Energy and Power

by David Pimentel
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Energy is defined as the capacity to do work. Although energy is found in many forms (Table 2.1), all forms have the capacity to do work. Light energy coming from the sun is the most important and universal type of energy, supporting all life on Earth. Plants have the capacity to capture, or "fix," light energy and convert it into chemical energy, which is used by the plants themselves and the animals that feed on them. Many human activities, most prominently agriculture and forestry, rely on solar energy. Solar energy is also fundamental to wind power, hydroelectric power, and other types of energy systems.

Radio, radar, micro, and television waves use electrical energy. The lifting or moving of objects by man or machine is a form of mechanical energy. Another form of energy – heat generated by the burning of wood, coal, oil, or gas – is used for cooking and to drive engines. Magnetic energy, which is produced from the interaction of positively and negatively charged matter, can be used to do work. Sound waves, another form of energy, are used in communications and other activities. A more recently discovered form of energy is nuclear energy, which is released from the bound atomic particles in, for instance, uranium. Humans have employed nuclear energy not only to create devastating bombs but also to produce electricity.

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Laws of Thermodynamics

The use or flow of energy is governed by the two laws of thermodynamics. *The first law of thermodynamics states that energy may be transformed from one type into another* (Table 2.1) *but can never be created or destroyed.* For example, light energy can be transformed into heat energy or into plant-food energy (chemical energy). In the process of this transformation, no energy is lost or destroyed; only its form is changed.

The second law of thermodynamics states that no transformation of energy will occur unless energy is degraded from a concentrated form to a more dispersed form. In the real world all energy transformations take place in open systems, because processes necessarily interact with their environment over finite time periods. *Thus, according to the second law, in the real world no transformation is 100 percent efficient.*

The second law states the existence of a spontaneous "direction" for energy transformations. For example, if a hot object is placed next to a cool object, heat will flow from the hot object to the cool one but never in the reverse direction. Because no transformation is 100 percent efficient, the temperature of the cool object will rise, but not enough to account for all the energy that is transferred from the hot object. In the transfer some energy is dispersed into the environment. Consider the example of a cup of boiling water mixed with a cup of cold water. The temperature of the resulting mixture is slightly lower than would be calculated by measuring the energy lost by the boiling water. The cold water is much warmer than it was initially,

Table 2.1 Some examples of energy conversion and energy-converting devices

To	From Mechanical	From Thermal	From Acoustical	From Chemical	From Electrical	From Light
Mechanical	Oar Sail Jack Bicycle	Steam engine	Barograph Ear	Muscle contraction Bomb Jet engine	Electric motor Piezo-electric crystal	Photoelectric door opener
Thermal	Friction Brake Heat Pump	Radiator	Sound absorber	Food Fuel	Resistor Spark plug	Solar cooker Greenhouse effect
Acoustical	Bell Violin Wind-up phonograph	Flame tube	Megaphone	Explosion	Telephone receiver Loudspeaker Thunder	
Chemical	Impact detonation of nitroglycerine	Endothermic chemical reactions		Growth and metabolism	Electrolysis	Photosynthesis Photochemical reactions
Electrical	Dynamo Piezo-electric crystal	Thermopile	Induction microphone	Battery Fuel cell	Transformer Magnetism	Solar cell
Light	Friction (sparks)	Thermoluminescence		Bioluminescence	Light bulb	Fluorescence

Source: After Steinhart and Steinhart, 1974a

but because some of the heat energy is lost to the environment, it will not be as hot as the average of the two initial temperatures.

All biological systems, including crops, follow the second law of thermodynamics when solar energy (a high-energy form) is converted into chemical energy. Plants utilize this chemical energy in the process of building their own tissue. Some of the energy being changed from light to chemical energy is lost as heat that dissipates into the surrounding environment.

Measures of Energy and Power

The basic unit of energy, following the International System (SI) of units, is the joule (J), but many other units of energy are used, such as the calorie, Btu (British thermal unit), quad, kWh (kilowatt hour), TOE (metric tons of oil equivalent), and TCE (metric tons of coal equivalent). Both the calorie and Btu, which are probably the most frequently used units, are based on measurements of heat energy. A calorie, or gram-calorie, is the amount of heat that is needed to raise 1 g of water 1°C at 15°C. The Btu is the amount of heat needed to raise 1 pound of water 1°F. Note that heat measurements are related not to the direct ability to do work but to the capacity to raise the temperature of matter or to change the state (solid, liquid, gas) of matter.

