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Electric Power Systems

There are many different types of power systems, such as the propulsion systems in automobiles and trucks and the hydraulic systems used in some industrial robots and for actuating scoops and blades in digging equipment. All power systems have certain fundamental elements. There is some sort of prime mover (such as a gasoline engine), a means of transport of the power produced (such as the drive shaft, transmission, differential and axles), and a means of using that power (wheels on the road). The focus of this book is on *electric* power systems, in which the means of transporting energy is the flow of electrical current against an electric potential (voltage). There are many different types of electric power systems as well, including the electrical systems in cars and trucks, propulsion systems in electric trains and cruise ships. The primary focus in this book will be the kinds of electric power systems incorporated in public utilities, but it must be kept in mind that all electric power systems have many features in common. Thus the lessons learned here will have applicability well beyond the utility system.

It has become all too easy to take for granted the electric utility service that is ubiquitous in the developed countries. Electric utilities are wired to nearly every business and residence, and standardized levels of voltage and frequency permit a wide range of appliances to be simply 'plugged in' and operated. Consumers don't have to give any thought to whether or not an appliance such as a television set, a computer or an egg beater will work. Not only will these appliances work when plugged in, but the electric power to make them work is quite reliable and cheap. In fact, the absence of useful electric power is quite rare in the developed countries in the world. Widespread failure to deliver electric power has become known as a 'blackout', and such events are rare enough to make the nightly news across the country. Even substantial distribution system failures due to weather are newsworthy events and very often cause substantial hardship, because we have all come to depend on electric power to not only keep the lights on, but also to control heating, cooling, cooking and refrigeration systems in our homes and businesses.

At the time of this writing, electric power systems in the United States and most of the developing world use as their primary sources of energy fossil fuels (coal and natural gas), falling water (hydroelectric power), and heat from nuclear fission. There are small but rapidly growing amounts of electric power generated from wind and solar sources and some

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electric power is generated from volcanic heat (geothermal energy). These 'renewables' are expected to grow in importance in the future, as the environmental impacts of the use of fossil fuels become more noticeable and as the fossil fuels themselves are exhausted. There are some differences between technologies involved in the older, existing power generation sources and the newer, sustainable technologies, and so in this book we will discuss not only how existing utility systems work but also how the emerging technologies are expected to function.

1.1 Electric Utility Systems

A very 'cartoon-ish' drawing of a simple power system is shown in Figure 1.1.

Electric power originates in 'power plants'. It is transmitted by 'transmission lines' from the power plants to the loads. Along the way the voltage is first stepped up by transformers, generally within the power plants, from a level that is practical for the generators to a level that provides adequate efficiency for long-distance transmission. Then, near the loads the electric power is stepped down, also by transformers, to a voltage useable by the customer. This picture is actually quite simplified. In modern utility systems there are thousands of power plants connected together through networks, and many more connections to loads than are indicated in Figure 1.1. The connections to actual loads is usually a bit more like what is shown in Figure 1.2. At the distribution level the connection is 'radial', in that there is one connection from the source of electric power (the 'grid'), and that is broken down into many load connections. Usually the distribution primary line is at a voltage level intermediate between the transmission level and the voltage that is actually used by customers.

