Energy

A Beginner's Guide

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Beginners GUIDES

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Energy will do anything that can be done in the world.
Johann Wolfgang von Goethe (1749–1832)

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Energy in our minds: concepts and measures

The word energy is, as are so many abstract terms (from hypothesis to sophrosyne), a Greek compound. Aristotle (384–322 B.C.E.) created the term in his *Metaphysics*, by joining εν (in) and ἔργον (work) to form ἐνέργεια (*energeia*, "actuality, identified with movement") that he connected with *entelechia*, "complete reality." According to Aristotle, every object's existence is maintained by *energeia* related to the object's function. The verb *energein* thus came to signify motion, action, work, and change. No noteworthy intellectual breakthroughs refined these definitions for nearly two subsequent millennia, as even many founders of modern science had very faulty concepts of energy. Eventually, the term became practically indistinguishable from power and force. In 1748, David Hume (1711–1776) complained, in *An Enquiry Concerning Human Understanding*, that "There are no ideas, which occur in metaphysics, more obscure and uncertain, than those of *power, force, energy* or *necessary connexion*, of which it is every moment necessary for us to treat in all our disquisitions."

In 1807, in a lecture at the Royal Institution, Thomas Young (1773–1829) defined energy as the product of the mass of a body and the square of its velocity, thus offering an inaccurate formula (the mass should be halved) and restricting the term only to kinetic (mechanical) energy. Three decades later the seventh edition of the *Encyclopedia Britannica* (completed in 1842) offered only a very brief and unscientific entry, describing energy as "the power, virtue, or efficacy of a thing. It is also used figuratively, to denote emphasis in speech." Little has changed in popular discourse since that, or indeed since Hume's, time, except the frequency of the term's misuse. At the beginning of the twenty-first century energy, its derivative verb (energize) and its adjective (energetic), are used ubiquitously and loosely as qualifiers for any number of animated, zestful, vigorous actions and experiences, and energy is still routinely confused with power and force. Examples abound: a powerful new chairman brings fresh energy to an old company; a crowd is energized by a forceful speaker; pop-culture is America's soft power.

Devotees of physical fitness go one step further and claim (against all logic and scientific evidence) they are energized *after* a particularly demanding bout of protracted exercise. What they really want to say is that they feel better afterwards, and we have a perfectly understandable explanation for that: prolonged exercise promotes the release of endorphins (neurotransmitters that reduce the perception of pain and induce euphoria) in the brain and hence may produce a feeling of enhanced well-being. A long run may leave you tired, even exhausted, elated, even euphoric – but never energized, that is with a higher level of stored energy than before you began.

Science of energy: origins and abstracts

Sloppy use of ingrained terms is here to stay, but in informed writing there has been no excuse for ill-defined terms for more than a hundred years. Theoretical energy studies reached a satisfactory (though not perfect) coherence and clarity before the end of the nineteenth century when, after generations of hesitant progress, the great outburst of Western intellectual and inventive activity laid down the firm foundations of modern science and soon afterwards developed many of its more sophisticated concepts. The ground work for these advances began in the seventeenth century, and advanced considerably during the course of the eighteenth, when it was aided by the adoption both of Isaac Newton's (1642–1727) comprehensive view of physics and by engineering experiments, particularly those associated with James Watt's (1736–1819) improvements of steam engines (Figure 1; see also Figure 19).

During the early part of the nineteenth century a key contribution to the multifaceted origins of modern understanding of energy were the theoretical deductions of a young French engineer, Sadi Carnot (1796–1832), who set down the universal principles applicable to producing kinetic energy from heat and

