Lecture 1-Part 1-Energy and the Environment

1.1 Introduction

There are environmental costs associated with the continued use of fossil fuels and these are causing a reappraisal of the way in which energy is used. This lecture investigates the global use of energy and its impact on economies and the environment.

Those of us living in developing countries don’t take energy for granted as compared to those who live in the developed countries. Nevertheless, we may not understand exactly what energy is but we certainly use it. Consider for a moment the number of everyday items of equipment, tools and appliances that run on electricity – lamps, washing machines, televisions, radios, computers and many other ‘essential’ items of equipment – which all need a ready supply of electricity in order to function.

Imagine what life would be like without electricity. Both our home and our working lives would be very different. Indeed, our high-tech, computer-reliant society would cease to function; productivity would fall drastically and gross domestic product (GDP) would also be greatly reduced.

1.2 Politics and Self-Interest

Any serious investigation of the subject of energy supply and conservation soon reveals that it is impossible to separate the ‘technical’ aspects of the subject from the ‘politics’ that surround it. This is because the two are intertwined; an available energy supply is the cornerstone of any economy and politicians are extremely interested in how economies perform. Politicians like short-term solutions and are reluctant to introduce measures that will make them unpopular. Also, many political parties rely on funding from commercial organizations. Consequently, political self-interest often runs counter to collective reason.

It is clear that the management and conservation of energy is strongly influenced by the collective mindset of society. With respect to this, we cannot ignore the role played by human nature, as it influences both politicians and consumers alike, and does not necessarily lead to outcomes that benefit either society or the environment.

1.3 What is Energy?

Consider a mass of 1 kg which is raised 1 m above a surface on which it was originally resting. It is easy to appreciate that in order to raise the weight through the distance of 1 m, someone, or some machine, must have performed work. In other words, work has been put into the system to raise the mass from a low level to a higher level. This work is the amount of energy that has been put into the system. So, when the weight is in the raised position, it is at a higher energy level than when on the surface. Indeed, this illustration forms the basis for the International System (SI) unit of energy, the 'joule ', which can be defined as follows:

One joule (J) is the work done when a force of 1 newton (N) acts on an object so that it moves 1 metre (m) in the direction of the force.

One newton (N) is the force required to increase or decrease the velocity of a 1 kg object by 1 m per second every second.

The number of newtons needed to accelerate an object can be calculated by:

$$F = m \times a \qquad 1.1$$

where m is the mass of the object (kg) and a is the acceleration (m/s^2). Given that the acceleration due to gravity is 9.81 m/s^2, a mass of 1 kg will exert a force of 9.81 N (i.e.1kg 9.81 m/s^2). Therefore the energy required to raise it through 1 m will be 9.81 J.

If the 1 kg mass is released it will fall through a distance of 1 m back to its original position. In doing so the potential energy stored in the 1 kg mass when it is at the higher level will be released. Notice that the energy released is equal to the work put into raising the weight. For this reason the term work is sometimes used instead of energy.

Perhaps a good way of viewing energy is to consider it as stored work. Therefore, potential energy represents work that has already been done and stored for future use.

Potential energy can be calculated by:

$$Potential\ Energy = m \times g \times h \qquad 1.2$$

where m is the mass of the object (kg), g is the acceleration due to gravity (i.e. 9.81m/s^2) and h is the height through which the object has been raised (m). As the weight falls it will possess energy because of its motion and this is termed *kinetic energy*. The kinetic energy of a body is proportional to its mass and to the square of its speed. Kinetic energy can be calculated by:

$$Kinetic\ energy = 0.5 \times m \times v^2 \tag{1.3}$$

where v is the velocity of the object (m/s). We can see that during the time the mass takes to fall, its potential energy decreases whilst its kinetic energy increases. However, the sum of both forms of energy must remain constant during the fall. Physicists and engineers express this constancy in the 'law of conservation of energy', which states that the total amount of energy in the system must always be the same

It should be noted that the amount of energy expended in raising the weight is completely independent of the time taken to raise the weight. Whether the weight is raised in 1 second or 1 day makes no difference to the energy put into the system. It does, however, have an effect on the 'power' of the person or machine performing the work. Clearly, the shorter the duration of the lift, the more powerful the lifter has to be.

Consequently, power is defined as the rate at which work is done, or alternatively, the rate of producing or using energy. The SI unit of power is the watt (W). Therefore, a machine requires a power of 1 W if it uses 1 J of energy in 1 second (i.e. 1 W is 1 J per second). In electrical terms, 1 W is the energy released in 1 second by a current of 1 ampere passing through a resistance of 1 ohm.

1.4 Units of Energy

Kilowatt-hour (kWh)

The kilowatt-hour (kWh) is a particularly useful unit of energy which is commonly used in the electricity supply industry and, to a lesser extent, in the gas supply industry. It refers to the amount of energy consumed in 1 hour by the operation of an appliance having a power rating of 1 kW.

