

**Energy Primer**  
**San Juan College Renewable Energy Program**

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## **INTRODUCTION**

The production, storage, distribution, and use of energy represent the largest human industry on Earth. Energy consumption, especially in developed countries, is strongly linked both to quality of life and health of economies. Our appetite for energy has never been greater, and there appears to be no end in sight. However, we are gradually realizing that the stress we place on the planet's climate and ecosystems with energy production and consumption are taking their toll.

It would be impossible to seriously discuss sustainable development without considering our energy supply. Few of us would like to return to the days before electricity, mechanical engines, and refined heating fuels. In fact, our current population level prohibits such a journey. It only makes sense, therefore, to discuss ways in which to meet human energy demand without depleting non-renewable resources and damaging the natural environment. This may require limiting energy consumption (to some degree). Of equal import, though, is to develop renewable sources of energy as quickly as possible.

There will not be an "overnight" switch from our traditional energy production methods. The magnitude of such a change of infrastructure is staggering. Rather, we would expect to see a long transition period where the traditional sources eventually become economically disadvantaged. The question currently posed to us is not whether we will change to renewable energy production, but when and how long will the phase-in period last.

At the turn of this new century we are facing an energy reality that was not entirely expected – we will not run out of fossil fuel in the near future. There are enough coal and oil reserves around the planet to sustain our current consumption rates for at least one hundred years. The pressure on humanity during these hundred years will come not from supply, but from the environment.

Traditional energy generation techniques will be with us for quite some time. A basic understanding of these techniques, and the fundamental physics underlying them is necessary to partake in energy debates at any level. We are all members of a highly technical society, and it is our democratic responsibility to understand it so that we (and those who represent us) can be intelligently connected to the political system.

The purpose of this primer is to introduce you to the science of energy (which will not change) and the technologies of energy production (which are transitory).

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**ENERGY**

The engineering definition of *energy* is the ability to do useful work. If something has energy, it can perform work. If a device does work, its energy decreases. If work is done on a device, its energy increases. This concept is directly tied to our common-sense picture of the world. A popular misconception is that *power* and *energy* are interchangeable terms. This is often seen in mass media. *Power* defines how quickly energy is used, or work is performed. Any statement of power must include not only the energy required to do the job, but also how long that job took to complete. Getting your car to the top of a hill requires a certain amount of energy determined by the mass of your vehicle and the vertical height of the hill (and the frictional losses involved in the trip). However, we all know that the fastest way to the top involves a “powerful” engine. Everyone’s gasoline contains the same amount of chemical energy, but an engine with a lot of power is capable of turning that energy into motion in a shorter period of time.

A big part of understanding energy and power involves sorting through the confusing maze of units that quantify them. The fact that we have to deal with both the metric and English systems of units doubles the trouble. Let’s start with energy.

<b>Energy</b>	<b>Metric</b>	<b>English</b>
Mechanical	kilojoule [kJ]	foot-pound [ft-lb]
Thermal	kJ	British thermal unit [Btu]
		Therm
		Calorie [Cal]
Electrical	kilowatt-hour [kWh]	kWh

Notice that there is large variety of units in the English system for describing thermal energy, and that the English system does not have its own units for electrical energy. The British Thermal Unit (Btu) is the amount of energy required to raise the temperature of one pound of water one degree Fahrenheit at atmospheric pressure and room temperature. A few conversions may be helpful:

- 1 kJ = 0.948 Btu = 737.6 ft-lb
- 1 Therm = 100,000 Btu
- 1 Cal = 4.187 kJ (this is the nutritional Calorie)
- 1 kWh = 3600 kJ

Units for power must include energy and time, but often they are combined into a new unit. In the metric system a Watt is defined as one Joule per second, so any time you see a [W] you could replace it with [J/s]. The table below shows common units for power.

