

Chapter 0

Introduction to Energy

Energy is defined as the ability to do work, and work is defined as pushing something through a distance with some force.

Example. The energy in a battery can push a saber saw blade through a distance of one inch with a force (in the direction of the motion) of 2 pounds. The work done equals the amount of energy taken (discharged) from the battery. In this case the energy was stored in the battery as chemical energy. On the way to doing work, this energy was transformed for a brief time into electrical energy to operate the motor that did the work.

Example. The chemical energy released by burning gasoline pushes a cylinder in an engine through five inches with a force of 50 pounds. Ultimately—with rods, gears, and wheels—this force is transferred to the car to push it up a hill.

Conservation of Energy. Energy may change form, but none of it is ever lost. This doesn't seem obvious because we're not aware of some of the forms of energy. For example, a falling lump of clay has energy, but all of the energy seems to disappear when the lump stops abruptly on hitting a table. Actually, the table heats up slightly at the point of impact, and the amount of heat (thermal energy) just equals the kinetic energy lost by the moving lump.

Forms of energy.

Thermal Energy. This involves heat, such as a tank of hot water or a piece of hot metal.

Kinetic Energy. This involves motion, such as moving hammerhead, a moving baseball, or a rotating flywheel.

Potential Energy. This involves something stationary being pulled or pushed by a force, such as a car at the top of a hill (pulled by gravity), a stretched rubber band, a tank of pressurized air, or two magnets held apart.

Chemical Energy. This involves energy stored in molecular bonds of chemicals, such as a fuel, food (a type of fuel), or a battery.

Nuclear Energy. This involves the force that binds protons and neutrons in a nucleus, such as the nuclear fusion going on in the Sun or the nuclear fission going on in an atomic reactor.

Radiant Energy. This involves electromagnetic waves (or photons), such as light, heat waves (infrared light), radio waves, X-rays, and gamma rays.

Electrical Energy. This involves voltage pushing electrical current through a wire.

Mass and Energy. Einstein showed that energy has mass and mass can be converted to energy according to the formula $E = mc^2$, where E is the energy, m is the mass, and c is the speed of light:

$$c = 299,792,458 \text{ meters/second} = 186,282 \text{ miles per second.}$$

It's important to take this relationship into account in understanding the conservation of energy. When two hydrogen atoms fuse to make one helium atom, they release radiant energy. If energy only changes form—never lost or created, where did this energy come from? It came from the mass of the atoms: the helium atom weighs less (has less mass)

than the two original hydrogen atoms. And this mass loss is exactly related to the energy released by $E = mc^2$.

Because energy has mass, the conservation of energy could equally well be called the conservation of mass. If all the radiation of the fusion of the two hydrogen atoms were kept contained in a box together with the atoms, the box and its contents would weigh the same before and after the fusion. That is, the radiant energy weighs as much (has the same mass) as the mass lost by the atoms. Similarly, a stretched rubber band weighs more than before it was stretched; the (very small) increase m in mass is related to the potential energy E stored in the rubber band according to $E = mc^2$.

History of Energy Conversion in the Universe. At the Big Bang (the moment of the creation of the Universe) there was a soup of mass/energy. At this point the conservation of energy is impossible to trace because there is no such thing as a “before” the Big Bang; we can’t say where the initial mass/energy came from. Then 379,000 years after the Big Bang the mass/energy coalesced into atoms—mostly hydrogen. Stars were formed as gravity pulled hydrogen together. The potential energy of the gravity was converted to thermal energy (heating the hydrogen) and other potential energy (compressing the hydrogen), and the heat and pressure fuses the hydrogen into helium. As we saw earlier, the fusion converts some mass (energy) into radiant energy (photons). The photons are absorbed by other molecules of hydrogen and helium in the star (such as our Sun), getting converted to thermal energy and heating the molecules. The hot molecules re-radiate the energy (with a different spectrum that depends on the temperature). This radiant energy travels through space to Earth, where some is absorbed as heat in the atmosphere, but some falls on wheat plants. Photosynthesis in the plants converts some (about 5%) of this radiant energy into chemical energy (calories) in the plant; the remainder simply heats the plant. A cyclist eats the wheat for breakfast and pedals up a hill, his muscles converting about 25% of the chemical energy into work (force through a distance up the hill). But the energy that did the work is not lost; it’s now in the form of potential energy (the height of the hill times the force of gravity on—the weight of—the cyclist and his bike.). The cyclist can reclaim the energy if he has an electric generator connected to his wheel. As he coasts down the hill, the generator converts the potential energy into electrical energy, which might power an electrical heater wrapped around a can of soup. At the bottom of the hill the cyclist can enjoy a nice hot bowl of soup. (As if he were not hot enough already! About 75% of the chemical energy metabolized by his muscles was converted to body heat.) So we see that eventually all energy is ultimately converted to heat. According to the laws of thermodynamics, some of this thermal energy can do work and be converted to other forms of energy again so long as it can find a cooler temperature to work with. But this process tends to equalize the temperatures, and eventually the Universe will be all one temperature. This is called the Heat Death of the Universe.

Units of Energy. The unit for energy in the scientific community is the joule, but energy is also measured in BTUs, calories, foot-pounds, horsepower-seconds, and watt-hours in industry.

$$1 \text{ BTU} = 1055 \text{ joules}$$

$$1 \text{ calorie} = 4.186 \text{ joules}$$

1 foot-pound = 1.356 joule

1 watt-hour = 3600 joules

1 horsepower-second = 746 joules

Calculating Energy.

