A PRIMER ON THERMODYNAMICS AND ENERGY ANALYSIS

Ivan M. Johnstone BSc (Physics), BARCH (Hons), PHD

Former Senior Lecturer, Department of Property, The University of Auckland

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

THERMODYNAMICS

introduction

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 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’.

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 gram (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 (3.6×10^6 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 energy is continually becoming unavailable for work because all natural processes dissipate energy to heat. 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 thermodynamics.

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.

ENERGY ANALYSIS

Introduction

In 1973 the OPEC oil embargo resulted in sharp increases in the price of oil throughout the world. This prompted many Governments to commission research on energy. The New Zealand Energy Research and Development Corporation (NZERDC) was established in 1974 and 309 research publications on issues of energy were published from 1974 to 1988.

In August 1974 the International Federation of Institutes for Advanced Study (IFIAS) held the first workshop on Energy Analysis to discuss the need for consensus on conventions and recommendations for further work (IFIAS, 1974). Four main approaches to the research field of Energy Analysis can be categorised as follows (Pearson, 1977):

a) Input-output Analysis

b) Process Analysis

c) Second Law Efficiency

d) Energetics

All approaches are valid, but a major advantage of Energetics is that it uses a general systems approach and circuit language diagrams to describe and analyse energy flows. Use of such diagrams enables easier understanding of the energy flows of systems. A similar general systems and diagramming approach is now used by modern day dynamic simulation modelling software such as AnyLogic, Stella, and Vensim. In this book I use Energetics symbols and diagrams to help explain the role of energy which flows through human settlements.

History of Energetics

Energy is involved in the transformation of all physical systems, including the growth and maintenance of different forms of life. Energy flows in ecosystems had been studied for many years by biologists before the 1970s and the discipline of Ecological Energetics was documented by John Phillipson (1966) in his book of the same title. Human settlements also form ecosystems through which energy and materials flow. The organisational patterns of human settlements are interrelated with these flows of energy and materials. An understanding of these flows within human settlements is essential to enable better planning for a transition from growth to steady state. Energetics provides the necessary tools to enable better understanding.

Energetics, as promoted by Howard Odum of Florida University, is a general systems development and extension of Ecological Energetics as applied to both ecosystems and human settlements. Energetics became a discipline in its own right when Howard Odum pointed out that "industrial man no longer eats potatoes made from solar energy; now he eats potatoes partly made of oil" in his book *Environment, Power, and Society* (1971). A full development of Energetics was published in Howard Odum's book *Ecological and General Systems: An Introduction to Systems Ecology* (1983).

Energy Flows

The study of energy flows within ecosystems is based on the First and Second Laws of Thermodynamics. The different types of energy flow can be categorised as follows (Adams, 1975, p. 115-8):

- Flow as transport and storage of matter: The flow of materials moving through an ecosystem, including storage.
- Flow as transduction and radiation of energy: Solar and thermal radiation, evaporation, convection, and conduction.
- Flow as conversion from one state to another: Examples include burning of fuel, photosynthesis, and water becoming steam.
- Flow as an energy cost of triggering energy release: For example, the energy of one system (human action) applied to the environment of a second system which releases greater energy (energy production).

Energetic Symbols

The following symbols and diagrams used by Odum (1976) help us to visualise the laws and flows of energy within ecosystems by introducing the idea of an ecosystem as a combination of interacting parts. The symbols might be familiar to those who have studied electronics or dynamic systems analysis.

The *Energy Circuit* symbol shows the direction and flow of energy from a *Source* of energy or a unit such as a *Storage Tank*.

Figure 1: Energy Circuit Symbol

The *Source* symbol is used for sources of energy that are external to the system under examination. The flow of energy from an energy source might be steady and constant such as that from a hydroelectric dam or intermittent such as that from wind turbines or photovoltaic panels.

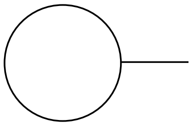

Figure 2: Source Symbol

The *Storage Tank* symbol represents a stock of energy such as fossil fuels in the ground, petrol in the tank of a car, the embodied energy stored in a building, the repository of information, water, and minerals in the ground.