Conversion factors for energy units are listed in Table 2.2. Note that the kilocalorie (kcal), or kilogram-calorie, equals 1000 calories, or gram-calories. The large Calorie, used in the field of nutrition, equals 1 kcal, or 1000 small calories.

Measurements of energy do not take into account the time required for the conversion process. Work, however, requires the expenditure or use of energy at a certain rate. The term "power" expresses the rate at which work is done and/or energy is expended. The basic unit of power is the Watt (W), which equals 1 joule/second, 14.3 kcal/minute, or 3.41 Btu/hour. Another unit of power commonly used is the horsepower (HP); 1 HP equals 746 W or 2542 Btu/hour.

Table 2.2 Energy conversion factors

Unit	Equivalents
1 kilojoule (kj)	1000 joules (J)
1 kilocalories (kcal)	1000 calories (cal); 4.184 kJ; 4184 J
1 British thermal unit (Btu)	0.252 kcal; 1.054 kJ; 1054 J
1 quad	1015 Btu;0.252 x 1015 kcal;1.054 x 1018 J
1 kilowatt hour (kWh)	3413 Btu; 860 kcal; 3.6 MJ
1 horsepower hour (Hph)	0.746 kWh; 2546 Btu; 642 kcal; 2.69 MJ
1 ton of coal equivalent (TCE)	7 x 106 kcal; 29.31 GJ
1 ton of oil equivalewnt (TOE)	107 kcal; 41.87 GJ

Note: Kilo (k) = 10^3; mega (M) = 10^6; giga (G) = 10^9; tera (T) = 10^{12}; peta (P) = 10^{15}

When the power level, or rate at which work is done, is multiplied by the time the work requires, we obtain the total flow of energy. For instance, the maximum work capacity or power level that a horse can sustain for a ten-hour working day is 1 HP. The power level of a person is about one-tenth of 1 HP; therefore a person working a ten-hour day produces an energy equivalent of only 1 Hph (horsepower hour), 2.7 MJ (megajoules), or 0.75 kWh. Put another way, one horse can accomplish the same amount of work as ten people in one hour. Horsepower and oxpower were some of the first substitutes for human power and contributed to improving the quality of human life. Certainly people tilling the soil in early agriculture were more productive when they used oxen and horses.

The tremendous effect of technological development on human activities can be appreciated by comparing manpower to the mechanical power of a tractor fueled with gasoline. One gallon (3.79 liters) of gasoline contains about 38,000 kcal of potential energy. When this gallon of gasoline fuels a mechanical engine, which is about 20 percent efficient in converting heat energy into mechanical energy, a equivalent of 8.8 kWh of work can be achieved. Hence, a single gallon of gasoline produces more power than a horse working at maximum capacity for 10 hours (7.5 kWh). Further, one gallon of gasoline produces the equivalent of almost three weeks of human work at a rate of 0.1 HP, or 0.075 kW, for 40 hours a week.

Biological Solar Energy Conversion in Agriculture

The survival of humans in their ecosystem depends upon the efficiency of green plants as energy converters. The plants convert sunlight into food energy for themselves and other organisms. The total foundation of life rests on plants' unique capacity to change radiated solar energy into stored chemical energy that is biologically useful for humans and other animals.

The amount of solar energy reaching 1 hectare (ha) each day in the temperate region ranges from 15 to 40 million kcal. Over a year's time the total solar energy received per ha ranges from 1.1 to 1.8 x 10^{10} kcal, with 1.4 x 10^{10} kcal as a reliable average. This is equivalent to the energy potential of nearly 452,000 gallons (1.7 million liters) of gasoline per year per ha. This sounds like a large quantity of energy, and indeed it is when considered as a unit. But each square millimeter (mm) receives only 0.0038 kcal per day, only enough to raise the temperature of 3.8 milliliters (ml) of water 1°C.

Green plants are able to capture only a small percentage (0.1 percent) of the sunlight reaching the earth (Whittaker and Likens, 1975; ERAB, 1981). Annually, the total light energy fixed by green plants in ecosystems is estimated to be about 400 x 10^{15} kcal, divided equally between terrestrial and ocean ecosystems (Pimentel et al., 1978). Note that although terrestrial systems cover only about a third of the earth, the plants in these systems fix about half of the total light energy captured.