Thermal Energy. The change in thermal energy E in a substance is given by $E = c_m \cdot m \cdot T$, where c_m is the specific heat capacity of the substance, m is the mass in grams, T is the temperature change in $^{\circ}\text{K}$, and E is measured in calories. For water $c_m = 1$. That is, adding 1 calorie of energy to 1 gram of water raises the temperature by 1°K . For iron $c_m = 0.107$, and for glass $c_m = 0.201$. Thermal energy can do work if a cooler “heat sink” is available. The heat engine that converts thermal energy to work involves hot gases that expand.

Kinetic Energy. Given a mass m traveling at a velocity v , its kinetic energy is $E = 0.5 \cdot m \cdot v^2$, where m is in grams, v is in meters/second, and E is measured in joules. A 145-gram baseball traveling at 40 meters/second has 116,000 joules of kinetic energy. Kinetic energy can do work as it is slowed down or stopped.

Potential Energy. Sometimes work (force F through a distance d) results in no heat dissipation (the case when raising a weight, stretching a spring, or pulling magnets apart). In that case, the process can be reversed and the energy reclaimed. Before the energy is reclaimed it stored as potential energy. So potential energy is measured by the work done to store that energy. The change in potential energy is $E = F \cdot d$, where F is in pounds, d is in feet, and E is in foot-pounds. Raising a 200-pound weight 3 feet (a man climbing five stairs) adds 600 foot-pounds of potential energy to the weight. Stretching a rubber band with a tension of 1 pound by 1 more inch adds $1/12$ foot-pound to the potential energy stored in the rubber band. (As the rubber band is stretched, the tension changes, so potential energy changes have to be calculated for small increments.)

Chemical Energy (fuel). The energy E stored in fuel is usually measured in BTUs (British Thermal Units). The chemical energy is converted to thermal energy by burning (combining it with oxygen). Fuel oil has 140,000 BTUs/gallon, so a 250-gallon tank holds 35,000,000 BTUs of chemical energy. The thermal energy can be used directly to heat a house, or a heat engine (such as a steam engine) can convert the thermal energy into work.

Chemical Energy (food). Food contains carbohydrates that are in a form the body can metabolize (burn). Some of the chemical energy is converted to thermal energy to maintain body temperature. Some can be converted to work by the muscles. The chemical energy available in food is measured in “large calories,” where 1 large calorie = 1000 calories. Unfortunately, a “large calorie” is called a “Calorie” for short, but capitalization is used to distinguish it in writing. There are 3.8 Calories (3800 calories) in a gram of white sugar. There are 3.6 Calories (3600 calories) in a gram of wheat flour.

Chemical Energy (battery). The chemical energy in a battery is measured by the amount of electrical energy it can produce. A typical 9-volt battery can provide 0.5 amp-hours of current (0.5 amps for 1 hour, or 0.1 amps for 5 hours). Since volts \times amps = watts, the battery stores $9 \times 0.5 = 4.5$ watt-hours of chemical energy. A 12-volt car battery can provide 70 amp-hours of current, so it stores $12 \times 70 = 840$ watt-hours of chemical energy. A lithium-ion battery can provide 102 watt-hours per pound (per 454 grams) of battery weight.

Nuclear Energy. The fission of 1 gram of uranium releases 8.8×10^{10} joules of radiant energy. Fusing 1 gram of hydrogen to helium releases 2.4×10^{11} joules (5.7×10^{10} calories) of radiant energy. Nuclear energy has the highest storage of energy per gram. That's why it's used for some submarines that must go a long time between refueling.

Radiant Energy. All the above forms of energy are stored energy—energy waiting to be turned into work, heat, or radiant energy. Radiant energy is active energy—photons moving at the speed of light. It's the energy that's created when matter is annihilated, as when matter and antimatter meet. It's also created from electrical energy when an antenna radiates radio waves. The vibrating molecules in a hot material (the filament of a light bulb) generate radiant energy as light. The Sun's radiation power hitting the Earth is 1360 watts per square meter. About 1000 watts per square meter can get through the atmosphere to the Earth's surface. So the radiant energy falling on 1 square meter in 1 second is 1000 watt-seconds, or 1000 joules. Gallium arsenide solar cells can convert 43% of this radiant energy into electrical energy. That is they can provide 430 joules of electrical energy per second (430 watts) from a square meter of sunlight.

Electrical Energy. This is another form of active energy; it's going somewhere. A voltage V pushes a certain amount of current I through a wire. The electrical power P in watts is given by $P = V \cdot I$, where V is in volts and I in is amps. The amount of electrical energy E transmitted in a given time t is $E = P \cdot t = V \cdot I \cdot t$, where t is in seconds and E is in joules. A 100-watt light bulb draws 0.87 amps of current from the 115-volt provided by the electric utility company. The amount of energy E it uses in an hour is $E = 115 \text{ volts} \times 0.87 \text{ amps} \times 3600 \text{ seconds} = 100 \text{ watts} \times 3600 \text{ seconds} = 360,000 \text{ joules}$. On your electric bill this energy is stated as 100 watt-hours, or 0.1 kilowatt-hours. Electric motors convert electrical energy into work.

Course Outline. In the next chapters we'll look at some of these forms of energy and learn to deal quantitatively with energy in practical, ever-day situations.

Chapter 1 – Kinetic Energy

Chapter 2 – Force and Acceleration

Chapter 3 – Potential Energy

Chapter 4 – Momentum and Center of Gravity

Chapter 5 – Work and Friction

Chapter 6 – Kinetic-Energy Transformers (Teeter-Totters)

Chapter 7 – Springs and Mechanical Oscillators

Chapter 8 – Pendulums

Chapter 9 – Power and Optimum Performance

Chapter 10– Electrical Power

Chapter 12– Thermal Energy