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# INTRODUCTION TO ENERGY

*No one is going to repeal the second law of thermodynamics, not even the democrats.* - Kenneth Boulding

## INTRODUCTION

Energy is involved in all physical systems, including the growth and maintenance of living organisms. The organisation of human settlements within an ecosystem is totally dependent on a sufficient flow of energy provided by technology. Studies of energy flows within human settlements are needed to enable better understanding of a transition from growth to steady state so that appropriate measures can be undertaken to alleviate the transition period.

## ENERGY LAWS

All forms of energy are inter-convertible and when conversions occur, they do so according to rigorous laws of exchange. The concepts of classical thermodynamics were derived and defined as the results of experiments in which macroscopic visible-to-the-eye properties of classical thermodynamics such as temperature, pressure, and volume could be measured directly. The principles and laws of classical thermodynamics were formalised by Clausius (1867) who based his work on the earlier writings of Rumford, Mayer, Joule, and Carnot.

### Work and heat

In thermodynamics, a sub-field of physics, the words 'energy' and 'work' have precise definitions with meanings which differ from colloquial use of these words. *Energy* is defined as 'the ability to do work on other bodies or as 'stored work'. *Work* is said to be done on a system if that system experiences a displacement as the result of a force parallel to, and in the same direction as that force. It is meaningless to talk of 'work in a system' or 'work of a system'. In thermodynamics, work is a macroscopic concept that refers to an interchange of energy between a system and its surroundings. There is a decrease in energy of a system when positive work is done by that system, unless there is some other energy transfer.

Work depends on the particular process by which a system is taken from a reference state to a second state. A result of mechanical work on, or by, a system can be a change in kinetic energy, a change in potential energy of the system as in the case of compressing a spring, or dissipation into heat as in the case of boring out the centre of a cannon.

'Heat' is defined as that energy which is transferred between a system and its surroundings solely by virtue of a temperature difference. An early 19th century theory incorrectly regarded heat as a liquid called 'caloric'. It is incorrect to refer to 'heat in a body' because heat is not a substance. Heat is energy in transit.

The unit of heat energy is the calorie which is defined as that amount of heat whose absorption by 1 gm of water at constant atmospheric pressure is accompanied by a temperature rise from 14.5 to 15.5 °C. Calories with a capital 'C' is a unit which is used by nutritionists to describe the energy stored in food and one Calorie is equal to one kilocalorie (1,000 calories) with a small 'c'.

The mechanical equivalent of heat is the joule where 4.185 joules is the amount of mechanical work required to effect the same change in state as that produced by the absorption of one calorie of heat. The units of Calories, calories, and joules are all units of heat energy, and each unit can be converted from one unit to another using a conversion factor.

One watt (W) is a unit of power as opposed to energy, being the rate of one joule of energy flow per second. One kilowatt (1 kW) being 1,000 watts is a more appropriate unit to describe electricity consumption. One kilowatt hour (kWh) is a unit which describes the electrical energy consumption by a household or firm at the rate of one kilowatt over one hour. This energy consumption can be converted to joules by multiplying the unit of power (watts) by the unit of time (seconds):

One kilowatt hour = 1,000 watts x 60 minutes x 60 seconds = 3,600,000 joules ($3.6 \times 10^6$ joules) or 3.6 megajoules (3.6 MJ)

**First Law of Thermodynamics - Conservation of Energy**

The First Law of Thermodynamics is also known as the Law of Conservation of Energy and can be stated as:

> *Energy may be transformed from one form into another, but energy is neither created nor destroyed.*

The First Law of Thermodynamics rules out any possibility of a perpetual motion machine of the first kind – a machine that will put out more energy in the form of work than is absorbed in the form of heat. Many attempts have been made to construct a perpetual motion machine and have failed.

**Second Law of Thermodynamics**

For a heat engine to be 100% thermally efficient, the engine is required to reject no heat to a reservoir. This requirement has proved to be a physical impossibility. The energy of heat comprises the internal energy of random molecular motion as opposed to the ordered kinetic motion of mechanical work. It is not feasible to completely convert the random molecular motion of heat to ordered molecular motion of mechanical work because the motions of each individual molecule would need to be fully controlled. Furthermore, part of the portion of heat that can be converted into mechanical work dissipates to the heat form of energy due to the unavoidable friction present in all machines. The degree of convertibility of energy - stored work - into applied work is often called availability. The Second Law of Thermodynamics can be stated as:

> *All physical processes proceed in such a way that the availability of the energy involved decreases.*

The Second Law of Thermodynamics is not deduced from the First Law of Thermodynamics, but stands as a separate law of nature. The First Law of Thermodynamics denies the possibility of creating or destroying energy, but does not preclude the possibility of running a power station that extracts heat from the atmosphere. The Second Law of Thermodynamics denies any possibility of perpetual motion of the second kind whereby a machine utilizes the internal energy of one, and only one, heat reservoir.