When only the temperate zone is considered, estimates are that only 0.07 percent of the 1.4 x 10^{10} kcal of sunlight per ha is fixed in terrestrial ecosystems (Reifsnyder and Lull, 1965). Thus, the net energy fixed by plants in the temperate zone averages about 10 million kcal/ha per year. Expressed as dry weight of plant material, this amounts to an average yield of 2400 kg/ha per year, ranging from near zero in some rock and desert areas to 10,000 kg/ha in some swamps and marshes (Whittaker and Likens, 1975).

In agricultural ecosystems, an estimated 15 million kcal of solar energy (net production) is fixed per ha per crop season. Even so, this amounts to only about 0.1 percent of the total solar energy reaching each ha during the year and equals about 3500 kg/ha of dry biomass. The amount of biomass varies with the crop and ranges from 200 kg/ha for low production crops under arid conditions to 15,000 kg/ha for corn and sugarcane. An average agricultural ecosystem produces an annual biomass per ha slightly greater than that in natural ecosystems. This is not surprising, as crop plants are grown on the most fertile soils and are usually provided with ample moisture and essential nutrients. Under optimal conditions, during sunny days in midsummer and when the plants are nearing maturity, crops such as corn and sugarcane capture as much as 5 percent of the sunlight energy reaching them. However, the harvested plant material is only about 0.1 percent because over much of the year, including winter, there is no plant growth.

A significant quantity of captured energy is, of course, utilized by the plant itself. For example, a soybean plant uses about 25 percent of the energy it collects for its own respiration and maintenance. About 5 percent of the energy is diverted to provide food for the nitrogen-fixing bacteria that are symbionts with the soybean plant. Another 10 percent is lost to insect pests and pathogens that feed on the plant. Thus, the net yield in beans plus vegetation is about 60 percent of the energy collected by the plant.

Most plants divert significant proportions – from 5 to 50 percent – of the energy they collect into their fruits and seeds, illustrating the high priority plants give to reproduction (Harper, 1977).

Humans have used breeding techniques to reallocate energy in plants and improve crop yields. For example, one of the factors contributing to the increased yields in new breeds of corn has been the change in energy allocation within the plant. In particular, the new breeds produce smaller tassels and less pollen, and the energy saved is reallocated to the production of corn grain. With corn plants, growing as densely as they do under normal cropping conditions, the smaller tassel and less abundant pollen are satisfactory for the production of corn seed.

Renewable Biological Energy Versus Fossil Fuel Energy

By the sixteenth century, England and France were running out of firewood, their most important source of renewable biomass (Nef, 1977). Humans used wood to cook and prepare foods and to heat the homes of the expanding population. They also used it to produce charcoal for the developing metal industry and to provide lumber for the growing shipbuilding and construction industries. Because of wood shortages, London and Paris were forced to turn to soft coal as a substitute fuel (Cook, 1976). Because soft coal is noxious when burned, wood remained the preferred fuel, and those who could afford its high price continued to burn wood. During the eighteenth century, coal was used primarily for heating, its use as a source of energy to replace human and horse power did not occur until the nineteenth century.

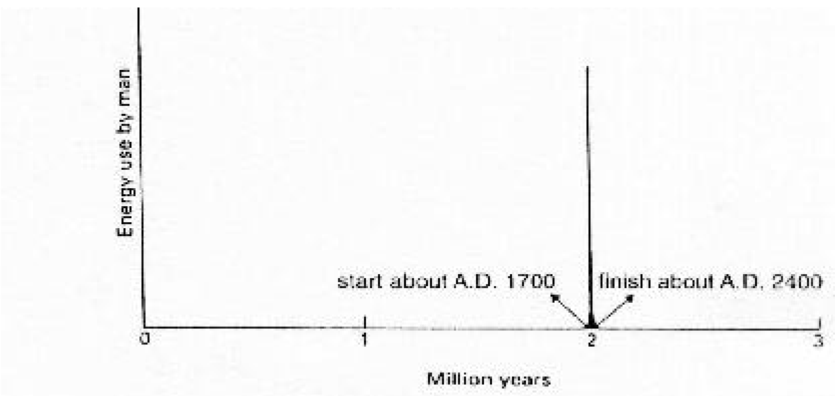
Coal was used extensively, however, to fuel pumps in mining operations. As mines were dug deeper, water began seeping into the mines and caused serious flooding problems. The mine operators used windmills, hand pumps, and windlasses to remove water, but with poor results. Then, in 1698, Thomas Savery invented the first steam-powered pump to remove water from the mines. This pump, however, proved dangerous to operate and was never fully adopted. About ten years later, Thomas Newcomen designed a much-improved steam-powered pump that was extensively employed in the mines. Thereafter coal could be mined more efficiently, and a good supply was ready to replace the declining supply of firewood. It was not until nearly 1000 years later that James Watt designed a truly efficient steam engine and pump. When the Watt pump was finally operational, it rapidly replaced the Newcomen steam pump.

