

Extracted, with the author's permission, from "A Guided Ascent of Mount Thermo: Engineering Thermodynamics for the Novice Climber" by Alan S Tucker. This is a Course Reader for the course ENME 225 Engineering Thermodynamics A, taught in the Department of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand.

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2.6 ENERGY: WHAT IT IS; WHERE IT IS; WHY WE NEED IT; HOW WE GET IT

Like many fundamental concepts such as mass and force, energy is difficult to define but, because it is part of our everyday experience, most of us have some idea of what is meant by the term. As we shall see later, a traditional mechanics definition along the lines that it is the capacity to perform work only tells part of the story and, in some situations, is quite misleading.

Energy exists naturally in many forms and, regardless of its form, the appropriate fundamental unit for expressing its magnitude is the joule, symbol J, which is precisely equivalent to the work produced by a force of 1 newton moving its point of application a distance of 1 metre in the direction of that force, suggesting immediately – and correctly – that work is a form of energy. Thus 1 joule is 1 newton-metre, or $[J] = [N\ m]$. In checking the consistency of units in our calculations (see Section 2.2.4), this is an equivalence of units which we use very frequently.

While, later on, it will become necessary to distinguish between the various forms of energy, and the situations under which it exists, we will concentrate for the moment on the fact that energy is possessed by, and stored within matter of all types. Usually we are unaware of this but it is always in there invisibly at molecular and atomic level. Two of the energy forms which exist at this sub-microscopic level are:

- Potential energy associated with intermolecular forces between molecules.
- Kinetic energy associated with the fact that the individual molecules may possess translational velocity.

The descriptive labels of these two energy forms at sub-microscopic level should remind us of two familiar energy forms that the same chunk of material – made up of atoms and molecules – may possess on a much larger scale, namely its potential energy through being elevated above some reference datum level in the earth's gravitational field; and the kinetic energy that it will possess if it has a velocity (either translational or rotational). We can easily quantify these large-scale versions of potential energy (mgz) and translational kinetic energy ($\frac{1}{2} mV^2$) but it is much more difficult to quantify the molecular level versions of potential and kinetic energy referred to above.

Moving down to the even smaller scale within the molecules themselves, and the atoms which make up those molecules, there is an unseen level of forces and activities that we can only imagine and, at best, observe external factors which are a consequence of those inner happenings. Aspects that are included in this are:

- Vibrational kinetic energy as the atoms in the molecule move with respect to each other. This activity is influenced by the temperature of the material and, not surprisingly, increases with temperature.
- Rotational kinetic energy as the molecules rotate around their centres of mass.
- Energy stored in the chemical bonds between the atoms that make up the molecules. This particular energy is released only when the chemical bonds are broken or modified as a result of a chemical reaction such as combustion.

While there are statistical and quantum mechanics methods for assessing all of these various "internal" energy forms¹, the inner detail (and quantification of it) is unimportant in most

¹ The use of the term "internal" energy is not only descriptive of the energy forms being discussed here but it is, in fact, the formal name that is adopted in subsequent chapters.

thermodynamic analyses. The important awareness that we must carry with us, however, is that there is hidden energy within all material that we may be able to tap into, even if only to the extent of doing so on a temporary basis to be followed later by an energy inflow to restore the material to its original energy state. When we combust a material, however, the accompanying energy release generally is a one-off release of the chemical energy in the bonds and it would require major chemical surgery (and associated large energy input) to restore the material to its pre-combustion condition.

What prompts us to play around with energy in this way? Just about all of our individual and societal activities involve energy expenditure in some shape or form, be it the simple act of walking or, just about at the other energy extreme, building and launching a spacecraft for the purpose of putting a man on the moon. Any expenditure of energy requires a source of energy so it is worth pondering for a moment on where such energy originates from, and in what forms it exists.

2.6.1 Energy Sources and Needs

There are a number of naturally-occurring energy forms available to us on earth:

- Thermal (solar, geothermal)
- Mechanical (wind, water, tides, physical energy output of humankind and other animals)
- Chemical (combustible fuels)
- Nuclear (fissile isotopes, e.g. U^{235})

The centre of our solar system, namely the sun, features very dominantly in either the original formation of these various energy forms – many of them dating to the formation of the solar system itself – or in the on-going maintenance of them.

