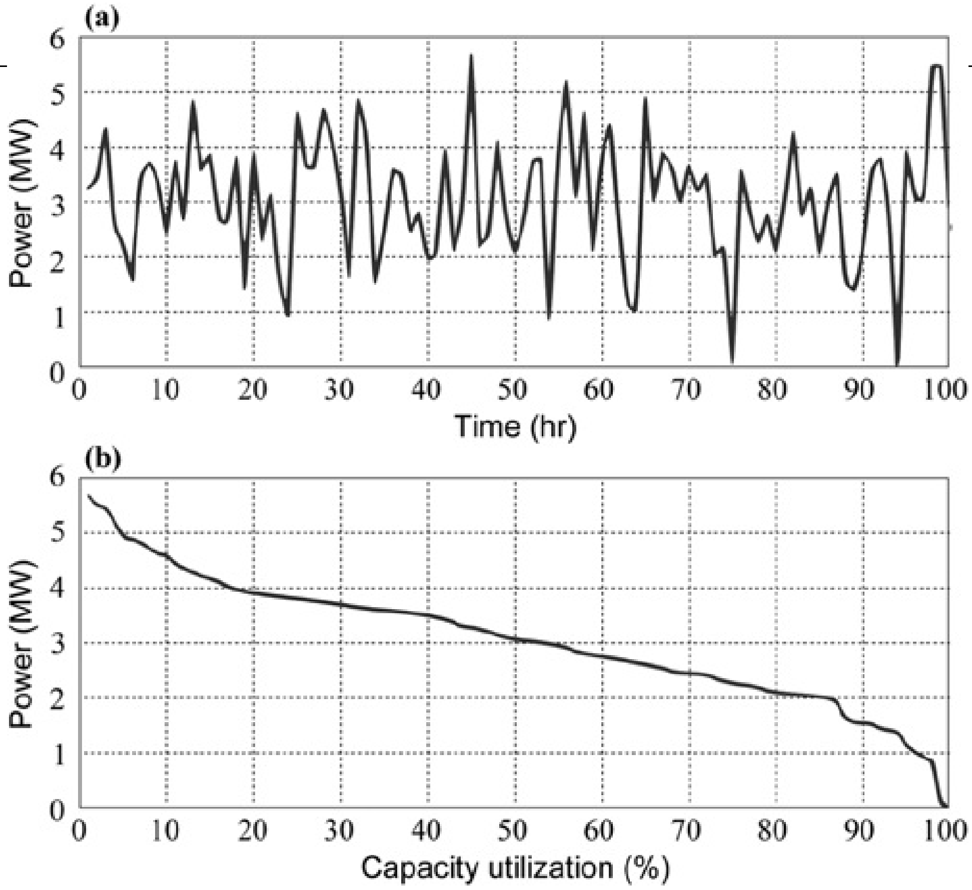
The smart grid will be capable of responding quickly to a sudden loss of supply—for example, du to a fire or mechanical breakdown—or to disruptions caused by lightning or sabotage. It will improve cost-effectiveness by switching suppliers if there is a change in price of one or another source of power (e.g., a drop in the price of solar power due to a hot summer, or a rise in oil prices due to pipeline leakage or political machinations). It can mitigate the daily fluctuations in supply across continents by shuffling power from one time zone to another. To some extent, the grid is already managed along these lines (pardon the pun), but smart-grid technology will enhance and speed up the response of suppliers to increasingly variable demand.

One final comment on power distribution is called for. So far, I have discussed power distribution on ~~a large scale for the purpose of demand management—to even out the required supply in the~~ face of variable demand. At a smaller scale—say, for a town or a factory—power distribution is necessar for a somewhat different purpose: to bridge between a grid outage and the supply of backup generato power. (We will see an interesting example of such bridging in the next section, with the world's biggest battery.) On the smallest scale—say, for the power supplied to your desktop computer—powe sometimes needs redistributing to ensure its even flow. The evenness of power flow is measured by *power quality*, and it is an important factor for many types of electrical equipment, which do not like to receive spikes of excess electrical power or loss of power, however brief. The most effective mean of distributing power on these three scales (grid management, bridging, and power quality) depends upon the scale.

POWER CURVES

I have hinted at the complexity of matching power demand with supply. This is a real problem that utility companies have had to address because it affects their bottom line in a big way. Suppliers mus allow for fluctuations in demand but do not want to provide more power than is necessary. To help them assess demand they often plot data that they have gathered on power usage as a *load duration curve*. The vertical axis of such a curve represents power demand or load (which, as we have seen, varies over time). The horizontal axis represents the fraction of time that a given load is required or exceeded (the *capacity utilization*).

Consider as an example the imaginary village of Sparksville, which receives electricity from its own municipal plant. The good citizens consume electrical power over a four-day period as shown in part (a) of the figure. The average load for Sparksville appears to be constant during this period but fluctuates about this value from minute to minute. The corresponding load duration curve is shown in part (b) of the figure. From this curve we see that for this four-day interval, half of the time 3 MW of power was being drawn from the municipal plant, but for 10% of the time demand exceeded 4½ MW (Over the four days, Sparksville drew power at an average rate of 3 MW, consuming 288 MWh of energy.) Such information enables the Sparksville power plant managers to decide how much power they should produce. Combining the load duration curve with a *price duration curve* (which plots the price of electricity instead of load) allows them to see how best to maximize profits for a given suppl of energy.



Electrical power consumption in Sparksville over approximately four days. (a) The average value fluctuates randomly, as in figure 1.5, though here for simplicity I assume no underlying daily variation. (b) The same data presented as a load duration curve. Capacity utilization is the fraction of time that a given power level is required or exceeded. Thus, 1 MW is required almost all the time, but 3 MW is needed only half the time (50% utilization).

Energy Storage

Why is electrical energy hard to store? We know that it can be done. Electric batteries power household equipment and an increasing number of cars. Major utility companies need energy storage to manage fluctuating demand, but of course we need energy storage at a more personal level as well. Some of the storage methods discussed here work well on a small scale, while others are better suited for large-scale applications. We will begin by looking at batteries. They are effective and are continually being made more so, but they are expensive. Another device for storing electricity is the capacitor, which stores energy by separating positive and negative charges (with an insulating material between the charges to prevent discharge). Capacitors can respond much more quickly than batteries and are useful in certain restricted circumstances, as when covering a sudden loss of power to a critical piece of equipment before a generator can switch on. But capacitors do not last long before discharging completely.

Consider, as a quirky example of a natural capacitor, a cumulonimbus thunderhead cloud. I am not suggesting that clouds could really be exploited as a means of storing electricity, but this example illustrates the severe limitation of a capacitor—it is a low-density form of stored energy. (The energy stored in clouds is huge, but only because clouds are huge. A capacitor the same size as a battery stores much less energy than the battery.) Capacitors—engineered ones, not my pie-in-the-sky example—are being actively developed for use in the automobile industry, but their characteristics a