The Watt steam engine and the internal combustion engine, developed in 1876, brought dramatic changes in energy consumption. These new fossil fuel-powered engines quickly replaced the less efficient wood-powered steam engines, the horse, and even human power. Production of goods increased, expenditure of energy increased, and each subsequent decade witnessed a further increase in the use of non-renewable fuel resources.

In the United States from 1700

to 1800, wood was the primary source of fuel. As late as 1850, more than 91 percent of the energy used in the United States came from wood burning (EOP, 1977). The supply of wood was sufficient in the eighteenth and earl nineteenth centuries, for two reasons. Not only was the population about 23 million people, or less than 9 percent the present level, but these early settlers consumed only about one-fifth the amount of energy consumed today. Furthermore, American forests had been harvested for only a relatively short period of time compared to European forests. Even so, as early as 1850 firewood was in short supply in the Northeast, especially for larger cities such as New York and Boston, because of the rapid clearing of forest land for agricultural production and the relatively heavy demand for firewood. The problem was worsened by the difficulty and high costs of transporting the bulky and heavy wood over increasingly long distances to the cities.

Obviously, forests cannot meet the high energy needs of today's large U.S. population. At present, fossil fuels account for 92.5 percent of the total fuel consumption in the United States. Of this, oil represents 40 percent, natural gas 28 percent, coal 26 percent, and nuclear fuels, 6 percent. Firewood accounts for only 4 percent and hydroelectric energy the remaining 3.5 percent of the total fuel. Fossil fuel consumption today is the highest it has ever been. Annual consumption for the world stands at about 319 quads (80.4 x 10^{15} kcal) and is increasing every year (IEA, 1991). The United States alone consumes 25 percent of all the fossil energy used in the world annually, amounting to 79 quads (19.9 x 10^{15} kcal) (IEA, 1991).



2.1 The epoch of the use of fossil fuels in the history of man on earth.

The epoch of fossil fuel use has been but a short interval in the more than one million years of human existence on earth (Figure 2.1). The era of reliance on fossil fuels will be but a small "blip" in history – about 400 years, or at most 0.1 percent of the time humans have been on earth. Because fossil fuels are nonrenewable resources, they eventually will be exhausted. Oil and gas supplies will be the first fossil fuels to run our. According to the best estimates, 30 to 50 years of these resources remain (Matare, 1989; Worldwatch Institute, 1992a). The United States has only 10 to 20 years of oil reserves remaining, based on current use rates (DOE, 1991a). U.S. oil imports now amount to 54 percent of the country's total use, and this share is expected to increase to about 70 percent by the turn of the century. Most of the European countries, Japan, and several other countries in the world import *all* of their oil, which places a strain on their economies.

The world's coal reserves are greater than those of oil and gas because the latter fuels have been more extensively used than coal. There is still an estimated 100-year supply of coal in the world (Hubbert, 1972; Matare, 1989; Worldwatch, 1992a). However, continued heavy use of fossil fuels may cause grave problems relating to global climate change (Schneider, 1989). In addition, the burning of fossil fuels results in major air pollution problems, and coal mining, especially strip mining, damages the environment, destroying vast areas of land valued for food and forest production and wildlife. On average, strip mining is safer for miners, is more economical, and requires less energy than deep underground mining, and it is 80 to 90 percent effective in recovering coal, whereas deep mining is only 50 percent effective. In deep mining small coal seams cannot be economically mined because of the danger of cave-ins.

Coal production requires less energy than oil drilling both in extraction and transportation. About 20 percent of the potential energy in oil is expended to extract and refine it (Cervinka, 1980), resulting in a yield of about 80 percent at point of use. By comparison, coal has a yield of about 92 percent (Cook, 1976). This means that about 108 kg of coal must be mined to produce the equivalent of 100 kg of coal energy, compared with 120 kg of oil pumped for 100kg of oil energy.

Coal reserves are scattered throughout the world. Western Europe has about 5 percent of the total, the United States about 20 percent. Russia is extremely well endowed, with nearly 56 percent of the estimated coal reserves.

Adjusting from oil and gas to coal will require many changes in lifestyle and industrial production methods. The world is indeed fortunate to have coal reserves as a backup energy resource until, renewable energy technologies are developed to supply a portion of the world's energy needs. •