Unfortunately these naturally-occurring energy forms generally do not coincide in their type (or, if they do, in their intensity) to the energy forms which humankind currently desires and uses, namely:

- Thermal energy (for comfort, food preparation and industrial processing)
- Mechanical energy (for agriculture, transportation and manufacturing)
- Electrical energy (for lighting, communication and electronics applications)

For example, the intensity of solar radiation at the earth's surface peaks at around 1000 W m^{-2} which, while certainly not insignificant, falls well short of the energy intensity we use in the thermal energy application of boiling a saucepan of water on a stovetop, regardless of whether the heating of that stovetop is by electricity or the burning of gas or coal. Furthermore, solar radiation is intermittent and largely uncontrollable.

Hence it is frequently necessary for us to *transform* energy from one form (often a naturally-occurring one) to another more desirable form, or to a more "intense" form of the same type of energy. Some of these energy transformations do in fact take place naturally but, unfortunately, the extremely desirable and versatile energy form of electricity is not one of those occurring in nature reliably and consistently (electric eels and lightning bolts don't really meet the criteria!). Thus, in the electricity-hungry world that we have become, appropriate energy transformations from what is available naturally, to electrical energy output are necessary and frequent.

Two naturally occurring energy transformations which go partway towards making electrical output possible will be described shortly but, before we do so, it is essential that we clarify an important distinction.

2.6.2 Energetic or Powerful: Are they the same?

Judging by the disregard that the media sometimes seem to have, particularly when describing the output or potential of an energy resource, it might appear that energy and power are synonymous terms. Alternatively, power often seems to be used as a synonym for electricity. Such confusion and ambiguity are unacceptable in any engineering context and particularly in thermodynamics.

Let's remind ourselves that in mechanical terms, power is the *rate* at which work is performed and since, as already noted, work is one form of energy, power is therefore more generally the rate at which energy is transferred or transformed. The respective units for energy [J] and power [W] (which is defined to be Js^{-1}) bear out this simple and fundamental relationship between them.

Energy has no rate associated with it: When you perform the task of raising the potential energy of your body by climbing up a flight of stairs, that change in potential energy is totally independent of how long it takes you to climb the stairs. If your body mass is 75kg; the flight of stairs has a vertical height of 3m; and gravitational acceleration is 9.81 ms^{-2} , that increase in potential energy of your body is $75 \text{ kg} \times 3 \text{ m} \times 9.81 \text{ ms}^{-2} = 2207 \text{ Nm}$ or 2207 J, regardless of whether you race up the stairs like an Olympic sprinter or pause for conversation partway up or take the lazy way out and use an elevator. What does change, however, is the associated power requirement because, to evaluate the power, those 2207 J must be divided by the time it takes for that energy change. Sprint up the stairs in say 2.2s and the power is $2207 \text{ J} / 2.2 \text{ s} = 1000 \text{ W}$ (or 1 kW); trudge up one heavy foot after the other and take 22s and the power level has dropped to 100W.

Another everyday reminder of the relationship between energy and power is in the usage of electricity. Various appliances have a power rating (a 60W electric light bulb; a 2kW heater) which tell us the rate at which the appliance will consume electrical energy. The longer any such device is used, the more energy it will consume. Thus the 2kW heater used for one hour (1 h – or 3600s) will have consumed $2 \text{ kW} \times 3600 \text{ s}$ or 7200 J of energy. Indeed, for convenience the electrical supply industry uses as its fundamental unit of energy the kilowatt-hour (kWh) so the more usual way of expressing the energy consumption of that heater over one hour of usage would be as 2 kWh. The very nature of this electrical energy unit reminds us that the inverse consequence of power being energy per unit time is that energy is power integrated over time.

