Canadian Nuclear Society

Energy and power fact sheet – a serving of unit soup

www.cns-snc.ca/ecc/cnsecc.html

joule newton
watt calorie
electron-volt

Do you understand energy and power? This fact sheet presents some simple concepts that are important for understanding energy and power, and how these relate to everyday life experience.

In the science of physics, energy is defined as "work done" – this is the product of force (applied to a mass) and distance covered. Using Système International (SI) units, the unit of energy is the joule (J), defined as 1 newton (N) multiplied by 1 metre (m). Power is defined as energy per unit time, and the watt (W) is 1 joule per second.

$$\begin{array}{ccc} \text{energy} & = & \text{force} \bullet \text{distance} \\ [\text{joule or J}] & & [\text{newton or N}] \bullet [\text{metre or m}] \end{array}$$

That's very basic stuff – let's make it real. A one-kilogram (kg) mass at the surface of the earth is pulled toward the centre of the earth by a gravitational force of approximately 9.8 newton. Lifting it straight up very slowly from a benchtop through a distance of 10.2 cm increases its gravitational potential energy by 1 J (9.8 N • 0.102 m). If the lifting was done in 1 second, the average power required would have been 1 W.

Release the mass, and it accelerates down toward the benchtop, converting that gravitational potential energy to kinetic energy – the energy of motion – until it collides with the bench.

Where did the energy go when the mass stopped after hitting the bench?

There was a noise when it hit the benchtop – so some kinetic energy was converted to sound. The benchtop may have been damaged by the collision, so some energy may have been converted to work in damaging the bench. In the end, most of the kinetic energy ends up as heat, warming up the benchtop, the mass, and the air.

Where did the energy required to lift the mass come from?

Assuming a person did the lifting, biochemical energy was used to increase the gravitational potential energy of the mass. The unit commonly used for chemical energy is the calorie (cal). One calorie is approximately 4.2 J – that required to raise the temperature of 1 g of water by 1°C. (Note: the energy content of food is often given in units of "Calorie"; this is actually a kilocalorie - 1,000 of the calories that we have just defined. This fact sheet sticks with the above definition of the calorie, even when discussing energy in food.) The person who lifted the mass had to consume food to develop the biochemical energy that powered the muscles. If the human body was perfectly efficient at lifting a 1-kg mass, it would have required about 0.24 cal. Carbohydrate and protein provide 4 kcal/gram (kcal/g), while fat provides 9 kcal/g. Thus, about 62 µg (microgram) of glucose would provide the energy for this experiment.

If a 50-kg person climbs a ladder, raising the person's centre of mass by 8.6 metres, their gravitational potential energy increases by 4.2 kJ. Assuming perfect efficiency, this requires 1 kcal or 0.25 g of glucose.

The average person consumes about 2000 kcal (2 Mcal) each day – athletes and the obese consume more, and someone who has limited mobility will have a lower basal metabolic level and consumes less. Dietary guides identify the energy content of different foods one might consume. Let us convert this to "physical" units.

$$2000 \bullet 1000 \bullet \text{calorie} \bullet 4.2 \frac{\text{joule}}{\text{calorie}} = 8.4\ \text{MJ}$$

$$24\ \text{hour} \bullet 60 \frac{\text{minute}}{\text{hour}} \bullet 60 \frac{\text{second}}{\text{minute}} = 86400\ \text{s}$$

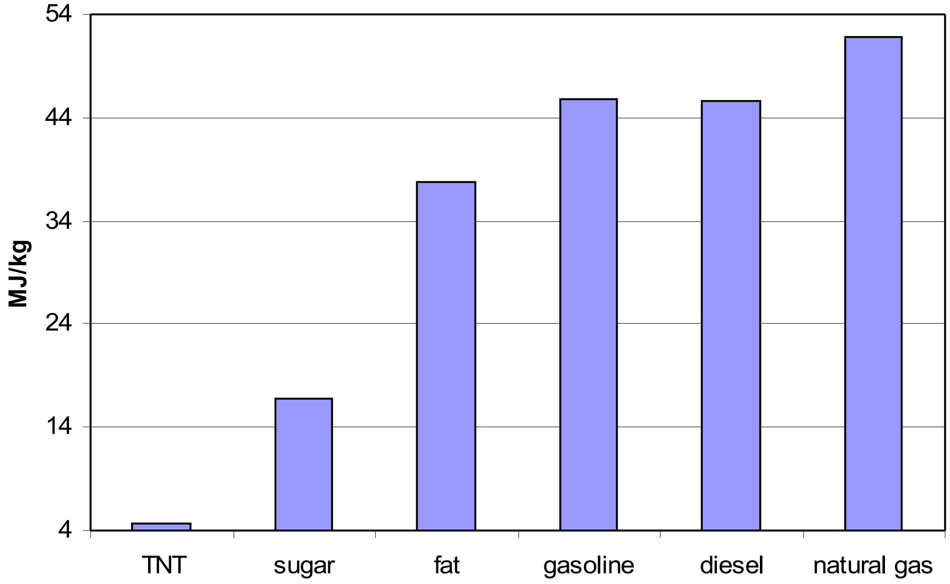
On average, if the human body were perfectly efficient at converting biochemical energy from food to heat, the 2 Mcal would correspond to 8.4 MJ – and, if expended over 24 hours, the power output would average 97.2 W. This is an interesting number – it turns out that air-conditioning systems for buildings such as theatres are sized assuming that the average person provides about 100 W of heat to the room. This is the same as that delivered by a 100-W incandescent light bulb (the light that doesn't escape out the window also ends up as heat).