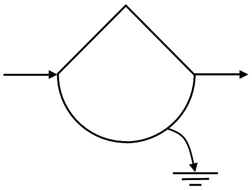

Figure 3: Storage Tank Symbol

The *Heat Sink* symbol, an arrow pointing down into the ground, represents the loss of degraded energy from a system and the depreciation and degradation of that system as the material of the system becomes dispersed. All *Storage Tanks* have a *Heat Sink* as a result of the Second Law of Thermodynamics.

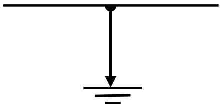

Figure 4: Heat Sink Symbol

The *Interaction* symbol*:* All processes involve the interaction of two or more types of energy and matter. All *Interactions* also have a *Heat Sink* as a result of the Second Law of Thermodynamics.

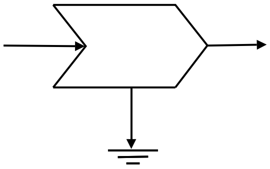

Figure 5: Interaction Symbol

The *Money Transaction* symbol represents the flow of money in the opposite direction to pay for the flow of embodied energy and materials contained in goods and services. Price is shown as an external source.

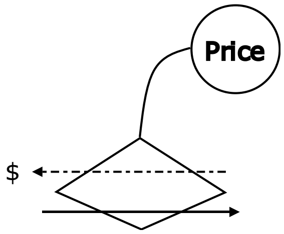

Figure 6: Money Transaction Symbol

The *Producer* symbol represents the processes, interactions, and storages that collects and transform low-quality energy into high-quality energy flows. An example is the process of photosynthesis where biomass is produced from diffuse solar energy.

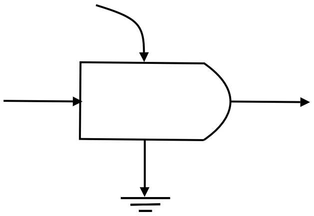

Figure 7: Producer Symbol

The *Self-Interaction* symbol represents processes where self-interaction results in a faster action that would otherwise take place. An example is where the interaction of a group of people building a house results in a quicker build than when each person works simultaneously alone without any interaction.

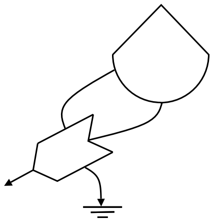

Figure 8: Self-interaction symbol

The *Consumer* symbol represents a system that maintains itself by using *Storage Tanks* and *Interactions* to make use of inflowing energy and materials. Examples include an organism, or a town and a city.

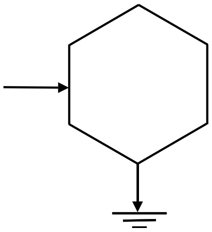

Figure 9: Consumer Symbol

The *Miscellaneous* symbol is used for subsystems as labelled.

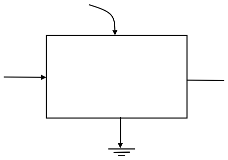

Figure 10: Miscellaneous Symbol for sub-systems

Figure 11 shows the flow of energy embodied in goods and services from a town to a farm which produces food for the town using energy from the sun.

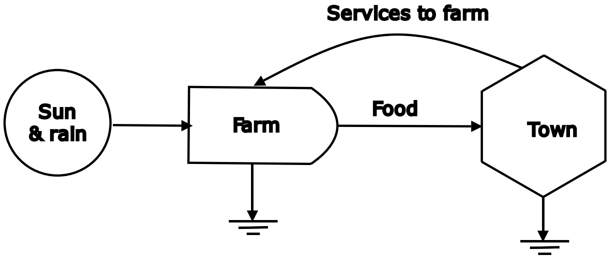

Figure 11: Example of flow of energy from farm to town (Odum, 1976, p50)

Figure 12 shows that energy is used to run processes and maintain order on a farm. Heat energy is dispersed whenever work is done on the farm. Farm buildings and machinery undergo depreciation and require maintenance. The fertility of the soil declines unless replenished with natural or artificial fertilisers.