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Power	Metric	English
Mechanical	Watt [W]	$\frac{\text{ft} \cdot \text{lb}}{\text{s}}$
		horsepower [hp]
Thermal	W	Btu/hr
		ton (refrigeration)
Electrical	W	W

Once again, the English system adds confusion. Metric power is common across the board. Here are a few more conversions:

$$1 \text{ W} = 1 \frac{\text{J}}{\text{s}} = 0.738 \frac{\text{ft} \cdot \text{lb}}{\text{s}} = 3.412 \text{ Btu/hr}$$

$$1 \text{ hp} = 550 \frac{\text{ft} \cdot \text{lb}}{\text{s}} = 746 \text{ W}$$

$$1 \text{ ton of refrigeration} = 12000 \text{ Btu/hr}$$

A special comment is appropriate. The kilowatt-hour [kWh] is *not* a unit of power. The electric utility bills you for energy, not power. A kilowatt [kW] is 1000 watts of power. When you multiply a kilowatt by 3600 seconds (1 hour) you get *energy* in kilojoules.

$$1 \text{ kWh} = 1 \frac{\text{kJh}}{\text{s}} = 1 \frac{\text{kJh}}{\text{s}} \frac{3600\text{s}}{\text{h}} = 3600 \text{ kJ}$$

The electrical meter on your house is adding up (integrating) your power usage over time. The result is energy, or kilowatt-hours.

## CURRENT ENERGY GENERATION TECHNOLOGIES

Essentially, we do two things with energy - either produce heat, or electricity. Mechanical motion can be derived from the heat (an engine) or electricity (a motor). Below we'll explore a variety of heat-producing fuels, mechanical engines, and electrical power production cycles.

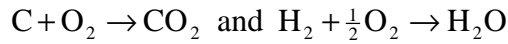
### HEAT & COMBUSTION FUELS

Heat is defined physically as the average kinetic energy (energy of motion) of the molecules of a substance, and is measured with temperature. Heat and thermal energy are equivalent terms. Heat will always flow from a high temperature to a low one. A vast array of refined and unrefined fuels is available in this country for producing thermal energy. Almost all of these fuels are hydrocarbons, substances that are mostly made up of

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hydrogen and carbon. Hydrocarbons are, almost exclusively, burned to release their chemical energy as heat. The burning process is called combustion and involves oxidation of carbon and hydrogen. A hydrocarbon fuel, an oxygen source (usually air), and a sufficiently high ignition temperature are required to start combustion.

Complete combustion would result in all of the carbon being converted to carbon dioxide and all of the hydrogen being converted to water (vapor). These individual chemical reactions are shown as follows.



Note that any fuel with carbon will produce carbon dioxide, and that burning hydrogen alone will not. If complete combustion ever really took place, however, the environment would be in much better shape. Many problems crop up along the way. Incomplete combustion can arise from either not having enough oxygen available, or not giving the fuel-air mixture enough time to react. This results in carbon monoxide production and the emission of raw hydrocarbons into the environment. The oxygen in the mixture is more strongly attracted to hydrogen than carbon, so in a competitive situation hydrogen will react, leaving carbon either unburned or attached to only one oxygen atom (carbon monoxide). In addition, at high temperatures (such as those in your automobile engine) the nitrogen in air reacts with oxygen to form oxides of nitrogen – hazardous and smog producing. If there is any sulfur content in the fuel to begin with (coal being the most infamous example) it will react with condensing water vapor to form sulfuric acid, a form of acid rain.

Unrefined fuels that are readily available include wood, coal, peat, and biomass. These materials are heavy on carbon, and light on hydrogen. They tend to produce less energy (on a mass basis) when burned than petroleum-based fuels and can have high degrees of impurities. Moisture content before combustion greatly reduces the amount of heat released – we all know what it's like to burn wood that hasn't been properly cured. The following table lists representative heating values based on the mass of the fuel combusted completely.

<b>Fuel</b>	<b>Heating value [Btu/lb]</b>
Wood (fresh cut)	4,400
Wood (air dried)	7,000
Wood (kiln dried)	8,500
Coal (low-volatile bituminous)	14,400
Coal (subbituminous)	10,000
Peat (air dried)	6,200
Cattle manure (dried)	7,400
Corncobs	9,300
Rice straw	6,000
Wheat straw	8,500
Coffee grounds	10,000
Municipal refuse	9,500
Scrap tires	16,400

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Biogas is a fuel produced by the anaerobic digestion of wastes. It is readily available wherever waste materials are stored (such as landfills). The chemical composition is approximately 62% methane and 36% carbon dioxide, with the rest being made up of various other compounds. The heating value is about 600 Btu/ft<sup>3</sup> (we will compare this value with other gaseous fuels below). It is also possible to refine ethanol from crop waste materials. Ethanol is used currently as a gasoline additive and is a large source of revenue in corn-producing states.

