ENERGY ANALYSIS & ENERGETICS

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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 between 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, and an understanding of these flows within human settlements is essential to enable better planning for a transition from growth to steady state. 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 in the following way. (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).

The symbols and diagrams used to help us visualise the laws and flows of energy within ecosystems introduce the idea of an ecosystem as a combination of interacting parts. The following symbols used by Energetics 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.

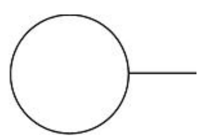

Figure 2 Source Symbol

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.

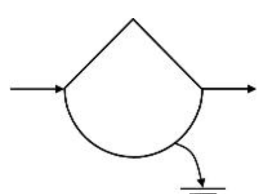

Figure 3 Storage Tank Symbol

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.

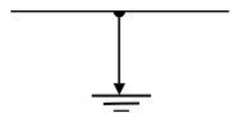

Figure 4 Heat Sink Symbol

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.

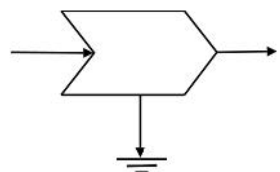

Figure 5 Interaction Symbol

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.

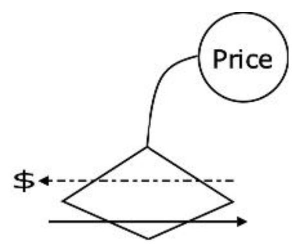

Figure 6 Money Transaction Symbol

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.

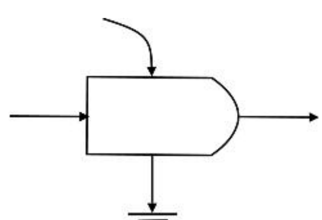

Figure 7 Producer Symbol

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.

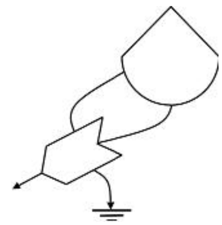

Figure 8 Self-interaction symbol

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 city.

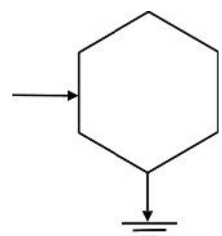

Figure 9 Consumer Symbol

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

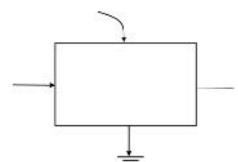

Figure 10 Miscellaneous Symbol for sub-systems

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.

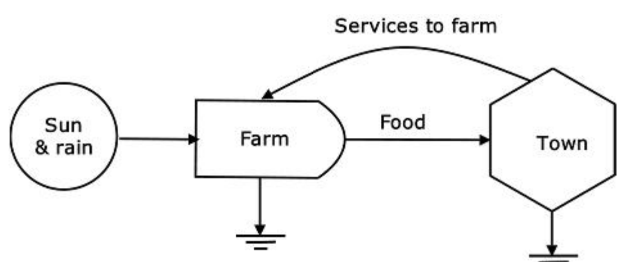

Figure 11 Example of flow of energy from farm to town

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.

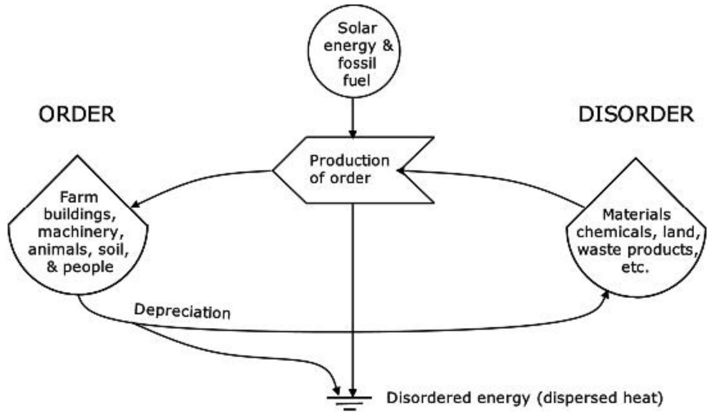

Figure 12 Example of the order – disorder cycle

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.