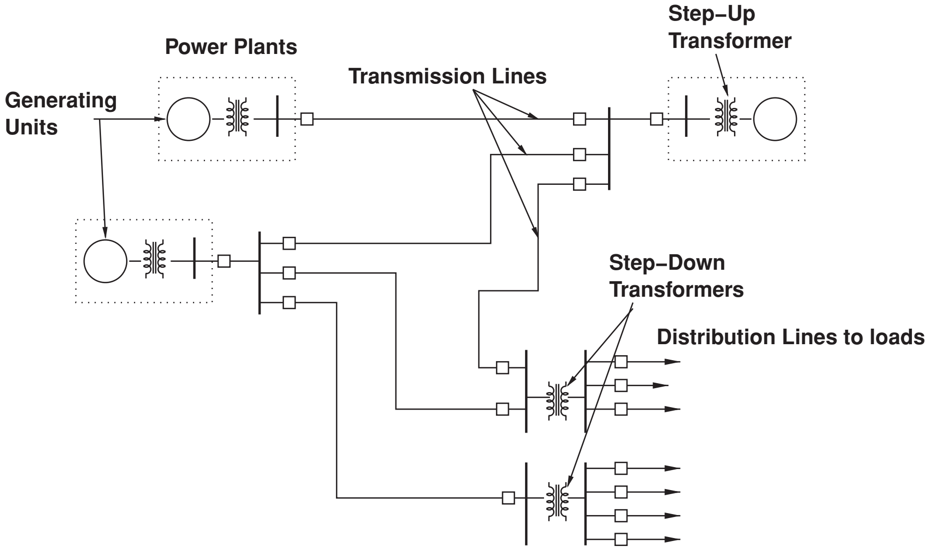

Figure 1.1 Cartoon of a simple power system

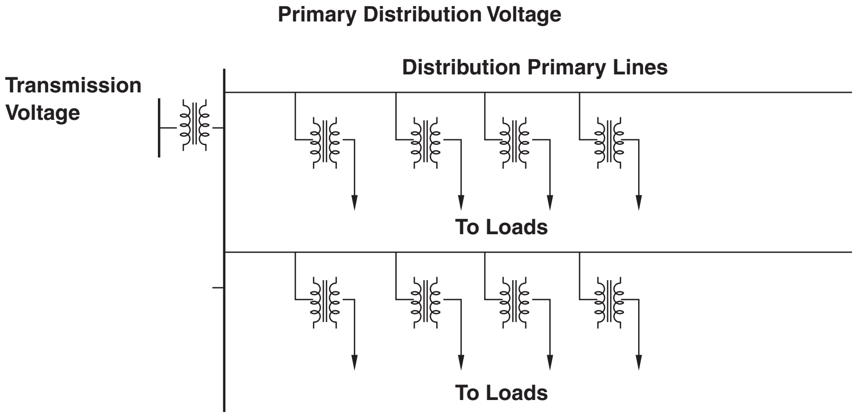

Figure 1.2 Distribution circuits

1.2 Energy and Power

1.2.1 Basics and Units

Before starting to talk about electric power systems it is important to understand some of the basics of energy and power. In the international system of units (SI), there are two basic units of energy. One is the joule (J), which is the energy expended by pushing a newton (N), a unit of force, over one meter. So a joule is a newton-meter. (A kilogram 'weighs' about 9.8 newtons at the surface of the earth). The other unit of energy is related to heat, and it is the Calorie. This story is complicated by the fact that there are actually two definitions of the Calorie. One is the heat (amount of energy) required to heat 1 gram of water 1 degree Celsius. This amounts to about 4.184 joules. The second definition is often called the 'kilogram Calorie', the amount of energy required to heat 1 kilogram of water 1 degree Celsius. This is obviously just 1,000 of the 'gram Calories', or 4,184 joules.

The basic unit of power is the watt, which is one joule/second. As it our predecessors crafted it, 1 watt is also 1 volt ×1 ampere. The volt is a unit of electrical potential and the ampere is a unit of current flow. Power is expressed in watts, kilowatts, etc., and a basic unit of energy is the kilowatt-hour (kWh), (3.6×10^6 J). Electricity is sold at retail by the kilowatt-hour and, usually, at wholesale by the megawatt-hour.

Another unit of heat that is commonly used in discussing power plants is the British Thermal Unit (BTU), which is the amount of heat required to raise 1 pound of water 1 degree Fahrenheit. This is about 0.252 kilogram calories or 1054 joules. In the United States, fuels are often sold based on their energy content as measured in BTUs, or more commonly in millions of BTU's (MBTU). See Tables 1.1 and 1.2.

1.3 Sources of Electric Power

There are two basic ways in which electric power is produced: by generators turned by some sort of 'prime mover' or by direct conversion from a primary source such as sunlight, or conversion of chemical energy in fuel cells. The prime movers that turn generators can be heat

Table 1.1 Some of the unit symbols used in this book

Unit	Unit of	Symbol
Ampere	current	A
British Thermal Unit	heat energy	BTU
Coulomb	charge	C
Calorie	heat energy	Cal
degree Celsius	temperature	°C
Farad	capacitance	F
Gauss	flux density	G
Hertz (cycles/second)	frequency	Hz
Henry	inductance	H
hour	time	h
Joule	energy	J
Kelvin	temperature	K
kilogram	mass	kg
meter	length	m
Newton	force	N
volt	electric potential	V
volt-ampere	apparent power	VA
watt	power	W
Weber	flux	Wb

engines such as steam turbines, gas turbines, internal combustion engines burning diesel fuel, natural gas or (rarely) gasoline, or turbines that convert power directly from falling water or wind. Geothermal heat is sometimes used to power heat engines in places where that heat is accessible (this is the major source of electric power in Iceland). Even sunlight has been used as the power input to heat engines.

1.3.1 Heat Engines

Most power plant ‘prime movers’ are heat engines that burn a primary fuel such as coal or natural gas and that use the energy released by combustion to produce mechanical power (generally turning a shaft) that is used to drive a generator to produce electrical power. We

Table 1.2 Multiplying prefixes used in this book

Prefix	Symbol	Multiple
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}

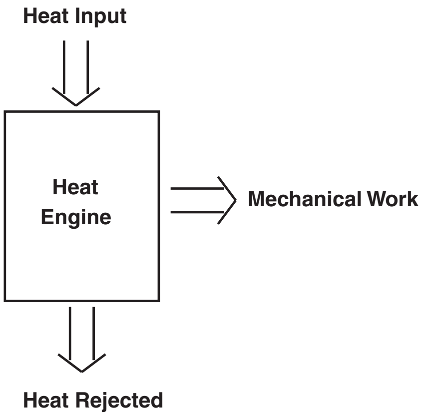

Figure 1.3 Energy balance

will, in later chapters of this book describe how generators work. Heat engines can convert only some of the heat energy that is input to the engines into mechanical work. The details of this are beyond our scope here, but as is shown in Figure 1.3, there will always be waste heat associated with a heat engine. Heat engines take energy at a high temperature and reject heat energy at a lower temperature. The difference between the heat input and rejected heat energy is what is converted to mechanical power, and efficiency is the ratio of mechanical power output to heat power input.