Most other fuel sources are either natural gas-based or refined petroleum products. Since natural gas is a big industry here in the Four Corners region we should focus on it. Natural gas, while containing many minor compounds, is mostly composed of methane (CH<sub>4</sub>). Of all the hydrocarbon fuels, it has the least amount of carbon content. This is particularly important when assessing the emission of greenhouse gasses (carbon dioxide being the most important). Hydrogen can be refined from natural gas, and the majority of this country's hydrogen is produced that way. Natural gas does not require large amounts of energy to process in chemical refineries. For these reasons, the industry markets it as "the clean energy source." Clean, that is, compared to burning coal – the real delinquent of the bunch. So dirty is burning coal in crude residential size furnaces that early eighteenth century London (England) was made practically intolerable because of air pollution (particulates). Today, we almost exclusively burn coal in large facilities with complex furnaces and pollution control devices. While we still have 200 years worth of coal reserves in this country, we would be wise to leave it in the ground. The atmosphere cannot get rid of that amount of pollution and greenhouse gases.

The other fuels important to our current energy cycle are all refined from petroleum (crude oil). Liquid fuels include gasoline, kerosene, diesel, and fuel oil – in order of decreasing volatility. That means diesel and fuel oil are safer to handle than gasoline or kerosene. This is the major reason diesel fuel is specified for marine use, where confined compartments might lead to dangerous levels of vapor concentration. Common gaseous fuels fall into the liquefied petroleum gas (LPG) category. While these fuels are commonly stored as liquids, they are gasses at atmospheric pressure. Propane, Butane, and mixtures of the two are commercially available for residential use. While all of these fuels are mixtures of various compounds, they are often treated as being composed of only one. The following table gives representative heating values for complete combustion (denoted as HV) and some chemical formulas for both liquid and gaseous fuels.

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Fuel	Formula	HV [Btu/lb]	HV [Btu/gal]	HV [Btu/ft <sup>3</sup> ]
Gasoline	C <sub>5</sub> H <sub>12</sub> -C <sub>12</sub> H <sub>26</sub>	18,700	115,000	-
Kerosene	C <sub>12</sub> H <sub>26</sub> - C <sub>16</sub> H <sub>34</sub>	18,500	126,000	-
Diesel	C <sub>15</sub> H <sub>32</sub> - C <sub>18</sub> H <sub>38</sub>	20,000	142,000	-
Fuel Oil	C <sub>15</sub> H <sub>32</sub> - C <sub>18</sub> H <sub>38</sub>	19,000	142,000	-
Methanol	CH <sub>3</sub> OH	9,300	63,000	-
Natural Gas	CH <sub>4</sub>	21,500	76,000	850
Propane	C <sub>3</sub> H <sub>8</sub>	21,500	91,500	2500
Butane	C <sub>4</sub> H <sub>10</sub>	22,600	110,000	3000
Biogas	-	-	-	600
Hydrogen	H <sub>2</sub>	51,600	-	290

The above numerical values are approximate and should be used for comparison purposes only. There are a wide variety of subtleties associated with heating values. There can be a significant difference between the Higher Heating Value (HHV) and the Lower Heating Value (LHV). The HHV assumes the water vapor produced by combustion will be condensed to extract extra thermal energy from the phase change. Furnace efficiencies are often based on the HHV. In most cases, however, it is not worth the trouble of condensing the water vapor and the LHV is more appropriate. Your automobile is a good example, it would not make sense to add heavy equipment to condense the water vapor within the engine. The numerical values in the table are LHV figures. The HV for natural gas was obtained from a recent PNM (Public Service Company of New Mexico) bill, and the value will vary depending on the quality of the gas. Values as high as 1000 Btu/ft<sup>3</sup> represent the high end, and 750 Btu/ft<sup>3</sup> the low end. Note that hydrogen is vastly superior on an energy per unit mass basis, but not nearly as good on a volumetric basis. The space program uses hydrogen for the mass advantage, and solves the volume problem by liquefying the hydrogen for on-board storage.

An additional difficulty arises when dealing with gaseous fuels because the volume changes with pressure and temperature. Very often quantities of gas are given as ft<sup>3</sup>, but what conditions are those numbers based on? The usual basis is called the "Standard Cubic Foot" (SCF) and is the volume the gas would have at a pressure of one atmosphere at sea level (14.7 psi), and 60°F. The actual volume, in ft<sup>3</sup>, can be radically different than SCF. Volume flow rates are often specified at SCFH, or standard cubic feet per hour. You will find such ratings on compression equipment.