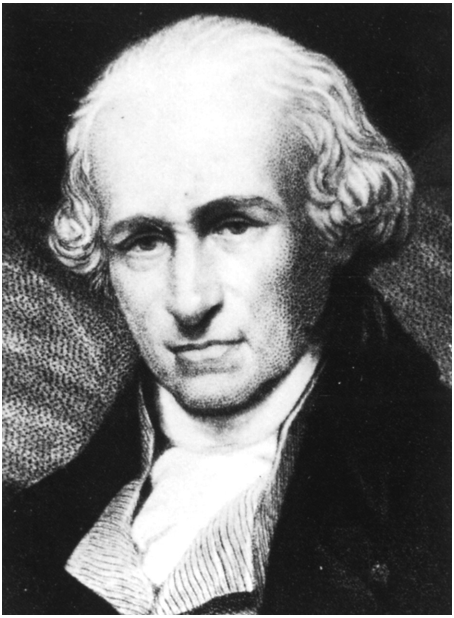

Figure 1 James Watt

defined the maximum efficiency of an ideal (reversible) heat engine. Shortly afterwards, Justus von Liebig (1803–1873), one of the founders of modern chemistry and science-based agriculture, offered a basically correct interpretation of human and animal metabolism, by ascribing the generation of carbon dioxide and water to the oxidation of foods or feeds.

The formulation of one of the most fundamental laws of modern physics originates in a voyage to Java made in 1840 by a young German physician, Julius Robert Mayer (1814–1878), as ship's doctor. The blood of patients he bled there (the practice of bleeding as a cure for many ailments persisted well into the nineteenth century) appeared much brighter than the blood of patients in Germany.

Mayer had an explanation ready: blood in the tropics does not have to be as oxidized as blood in temperate regions, because less energy is needed for body metabolism in warm places. But this answer led him to another key question. If less heat is lost in the tropics due to radiation how about the heat lost as a result of physical work (that is, expenditure of mechanical energy) which clearly warms its surroundings, whether done in Europe or tropical Asia? Unless we put forward some mysterious origin, that heat, too, must come from the oxidation of blood – and hence heat and work must be equivalent and convertible at a fixed rate. And so began the formulation of the law of the conservation of energy. In 1842 Mayer published the first quantitative estimate of the equivalence, and three years later extended the idea of energy conservation to all natural phenomena, including electricity, light, and magnetism and gave details of his calculation based on an experiment with gas flow between two insulated cylinders.

The correct value for the equivalence of heat and mechanical energy was found by the English physicist (see Figure 2) James Prescott Joule (1818–1889), after he conducted a large number of careful experiments. Joule used very sensitive thermometers to measure the temperature of water being churned by an assembly of revolving vanes driven by descending weights: this arrangement made it possible to measure fairly accurately the mechanical energy invested in the churning process. In 1847 Joule's painstaking experiments yielded a result that turned out to be within less than one percent of the actual value. The law of conservation of energy – that energy can be neither created nor destroyed – is now commonly known as the first law of thermodynamics.

In 1850 the German theoretical physicist Rudolf Clausius (1822–1888) published his first paper on the mechanical theory of heat, in which he proved that the maximum performance