Where does this biochemical energy come from?

The human body combines sugars and fats with oxygen to release chemical energy, producing carbon dioxide and water. Sugars and fats are large, complex organic molecules with many carbon-carbon and carbon-hydrogen bonds. These are among the most energetic chemical reactions in terms of energy released per amount of fuel. The following bar graph shows that the energy density for oxidation of fats approaches that of gasoline, while the explosive 2,4,6 trinitrotoluene (TNT) has a much lower energy density. Sugars and fats include a small amount of the oxygen required for combustion – the body must add more. (TNT includes all the oxygen required for combustion. Despite its comparatively low energy density, its ability to explode when triggered makes it useful.)

The graph also shows that natural gas, of which the principal constituent is methane, has a higher (specific) energy density at 52 MJ/kg. Hydrogen, not shown in the graph, has an even higher value, about 120 MJ/kg.

Energy density for oxidation of selected compounds

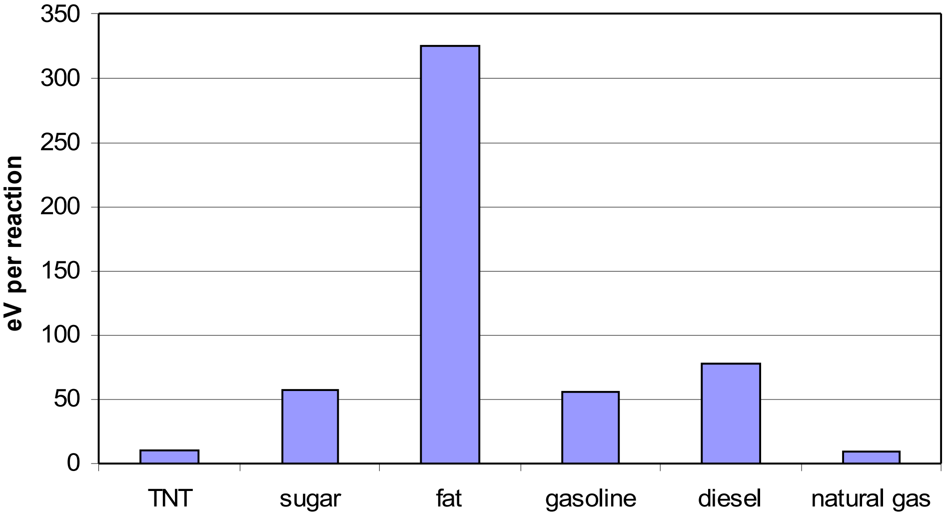


To compare the chemical reactions at work, we will express this data in terms of the energy per molecule oxidized. Sugars, fats and gasoline each represent a collection of different molecular masses. By using representative values, it is possible to provide an indicative comparison. Frequently, the energy of an individual atomic or molecular reaction is described using the electron-volt [eV] as the unit of energy. This is the amount of energy that one electron would gain passing through an electric potential difference of 1 V.

$$1\,\text{eV} = 1.602 \bullet 10^{-19}\ \text{J}$$

The following bar graph compares these same compounds. The value of 325 eV for oxidation of a molecule of fat represents the total obtained from several intermediate biochemical steps. A better value to compare with the others is about 100 eV per biochemical process step. Each hydrogen atom contributes about 1 eV (not shown).

Energy for oxidation of selected compounds using representative molecular masses



Nuclear Energy

Molecular energy values represent interactions involving the electron clouds of the atoms in the molecules, that is, they originate in the electromagnetic force. It is interesting to compare molecular energies with those originating in the nuclear, or strong, force that is associated with nuclear interactions. Individual radioactive decay events that produce alpha particles release energies up to about 10 million-electron-volts (MeV): 100,000 times that of the most energetic chemical reactions. The fission of a single ^{235}U nucleus releases a total energy of about 200 MeV: 2 million times that of the most energetic chemical reactions. Of this total, approximately 180 MeV are instantly available. (On the scale of the graph above, the fission bar would be 30 km high!)