Therefore:

$$1kWh = 3.6 \times 10^6 J \tag{1.4}$$

British thermal unit (Btu)

The British thermal unit (Btu) is the old imperial unit of energy. It is still very much in use and is particularly popular in the USA:

$$1\ Btu = 1.055 \times 10^{3} J \qquad 1.5$$

Therm

The therm is a unit that originated in the gas supply industry. It is equivalent to 100,000 Btu:

$$1\ therm = 1.055 \times 10^{8} J \qquad 1.6$$

Tonne of oil equivalent (toe)

The 'tonne of oil equivalent' (toe) is a unit of energy used in the oil industry:

$$1\ \text{toe} = 4.5 \times 10^{10} J \qquad 1.7$$

Barrel

The barrel is another unit of energy used in the oil industry. There are 7.5 barrels in 1 toe:

$$1\ barrel = 6 \times 10^{9} J \qquad 1.8$$

Calorie

In the food industry the calorie is the most commonly used unit of energy. It is in fact the amount of heat energy required to raise 1 g of water through 1°C:

$$1\ \text{calorie} = 4.2 \times 10^{3} J \qquad 1.9$$

1.5 The Laws of Thermodynamics

Thermodynamics is the study of heat and work, and the conversion of energy from one form into another.

The first law of thermodynamics.

The first law of thermodynamics is also known as the law of conservation of energy. It states that the energy in a system can neither be created nor destroyed. Instead, energy is either converted from one form to another, or transferred from one system to another. The term ‘system’ can refer to anything from a simple object to a complex machine. If the first law is applied to a heat engine, such as a gas turbine, where heat energy is converted into mechanical energy, then it tells us that no matter what the various stages in the process are, the total amount of energy in the system must always remain constant.

The second law of thermodynamics

While the first law of thermodynamics refers to the quantity of energy that is in a system, it says nothing about the direction in which it flows. It is the second law that deals with the natural direction of energy processes. For example, according to the second law of thermodynamics, heat will always flow only from a hot object to a colder object.

In another context, it explains why many natural processes occur in the way they do. For example, iron always turns to rust; rust never becomes pure iron. This is because all processes proceed in a direction which increases the amount of disorder, or chaos, in the universe. Iron is produced by smelting ore in a foundry, a process which involves the input of a large amount of heat energy. So, when iron rusts it is reverting back to a ‘low-energy’ state. Although it is a difficult concept to grasp, disorder has been quantified and given the name ‘entropy’. Entropy can be used to quantify the amount of useful work that can be performed in a system. In simple terms, the more chaotic a system, the more difficult it is to perform useful work.

In an engineering context it is the second law of thermodynamics that accounts for the fact that a heat engine can never be 100% efficient. Some of the heat energy from its fuel will be transferred to colder objects in the surroundings, with the result that it will not be converted into mechanical energy.

“The Second Law of Thermodynamics states that "in all energy exchanges, if no energy enters or leaves the system, the potential energy of the state will always be less than that of the initial state." This is also commonly referred to as entropy. A watchspring-driven watch will run until the potential energy in the spring is converted, and not again until energy is reapplied to the spring to rewind it. A car that has run out of gas will not run again until you refuel the car. Once the potential energy locked in carbohydrates is converted into kinetic energy (energy in use or motion), the organism will get no more until energy is input again. In the process of energy transfer, some energy will dissipate as heat. Entropy is a measure of disorder: cells are NOT disordered and so have low entropy. The flow of energy maintains order and life. Entropy wins when organisms cease to take in energy and die.”

The second law states that there exists a useful state variable called entropy S. The change in entropy delta S is equal to the heat transfer delta Q divided by the temperature T.