The Second Law of Thermodynamics may appear equally simple to understand as the First Law of Thermodynamics, but the Second Law of Thermodynamics is very deceptive (Andrews, 1980) and there are many far reaching implications which connect back to this law. An outcome of the Second Law of Thermodynamics is that all forms of energy ultimately degrade into dispersed heat energy. There is no process whose sole result is the complete transformation of energy into another form of energy which is of higher grade than heat. This is why it is impossible to drive a steamship across the ocean by extracting heat from the ocean or why the perpetual motion machine does not exist. In other words, there are some fixed limits to technological innovation, placed there by fundamental laws of nature.

**Entropy**

In a low entropy system the energy is free in the sense that it is available for producing mechanical work, whereas in a high entropy system the energy is said to be bound. Lord Kelvin first developed the principle of the degradation of energy which states because all natural processes dissipate energy to heat, energy is continually becoming unavailable for work. Within the isolated system of the Universe there is a continuous and irrevocable degradation of free into bound energy.

The change in entropy for reversible and irreversible processes is formalized by the Second Law of Thermodynamics, the law of entropy, which states:

> *When all systems taking part in a process are included, the entropy S of the total system either remains constant or increases.*

In mathematical terms:

$$\Delta S \ \text{(universe)} \ \geq \ 0.$$

An open system may exchange both energy and matter with the outside, whereas a closed system exchanges only energy and not matter with the outside. Although the entropy of an isolated system remains either constant or increases, the entropy of open sub-systems may decrease. Life forms are an example of low entropy systems which, in order to retain the form of low entropy, need to continually take in energy and matter in the form of food and consume more than one unit of food in order to gain one unit in weight. During periods of increase in size and numbers, the entropy of living organisms decreases while the entropy of the combined system, which includes their life support systems, simultaneously increases. Contrary to being a violation to the law of entropy, life forms comprise systems that hasten the increase of entropy in the universe (Schrödinger, 1967, pp. 73-7).

**Entropy as a measure of order and disorder**

There are many different forms and interpretations of the law of entropy that incorporate the statistical mechanics concept of entropy as comprising a measure of order and disorder. In developing the kinetic theory of gases, Maxwell (1871) set up a model depicting the molecules of a gas as bounding in all directions and velocities off each other and the walls of a perfectly elastic container. Along with Boltzmann (1877), he developed an equation which showed that the distribution of molecular velocities of a gas at a particular temperature comprised a few molecules moving very slowly or very quickly with the larger percentages moving at intermediate velocities. A rise in temperature causes the average velocity of the molecules to rise – an increase in the kinetic energy of the molecules – while a drop in temperature caused the average velocity to fall. Mechanical work, as opposed to the haphazard motions of individual molecules against intermolecular forces, involves the orderly motion of molecules. Whenever mechanical work is dissipated into heat, the temperature of the system rises and the disorderly motion of molecules increases.

The kinetic theory of gases pictures temperature and heat as involving molecular movement and an interpretation of the Second Law of Thermodynamics as being a tendency for nature to proceed from a state of order to disorder thus providing a qualitative and supplementary understanding of the laws of classical thermodynamic.

The Law of Entropy can be stated as:

> *In spontaneous processes, concentrations tend to disperse, structure tends to disappear, and order becomes disorder.*

There is a degree of similarity between statistical mechanics and quantum theory. Both theories have an explanatory and predictive value relating to microscopic phenomena and utilise the theory of probability. However, by making use of probability theory, statistical mechanics allows the possibility of water being able to spontaneously separate into a hotter and colder region. Human experience denies this possibility. According to statistical mechanics, even though this possibility is very small and may not occur within the time frame of any human experience, the possibility nonetheless exists.