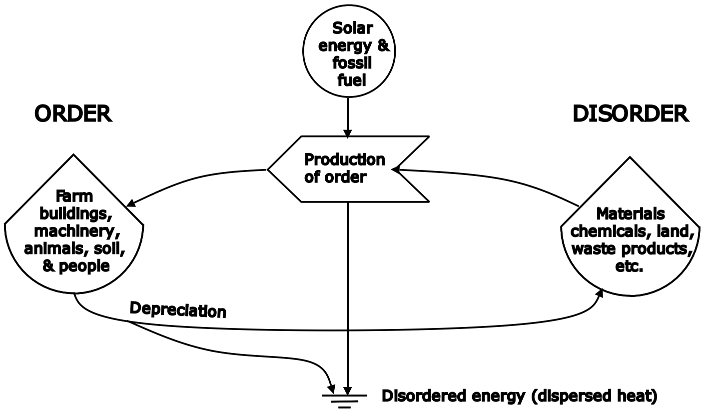

Figure 12: Example of the order – disorder cycle (Odum, 1976, p40)

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. Figure 13 shows the scale of quality of energy and some of the conversion factors for going from one form of energy to another. These factors include the energy cost of any machinery that the conversion process might require.

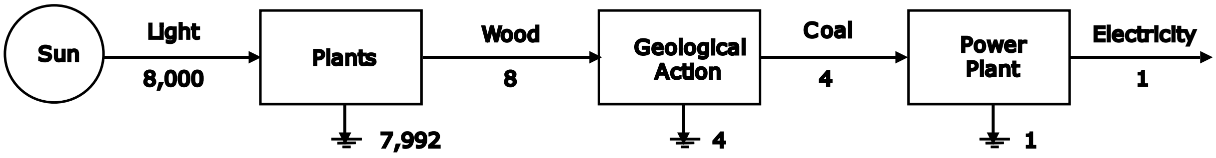

Figure 13: Scale of Energy Quality (Odum, 1976, p32)

The degree of convertibility of energy - stored work - into applied work is often called availability. 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.

Figure 14 shows that human activity is involved with the conversion of low-grade energy to high-grade energy. This high-grade energy has greater availability to do useful work.

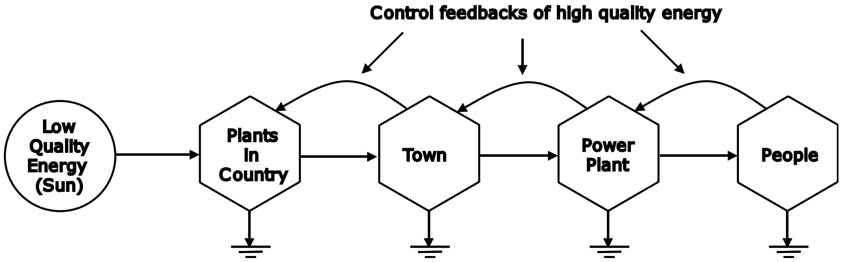

Figure 14: Energy Conversion (Odum, 1976, p77)

High-grade energy can be used in conjunction with a larger flow of low-grade energy to produce high-grade energy. Figure 15 shows a flow of 10 units of high-grade energy being used to transform a flow of 100 units of low-grade energy into a flow of 20 units of high-grade energy. During the transformation process a flow of 90 units of heat energy is generated.

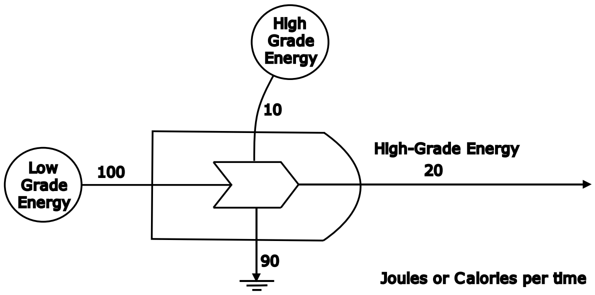

Figure 15: High grade energy acting as an amplifier of low-grade energy (Odum, 1976, p78)

Figure 16 shows a flow of 10 units of high-grade energy being transformed into a flow of 2 units of medium-grade energy. During the transformation process a flow of 8 unit of energy is generated. High-grade energy is wasted if it used for purposes which can be provided by using low-grade energy. An example is using an electric bar heater to heat a room in a home when passive solar house design can achieve the same result.