### HEAT ENGINES FOR MECHANICAL ENERGY

We are all familiar with devices that convert thermal to mechanical energy. The vast majority of moving vehicles on the planet uses such devices. In all of them a fuel is combusted to release its stored chemical energy. Then the high-energy combustion gases are passed through a mechanism that extracts the thermal energy and converts it to motion, usually rotational. The laws of thermodynamics, which will be discussed later, determine the efficiencies of these devices. For now, it is sufficient to accept that these

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laws greatly restrict the amount of energy we can get out of an engine. Even if we could build a “perfect” engine (no friction, complete combustion, etc.) it would not be even close to converting 100% of the chemical energy to useful work.

Combustion engine designs are split into two categories – internal combustion and external combustion. Today we are most familiar with the internal combustion variety because they power our automobiles. These devices burn chemical fuel inside the engine itself. Because of that they must be designed to run on a particular fuel (and fuel quality). Examples include gasoline and diesel cycle engines. Combustion (or gas) turbine engines are also classified as internal combustion. These engines are used on aircraft, and occasionally for generation of electricity in stationary power plants. Turbine engines are very simple (essentially only one moving part) and reliable, just what you want in an airplane.

One hundred fifty years ago most people would have been more familiar with external combustion engines, which were called steam engines. Ships, trains, and even automobiles ran on these engines, which burned a fuel (usually wood or coal) outside of the engine. In these cases the high-energy fluid came not from the combustion gases, but from the heating of water until it became a high pressure, high temperature gas. This high-energy gas was converted into mechanical motion through means similar to the internal combustion engine. If you think that steam engines are relegated to historical attractions in today’s world, you’re mistaken. The vast majority of our electricity in this country is generated with steam driven turbine engines because they are efficient and extremely reliable. The Stirling cycle engine is another example of an external combustion engine. It generally runs on air, which is alternately heated and cooled. The popularity of Stirling cycle engines is currently increasing. One advantage to external combustion is that the engine doesn’t care what fuel is used to run it. Anything that burns and produces sufficient heat is acceptable. Garbage burning electrical generation plants use this concept to great advantage.

## ELECTRICITY

Certainly one our most useful forms of energy is electricity. This is due to the fact that electricity is highly ordered, which means that it can easily be converted to other forms of energy (especially heat). A few basic concepts here will go a long way toward broadening your understanding of electrical energy. The two main players in all electrical applications are *voltage* and *current*.

Voltage is a measurement of electrical potential energy. Literally, it represents the potential to do work – not necessarily doing it, though. It is quite possible to have voltage and not do work. Pick up any battery in a store and it will have voltage (hopefully), but won’t be doing anything with that potential energy. This is similar to having a reservoir of water on top of a hill. You know it can flow down to a lower potential, but it won’t do so until you provide a path to the bottom.

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Current represents a flow of energy from one place to another. This flow is usually measured in Amperes (Amps) and consists of moving electrical charge. Current is what actually allows you to do work with electricity. If you have a source of electrical energy, a battery or wall socket, you can provide a path for current to flow (with wires, generally) and the energy will move from the source to the device you want to operate. Electrical energy consumption requires a voltage *and* a current.

Electrical power is a measure of how quickly electrical energy is supplied or consumed. If you know both the voltage and current you can calculate electrical power by multiplying the two values with appropriate units:

$$\text{power [W]} = \text{voltage [Volts]} * \text{current [Amps]}$$

This relationship suggests an important concept when using or delivering power. The same power can be had with low voltage and high current, or high voltage and low current. High current levels require large conductors (wires) so that they won't heat up significantly and therefore waste energy, or start a fire. We often want to avoid such expensive wire and so choose higher voltages, which result in lower currents. Residential examples include electric dryers and ranges that are wired for 240 V, as opposed to 120 V in the rest of the circuits.

No doubt you have heard of two electricity types – AC and DC. AC stands for alternating current (although it applies to alternating voltages as well), and DC for direct current (or constant voltage). AC is provided by the utility to your residence and DC is available from batteries or special power supplies that convert AC to DC, called rectifiers. While motors, heaters, and incandescent light bulbs can use AC, most electronic devices and appliances require DC power. Therefore, AC must be converted to DC using rectifiers. Luckily this process is fairly efficient, but some energy will be lost. An important aspect of AC energy is that it cannot be stored in electrical form, unless it is first converted to DC (battery storage). That means that if a power plant produces more energy than it can distribute, the energy must be wasted. Large electrical grids usually provide the means to find users for the excess, but this is not always the case.