Shannon and Weaver (1949) also used the theory of probability in the development of information theory in response to a study of how to most efficiently transmit a signal of information through telephone lines subject to noise interference. Shannon used the term 'entropy' to describe the measure of the 'amount' of information in the transmission of a signal perhaps on the basis of similarity in mathematical form to Boltzmann's equation for thermodynamic entropy. The information theory use of the term ‘entropy’ would seem to be metaphorical rather than a relationship of process because entropy is a measure of order and disorder in statistical mechanics, whereas the meaning of a message is irrelevant. The concept of entropy has also been utilised to define the arrow of time as being in the same direction as followed by all natural processes due to dictates of the Second Law of Thermodynamics (Coveney & Highfield, 1990).

Georgescu-Roegen (1971) regards Boltzmann's statistical approach to entropy opens the door to vacuous interpretations of what entropy means and that statistical mechanics is logically flawed by being underpinned by classical mechanics which denies qualitative change in the universe. The position adopted by Georgescu-Roegen is that entropy is neither reducible to locomotion nor to probability nor any subjective element. According to Georgescu-Roegen (1971, p. 9):

> “The entropic phenomenon of a piece of coal burning irrevocably into ashes is neither a flow of probability from a lower to a higher value, nor an increase in the onlooker's ignorance, nor man's illusion of temporal succession.”

The law of entropy was derived as a physics of the economic use of heat in an engine and not from the principles of classical mechanics that reduces all phenomena to reversible locomotion. As Georgescu-Roegen (1971, p. xiii) emphasises:

> “...the discovery of the Entropy Law brought the downfall of the mechanistic dogma of classical physics which held that everything which happens in any phenomenal domain whatsoever consists of locomotion alone and, hence, there is no irrevocable change in nature.”

The First Law of Thermodynamics does not contradict the laws of mechanics, but the Second Law of Thermodynamics, the law of entropy, is in direct contradiction with the laws of classical mechanics in that the law of entropy introduces the element of an irrevocable qualitative change when systems undergo any process.

**The grading of an energy source**

Different forms of energy differ in their ability to do useful work. A calorie of dispersed heat cannot do any work. Sunlight must first be concentrated to be able to do useful work. However, different kinds of energy are not equally convertible into useful work. It takes energy to concentrate energy. Some energy must be degraded in order to concentrate what is left.

Energy in forms having high availability is called high grade energy. Low grade energy is the energy which only a small fraction can be converted to applied work. An example of high-grade energy is the energy stored in fossil fuels and electricity. Sunlight is an example of low-grade energy. Thermal energy is a special case. The greater the difference between the heat source and its environment, the greater is the availability. The hot core in a nuclear reactor is energy of high availability while that of a domestic radiator is of low availability or low-grade energy.

The grading of an energy source can be classified in terms of the energy level of the source – a measure of its energy intensity in terms of energy per unit mass – and its energy grade that is a measure of energy quality. A high energy level system has the characteristics of high temperature, pressure, or enthalpy (heat of combustion).

The energy grade of a source can be separated into either work forms or heat forms of energy. Work forms of energy include mechanical work, electrical energy, waterpower, wind power, and the kinetic energy of a jet stream. Because work can be completely transformed into heat – the reverse transformation of heat cannot completely transform heat into work due to the Second Law of Thermodynamics – work forms of energy are given a higher classification than heat forms. This distinction becomes less significant with high temperature sources of energy.

Heat forms of energy – heat from fusion/fission, heat from combustion, and heat from friction – are graded in descending order according to the temperature of the source. The energy grade of a source serves to qualify the energy level. When two energy sources have the same level but different grades, the ordering of the lower grade source can be adjusted downwards to reflect a lower availability.

**Efficiency of energy conversion**

We are concerned with how efficiently energy is used in transport, industry, agriculture and many other processes. By using energy in efficient ways, not only do we use less of our non-renewable resources, but also less energy ends up in the environment as low grade heat.

When energy is transformed from one form to another, each transformation is accompanied by a degradation of energy due to the Second Law of Thermodynamics. The efficiency of energy conversion is the ratio of the desired output energy, or work, to the necessary input energy, a ratio that can range from about 5% for an incandescent light bulb.

Moore (1981) recommends the following guidelines to ensure that the conservation of free or available energy is maximised when energy is supplied in a converted form in order to carry out a task.

- Firstly, there should be a minimum number of energy conversion steps. Each unnecessary energy conversion step involves an unnecessary loss in free energy because there is a severe penalty in transforming the energy of heat into mechanical work.
- Secondly, heat should be converted into work at the highest possible temperature and should be undertaken only once.
- Thirdly, the direction of any series of energy conversion processes should proceed from those with maximum conversion efficiencies to those with a lower efficiency of conversion.
- Fourthly, energy should ideally be stored in work reservoirs such as compressed air, mechanical springs, and pressurised liquids because such devices provide the potential for minimal energy storage loss.