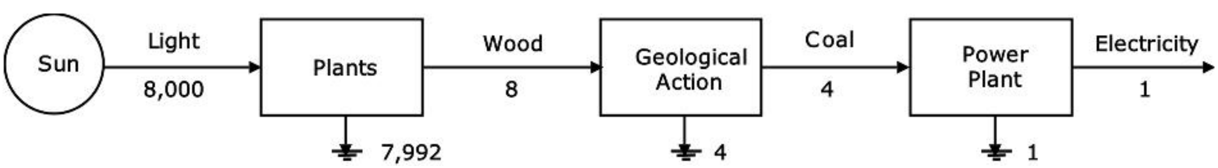

Figure 13 Scale of Energy Quality

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.

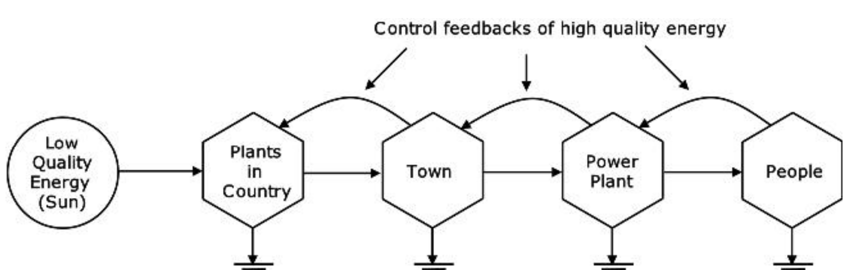

Figure 14 Energy Conversion

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.

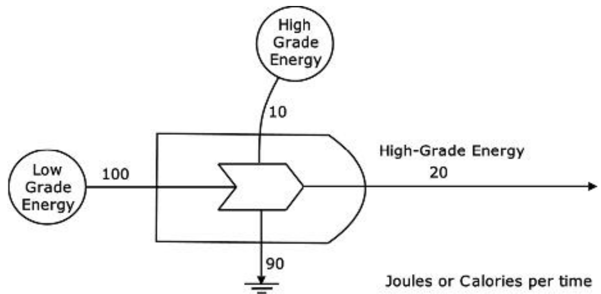

Figure 15 High grade energy acting as an amplifier of low-grade energy

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.

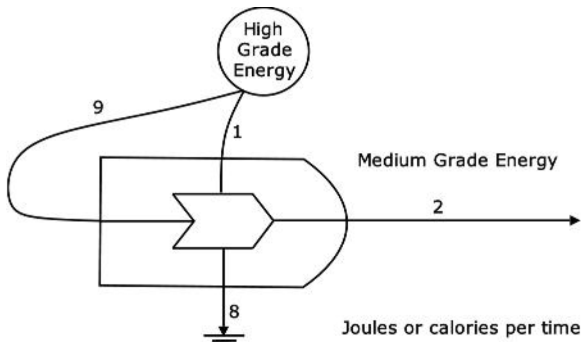

Figure 16 Wasteful use of high-quality energy to produce medium-quality energy

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 has to be used 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, 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.

An outcome of the Second Law of Thermodynamics is that all forms of energy, ultimately degrades 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 a "perpetual motion machine" does not exist. In other words, there are some fixed limits to technological innovation placed there by fundamental laws of nature. The second law efficiency approach focuses on the task at hand and gives a measure of how much improvement in performance is theoretically attainable.

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.

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 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 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 (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 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.

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, 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.