Keep an eye out for media misunderstandings of these simple concepts: A particular electricity generating station should always have its power capacity expressed in megawatts whereas its contribution of energy over a period of time – generally a year – should be expressed in units such as gigawatt-hours (GWh). If the power capacity is multiplied by the number of hours in a year the resultant figure virtually always will exceed the plant's annual energy output because it will not operate at 100% capacity for 24 hours a day, 365 days a year. Indeed, this ratio represents an important operational parameter called the load factor of the plant which has a profound influence on the economics of the plant and the cost of the electricity it produces.

Author's Message #2.6

Careful consideration of, and attention to the difference between energy and power often is revealed in the way those working in thermodynamics (or anything related to energy in the broadest sense of the word) go about problem solving and writing – particularly in terms of setting up appropriate and consistent equations, and in the use and appropriateness of units.

2.6.3 Illustrations from Nature

Let's now consider two naturally occurring energy transformations which go partway towards making that desirable energy form of electricity possible:

- (a) The hydrological cycle (which we tap into with hydro-electric power plants);
- (b) The mechanism by which fossil fuels were formed (which we tap into in thermal power plants which use the combustion of coal, oil or natural gas as their energy source).

Both of these originate from relatively low intensity solar radiation and yet they are capable of producing extremely high power outputs. The fundamental mechanisms by which each of them is able to effectively concentrate the original quite diffuse energy form is very different, however. The descriptions which follow outline not only the energy transformations taking place but also some of the associated transformations in the phase (solid, liquid or gaseous) of the materials involved in those energy transformations. Thus they are non-quantitative examples from nature of some of the territory encompassed by thermodynamics (as defined in Section 1.1).

(a) Hydrological Cycle

Here the collector of the solar radiation energy source is extremely large in area, being all water surfaces such as the oceans and lakes. The effect of radiation absorbed in the surface layer of the water is to provide the energy input required to bring about the phase transition from liquid water to gaseous water vapour, a process which we call evaporation. Contrary to the understanding that some readers may have at this stage, this transition does not require the normal boiling point of 100°C to be achieved; rather it requires an energy input sufficient to satisfy the much greater internal energy level that the gaseous phase possesses because of the much enhanced mobility of the molecules in that phase. We are talking here about exactly the same mechanism that causes a puddle of rainwater to gradually disappear when the sun shines upon it².

Once the water molecules have escaped in this way from the constrained liquid surface into the relative freedom of the gaseous phase, they are able to be carried away by buoyancy forces and/or air currents to higher altitude, gaining potential energy as they do so. Through complex meteorological processes the vapour may condense into a dispersion of very fine water droplets which are visible as clouds. In this process of condensation from gas back to liquid, there is a release of energy effectively equivalent to that which was required to evaporate the liquid to gas back at sea level, having a warming effect on the atmosphere at that point. Under particular conditions and cloud types, the dispersion of extremely fine liquid droplets may coalesce into larger droplets having sufficient mass for the downwards gravitational force to dominate and, lo and behold, we have rain falling back towards earth.

If the point at which the raindrops reach the earth's surface is at a higher altitude than the level of the liquid water from which the whole process originated – generally sea level – then there is a gain in potential energy of the water. In the normal course of events, that potential energy will cause the elevated liquid to flow downwards (we all know of water's propensity for flowing downhill), eventually returning via river systems to the water level from whence it came in the first place. This cycle has been steadily doing its thing for millions of years with some relatively short-term perturbations (ice ages for example or, on a much shorter time cycle, storms and floods).

Then, along came humankind and it was realised, after a few thousand years of ignorance, that by intercepting the return water flow while it was still at an elevated position, its potential energy could be harnessed to produce a power output. Water wheels for powering flour mills were one of the earlier applications but we have progressed on from that relatively primitive technology to much more sophisticated "water wheels" driving very large capacity alternators for the generation of electricity. Furthermore, by damming the river and providing a large storage volume of water (and its associated potential energy), seasonal fluctuations in the river water flow can be accommodated without causing in-phase fluctuations in the power output from the plant (see Figure 2.12).