Electrical energy production is a deceptively simple process. Just turn the shaft of an electric motor and electrical energy will flow out of the wires. The motor, in this case, is referred to as either an alternator (AC) or generator (DC). It's important to keep in mind, though, that the device itself can also be used as a motor – supply electrical energy to the wires and the shaft will rotate. Virtually all the electricity generated in this country involves rotating the shaft of a motor. The only differences are the means of providing the rotation. In nearly every case a turbine is connected to the motor shaft. The turbine has blades that respond to fluid pressure by rotating. Power for the turbine is provided by steam that can be heated by burning a fuel or from a nuclear reaction. Most generating facilities operate in this fashion. However, you can also turn the turbine with flowing water (hydroelectric power), or by burning fuel inside a gas turbine engine (basically an aircraft engine connected to an alternator).

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Lest we get lost in the confusion of so many choices, let's look at a common example. Your automobile had to generate its own electricity in order to power lights and electronic components. A belt from the engine rotates an alternator (with which most of us are familiar because they frequently need replacement) that produces AC electricity. However, your vehicle's electrical system is based on a standard 12 V battery, which implies DC. The energy from the alternator must first be rectified to DC before it can be sent to the battery. Energy not used immediately is stored in the battery by chemical means. Why use DC in the electrical system? (Because AC energy can't be stored). So, you all have complete power generating, conditioning, and storage systems in your vehicles. A heat engine (the car's engine) turns chemical energy (liquid hydrocarbon fuel) to mechanical, then to AC electrical in the alternator, then to DC electrical, and finally back to chemical energy in the battery. Sounds like a big complicated circle, doesn't it?

It's important to keep the big picture in mind when considering uses of electricity. Remember where electrical energy is coming from and how it is produced. You should realize that using electricity for heating is an insanely wasteful activity. The power plant already generated a huge quantity of heat, but then refined it to a much more organized form of energy – electricity. That refinement process, however, involves large inefficiencies (wasted heat). You're much better off heating by combusting a fuel directly than forcing a conversion of heat to electricity and then back to heat. There are good reasons for electrical heating being much more expensive than natural gas. Not only does it cost more, but those large inefficiencies mean the environment suffers more from pollution – especially if your local power plant burns coal.

Since most electrical energy is generated at large facilities, often in remote locations close to fuel sources, distributing the energy to consumers is an important consideration. Energy losses on route to the customer are the responsibility of the utility. Therefore, they want to make sure those losses are as small as possible. A reasonable estimate for a large facility is 8% distribution loss. That means 8% of the electrical energy generated at the plant is sent to the atmosphere as heat from the wires and transformers. This is significant! It's not easy to get power to your location, and we all pay for inefficiencies in both cost and environmental impact. In order to keep distribution losses to a reasonable level, the utility will transform the voltage up to an extremely high level for long distance wires. Several hundred thousand volts is not unusual. This high voltage keeps the current low and the line losses to a minimum. However, it would be extremely negligent for the utility to provide energy to you at such voltages – few of us would survive it. So, when the power lines get close to your city they first enter a substation that transforms the high voltage to a lower value. From there the energy will go out through various local circuits. The closer the energy gets to your location the lower the voltage, until it reaches the final transformer (cylindrically shaped objects on poles for above ground applications) where it is reduced to the nominal 120/240 Volts AC. The utility wants this last transformation to take place as close as possible to your electrical service entrance to minimize the loss. Remember that you only pay for the usage indicated on your meter. It is interesting to note that George Westinghouse pioneered this method of distribution. He had very little knowledge of electricity, but was experienced in delivery of liquid and gas products

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through pipelines. The same principles applied – increase the pressure for long distance travel, then decrease it near the point of use for safety reasons. The ability to easily transform AC electricity to various voltages was the major reason for deciding to use AC as the electrical standard. Thomas Edison, the more famous contemporary of George Westinghouse, pushed for a national standard of DC electricity because of the long life associated with DC electrical lighting (the major use for electrical energy at the time). Some of his original bulbs still burn at his house (now a museum) in Pennsylvania. The challenges of distribution, however, resulted in the switch to an AC electrical grid.