There is a well known bound on efficiency of a heat engine, called the ‘Carnot efficiency’, and that is associated with the temperature of the input heat and the temperature of the rejected heat. This is:

$$W_\mathrm{m} < Q_\mathrm{h} \frac{T_\mathrm{h} - T_\ell}{T_\mathrm{h}}$$

where Q_h is the input energy. Mechanical work is the difference between heat input and heat rejected, and the efficiency depends on the heat input temperature T_h and heat rejection temperature T_ℓ. Practical heat engines do not approach this Carnot limit very closely, but this expression is a guide to heat engine efficiency: generally higher heat input temperatures and lower heat rejection temperatures lead to more efficient heat engines.

In discussing power plant efficiency, we often note that one kilowatt-hour is 3.6 MJ or 3,414 BTU. The fuel energy input to a power plant to produce one kilowatt hour is referred to as its ‘heat rate’, and this is inversely related to its thermal efficiency. A power plant that has a heat rate of, say, 10,000 BTU/kWh would have a net thermal efficiency of $\eta = \frac{3414}{10000} \approx 0.3414$.

1.3.2 Power Plants

Figure 1.4 shows a cartoon of a power plant that burns fossil fuels. The heat engine in this case is a steam turbine. Water is first compressed and pumped into a ‘boiler’, where a fire heats it into steam. The steam is expanded through a turbine which turns a generator. The turbine exhaust is then fed to a ‘condenser’ where the waste heat is rejected. There are several

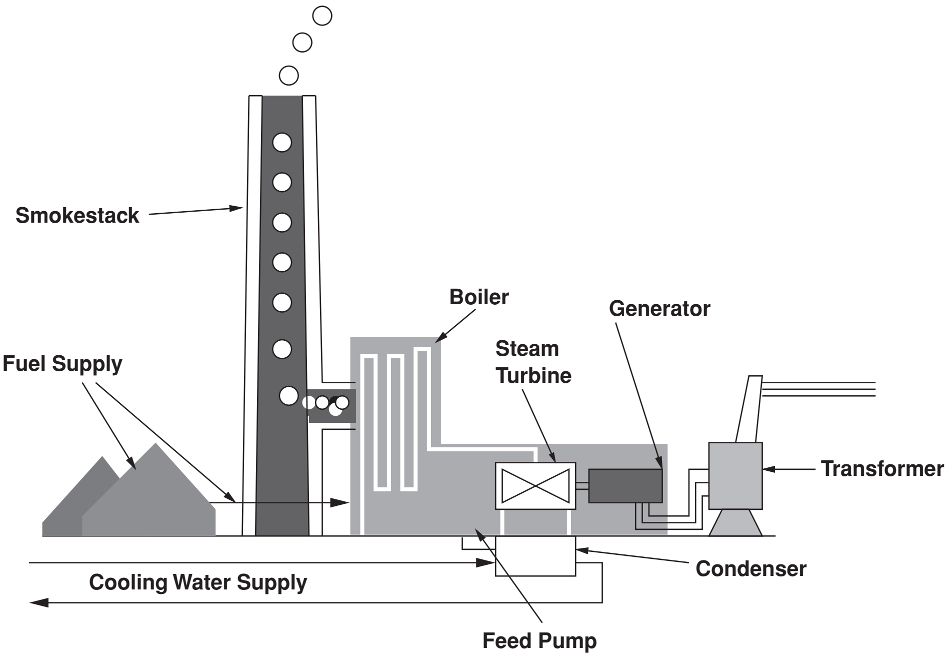

Figure 1.4 Cartoon of a fossil fired power plant

different recipients of the rejected heat, depending on the situation: rivers, lakes, the ocean, purpose built cooling ponds or cooling towers are all used. Generated electricity is generated at ‘medium’ voltage (‘medium voltage’ is generally taken to be between 1 kV and 100 kV, but power plant generators are generally limited to about 30 kV) and is usually stepped up to ‘high’ (100 to 230 kV) or ‘extra high’ (230 to 800 kV) voltage for transmission.

While Figure 1.4 shows a coal-fired power plant, similar steam turbine-based power plants can burn any of the fossil fuels, wood or even municipal garbage, and often such plants are built in such a way that they can burn different fuels, based on which fuel is cheapest at a given time.

There are also power plants that employ gas turbines, as opposed to steam turbines, or even some power plants that have gas turbine engines on the same shaft as steam turbine engines. The ‘simple cycle’ gas turbine engines are based on the same technology as jet engines that power aircraft (‘aero derivative’). ‘Binary cycle’ power plants use a gas turbine engine with the exhaust gas rejecting heat to a steam cycle and can achieve higher efficiency than simple cycle gas- or steam- turbine engines, but with a higher level of complexity.

1.3.2.1 Environmental Impact of Burning Fossil Fuels

Fuels such as coal often have contaminants such as sulfur or mercury that have adverse environmental effects, and there has been, in recent years, substantial development of methods to mitigate those effects.

Table 1.3 Carbon analysis of hypothetical power plants

Fossil fuel carbon analysis	Coal	No. 6 Fuel Oil	Natural Gas
Fraction carbon	0.807	0.857	0.750
Fraction hydrogen	0.045	0.105	0.250
HHV (BTU/kg)	30 870	40 263	50 780
HHV (kJ/kg)	32 573	42 438	53 522
kg CO_2/kg fuel	2.959	3.142	2.750
kg CO_2/MBTU	95.9	78.0	54.2
kg CO_2/kWh (at 10 000 BTU/kWh)	0.959	0.780	0.542
kg CO_2/hour (at 1000 MW)	323 939	248 365	196 928
kg CO_2/hour	958 536	780 446	541 552

Mercury, for example, is toxic in surprisingly small quantities. When coal containing trace amounts of mercury is burned, the mercury is released in the effluent gas and/or 'fly ash' (solids in the effluent gas) and then gets into some food chains such as fish. As big fish eat small fish the mercury is concentrated. As fish are generally fish eaters this process is repeated until fish near the top of the food chain are caught by the carnivores at the top of the food chain (people). Sometimes toxic levels of mercury are present in those big fish.