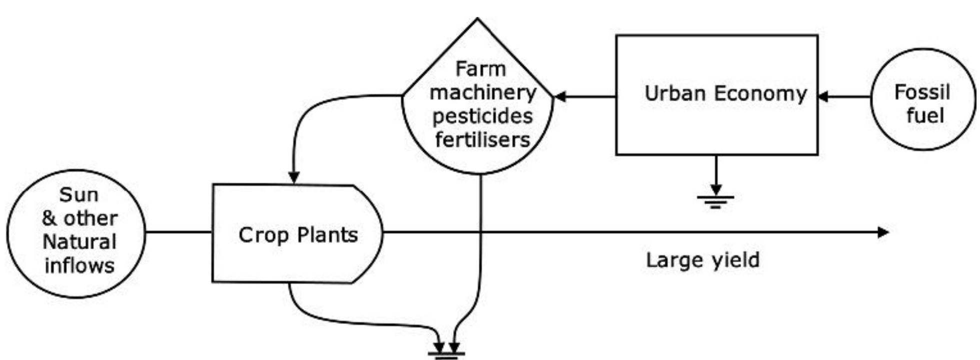

Figure 17 Oil subsidy in agriculture

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. Higher yields allow less land to be used and, as a result, sunlight has been used less and less while fossil fuels have been used more and more. A number of farmers are aware of this energy-crop yield relationship and now use less energy in their farming by using permaculture methods. Crop yields are less, but costs are also less, and these farmers are able to continue farming profitably by doing so more efficiently.

The so-called Green Revolution was largely due to the breeding of new strains of grain and especially the hidden subsidy of crop yields by fossil fuels. In considering the carrying capacity of farmland, the above relationship shows that as population grows and energy resources diminish, food production falls. We have lived in an age where energy has subsidised growth. The time for paying the true costs will occur within the 21st century.

Likewise, 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.

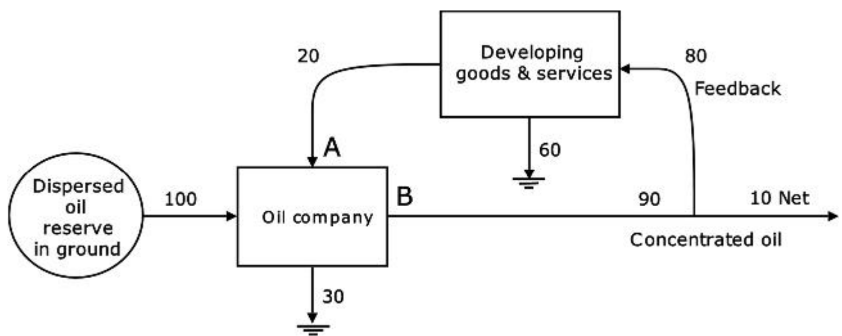

Figure 18 Example of oil reserve near the end of its life

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.

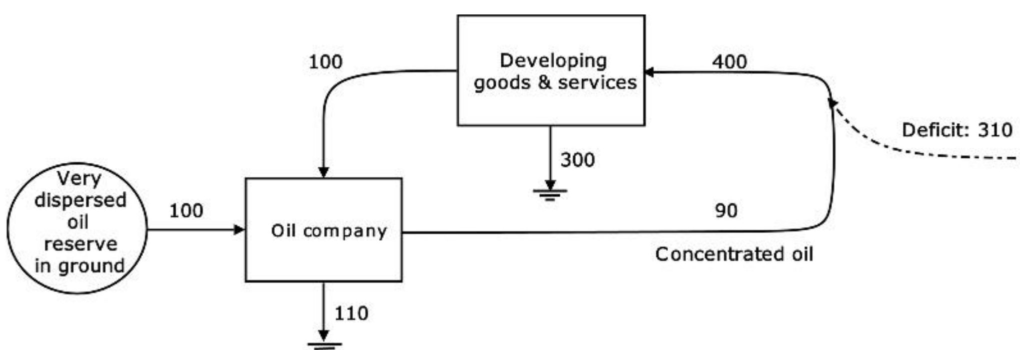

Figure 19 Example of oil reserve which cannot sustain its own extraction and refining

ERoEI (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.

Comparisons of the EROI of different renewable energy sources and the ESORI of different storage systems are addressed in a separate chapter.

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 cannot determine actual physical limits to technology. 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.

SUMMARY *** to be added

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