

AN OVERVIEW OF CONCEPTS AND UNITS

A deep understanding of the peculiarities and complexities of different forms of energy and their stores and conversions requires quantification of these qualities and processes. For this, we must introduce a certain number of scientific concepts and measures and their associated units.

The first problem we encounter in formulating a way to talk about energies is that the common usages of many of the key terms are misleading. As Henk Tennekes has noted, "We have made a terrible mess of simple physical concepts in ordinary life." Few of these muddles are as ubiquitous and annoying as those involving terms such as "energy," "power," and "force."

A knowledge of basic mechanics helps get us started in sorting these terms out. *Force* is defined as the intensity with which we try to displace—push, pull, lift, kick, throw—an object. We can exert a large force even if the huge boulder we are trying to push remains immobile. We accomplish *work*, however, only when the object of our attention moves in the direction of the applied force. In fact, we define the amount of work performed as the prod-

uct of the force applied and the distance covered. *Energy*, as the common textbook definition puts it, is "the capacity for doing work" and thus will be measured in the same units as work. If we measure force in units of newtons (N, named for Sir Isaac Newton) and distance in meters (m), our measure of work will be the awkward-sounding Newton-meter. To simplify, scientists call one Newton-meter a joule (J), named for James Prescott Joule (1818–1889), who published the first accurate calculation of the equivalence of work and heat. The joule is the standard scientific unit for energy and work. *Power* is simply a rate of doing work, that is, an energy flow per unit of time; its measure is thus joules per second. We call one joule per second a watt (W) after James Watt (1736–1819), the inventor of the improved steam engine and the man who set the first standard unit of power, which as it happens was not the watt but the horsepower (hp), a unit equal to roughly 750 W.

To go further we need to move from pushing and shoving (which we call mechanical or kinetic energy) to heating (thermal energy). We define a unit called the calo-

ric as the amount of heat needed to raise the temperature of one gram of water from 14.5 to 15.5°C. (You needn't worry about why we define it this way.) Using this unit will help us compare thermal energies, but again it does not offer an all-encompassing measure that will allow us to compare different forms of energy.

At this point you might be asking, What is energy? This turns out to be a hard question to answer. Even one of the grand summations of modern physics is of little help: "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," wrote Richard Feynman in his famous *Lectures on Physics*. If forced to choose, I would opt for David Rose's evasive answer: Energy "is an abstract concept invented by physical scientists in the nineteenth century to describe quantitatively a wide variety of natural phenomena."

Our modern understanding of energy includes a number of profound realizations: that mass and energy are equivalent; that many conversions link various kinds of energies; that no energy is lost during these conversions (this is the first law of thermodynamics); and that this conservation of energy is inexorably accompanied by a loss of utility (the second law of thermodynamics). The first realization—initially called an "amusing and attractive thought" in a letter Einstein wrote to a friend—is summed up in perhaps the best known of all physical equations: $E = mc^2$.

The second realization is demonstrated constantly by myriads of energy conversions throughout the universe. Gravitational energy sets galaxies in motion, keeps the Earth orbiting around the Sun, and holds down the atmosphere that makes our planet habitable. Conversion of nuclear energy within the Sun releases an incessant stream of electromagnetic (solar, radiant) energy. A small share of that energy reaches the Earth, which itself also releases

geothermal energy. Heat from both these processes sets in motion the atmosphere, the oceans, and the Earth's huge tectonic plates.

A tiny share of the Sun's radiant energy is transformed through photosynthesis into stores of chemical energy that are used by many kinds of bacteria and by plants. Heterotrophs—organisms ranging from bacteria, protists, and fungi to mammals—ingest and reorganize plant tissues into new chemical bonds and use them also to generate mechanical (kinetic) energy. Chemical energy stored over many millions of years in fossil fuels is released through combustion in boilers and engines as thermal energy, which many processes then convert into mechanical, chemical, or electromagnetic energy.

The second law of thermodynamics addresses the inescapable reality that the potential for useful work steadily diminishes as we move along energy conversion chains. There is a measure associated with this loss of useful energy, and it is called *entropy*. While energy is conserved in any conversion, the conversion can only increase the entropy of the system as a whole. There is nothing we can do about this decrease of utility. A barrel of crude oil is a low-entropy store of very useful energy that can be converted to heat, electricity, motion, and light. Hot air molecules leaving an engine exhaust or surrounding a light bulb represent a high-entropy state in which there is an irretrievable loss of utility.