Sulfur oxides and nitrogen oxides, the result of oxidation of nitrogen in the air, are the stuff of 'acid rain'. There are different oxidation states of both nitrogen and sulfur, so that this type of pollution is often referred to as 'SO_X and NO_X'. Not only do these chemicals produce acid rain, but they can (and do) react with hydrocarbons present in the air to form a visible haze that is often referred to as 'smog'. Methods of mitigating these pollutants have been developed but are beyond our scope here.

Fossil fuels generally contain carbon and hydrogen (which is why they are called 'hydrocarbons', and the chief effluents of power plants are water vapor and carbon dioxide. The latter is a 'greenhouse' gas, and while it appears naturally in the atmosphere of the Earth, there are indications that man-made injections of carbon dioxide are raising the levels of CO_2, with possible impacts on the earth's heat balance ('global warming'). For this reason, it seems important to understand the carbon content of fuels.

Table 1.3 shows a simple analysis of carbon effluent for a 1,000 MW power plant assuming a 'heat rate' of 10,000 BTU/kWh. It should be noted that this heat rate, while it is within the range of numbers actually encountered, is not necessarily typical for any particular plant. The fuels assumed in Table 1.3 are bituminous coal, heavy fuel oil (# 6 is what comes out near the bottom of the refinery distillation column) and natural gas. It should also be noted that these numbers are roughly correct, but that all of these fuels come with ranges of the various quantities. For example, the energy content of bituminous coal varies between about 23 000 and about 31,000 BTU/kg. Natural gas is primarily methane, which is 75% carbon and 25% hydrogen, but most sources of natural gas have some heavier components (ethane, propane, butane, etc.). Note that coal, which also can have varying fractions of carbon and hydrogen, has some non-combustible components (water, inorganic solids) as does fuel oil. The 'higher heating value' (HHV) for these fuels assumes that all of the heat released when the fuel is burned can be used, including the heat of vaporization of water that is produced when the hydrogen is combined with oxygen. This is often not the case, and the 'lower heating value' is somewhat less.

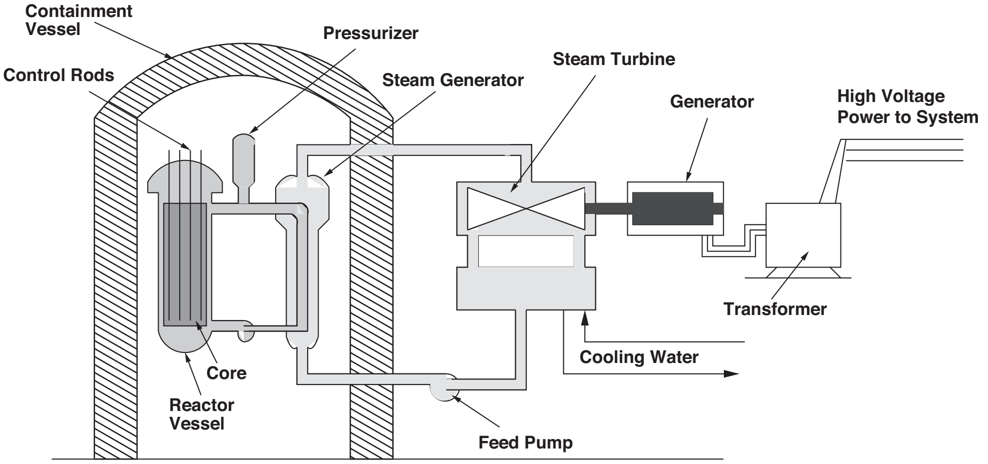

Figure 1.5 Cartoon of a nuclear power plant

Note that the amount of carbon dioxide produced when burning natural gas is substantially smaller, per unit of energy produced, than when coal or fuel oil is burned, and for that reason natural gas is sometimes thought of as a 'cleaner' fuel.

1.3.3 Nuclear Power Plants

Nuclear power plants employ the same thermodynamic cycle as most fossil fueled plants. Because of the relatively difficult environment for the materials that carry high-pressure water (it is radioactive in there), the high end temperature of a nuclear power plant cannot be as high as it can in fossil-fueled plants and so thermal efficiency tends to be a bit lower.

The reactor in a nuclear power plant generates heat through fission of heavy atoms into two (or more) lighter atoms. When an atom of uranium (U^{235}), the isotope of uranium that is capable of fission, splits, about 1/5 of an atomic mass unit (AMU) is converted to energy. Since the mass fraction of U^{235} in natural uranium is about 0.7%, were all of the fissile isotope to be converted to energy, a fraction amounting to about $\frac{0.2}{235} \times 0.007 \approx 6.1 \times 10^{-6}$ of the natural uranium would be converted to energy. That turns out to be quite a lot of energy, however, because $E = MC^2 = M \times 9 \times 10^{16}$ J/kg, or one kilogram of natural uranium would yield about $6.1 \times 10^{-6} \times 9 \times 10^{16} \approx 5.5 \times 10^{11}\text{J} \approx 1.53 \times 10^5\text{kWh}$. If the plant operates with a thermal efficiency of 33%, That would mean about 51,000 kWh/kg of natural uranium. This compares with perhaps 3 or 4 kWh/kg for coal.