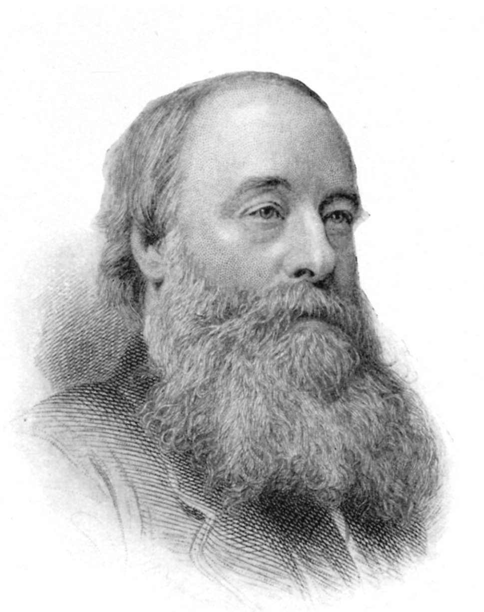

Figure 2 James Prescott Joule

obtainable from an engine using the Carnot cycle depends solely on the temperatures of the heat reservoirs, not on the nature of the working substance, and that there can never be a positive heat flow from a colder to a hotter body. Clausius continued to refine this fundamental idea and in his 1865 paper he coined the term *entropy* – from the Greek τρόπος (way) – to measure the degree of disorder in a closed system. Clausius also crisply formulated the second law of thermodynamics: entropy of the universe tends to maximum. In practical terms this means that in a closed system (one without any external supply of energy) the availability of useful energy can only decline. A lump of coal is a high-quality, highly ordered (low entropy) form of energy; its combustion will produce heat, a dispersed, low-quality, disordered (high entropy) form of energy. The sequence is irreversible: diffused heat (and emitted combustion gases) cannot be ever reconstituted as a lump of coal. Heat thus occupies a unique position in the hierarchy of energies: all other forms of energy can be completely converted to it, but its conversion into other forms can never be complete, as only a portion of the initial input ends up in the new form.

The second law of thermodynamics, the universal tendency toward heat death and disorder, became perhaps the grandest of all cosmic generalizations – yet also one of which most non-scientists remain ignorant. This reality was famously captured by C. P. Snow (1905–1980), an English physicist, politician, and novelist, in his 1959 Rede Lecture *The Two Cultures and the Scientific Revolution*:

> A good many times I have been present at gatherings of people who, by the standards of the traditional culture, are thought highly educated and who have with considerable gusto been expressing their incredulity at the illiteracy of scientists. Once or twice I have been provoked and have asked the company how many

> of them could describe the Second Law of Thermodynamics. The response was cold: it was also negative. Yet I was asking something which is about the scientific equivalent of: "Have you read a work of Shakespeare's?"

Despite its supposed universality, the second law appears to be constantly violated by living organisms, whose conception and growth (as individuals) and whose evolution (as species and ecosystems) produces distinctly more ordered, more complex forms of life. But there is really no conflict: the second law applies only to closed systems under thermodynamic equilibrium. The Earth's biosphere is an open system, which incessantly imports solar energy and uses its photosynthetic conversion to new plant mass as the foundation for greater order and organization (a reduction of entropy).

Finally, the third law of thermodynamics, initially formulated in 1906 as Walther Nernst's (1864–1941) heat theorem, states that all processes come to a stop (and entropy shows no change) only when the temperature nears absolute zero (–273°C).

The first decade of the twentieth century brought a fundamental extension of the first law of thermodynamics when, in 1905, Albert Einstein (1879–1955) concluded that mass is itself a form of energy. According to perhaps the world's most famous equation – $E = mc^2$ – energy is equal to the product of mass and the square of the speed of light. As a result, just six tonnes of matter contain energy that is equivalent to the world's annual consumption of commercial energy in 2015 – but this astonishing potential remains just that, as we have no means to unlock the mass energy in limestone or water.

The only time when we commercially convert a relatively large (but still very small) share of mass into energy is in nuclear reactors: the fission (splitting) of the nuclei of one kilogram of uranium-235 releases an amount of energy equivalent to

190 tonnes of crude oil as it diminishes the initial mass by just one gram, or a thousandth of its original mass. In contrast, burning one kilogram of crude oil will diminish the mass of the fuel (and of the oxygen needed for its combustion) by only one ten billionth; too small a reduction to measure.

After less than a century of vigorous scientific effort the understanding of the nature of energy phenomena was virtually complete. But despite this large, and highly complex, body of scientific knowledge, there is no easy way to grasp the fundamental concept, which is intellectually much more elusive than is the understanding of mass or temperature. Richard Feynman (1918–1988), one of the most brilliant physicists of the twentieth century, put it with disarming honesty in his famous 1963 *Lectures on Physics*:

> It is important to realize that in physics today, we have no knowledge of what energy *is*. We do not have a picture that energy comes in little blobs of a definite amount. It is not that way. However, there are formulas for calculating some numerical quantity ... It is an abstract thing in that it does not tell us the mechanism or the *reasons* for the various formulas.