Loss of complexity and the rise of homogeneity are the unavoidable consequences of this unidirectional entropic dissipation in any closed system. (You can see this if you compare the multitude of complex organic molecules making up crude oil with the sameness of the few kinds of simple molecules making up hot exhaust gas.) In contrast, all living organisms—from bacteria to civilizations—are open systems, constantly importing and exporting energy, and hence are able to maintain themselves in a state of chemical and thermodynamic disequilibrium. They are

temporarily defying the entropic trend as their growth and evolution bring greater heterogeneity and higher complexity.

Using unadjusted units to quantify this multitude of processes would be inconvenient: actual figures would nearly always be either trailed or preceded by many zeros. Both joules and watts represent very tiny amounts of measured energy and power: about thirty micrograms of coal—or two seconds' worth of a vole's metabolism account for one joule. One watt is the power of a very small burning candle or a hummingbird's rapid flight.

Multiples are inevitable, and we therefore introduce a series of prefixes to abbreviate the most useful multiples: a kilogram of good coal contains nearly thirty million joules, or thirty megajoules (MJ), of energy, and the world now consumes fossil fuels at the rate of roughly ten trillion watts (TW). We attach the same prefixes to the units that we use to measure electrical energy: Volts (V), which are a measure of the difference in electric potential between two points of a conductor, and amperes (A), which measure the intensity of an electric current. The power of an electrical system is the product of voltage and current, which means that one volt-ampere is also one watt.

Table 1 lists the complete set of multiples as well as the submultiples, which are needed much less frequently when we are dealing with everyday energy flows. Magnitudes of some energy stores and flows are listed in tables 2 and 3. Examples of power ratings of continuous energy conversions are given in table 4, and those of ephemeral phenomena are shown in table 5.

Rates and ratios are important for understanding energy stores, flows, and effects. *Energy density*—the amount of energy stored in a unit mass of a resource (joules per kilogram, J/kg)—is a useful comparative measure for foodstuffs and fuels. Humans would need a daily intake of many kilograms of low-energy-density foods

Table 1 Prefixes of Scientific Units

| Prefix | Abbreviation | Scientific notation |
|--------|--------------|---------------------|
| deka | da | 10^1 |
| hecto | h | 10^2 |
| kilo | k | 10^3 |
| mega | M | 10^6 |
| giga | G | 10^9 |
| tera | T | 10^{12} |
| peta | P | 10^{15} |
| exa | E | 10^{18} |
| deci | d | 10^{-1} |
| centi | c | 10^{-2} |
| milli | m | 10^{-3} |
| micro | μ | 10^{-6} |
| nano | n | 10^{-9} |
| pico | p | 10^{-12} |
| femto | f | 10^{-15} |
| atto | a | 10^{-18} |

Table 2 Energy Stores

| Energy of | Magnitude |
|-------------------------------------|------------|
| Global coal resources | 200,000 EJ |
| Global plant mass | 10,000 EJ |
| Latent heat of a thunderstorm | 5 PJ |
| Coal load in a 100-t hopper car | 2 TJ |
| Barrel of crude oil | 6 GJ |
| Bottle of white table wine | 3 MJ |
| A small chickpea | 5 kJ |
| Fly on a kitchen table | 9 mJ |
| A 2-mm raindrop on a blade of grass | 4 μ J |

Table 3 Energy Flows

| Energy of | Magnitude |
|------------------------------------|------------|
| Solar radiation reaching the Earth | 5500000 EJ |
| Global net photosynthesis | 2000 EJ |
| Global fossil fuel production | 300 EJ |
| Typical Caribbean hurricane | 38 EJ |
| Largest H-bomb tested in 1961 | 240 PJ |
| Latent heat of a thunderstorm | 5 PJ |
| Hiroshima bomb of 1945 | 84 TJ |
| Basal metabolism of a large horse | 100 MJ |
| Daily adult food intake | 10 MJ |
| Striking a typewriter key | 20 mJ |
| Flea hop | 100 nJ |

Table 4 Powers of Continuous Phenomena

| Energy flows | Power |
|--|--------|
| Global intercept of solar radiation | 170 PW |
| Wind-generated waves on the ocean | 90 PW |
| Global gross primary productivity | 100 TW |
| Global Earth heat flow | 42 TW |
| Worldwide fossil fuel combustion | 10 TW |
| Florida Current between Miami and Bimini | 20 GW |
| Large thermal power plant | 5GW |
| Basal metabolism of a 70-kg man | 80 W |