## **ENERGY EFFICIENCY**

Energy cannot be created or destroyed, only converted from one form to another. This is the basic premise of the law of energy conservation. This is not to say, however, that all forms of energy are equally useful to us. Organized forms of energy (electricity) are much easier to use than disorganized ones (such as heat). Efficiencies of conversion from disorganized energy to an organized form are generally low, while it is possible to convert 100% of organized energy to a disorganized state. Since efficiency is used widely to describe the merits of various energy technologies it is important to understand how the numbers are generated. Efficiency for a generation device is defined as follows.

$$\text{efficiency} = \frac{\text{energy out}}{\text{energy in}}$$

The ratio indicated must be less than 1.0 since energy cannot be converted to a more organized form without loss. The ratio multiplied by 100 would give the percentage efficiency. While efficiency is a simple concept, the way in which efficiency numbers are generated is not. It is imperative to find out what factors are included in the denominator (energy in).

Your automobile engine is approximately 25% efficient (perhaps around 30% for a diesel cycle). This means that for every four gallons of fuel you purchase, only one gallon actually gets converted to motion. The other three gallons end up as heat transferred to the atmosphere. The “energy in” used to calculate the efficiency is the chemical energy (lower heating value) available from burning the fuel. It does not include inefficiencies in fuel production. On the other hand, the efficiency of a coal-fired power plant can be as high as 40% - including the energy required to mine and process the coal. An overall efficiency is easily calculated by multiplying the efficiencies of each individual process. The only way to fairly compare the automotive efficiency with that of the power plant would be to adjust either one of them for fuel production. Obviously, that will make the automotive engine look even worse. We certainly would not want our utilities to generate electricity with standard internal combustion engines. Neither of these efficiency values gives any indication, however, of the amount of environmental damage caused by fuel production and combustion. The science of energy is not equipped to handle this issue, and it never will be. Environmental economics are vague, at best.

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While scientific efficiencies are accurate measures of the underlying physics, decisions based only on numerical values can lead to big mistakes. As an example, let's look at the efficiency of a solar photovoltaic panel (PV). It converts the energy contained in a portion of the solar energy radiation spectrum to DC electricity. The conversion efficiency would be calculated as:

$$\text{PV efficiency} = \frac{\text{DC electrical energy out}}{\text{Solar radiant energy in}}$$

Commercially available crystalline silicon PV modules have an efficiency of approximately 14%. Current laboratory maximum efficiencies are beginning to exceed 30%, but only on a small scale under controlled conditions. The previously mentioned 14% doesn't exactly grab one's attention as it is only about half the value for a Diesel cycle engine. However, we can't forget to scrutinize the "energy in" quantity. We do not have to pay for solar energy, and there is no environmental damage associated with that type of fuel. Granted, we don't have access to the fuel all the time, but remember that DC electrical energy can be stored in batteries (about 85% efficient) for later use.

<b>Generation</b>	<b>Energy</b>	<b>Efficiency [%]</b>
Coal Plant	Electrical	24 – 34
PV Modules	Electrical	12 – 14
Solar Thermal	Electrical	25
Wind	Electrical	25
Human	Mechanical	0.25

## **ENERGY CONVERSION**

We've been discussing energy conversion all along, but have yet to take a scientific look at the rules governing such conversions. A quick review of the laws of thermodynamics is a prerequisite for energy conversion discussion, and we will be very quick about it. One of the important laws only applies only to conversions involving heat transfer, so we need to distinguish those devices from others.

### **THERMODYNAMICS**

Thermodynamics deals, literally, with the movement of heat. First, however, we need to get a good mental picture of what heat actually is. Earlier, heat was described as the average kinetic energy of molecules. The hotter the substance the faster the molecules move. This is a good start. It's very important to realize that there is no distinguishable order to this movement, it's random. If you have ever watched a playground full of young children running aimlessly about you'll realize that when looking at only one or two children order (or purpose) is recognizable, but this order disappears when broadening your view to the entire group. Such is the nature of large numbers of moving particles. Now, expand the concept. Think of *huge* numbers of these molecules - impossibly huge. Any attempt to discover order in all this chaos would be an incredibly daunting task.

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Admittedly, there is a great deal of energy represented by all that motion, but asking it to organize itself for one particular purpose would be orders of magnitude harder than asking a planet full of children to stand still and sing the same note at the same time. Accomplishing an organized task with heat is a difficult proposition. The laws of thermodynamics must account for the average behavior of statistically large numbers of particles.