Difficult as it is, we have to try to make that abstract thing more accessible.

Fundamental concepts: energies, conversions, efficiencies

By far the most common definition of energy is "the capacity for doing work" but the full implication of this simple statement becomes clear only when you go beyond thinking about work as mechanical exertion– in physics terms, energy transferred through application of force over a distance, in common terms a labor to be performed, be it typing a letter or transplanting rice seedlings – and apply the term in a generic manner to any process that produces a change (of location, speed, temperature, composition) in an affected system (an organism, a machine, a planet). If you were to sit motionless in a quiet room for the next ten minutes, contemplating this statement, you would not have accomplished any work, in the narrow, strictly physical and commonly used, sense of applying force to a mechanical task.

But even as you sit motionless your metabolism is performing a great deal of work, as energy obtained from digested food is used (noting just the four key processes) to power your breathing, importing oxygen and exhaling carbon dioxide, to maintain the core temperature of your body at 37°C, to pump blood and to create the numerous enzymes that control everything from digestion to the transmission of nerve signals. By thinking hard about an abstract concept you do actually use a bit more energy but making all those additional neuronal connections in your brain amounts to an entirely negligible mark-up. Even when you are fast asleep, your brain accounts for about twenty percent of your body's metabolism and even a taxing mental exercise will raise that share only a little.

Outside a quiet room, the work done by various energies is accomplished in myriad ways. The lightning that slashes through summer skies works in a very different way from a giant harbor crane picking up large steel crates from a pier and stacking them up to a dizzying height on a container ship – and the differences are due to one of the most fundamental physical realities, the existences of multiple forms of energy and their conversions, on space and time scales ranging from galactic to sub-atomic and from evolutionary to ephemeral. Lightning works in a tiny fraction of a second, illuminating and heating the atmosphere and decomposing molecules of nitrogen, that is, converting the electrical energy of cloud-to-cloud or cloud-to-earth discharge to electromagnetic, thermal, and chemical energy. In contrast, the motors of stacking cranes in container ports work around the clock, converting electrical energy into mechanical energy and then into the potential energy of loaded cargo.

Energy is not a single, easily definable entity, but rather an abstract collective concept, adopted by nineteenth-century physicists to cover a variety of natural and anthropogenic (generated by humans) phenomena. Its most commonly encountered forms are heat (thermal energy), motion (kinetic or mechanical energy), light (electromagnetic energy) and the chemical energy of fuels and foodstuffs. Some of their conversions are the very fundamentals of life: during photosynthesis a small share of the electromagnetic energy of light becomes the chemical energy of bacteria and plants, and cooking and heating is done by converting chemical energy in biomass (wood, charcoal, straw) or fossil fuels (coals, oils, gases) to thermal energy (Figure 3). Others are a matter of convenience enjoyed on large scales: the conversion of chemical energy to electrical energy in batteries operates billions of mobile phones, music players, and radios. And some are quite rare: for example, the gamma-neutron reactions that are produced by converting electromagnetic energy to nuclear energy are used only for specialized scientific and industrial tasks.

Kinetic energy is associated with all moving masses, be they heavy, tank-penetrating shells made of depleted uranium or wispy clouds ascending above a tropical rainforest. Its manifestations are easy to perceive and its magnitude easy to calculate, as it is simply half of the moving object's mass (m) multiplied by the square of its velocity (v): $E_k = \frac{1}{2} mv^2$. A key thing to note is that kinetic energy depends on the square of the object's velocity: doubling the speed imparts four times more energy, tripling it nine times more – and hence at high speed, even small objects can become very dangerous. Tornado winds, in excess of 80 meters per second (nearly 290 km/h) can drive featherweight pieces of straw into tree trunks; tiny space debris (a lost bolt) traveling at 8,000 m/s could pierce the pressurized suit of a space-walking