Virtually all commercial nuclear power plants are 'light water' moderated (LWR) and are either of the 'pressurized water' or 'boiling water' type. Figure 1.5 is a cartoon sketch of a pressurized water reactor type power plant. Moderation here means reducing the energy of the neutrons that are emitted from fissioning nuclei to the level that is best for initiating fissioning of other nuclei. When a nucleus of uranium splits, it emits, among other things, a few 'fast' neutrons. These fast neutrons, while they can convert U^{238} to plutonium, are not very effective at inducing fission in U^{235}. Passing through the water that surrounds the fuel rods, the neutrons are slowed down, giving up energy and becoming 'thermal neutrons' (about 0.025 eV), to the point where they are effective in inducing fission. In fact, since slower neutrons are more effective in inducing fission, there is a negative reactivity coefficient with temperature that tends to stabilize the chain reaction. Further control is afforded by the 'control rods' that absorb neutrons. Dropping the rods fully into the reactor stops the chain reaction. The plutonium produced by fast neutrons interacting with U^{238} includes a fissile isotope that is subsequently fissioned and this contributes more to the energy produced.

There is no carbon emitted by nuclear power plants in normal operation. The byproducts of the nuclear reaction, however, are really nasty stuff: lethally radioactive, hot and poisonous. Fortunately there is not a great deal of spent fuel produced and so it can be (and is) simply contained. There is still much public debate about what to do with spent fuel and development of techniques for processing it or for stabilizing it so that it can be stored safely. Of particular interest is the fact that the plutonium present in spent fuel can be used to make nuclear explosives. The plutonium can be separated chemically, whereas fissile U^{235} cannot. This is both good and bad news: good because plutonium is a useful fuel that can be mixed in with uranium and burned in reactors; bad because it facilitates fabrication of nuclear explosives, making securing spent fuel from potential terrorists or failed states very important, an added expense of the nuclear fuel cycle.

At the time of this writing (2009), there were 104 nuclear power plants in the United States, producing about 20% of the electric energy used in the country.

1.3.4 Hydroelectric Power

Hydroelectric power plants take advantage of falling water: under the influence of gravity, water descending through a pipe exerts force on a turbine wheel which, in turn, causes a generator to rotate. Figure 1.6 shows a cartoon style cutaway of a hydroelectric unit (or 'waterwheel'). For hydrodynamic reasons these units tend to turn relatively slowly (several tens to a few hundred r.p.m.), and can be physically quite large.

Power generated by a waterwheel unit is:

$$P = \rho_{\text{water}} \boldsymbol{g} h \dot{v} \eta_t$$

where ρ_{water} is mass density of water (1000kg/m^3, $\boldsymbol{g}$ is acceleration due to gravity (about 9.812m/s^2), h is the 'head' or height the water falls, $\dot{v}$ is volume flow of water and η_t is efficiency of the turbine system.

Hydroelectric power plants, even though they produce a relatively small fraction of total generation, are very important because their reservoirs provide energy storage and their generation can be modulated to supply power for variations in load over time. In fact, some 'pumped hydro' plants have been built solely for storage. Two reservoirs are established at different elevations. The hydroelectric generators are built so they can serve not only as generators but also as pumps. When electric power is in surplus (or cheap), water is pumped 'uphill' into the upper reservoir. Then, when electric power is in short supply (expensive), water is allowed to flow out of the upper reservoir to provide for extra generation. The lower reservoir is often a river and the upper reservoir might be formed by hollowing out the top of a mountain.