The first law is simple to understand and work with. It states that energy cannot be created or destroyed, but can only change form. The quantity of energy, in other words, is conserved (in the scientific sense). An example from your automobile goes as follows. Fuel is burned within your engine releasing great amounts of heat. Did you create that energy? No, you only changed it from the energy in chemical bonds to sensible thermal energy. Then your tank runs dry and your vehicle coasts gently to a stop. Did you destroy the energy released from the fuel? No, the vehicle changed some of it to kinetic energy (motion) while it was moving, but most of it left the vehicle as heat (even sound energy eventually heats up the air molecules and dissipates). OK then, what happened to the kinetic energy as the vehicle slowed and stopped? It too was turned to heat by various frictional mechanisms. Overall, you converted a certain amount of energy to heat using combustion. In the end that same amount of energy must have left the vehicle by the time it comes to rest by the side of the road. The quantity of energy was conserved. What the first law doesn't tell you is that some forms of energy have higher quality (are more useful) than other forms. That is left to the second law.

The second law is more difficult to grasp. A basic statement would tell you that it is impossible to build a device that will convert all available thermal energy to useful work. Impossible, that's a strong word – and it's meant to be. That means no device, which converts heat to work can be 100% efficient. Asking your vehicle engine to convert all of the thermal energy from combusting the fuel would be more difficult than asking that planet full of children to all sing the same note. You just can't expect all the molecules in the engine to push on the pistons in the right direction at the right time. Statistically speaking, it will never happen. More correctly, the probability of such an event occurring is almost infinitely small.

A more advanced statement of the second law says that the disorder (entropy) of an isolated system can only increase, or stay the same. That isolated system can never become more ordered than it was to begin with. If you heat up a rock in your oven to, say, 350°F and then casually toss it into a pail of water at 60°F, the thermal energy in the rock will transfer to the water. No big surprise. Your physical experiences have “taught” you that lesson over and over again. Yet the first law (conservation of energy) would not tell you that. It only says that the amount of energy leaving one object must equal that entering the other. The first law would not be violated if energy flowed from the cool water to the hot rock. Why can't that be possible? Well, for the same reason that throwing shards of broken glass into the air never results in a fully formed cup falling back into your hand. Two objects at different temperatures, in the same environment, represent ordering of the system. A more disordered system results when energy transfers to make all objects the same temperature. Once that happens, you can no longer use the thermal

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energy for useful tasks. In this vein, the larger the difference in temperature between the rock and the water, the more order is present. As a result you can accomplish a job with greater efficiency. The quality of thermal energy is, therefore, proportional to temperature. The higher the temperature, the more useful the energy. All devices that strive to convert heat to work with reasonable efficiency must use high quality (high temperature) energy. With energy, as with many other aspects of life, you have to start with quality ingredients if you expect a quality result. Anyone can build a steam engine – just hold a pinwheel in the steam flowing from a whistling teapot. But if you could start with a much higher temperature steam, and direct it more effectively upon the blades of your turbine, and reduce the frictional losses within the turbine you'd be engineering a device akin to those at almost every electrical power plant. Remember, however, that no matter how good a designer you are, or how good the materials, or how high the temperature, you will never convert all of the thermal energy to work. It's just not probable.

Now that we have at least a vague feeling as to why the second law makes energy conversion difficult, it is appropriate to discuss which conversion devices are governed by that law and which are not. Anytime heat is converted to mechanical energy (steam turbine, automobile engine) the second law applies. All these devices depend on expanding a hot, high-pressure gas against a physical surface. Since not all of the random motions of the gas molecules can be directed as desired, you can only change a fraction of the thermal energy to work. The French engineer Sadi Carnot developed an expression for the maximum possible efficiency of such a conversion in 1824 as a result of studying the work his father accomplished with hydrodynamic power (water wheels). It states that a perfectly designed and constructed engine (not possible, by the way, because of frictional effects) has an efficiency that depends only on the maximum temperature of the fluid, and the temperature of the environment. That's all folks. The simple expression is:

$$\text{Carnot Efficiency} = \frac{T_{\text{high}} - T_{\text{low}}}{T_{\text{high}}}$$

The temperatures must be in an absolute scale (Kelvin or Rankine). The only ways to increase a heat engine's efficiency are to either raise the high temperature, or lower the low temperature. An example for a typical steam driven turbine at an electrical plant involves a high temperature of approximately 600°C (873 K) and an environmental temperature of around 25°C (298 K). Therefore, the maximum efficiency possible for the turbine alone is:

$$\text{Carnot Efficiency} = \frac{873 - 298}{873} = 0.66 \text{ or } 66\%$$

That number doesn't include inefficiencies associated with turbine friction (mechanical and fluid), the fuel, boiler, or electrical generator. So, when modern power plants are operating with an overall efficiency of around 40% we shouldn't feel so badly. Why doesn't the power plant just produce hotter steam to increase efficiency? Well,

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because 600°C is approaching the physical handling limits of common piping materials. Using exotic materials is not worth the extra expense at the present low cost of fuel.