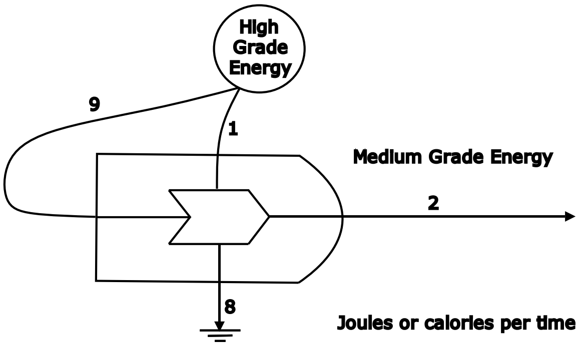

Figure 16: Wasteful use of high-quality energy to produce medium-quality energy (Odum, 1976, p78)

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. Work can be completely transformed into heat, but the reverse transformation of heat cannot completely transform heat into work due to the Second Law of Thermodynamics. Work forms of energy are therefore 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.

Exergy

Exergy is available energy, the maximum fraction of an energy form which, in a reversible process, can be transformed into work. Exergy analysis quantitatively evaluates and detects thermodynamically inefficient processes of energy production and transformations. Exergy can also be applied to take into account the quality of minerals used as resources to manufacture goods. Diluted or dispersed minerals in the ground are more difficult to mine, collect, and refine than more concentrated sources. A measure which takes the concentration of minerals into account is its chemical potential or chemical exergy. For example, the chemical potential of pure iron is much higher than the chemical potential of an iron ore diluted by other rocks.

A standard reference point of exergy is needed for different natural minerals in the ground, and hence the concept of ‘Thanatia’ which is a hypothetical version of our planet Earth where all mineral deposits have been exploited and their materials have been dispersed throughout the crust. With Thanatia as a reference level, the exergy of different minerals in the ground can be estimated and compared. By adding up all the exergy expenditures of mining and refining, the rarity of minerals and their embodiment in final products can be assessed.

There can be no production of goods and services without exergy destruction. Unlike energy, exergy is not subject to the law of conservation. Loss of natural resources is an objective physical reality which cannot be fully expressed using subjective monetary valuations. Loss of natural resources also cannot be expressed in terms of weight or energy alone, as these measures do not fully capture quality and value. The ‘exergy cost’, the embodied exergy of any material which takes the concentration of resources into account measured with reference to the ‘dead state’ of Thanatia is a measure of the loss of natural resources. An exergy destruction footprint can be established for same-purpose products which use different resources and processes during manufacturing and the full life cycle of maintenance, replacement, and recycling. By using exergy analysis, better choices of resources and processes can be rationalised before production begins.

Emergy

Emergy is the total energy used or embodied in the life cycle of a product in terms of the available energy of one kind that is used to directly and indirectly to make a product or service. Emergy is measured in units of emjoules or emcalories, units that refer to the available energy consumed in transformations. The type of energy is arbitrary and Emergy can be measured in terms of fossil fuel equivalents (FFE), electrical energy (MJe), or Solar Energy (seJ). Different products and processes make use of different forms of energy, each of which give rise to different levels of CO_2 contributions to the atmosphere. Use of Emergy alone is therefore inadequate for making true comparisons of the environmental impact of different products. The same applies for Exergy.

First and Second Law Efficiencies

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 with subsequent reductions in greenhouse gas emissions, but also less energy ends up in the environment as low-grade heat.

The first law efficiency is the ratio of the amount of energy delivered to perform a task to the amount of energy that must be applied to achieve this task. This first law approach is concerned only with the efficiency of one particular method of performing the task and disregards alternative methods which may perform the same task with less energy consumption. The second law efficiency, on the other hand, is the ratio of the minimum amount of available work needed to perform a task to the actual amount of available work used to perform this task. The second law efficiency approach focuses on the task at hand and gives a measure of how much improvement in performance is theoretically attainable.

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 is no differentiation between energy losses caused by imperfections in the energy conversion process. 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 <u>minimum</u> amount of available energy required to carry out a task to the <u>actual</u> 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 (exergy) 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 can 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.

Moore (1981) recommends the following guidelines to ensure that the conservation of free or available energy (exergy) 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.