from / to	electro-magnetic	chemical	thermal	kinetic	electrical	nuclear	gravitational
electro-magnetic		chemiluminescence	thermal radiation	accelerating charge phosphor	electro-magnetic radiation electro-luminescence	gamma reactions nuclear bombs	
chemical	photo-synthesis photo-chemistry	chemical processing	boiling dissociation	dissociation by radiolysis	electrolysis	radiation catalysis ionization	
thermal	solar absorption	combustion	heat exchange	friction	resistance heating	fission fusion	
kinetic	radiometers	metabolism muscles	thermal expansion internal combustion	gears	motor electro-strictions	radioactivity nuclear bombs	falling objects
electrical	solar cells photo-electricity	fuel cell batteries	thermo-electricity thermionics	conventional generator		nuclear batteries	
nuclear	gama-neutron reactions						
gravitational				rising objects			

Figure 3 Energies and their conversions

astronaut, and (although the risk has turned out to be very small indeed) a space vehicle can be damaged by a micrometeoroid traveling at 60,000 m/s.

Potential energy results from a change in the spatial setting of a mass or of its configuration. Gravitational potential energy, resulting from a changed position in the Earth's gravitational field, is ubiquitous: anything lifted up acquires it, be it rising water vapor, a hand lifted in a gesture, a soaring bird, or an ascending rocket. Water stored behind a dam in order to fall on turbine blades and generate electricity is a practical example of using gravitational potential energy to a great economic advantage:

nearly twenty percent of the world's electricity is generated this way. The potential energy of water stored behind a dam (or a rock precariously poised on a weathering slope) is simply a product of the elevated mass, its mean height above ground (h) and the gravitational constant (g): $E_p = mgh$. Springs that have been tensioned by winding are a common example of the practical use of elastic potential energy that is stored due to their deformation and released as useful work as the coil unwinds and powers a watch or a walking toy.

Biomass (living, in plants, micro-organisms, animals, and people; and dead, mainly in soil, organic matter, and tree trunks) and fossil fuels (formed by the transformation of dead biomass) are enormous stores of chemical energy. This energy is held in the atomic bonds of tissues and fuels and released through combustion (rapid oxidation) which produces heat (an *exothermic* reaction). This results in new chemical bonds, the formation of carbon dioxide, frequently the emission of nitrogen and often sulfur oxides, and, in the case of liquid and gaseous fuels, the production of water.

HEAT

Heat of combustion (or specific energy) is the difference between the energy of the bonds in the initial reactants and that in the bonds in the newly formed compounds. The poorest fuels (wet peat, wet straw) release less than a third of the thermal energy produced by burning gasoline or kerosene. The energy content of a fuel, foodstuff, or any other combustible material can easily be determined by burning an absolutely dry sample of it in a calorimeter (a device that measures the heat given off during chemical reactions). Heat is produced by a number of other energy conversions: nuclear fission is a major commercial process whose heat is used to generate electricity, heat arising due to the resistance to the flow of electric current is used to prepare food, boil water, and warm interior spaces, and friction produces a great deal of unwanted (inside vehicle transmissions) as well as unavoidable (between vehicle tires and road) heat.

HEAT (*cont.*)

Once produced, heat can be transferred in three ways: conduction (that is direct molecular contact, most commonly in solids), convection (by moving liquids or gases) and radiation (the emission of electromagnetic waves by bodies warmer than their surrounding). Most of the heat that radiates at ambient temperatures from the Earth's surface, plants, buildings, and people is invisible infra-red radiation, but hot (above 1,200°C) objects (such as the coiled tungsten wires in light bulbs, molten steel in electric arc furnaces or distant stars) radiate invisible light, also.

Latent heat is the amount of energy needed to effect a physical change with no temperature change: changing water to steam (latent heat of vaporization) at 100°C requires exactly 6.75 times more energy than the changing of ice into water at 0°C.