Note that the energy released in both chemical and nuclear reactions comes from the conversion of some of the mass of the atoms, molecules, or nuclei into energy – this is encapsulated in Einstein's famous equation expressing the equivalence of mass and energy: $E = mc^2$. This equation is sometimes falsely assumed or interpreted to apply to nuclear reactions only, whereas it applies equally to chemical reactions (except that chemical energies are many order of magnitude smaller, as we have seen above.)

Engines – doing useful things with heat energy

Heat energy is used to keep buildings warm. Some high-efficiency home furnaces operate with over 90% efficiency. Energy losses include intake of air for combustion, imperfect combustion, driving the exhaust gases out to a safe location, and pumping condensed water from the combustion heat exchanger to a drain.

To convert heat energy into mechanical energy, engines are used. All "heat engines" operate by moving energy from a high-temperature "source" to a low-temperature "sink", while converting some fraction of the heat energy obtained from the heat source to mechanical energy.

A gasoline- or diesel-fuelled engine in a transportation application controls the expansion of the hot gases resulting from combustion of the fuel to push pistons that turn a crankshaft, and ultimately turn the wheels or propeller of the vehicle. The conversion of heat energy to mechanical energy is an inherently inefficient process. The physics of heat engines is part of the science of thermodynamics. Typical automobile engines have a maximum efficiency of about 20%. For many engines, it is possible to use the "waste heat" energy for other purposes. In winter, the car heater uses heat from the engine to warm the air in the car. In summer, the engine drives an air-conditioner compressor to cool the air in the car (reducing its fuel efficiency), and rejects more waste heat to the air around the car.

Large engines that are not required to be mobile or operate in adverse environments can achieve higher efficiencies. Fossil-fuel-fired and nuclear electric power plants boil water to produce high-pressure steam that drives a turbine and an electric generator, routinely achieving just over 30% efficiency. The steam is exhausted from the turbine to a condenser that operates at low pressure. The extra heat energy is absorbed by the condenser and discharged to the environment – bodies of water, or to the atmosphere via cooling towers that evaporate water. To increase the efficiency further requires increasing the steam temperature and pressure. Power plants that heat the water at pressures above the critical pressure use “supercritical water” to attain higher temperature and pressures, achieving over 40%. (Above the critical pressure, steam bubbles do not form in the water.) Combined-cycle plants use large gas turbines (natural-gas fuelled) to drive an electrical generator and use the heat of the exhaust gases to boil water, producing steam that drives a turbine and helps drive the generator. These may exceed 60% efficiency.

Direct conversion

Devices such as fuel cells convert the chemical energy available from oxidation to electrical energy directly, using hydrogen as the fuel. This conversion can achieve efficiencies of about 50%. However, hydrogen is not available naturally as a fuel; thus, it is not classed as a basic energy source, but rather as an energy “currency”. It may be produced from natural gas or oil, using combustion processes to provide the necessary energy, or it may be produced by electrolysis of water, using electrical energy provided by some other source.

Photovoltaic solar panels convert sunlight directly into electrical energy. High-performance solar cells can achieve 25% efficiency. Multilayer solar cells (stacked cells sensitive to different wavelengths) are expected to approach 50% efficiency.

Energy Storage

The technologies available for storing energy are limited.

- Electrical energy may be stored in a battery as chemical energy for subsequent use.
- Chemical fuels, such as hydrogen, may be produced as a source of stored energy.
- At suitable hydroelectric generating facilities, water may be pumped uphill at times when excess generating capacity is available, and then used to generate electricity when required.
- Air may be pumped at high pressure into underground structures, to be released at a later time (similar to pumping water uphill).
- Mechanical devices such as flywheels may be used to store limited amounts of energy.

All energy-storage technologies have limited efficiency.

Availability

For some uses, it is important that the energy be there when you need it – available on demand. This is especially important for electrical energy, which cannot be stored in large amounts. Examples of such uses include elevators, traffic lights, medical equipment. Other uses may be interrupted when the energy they require is not available.

All forms of electrical generation have limited availability. Equipment may need maintenance or fail. Hydro dams may suffer shortages of water in dry seasons. Wind turbines may not have useful wind for several days. Cloudy weather and hours of no sunlight limit the performance of solar panels. The electrical utilities must have a range of sources available to supply the forecast demand, and deliver their performance when needed.

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