Net Energy

All processes aimed at producing high-grade energy in the form of fuel, goods, and services involve the use of high-grade energy. In previous sections, low-grade energy of the sun was shown to be upgraded by the interaction of this incoming flow of low-grade energy with feedback loops of high-grade energy. In tapping high-grade energy resources such as oil, coal, and gas, high-grade energy in the form of machinery, fuel for machinery, and the expertise and labour of people are used. For each unit of energy extracted from the ground, there is an energy cost involved in doing so. Whether or not the extraction of high-grade energy resources results in net energy depends upon the energy cost of extraction. In some cases, the production of high-grade energy involves heavy subsidies of high-grade energy. An example of this is the oil subsidy in agriculture to produce the energy content in food provided by larger crops as shown in Figure 17.

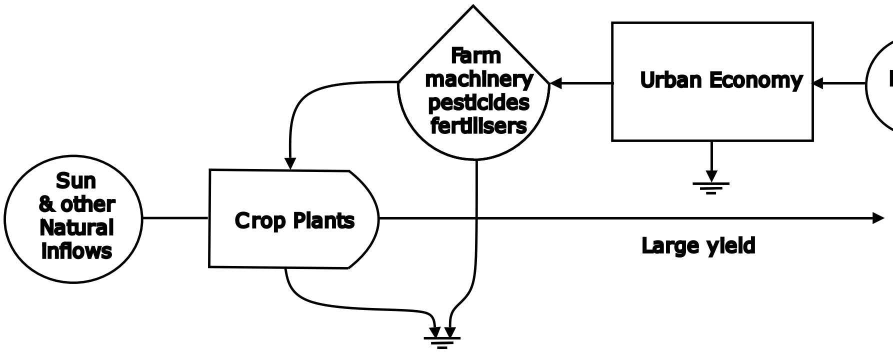

Figure 17: Oil subsidy in agriculture (Odum, 1976, p87)

Beyond a certain level of energy inputs, further energy inputs in the form of fertilisers, pesticides, and machinery result in diminishing returns in crop yields. Because the cost of energy has been small compared to the price received for the crop yield, it has been profitable to continue using cheap energy, even though this is an inefficient way of doing so. A number of farmers are aware of this energy-crop yield relationship and now use less energy in their farming by using permaculture methods. These farmers are able to farm profitably by doing so more energy efficiently.

It is of urgent priority to determine whether current or alternative renewable energy sources generate net energy by taking into account all hidden energy subsidies. Price alone cannot determine whether an energy source can produce net energy. Figure 18 shows an example of a dispersed oil reserve near the end of its life where the energy costs of extracting and refining the oil are high. Energy used in the process still results in a net outflow of high-grade energy.

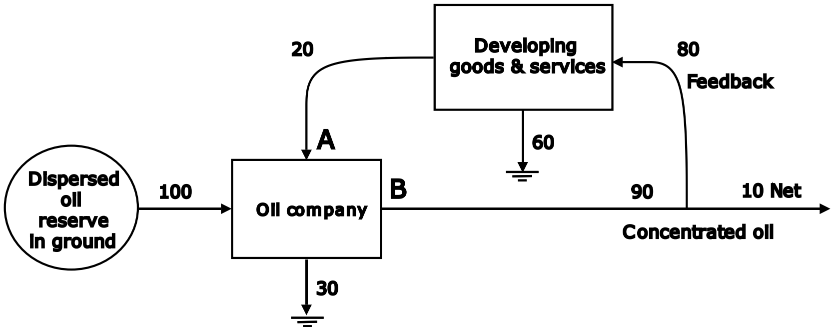

Figure 18: Example of oil reserve near the end of its life (Odum, 1976, p82)

Figure 19 shows an example of a very dispersed oil reserve which is no longer able to produce net energy due to very high energy costs of extraction and refining. To maintain the process, another source of high-grade energy is required to make up for the deficit. The oil reserve can no longer sustain its own extraction and refining.