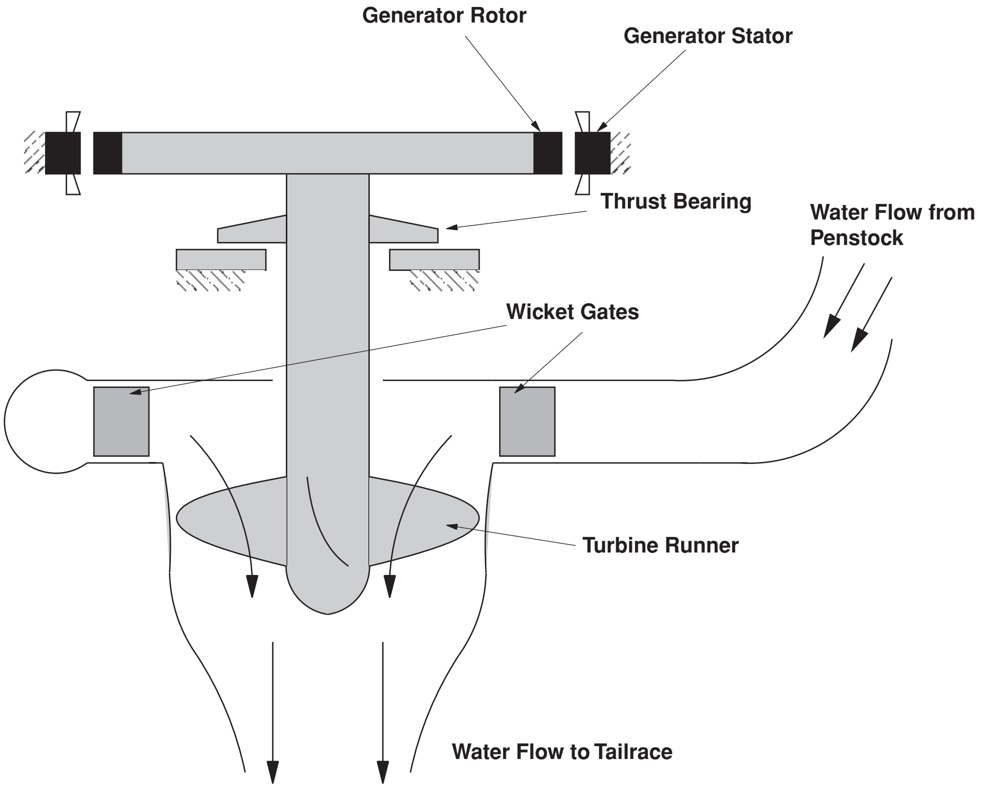

Figure 1.6 Cartoon of a hydroelectric generating unit

Hydroelectric power generation is the oldest and largest source of sustainable electric power, but other renewable sources are emerging.

1.3.5 Wind Turbines

Among the emerging 'sustainable' sources of electric power, wind is both the largest and fastest growing. Figure 1.7 shows a view of a wind farm, with a number of 1.5 MW wind turbines. These units have a nearly horizontal axis with a blade disk diameter of about 77 m and 'hub height' of 65 to 100 m, depending on site details.

Power generated by a wind turbine is, approximately:

$$P = \frac{1}{2} C_{\mathrm{p}} \rho_{\mathrm{air}} A u^3$$

where ρ is air density (about $1.2\mathrm{kg/m}^3$) and u is air velocity, so that $\frac{1}{2}\rho u^2$ is kinetic energy density of wind entering the disk of area A and C_{p} is the 'power coefficient', a characteristic of wind speed, rotor angular velocity and blade pitch angle. It has a theoretical maximum value of about 59% but as a practical matter usually does not exceed about 50%. Because

Figure 1.7 Turbine top view of the Klondike wind farm in Oregon, USA. Photo by Author

this coefficient is a function of wind and rotor tip speed (actually of the advance angle), wind turbines work best if the rotational speed of the rotor is allowed to vary with wind speed. More will be said about this in the discussion the kinds of machines used for generators, but the variable speed, constant frequency (VSCF) machines used for wind generators are among the most sophisticated of electric power generators. They start generating with wind speeds of about 3 m/s, generate power with a roughly cubic characteristic with respect to wind speed until they reach maximum generating capacity at 11–13 m/s, depending on details of the wind turbine itself, and then, using pitch control, maintain constant rotational speed and generated power constant until the wind becomes too strong, at which point the turbine must be shut down. This ‘cut out’ speed may be on the order of 30 m/s.

A cartoon showing the major elements of a wind turbine is shown in Figure 1.8. Turbine blades are mounted to a nose cone that contains pitch adjusters to control speed. The relatively low turbine speeds are increased by a factor of perhaps 80 by a gear box, usually made up of one planetary and two bull gear and pinion gear stages. The generator is often a doubly fed induction generator: a wound rotor induction machine with a cascade of power electronics to couple the rotor windings with the stator windings and local power system and to provide constant frequency, variable speed capabilities.

The wind turbine is mounted on a tower that is usually implemented as simple steel tube, on the order of 65 to 100 m in height. The nacelle is mounted on a yaw mechanism to point the turbine at the wind. Both the yaw mechanism and the main turbine blades have braking mechanisms (not shown in the figure). In some wind turbines there is a transformer in the nacelle to couple the low voltage of the generator to the medium voltage used to carry electric power from the wind turbines to the point of common contact with the utility system (POCC).

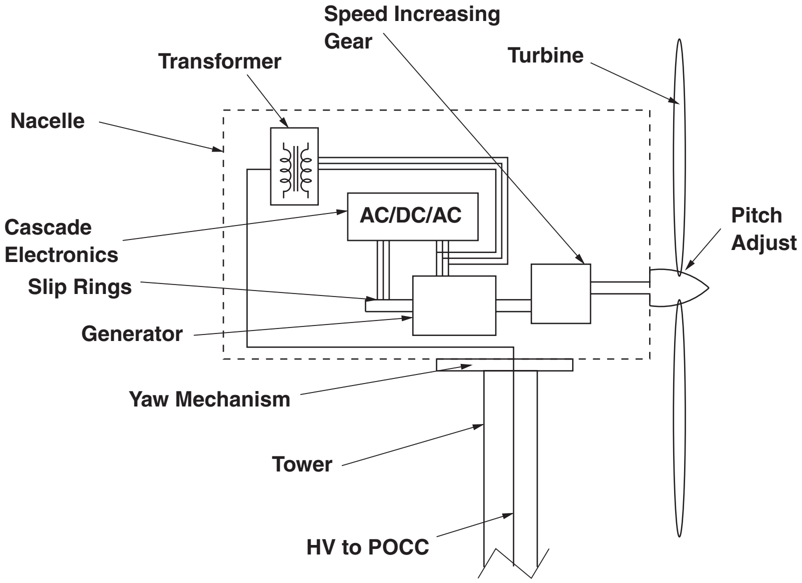

Figure 1.8 Wind turbine components

1.3.6 Solar Power Generation

Generation of electric power is another source of energy that is very small but growing rapidly. Radiation from the sun, in the visible and infrared, amounts to about 1 kW per square meter in the vicinity of the earth. Were it possible to economically capture all of this energy we would not be considering any of the other means of power generation. It is, of course, not possible for a variety of reasons:

1. The atmosphere captures and scatters some of the solar radiation, which is why the sky is blue and sunsets are red. This effect is stronger in latitudes away from the equator.
2. Because the earth turns, half the time the sun is not visible at all. And for much of the day the sun is near or not very far from the horizon. Solar arrays that track the sun are expensive and complex, with moving parts that must be maintained. Solar arrays that do not track the sun absorb less energy than is available.
3. Clouds interfere with solar radiation in most parts of the earth, and surfaces of solar arrays can be fouled by dust and other crud that falls from the sky.
4. Existing technologies for conversion of solar radiation into electricity are, currently, expensive relative to other sources.

There are two principal means of solar generation of electricity. One employs heat engines similar to fossil fuel or nuclear generation, using sunlight to heat the top end of the heat engine cycle. Often this is in the form of a ‘solar tower’, with the element to be heated at the focus of a lot of mirrors. The operational issues with this sort of a system are chiefly associated with

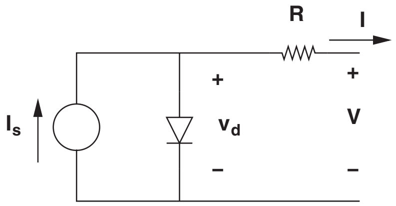

Figure 1.9 Equivalent circuit model of a solar cell

tracking and focusing the sunlight on the top element. The method of operation of the power plant is similar to that of any other heat engine.

The second means of generating electricity from sunlight employs photovoltaic cells. These are large area junction diodes that, when sunlight shines on them and splits electron/hole pairs, produce a current. The cost and efficiency of these cells are not very favorable at the present time, although for certain applications such as powering space stations (where solar energy is more abundant than it is on the surface and where other fuels are very expensive) or powering remote, low power services would otherwise be very expensive, they are the power source of choice. There has been and continues to be substantial development of solar cells and it is to be anticipated that cost and performance will continue to improve.

An equivalent circuit model of a solar array is shown in Figure 1.9. The source current I_s is the result of absorption of photons in sunlight that cause separation of valence electrons from their atoms. The resulting hole/electron pairs fall across the high field gradients present at the diode junction. Because any voltage resulting from this current tends to forward bias the actual junction, the voltage available is limited. One can readily deduce that the cell current is:

$$I = I_\mathrm{s} - I_0 \left(e^{\frac{v_d}{\frac{kT}{q}}} - 1 \right)$$

Here, I_s depends on the strength of solar radiation actually reaching the junction and on how strongly it is absorbed and on the junction area. I_0 also depends on junction area and on how the cell was constructed. The voltage $\frac{kT}{q}$ is about 25 mV at room temperature. A representative curve of output current vs. voltage is shown in Figure 1.10.

One aspect of solar cell generation requires some discussion. The characteristic curve of current vs. voltage depends on both solar irradiance and temperature. When shorted, the panel produces a certain current. When open it produces a certain voltage. At both extremes the panel produces no power. The output is maximum somewhere in the middle. The trouble is that the maximum power point as shown in Figure 1.11 is a function of both temperature and radiation, so there is no simple way of loading the cells to get the maximum amount of power from them. The problem of maximum power point tracking (MPPT) has become an item of competitive art among manufacturers of solar cells and the electronics that go with them.

Large solar photovoltaic systems intended for connection with the utility network must employ electronic systems that absorb electric power from the cells, implement maximum power point tracking, and then convert the resulting DC power into utility frequency AC, single-phase (for small systems) or polyphase (for larger systems). The inverter systems involved will be covered later in this text.