Table 5 Powers of Short-Lived Phenomena

| Energy flows | Duration | Power |
|--------------------------------|----------|--------|
| Richter magnitude 8 earthquake | 30 s | 1.6 PW |
| Large volcanic eruption | 10 h | 100 TW |
| Thunderstorm's kinetic energy | 20 min | 100 GW |
| Large WWII bombing raid | 1 h | 20 GW |
| Average U.S. tornado | 3 min | 1.7 GW |
| Four engines of Boeing 747 | 10 h | 60 MW |
| Watt's largest steam engine | 10 h | 100 kW |
| Running 100-m dash | 10 s | 1.3 kW |
| Machine-washing laundry | 20 min | 500 W |
| Playing a CD | 60 min | 25 W |
| Candle burning to the end | 2 h | 5 W |
| Hummingbird flight | 3 min | 0.7 W |

such as fruits and vegetables to maintain themselves, whereas less than half a kilogram of rice, which has a high energy density, will do. Conversely, gasoline makes a great portable fuel because its energy density is nearly three times that of air-dried wood. Table 6 shows the energy densities of some common fuels, foods, and their metabolic products.

Power density—the rate at which energies are produced or consumed per unit of area (watts per square meter, W/m^2)—is a critical structural determinant of energy production systems. The power density of fuel production from a large open-cast mine extracting excellent bituminous coal from a thick seam is easily more than $1000 W/m^2$; the power density of electricity generation in a large hydrostation whose dam creates the huge reservoir needed to store a sufficient volume of water may be as low as a few W/m^2 . In order to illustrate the spatial aspect of various energy conversions, values of power densities are

Table 6 Ranges of Energy Densities of Common Fuels and Foodstuffs

| Energy density | (MJ/kg) |
|-----------------------|-----------|
| Hydrogen | 114.0 |
| Gasolines | 46.0–47.0 |
| Crude oils | 42.0–44.0 |
| Pure plant oils | 38.0–37.0 |
| Natural gases | 33.0–37.0 |
| Butter | 29.0–30.0 |
| Ethanol | 29.6 |
| Best bituminous coals | 27.0–29.0 |
| Pure protein | 23.0 |
| Common steam coals | 22.0–24.0 |
| Good lignites | 18.0–20.0 |
| Pure carbohydrates | 17.0 |
| Cereal grains | 15.2–15.4 |
| Air-dried wood | 14.0–15.0 |
| Cereal straws | 12.0–15.0 |
| Lean meats | 5.0–10.0 |
| Fish | 2.9–9.3 |
| Potatoes | 3.2–4.8 |
| Fruits | 1.5–4.0 |
| Human feces | 1.8–3.0 |
| Vegetables | 0.6–1.8 |
| Urine | 0.1–0.2 |

Table 7 Efficiencies of Common Energy Conversions (percent)

| Conversions | Energies | Efficiencies |
|--------------------------------|----------|--------------|
| Large electricity generators | M → e | 98–99 |
| Large power-plant boilers | c → t | 90–98 |
| Large electric motors | e → m | 90–97 |
| Best home natural-gas furnaces | c → t | 90–96 |
| Dry-cell batteries | c → e | 85–95 |
| Human lactation | c → c | 85–95 |
| Overshot waterwheels | m → m | 60–85 |
| Small electric motors | e → m | 60–75 |
| Large steam turbines | t → m | 40–45 |
| Improved wood stoves | c → t | 25–45 |
| Large gas turbines | c → m | 35–40 |
| Diesel engines | c → m | 30–35 |
| Mammalian postnatal growth | c → c | 30–35 |
| Best photovoltaic cells | r → e | 20–30 |
| Best large steam engines | c → m | 20–25 |
| Internal combustion engines | c → m | 15–25 |
| High-pressure sodium lamps | e → r | 15–20 |
| Mammalian muscles | c → m | 15–20 |
| Traditional stoves | c → t | 10–15 |
| Fluorescent lights | e → r | 10–12 |
| Steam locomotives | c → m | 3–6 |
| Peak crop photosynthesis | r → c | 4–5 |
| Incandescent light bulbs | e → r | 2–5 |
| Paraffin candles | c → r | 1–2 |
| Most productive ecosystems | r → c | 1–2 |
| Global photosynthetic mean | r → c | 0.3 |

Energy labels: c—chemical, e—electrical, m—mechanical (kinetic), r—radiant (electromagnetic, solar), t—thermal

shown in figures 1 and 2, graphs plotting areas against power.