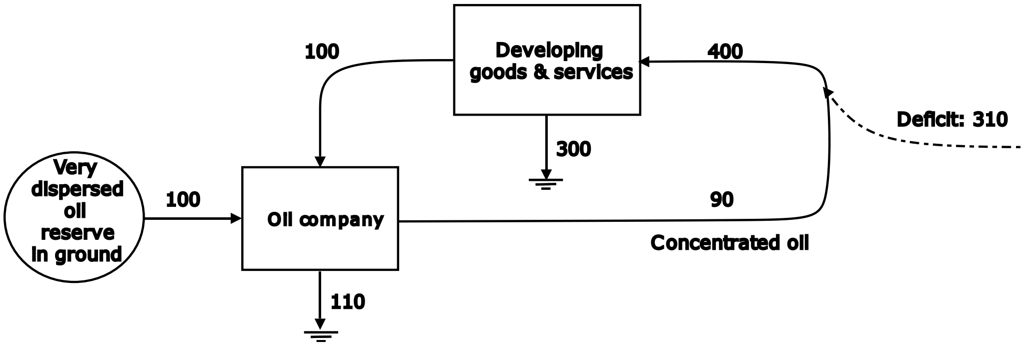

Figure 19: Example of oil reserve which cannot sustain its own extraction and refining (Odum, 1976, p83)

Energy Returned on Energy Invested (EROI)

The energy return on energy invested (EROEI or ERoEI) or energy return on investment (EROI) is the ratio of the amount of usable energy (exergy) delivered from a particular energy source to the amount of exergy used to obtain that energy resource.

$$EROI = \frac{Exergy\ Delivered}{Exergy\ Required\ For\ Delivery}$$

If the EROI of an energy source is less than or equal to 1, then the energy source is an “energy sink” and not a sustainable energy source. Although it takes more exergy to deliver hydrogen than the exergy of the delivered hydrogen, it might be useful in some cases to use hydrogen as a carrier of energy and likewise with the storage of energy in a battery. The Energy Store on Energy Invested (ESORI) is used to analyse energy storage systems.

Criticism of Energy Analysis by Economists

Economists have two main criticisms against the encroachment of Energy Analysis into their field as follows (Pearson, 1977):

a) The price mechanism takes energy and other resource factors into account and is a better tool than Energy Analysis for allocation and decision making.

b) Energy Analysis gives no credit for capital and no allowance is made for improvements in technology.

The first criticism is easily countered. A process might be technically feasible, but is not necessarily viable. Energy Analysis compares different methods of energy generation at a comprehensive level by including externalities that are overlooked or ignored by conventional financial accounting methods. Energy Analysis can show whether a particular method of energy production is not only feasible, but also viable by being truly sustainable in the long term without the need for ongoing energy subsidies of fossil fuels. This applies especially to the technologies of nuclear fission, photovoltaics, wind turbines, battery storage, and bio-fuels.

With regards to the allocation and decision-making of our finite resources of fossil fuels, the price mechanism has clearly failed. The pricing of fossil fuels over the past 40 years has not provided adequate signals of the need to transition from fossil fuels to renewable energy, and nor has it provided any indication of an impending peaking of all forms of fossil fuels.

With regards to the second criticism, it is Energy Analysis and not Economics that indicates the need to transition from fossil fuel based infrastructure to that of infrastructure required by renewable energy. Economics alone cannot determine actual physical limits to technology and resources. Economics alone will not ensure sustainability of our human settlements. Both Economic Analysis and Energy Analysis are needed to guide a transition from growth to steady state.

REFERENCES

Adams, R.N. *Energy and Structure: A Theory of Social Power.* London, University of Texas Press, 1975.

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.

Connolly, T.J. and Spraul, J.R. *Report of the NSF-Stanford workshop on net Energy Analysis.* Stanford, Institute for Energy Studies, 1975.

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.

IFIAS. *Energy Analysis Workshop on Methodology and Convention.* Ulriksdals Slott, Solne, Sweden, 1974.

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

Odum, H.T. and E.G. Odum. *Energy Basis for Man and Nature*. New York, McGraw-Hill, 1976.

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.

Odum, H.T. *Ecological and General Systems: An Introduction to Systems Ecology.* Niwot Colorado, University Press of Colorado, 1984 Revised Edition.

Odum, H.T. *Environment, Power, and Society.* London, Wiley, 1971.

Pearson, R.G. *Energy Analysis.* NZERDC Report No. 30, Auckland, 1977.

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

Phillipson, J. *Ecological Energetics*. London, Edward Arnold, 1966.

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.