The heating of water also accounts for most of the difference between the gross (or higher) heating value of fuels and their net (lower) heating value. The first is the total amount of energy released by a unit of fuel during combustion with all the water condensed to liquid (and hence the heat of vaporization is recovered); the second subtracts the energy required to evaporate the water formed during combustion. The difference is around one percent for coke (virtually pure carbon, whose combustion generates only carbon dioxide), around ten percent for natural gases and nearly twenty percent for pure hydrogen (whose combustion generates only water). The gap may be even larger for wood, but only a small part of the difference is due to hydrogen present in the fuel. Fresh (wet) wood simply contains too much moisture (sometimes more than seventy-five percent): most of the thermal energy released by the combustion of unseasoned (green) wood goes into evaporating water rather than warming a room and if wet wood has more than sixty-seven percent of water it will not ignite.

The efficiency of energy conversion is simply the ratio of desirable output to initial input. Photosynthesis is perhaps the best example of a highly inefficient process: even for the most productive crops no more than four to five percent of the solar radiation that strikes their fields every year will be transformed into new plant mass (phytomass), and the global annual average of the process (commonly prevented by excessive cold or lack of moisture) equates to a meager 0.3 percent. When the initial input is limited only to photosynthetically active radiation (wavelengths that can be absorbed by plant pigments, which average about forty-five percent of the incoming sunlight) the useful transfer doubles but globally still remains below one percent. High energy loss during a low-efficiency conversion simply means that only a very small part of the original energy input could be transformed into a desired service or product: no energy has been lost (the first law of thermodynamics), but (as the second law of thermodynamics dictates) a large share of the initial input ends up as unusable, dispersed heat.

In contrast, there is no shortage of processes, devices, and machines whose efficiency is greater than ninety percent. Electricity can be converted to heat by a baseboard resistance heater with one hundred percent efficiency. Healthy people on balanced diets can digest carbohydrates (sugars, starches) with an efficiency of as much as ninety-nine percent, the best natural gas furnaces can convert between ninety-five and ninety-seven percent of the incoming fuel into heat inside a house, more than ninety-five percent of electricity gets converted into the rapid rotation of large electrical motors, and, conversely, the giant turbines in thermal stations convert up to ninety-nine percent of their mechanical energy into electricity as they rotate in a magnetic field.

Despite their diverse manifestations – ranging from the blinding light of our nearest star to the imperceptible but deadly ionizing radiation that can escape from a malfunctioning nuclear reactor, from the high-temperature combustion in rocket engines to the amazingly intricate enzymatic reactions that proceed at ambient temperature and pressure – all energy phenomena can be quantified with the help of a small number of universal units. While many traditional yardsticks are still in everyday use around the world, modern scientific and engineering quantifications are based on the *Système*

International d'Unités (International System of Units, commonly abbreviated as SI) that was adopted in 1960. In this book I will use only the appropriate SI units: the complete list, as well as the prefixes to indicate multiples and submultiples, will be found later in this chapter.

Quantitative understanding: the necessity of units

The SI specifies seven fundamental measures: length, mass, time, electric current, temperature, amount of substance, and luminous intensity. These units are used directly, to measure the seven common variables, as well as to derive more complex quantities. The latter category includes some relatively simple units used in everyday situations (area, volume, density, speed, pressure) as well as more complex concepts deployed in science and engineering (force, pressure, energy, capacitance, luminous flux). Only three fundamental variables – mass (M), length (L), and time (T) – are needed to derive the units repeatedly encountered in energy studies. Area is obviously L^2, and volume L^3, mass density M/L^3, speed L/T, acceleration (change of speed per unit of time) L/T^2, and force, according to Newton's second law of motion, ML/T^2 (mass multiplied by acceleration). Energy is expended (work is done) when a force is exerted over a distance: energy's dimensional formula is thus ML^2/T^2.

The scientific definition of *power* is simply the rate of energy use: power equals energy per time, or ML^2/T^3. One of the most common abuses of the term, found even in engineering journals, is to confuse power with electricity and to talk about power generating plants: in reality, they generate electrical energy at a variable rate, determined by industrial, commercial, and household demand for kinetic energy (produced by electric motors),