The *efficiency* of an energy conversion is the ratio of the amount of energy output to the amount input. This measure is used to describe the performance of energy converters such as boilers, engines, photovoltaic cells, or lights. Efficiencies of common converters are listed in table 7. *Energy intensity* is the cost of a product or service in energy terms. Titanium and aluminum are highly energy-intensive, for example, whereas iron and glass are fairly cheap. Typical ranges of the energy costs of common materials are given in table 8.

Technical advances keep pushing efficiencies up and energy intensities down: today's best lights are about twenty times as efficient as the first light bulbs of more than a hundred years ago, and production of a kilogram of steel now requires less than one-tenth the energy it did two centuries ago.

The best way to understand the world of energy and power units is to get a small calculator and do exercises rooted in the realities all around us. How much energy does it take to play Mozart's last piano concerto? What volume of gasoline contains energy equivalent to a cord of stacked, air-dry wood? What is the kinetic power of an arrow shot from a modern compound bow? How much more powerful are the four engines of a Boeing 747 than the eight engines on B-52 bomber? What share of daily metabolism can be supplied by a slice of whole-wheat bread?

If you are so inclined, the figures listed in the tables given here, the ranges shown in the power density figure, and the hundreds of numbers scattered through the book will lead you to a virtually unlimited supply of such challenges—and hence to an insider's understanding of energies.

Table 8 Typical Energy Costs of Common Materials (MJ/kg)

| Material | Energy cost | Made or extracted from |
|-------------------|-------------|------------------------|
| Aluminum | 227–342 | Bauxite |
| Bricks | 2–5 | Clay |
| Cement | 5–9 | Clay and limestone |
| Copper | 60–125 | Sulfide ore |
| Glass | 18–35 | Sand, etc. |
| Iron | 20–25 | Iron ore |
| Limestone | 0.07–0.1 | Sedimentary rock |
| Nickel | 230–70 | Ore concentrate |
| Paper | 25–50 | Standing timber |
| Polyethylene | 87–115 | Crude oil |
| Polystyrene | 62–108 | Crude oil |
| Polyvinylchloride | 85–107 | Crude oil |
| Sand | 0.08–0.1 | Riverbed |
| Silicon | 230–235 | Silica |
| Steel | 20–50 | Iron |
| Sulfuric acid | 2–3 | Sulfur |
| Titanium | 900–940 | Ore concentrate |
| Water | 0.001–0.01 | Streams, reservoirs |
| Wood | 3–7 | Standing timber |

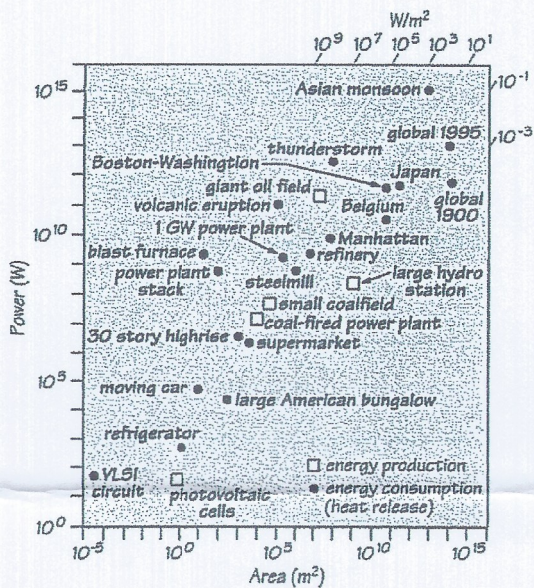


Figure 1
Power densities of various energy production
and consumption phenomena.

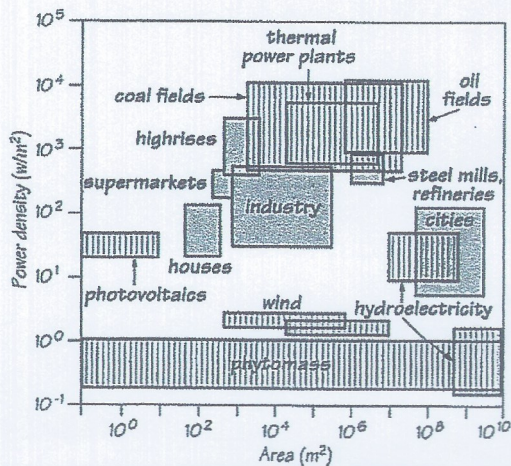


Figure 2
Typical ranges of areas and power densities in large-scale
modern energy production (lines) and in household
and industrial consumption (dots).