The overall mechanism by which intercepting the hydrological cycle enables us to extract very large amounts of power³ from an original solar energy source having an intensity of less than 1000

² Indeed, the water in the puddle will gradually disappear, even if the sun doesn't shine - assuming there's no more rain for a while! The mechanism of mass transfer is at the heart of the evaporation process, driven by the difference in concentration of water molecules in the liquid (high) and water molecules in the atmospheric air above (low). This process is still dependent on the input of energy into the surface but a small difference of temperature may be sufficient for this to occur. The rate of evaporation also depends on the relative humidity of the atmospheric air.

³ When completed, the China's Three Gorges scheme will be the world's largest hydroelectric system with a total power output of 18,200 MW from 26 turbo-alternators, each producing 700 MW.

$W\ m^{-2}$ is the enormous ratio between the area of water over which the relatively low intensity solar radiation is intercepted, and the cross-sectional area of the water flow in the river at the point at which we intercept that flow. Because this is an effectively constant area ratio, this “amplification” of the original energy intensity can be carried out on a more or less continuous basis, enabling us to view hydroelectricity as an essentially inexhaustible and self-renewing energy source.



Fig. 2.12 Intercepting the hydrological cycle with a hydro-electric plant

(b) Formation and utilisation of fossil fuels

While low intensity solar radiation is again the original energy form, the process of transformation, and the mechanism of intensification are totally different in this case from those of the hydrological cycle.

The growth of vegetation of all varieties and, in turn, the organisms and living creatures which directly or indirectly consume vegetation, is dependent on the process of **photosynthesis**. In this process, a portion of the energy in incident solar radiation is utilised as the energy input to a chemical process in which carbon dioxide (CO_2) and water (H_2O) are chemically combined in a reaction which produces carbohydrate plant material and releases oxygen (O_2). The energy transformation that takes place is from the incident solar radiation to energy stored chemically in the atomic bonds of the carbohydrate's molecular structure. This process will continue as long as the plant remains in a living state and the necessary chemical ingredients of CO_2 and H_2O are accessible to it so that the plant itself is the energy transformer, building up over a period of time a store of chemical energy derived from the original solar energy incident on the plant during its lifetime (see Figure 2.13(a)).

In the natural course of events, the plant (or the living creature which ingested the plant and hence inherited its stored chemical energy) will die and, with dying, its ability to act as a solar-to-chemical energy converter ceases. The same reaction that produced the carbohydrate material and oxygen when the plant was living then reverses *provided* the dead matter has access to oxygen – a so-called **aerobic** environment. Not only is the chemistry reversed but so also is the energy flow so that the aerobic decay of carbohydrate material is an energy-releasing process. (See Figure 2.13(b)) Essentially, then, through the complete life and death cycle of the plant (or living creature that ate it) the net energy absorbed by the plant during its lifetime is returned back to the environment when its decay has been completed. Historically this life and death cycle of overall energy balance has been going on for millions of years and represents the fate of almost all vegetation that has ever existed on earth.