**First and second law efficiencies**

The first and second law efficiencies are measures of the efficiency in carrying out a specific task such as heating or lighting a building or providing a transportation network.

The first law efficiency is the ratio of the energy delivered by the process in the form and location necessary to achieve that task to the amount of energy supplied to the process. The first law efficiency can be used as a measure of energy conservation in carrying out a task, but in doing so the quality of energy conserved is not taken into account. There no differentiation between energy losses caused by imperfections in the energy conversion process and energy losses due to the Second Law of Thermodynamics cannot be avoided even by perfect technology. These factors are included in the second law efficiency.

The second law efficiency is the ratio of the minimum amount of available energy required to carry out a task to the actual amount of available energy used. The second law efficiency is a measure of how much the performance of a task falls short of what is theoretically possible, and can be used as a measure of the conservation of free, or available energy in carrying out a task.

An examination of the task of heating a house provides an illustration of the difference between first and second laws efficiencies. In an example provided by Ehrlich et al. (1977), a standard furnace is able to deliver 1 unit of energy for heating a house for every 1.5 units of energy extracted from its fuel. The first law efficiency is

$$\frac{1 \text{ unit of heat}}{1.5 \text{ units supplied}} = 67\ \%.$$

By using the most efficient Carnot heat pump where the Coefficient of Performance (COP) is solely dependent on the temperature difference inside and outside the house, the minimum amount of available work required to deliver 1 unit of heat is 0.07 units. The available work in a chemical fuel is approximately equal to its heat of combustion or enthalpy. The available work used by the furnace remains at 1.5 units. The second law efficiency is

$$\frac{0.07 \text{ units minimum available work}}{1.5 \text{ units available work of furnace}} = 4.7\ \%.$$

The second law efficiency is based on comparing actual processes with idealistic processes that do not necessarily include a realistic time frame. There is a trade-off between efficiency and power. An infinitesimally slow reversible process may be carried out with maximum efficiency, but with a penalty of a power output approaching zero. A very rapid process, on the other hand, approaches a maximum power input but at zero efficiency and zero power output. Life forms and the activities of humankind require energy processes to be carried out at an intermediate range of rates that fall well short of the maximum second law efficiency. Odum & Pinkerton (1955) proposed that natural systems tend to operate at an efficiency that produces a maximum power output but Peet & Baines (1986) caution that although the maximum power principle represents deduction from a wide range of empirical observations, its universality has yet to be proved or generally accepted.

**REFERENCES**

Andrews, F.C. *Clarification and obfuscation in approaching the laws of thermodynamics*. Washington D.C., American Chemical Society, 1980.

Boltzmann, K. *On the Relation of a General Mechanical Theorem to the Second Law of Thermodynamics*, English translation from Sitzungsberichte der kaiserlichen Akademie der Wissenschaften, Vienna, 1877.

Clausius, R. *The mechanical theory of heat, with its applications to the steam-engine and to the physical properties of bodies.* London, Van Voorst, 1867.

Coveney, P. and Highfield, R. *The arrow of time: A voyage through science to solve time's greatest mystery.* London, W. H. Allen, 1990.

Ehrlich, P.R., A.H. Ehrlich and J.P. Holdren. *Ecoscience Population, Resources, Environment.* San Francisco, W.H. Freeman & Co., 1977.

Georgescu-Roegen, N. *The Entropy Law and the Economic Process.* Cambridge, Massachusetts, Harvard University Press, 1971.

Maxwell, J.C. *A theory of Heat*. London, Longman, 1871.

Moore, D.F. *Thermodynamic principles of energy degrading.* London, MacMillan Press, 1981.

Odum, H.T. and Pinkerton, R.C. 'Time's speed regulator: The optimum efficiency for the maximum power output in physical and biological systems', *American Science*, v. 43, 1955, pp. 331-43.

Peet, N.J. and Baines, J.T. *Energy Analysis: A review of Theory and Practice*. Auckland, NZERDC Publication No 126, 1986.

Schrödinger, E. *What is Life? Mind and Matter.* London, Cambridge University Press, 1967

Shannon, C.E. and Weaver, W. *The mathematical theory of communication*. Urbana, University of Illinois, 1949.

**RECOMMENDED READING** ***publications to be added