Heat engines are not the only devices limited by the second law. Any refrigerator, vapor compression air conditioner, or heat pump also falls under its jurisdiction. Think, for just a moment, how these devices work. They use a mechanical compressor (electrically driven, usually) to induce a transfer of heat in the opposite direction of its natural flow. Your refrigerator somehow convinces heat to flow from the cold storage space to the warm kitchen. Since heat doesn't want to move in that direction, we have to go through elaborate means to accomplish the task. Just as the second law commands that thou shall not convert all heat transferred to work, it also requires that thou shall not convert all work into useful heat transfer. A large percentage of the compression work will end up as heat not able to contribute to the desired effect (cooling the refrigerator compartment, for example).

Luckily, not all energy conversion devices are heat-driven. The ones that aren't escape the *thermal* confines of the second law. There are many examples and but a few will be mentioned here. First consider the previously mentioned photovoltaic panel. It converts radiant energy directly into electricity without a heat engine. It uses energy inherent in sunlight to knock electrical charge carriers (electrons and their subsequent "holes") loose in a special sandwich of semiconductor materials. These charge carriers can then flow through an outside circuit to carry their extra energy to an electrical device. Since heat is not involved, the efficiency is limited by other, non-thermodynamic, considerations. Fuel cells, which convert chemical energy to direct current electricity, do not involve heat engines. Their theoretical efficiencies are much greater than those suggested by Carnot's relation. The second law does not limit hydroelectric generation (water turbines) either. In this, gravitational potential energy (water up a hill) is converted to mechanical energy by physical pressure. However, unlike the automobile engine, most of the energy in the fluid comes from pressure not temperature. Fluid pressure is much more organized than heat. Wind turbines are very similar to hydroelectric generation, only they involve a fluid that is compressible. Finally, there is a way to convert thermal energy directly to electricity through the use of specialized semiconductor devices. These products bear more resemblance to PV cells than anything else. Anyone with an old gas furnace that does not connect to any electrical supply uses a thermoelectric generator to produce enough voltage to drive the thermostat circuit. As yet, they are not economically feasible on a large scale, and do suffer from many other inefficiencies.

### **INTELLIGENT USE OF ENERGY**

This final section could also be entitled "Energy Conservation" without any loss in meaning. We should be getting the picture by now that any time we use energy we stress the environment. Even relatively benign devices, such as wind turbines, require energy and materials that deplete our natural resources. *Every form of energy production is dirty!* So, that being the case, let's play our cards of logic and make some intelligent choices.

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- Fact: every form of energy production depletes resources
- Fact: every form of energy production and consumption degrades the environment
- Fact: every energy conversion involves inefficiency

The obvious (although farcical) solution would be to stop producing and using energy. Since that is, arguably, not an option we need to consider intelligent alternatives.

- Fact: some energy production methods are less efficient than others
- Fact: some energy production methods use more resources
- Fact: some energy production methods are more damaging to the environment

We all know this to be the case. Here's a logical approach to the problem from a perspective not tainted by the status quo, but one that stays true to fundamental energy physics and ecological economics.

- Reduce energy consumption through conservation
  - ✘ Energy efficient vehicles, industrial processes, buildings, and appliances should be of the highest priority.
- Develop energy sources that are low or non-polluting
  - ✘ Wind, solar electric, solar thermal, and hydroelectric (in moderation) constitute many of the current choices.
- Avoid thermally-based energy sources (severely limited by the second law of thermodynamics)
  - ✘ Phase out hydrocarbon combustion-based energy production (after tens of thousands of years of human "progress" we're still burning things for energy)
  - ✘ Phase in fuels cells, combustion of pure hydrogen (for heat only), photovoltaics, hydroelectric, wind turbines, etc.
- Use traditional energy sources mainly for demand-side management
  - ✘ We will always need to supplement renewable energy systems (low energy density, limited use periods) with the much higher energy density sources used today. It is more important to work on the meat of the problem, than to try to completely eliminate the undesirable.
- Do not force technological solutions before they are ready
  - ✘ It makes no sense to release inferior quality energy sources and consumer products before their technical hurdles have been cleared. This delays real progress by giving these technologies bad names in the public eye.