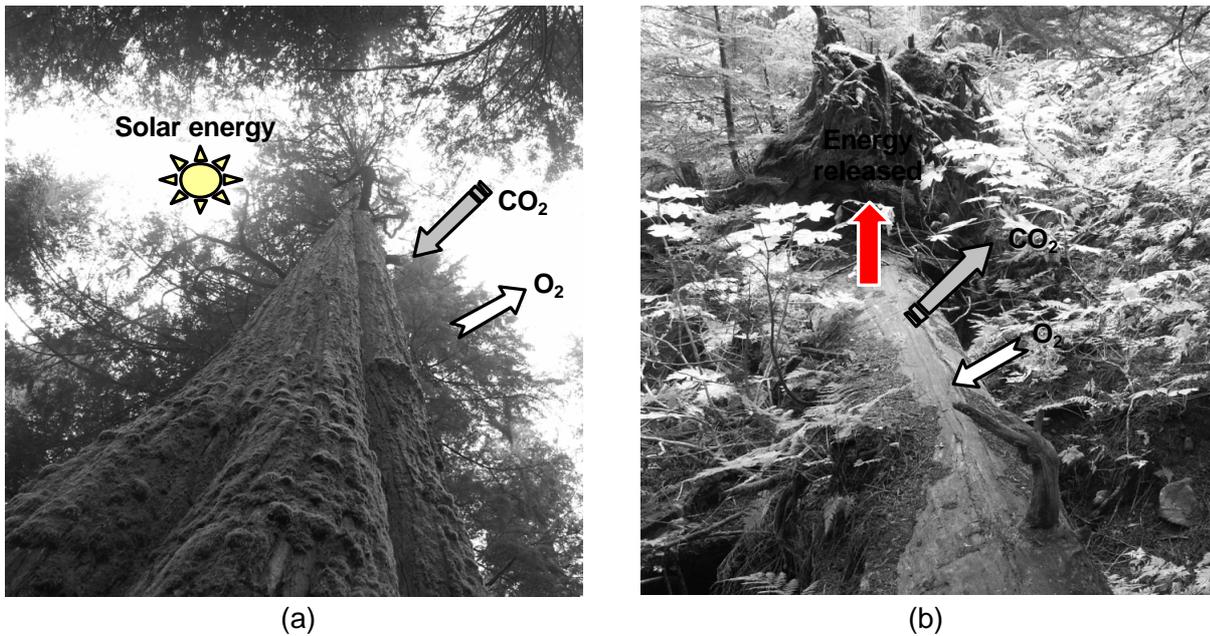


Fig. 2.13 Natural formation (a), and the normal aerobic decay (b) of carbohydrate material

Consider, though, the unusual circumstance of the living carbohydrate material suddenly finding itself in an **anaerobic** environment in which it no longer has access to oxygen. This can and has happened naturally through chance circumstances such as mud slides, flooding, and sinking to the floor of the ocean. In such an environment the reverse decay cannot occur so that the stored chemical energy remains locked in place and will stay there until somebody or something comes along and literally allows it to see the light of day again. We're talking here about events that took place long, long ago over a period of several million years. In the intervening period, the stored carbohydrate material has been subjected to considerable geological stress which has refined its structure and physical properties to some extent, but the all-important chemical energy in its atomic bonds has remained essentially intact. These carbohydrate materials are our coals, oils, natural gases, oil shales, etc. of today.

This purely-by-chance method of storing chemical energy continues to some extent even today but it has always been a very pedestrian process. In fact if we total up the amount of chemical energy estimated to have existed in all forms of fossil fuels (before we started extracting them at an accelerating rate) and divide this by the 600 million years or so during which those fuels were formed, the historical average rate of energy deposition is only around 12 MW. This may sound a lot but, when it is reduced to a per capita basis (2 **milliwatts**) and compared with the rate at which each of us consumes all forms of energy today (approximately 2.2 kW, averaged over the world's population, with some so-called developed societies around 10 kW continuous per capita), the insignificance of this as a continuing source of energy is frighteningly apparent – particularly when we add in the fact that the world derives around 80% of its energy from fossil fuels. Not surprisingly, then, fossil fuels are regarded as non-renewable energy resources.

The very low *energy* lay-down rate of fossil fuels does not, however, prevent us from extracting extremely high *power* outputs from them: to do this, all that is required is to release the stored chemical energy (by combustion) within a time period which is extremely small in comparison with the time taken for that chemical energy to be deposited originally. Remembering the simple relationship between energy, power and time, the original chemical energy is obtained by integrating a very small power input over a very long period of time. If, in reverse, we release that stored energy over a very short time period, the power output is then much greater than the original power input level. This is in marked contrast to the hydrological cycle in which a very large area ratio was the means of stepping up the power level. It is the fact that we need to compress the time taken between energy collection and energy release to get an acceptable power output from fossil fuels that means that they are non-renewable whereas tapping into the hydrological cycle gives us a renewable resource.

Both these natural energy transformation processes give us some feel for different energy forms and how some energy transformations occur. In such natural processes we have little concern, and certainly little control over the efficiency – that is the ratio of energy output in the required form to original energy input - with which the transformations occur but when we try to convert energy forms ourselves, efficiency is a very important consideration as we shall discover later.