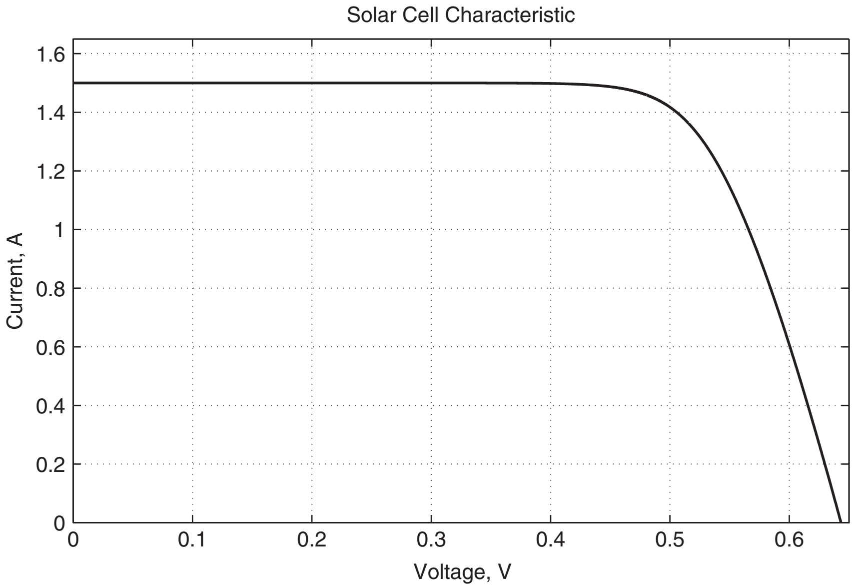

Figure 1.10 Output current vs. voltage

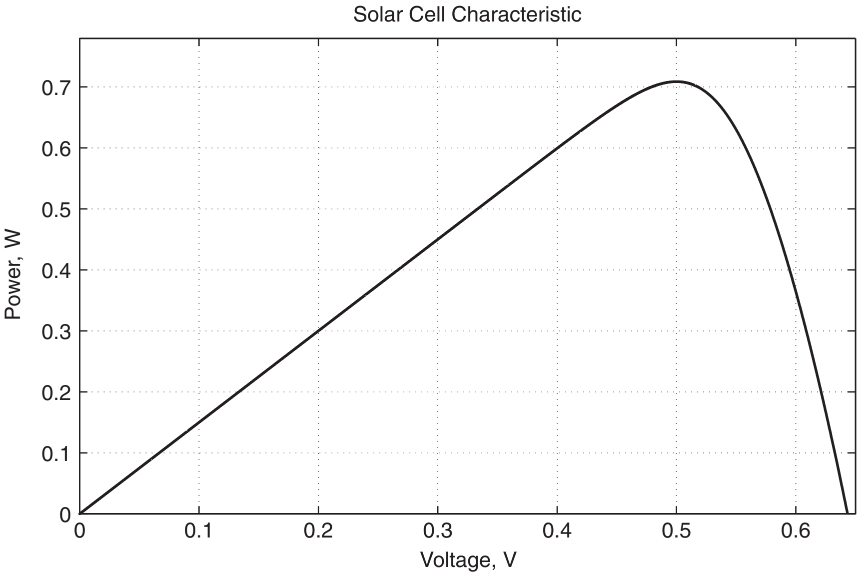

Figure 1.11 Output power vs. voltage

Table 1.4 Fraction of capacity and energy produced

	Generating capacity	Supplied energy
Coal	30.5%	48.5%
Natural gas	40.9%	21.6%
Nuclear	9.9%	19.4%
Conventional hydroelectric	7.5%	6.0%
Petroleum	5.9%	1.6 %
Wood	0.7%	0.9%
Wind	1.6%	0.8%
Other biomass	0.4%	0.4 %
Geothermal	0.2 %	0.4 %
Other gases	0.2 %	0.3 %
Solar	0.04%	0.01%

Source: United States Energy Information Administration, Electric Power Annual 2007.

1.4 Electric Power Plants and Generation

According to the United States Energy Information Administration, at the end of 2007 the country had 17,342 generating facilities with a total capacity of between 995,000 and 1,032,000 MW, depending on season. (Note: heat engines have higher capacity in cold weather.) In 2007 those plants produced a total of 4,156,745 GWh of electrical energy. Table 1.4 shows a breakdown of the fraction of generating capacity and generated electric energy represented by each source technology in the United States in that year.

The differences in fractions of capacity and energy generated are related to economics: nuclear and coal plants are expensive to build but cheap to run; natural gas plants are just the opposite. The share of renewables is very small, but it is growing fast.

Electric power is a big business that has come to have a profound impact on the lives of everyone living in the industrialized world. In the following chapters we will describe generation, transmission, distribution, handling and, to some extent, use of electric power.

1.5 Problems

1. Your household electrical system has a circuit that is single phase and employs a voltage of 240 V, RMS. What can a circuit with a 50 A breaker handle?
   - In Watts?
   - A heater, rated in British Thermal Units/hour.
2. What is the ‘heat rate’ (BTU/kWh) of a power plant with a net thermal efficiency of 50%?
3. Using the data of Table 1.3, what is the amount of coal required for a power plant with a heat rate of 11,000 BTU/kWh to produce 1000 MW for a year?
4. What is the carbon dioxide emission rate of a coal fired power plant with a heat rate of 9,500 BTU/kWh:
   - Per hour if the rating of the plant is 600 MW?

- Per kWh?

Use the data contained in Table 1.3.

5. What is the carbon dioxide emission rate of a natural gas fired power plant with a thermal efficiency of 53%?
   - Per hour if the rating of the plant is 600 MW?
   - Per kWh?

   Use the data contained in Table 1.3.
6. A nuclear power plant 'burns' Uranium enriched to about 4% U^{235}, the fissile isotope. If this plant achieves a 'burnup' of 50% (that is, it converts half of the fissile component of the fuel), how much enriched uranium is required for the plant to make 1000 MW for a year? Assume a heat rate of 12,000 BTU/kWh.
7. Assume the density of air to be $1.2 \mathrm{kg/m^3}$. What diameter wind turbine is required to capture 1.5 MW at a wind speed of 10 m/s if the turbine coefficient of performance is 40%?
8. What is the water volume flow rate for a 100 MW water turbine operating with a 'head' of 20 meters, assuming an efficiency of the turbine and generator of 80%? (Water has a mass density of $1000 \mathrm{kg/m^3}$).