$$delta\ S = {}^{delta\ Q}/_{T} \qquad 1.10$$

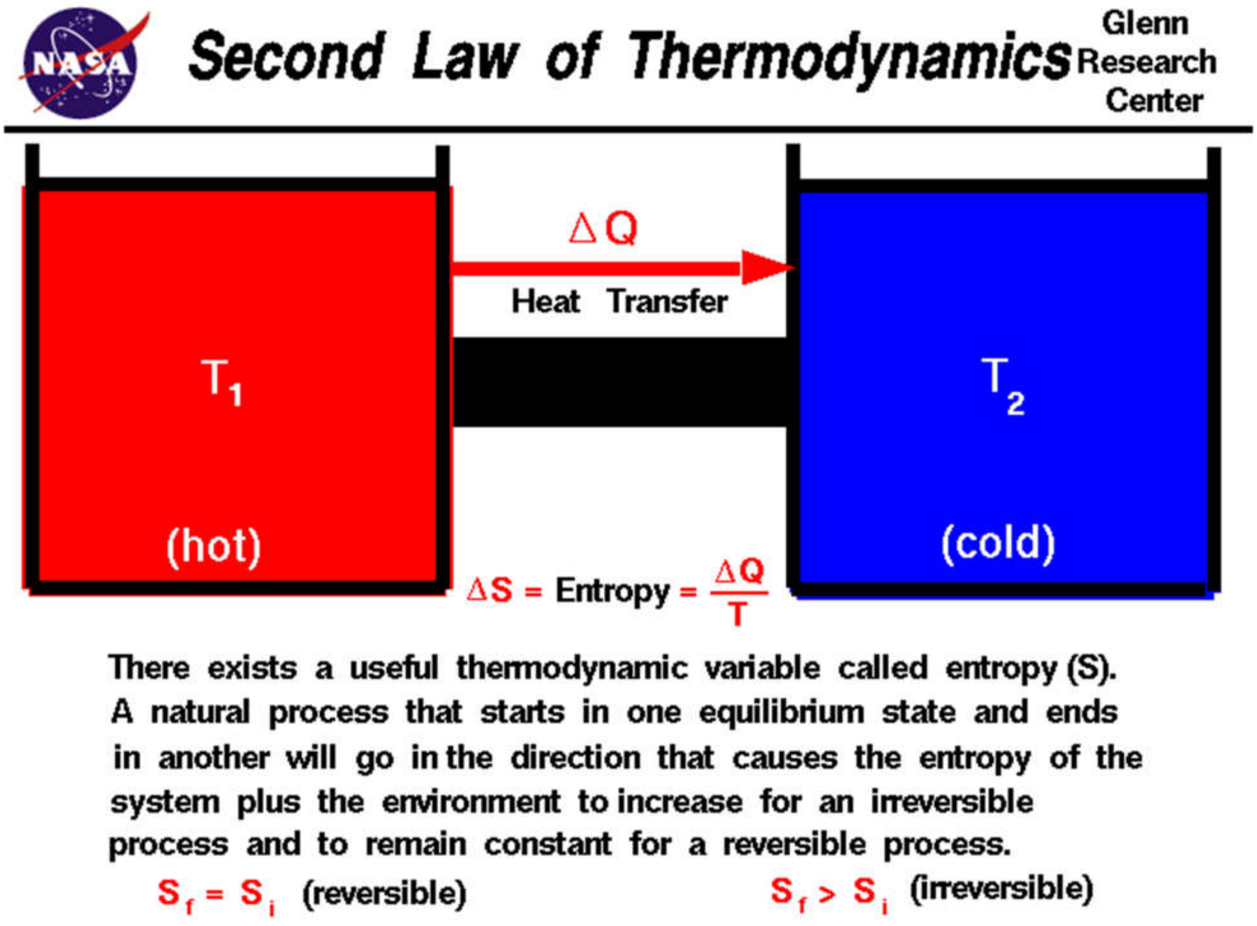
For a given physical process, the combined entropy of the system and the environment remains a constant if the process can be reversed. If we denote the initial and final states of the system by "i" and "f":

Sf = Si (reversible process)

An example of a reversible process is ideally forcing a flow through a constricted pipe. Ideal means no boundary layer losses. As the flow moves through the constriction, the pressure, temperature and velocity change, but these variables return to their original values downstream of the constriction. The state of the gas returns to its original conditions and the change of entropy of the system is zero. Engineers call such a process an isentropic process. Isentropic means constant entropy. The second law states that if the physical process is irreversible, the combined entropy of the system and the environment must increase. The final entropy must be greater than the initial entropy for an irreversible process:

Sf > Si (irreversible process)

An example of an irreversible process. A hot object is put in contact with a cold object. Eventually, they both achieve the same equilibrium temperature. If we then separate the objects they remain at the equilibrium temperature and do not naturally return to their original temperatures. The process of bringing them to the same temperature is irreversible.



There exists a useful thermodynamic variable called entropy (S). A natural process that starts in one equilibrium state and ends in another will go in the direction that causes the entropy of the system plus the environment to increase for an irreversible process and to remain constant for a reversible process.

$S_f = S_i$ (reversible) $S_f > S_i$ (irreversible)

FIG 1.1 The second law of thermodynamics illustration

The third law of thermodynamics.

The third law of thermodynamics is concerned with absolute zero (i.e. -273°C). It simply states that it is impossible to reduce the temperature of any system to absolute zero.

The first and second laws of thermodynamics are well illustrated by the ideal heat engine shown in Figure 1.2. Heat engines are devices, such as internal combustion engines and gas turbines, which convert thermal energy into mechanical work. They do this by exploiting the temperature gradient between a hot 'source' and a cold 'sink'. As heat flows from the hot 'source' to the cold 'sink' it passes through the 'working' part of the engine where it is converted into mechanical energy.

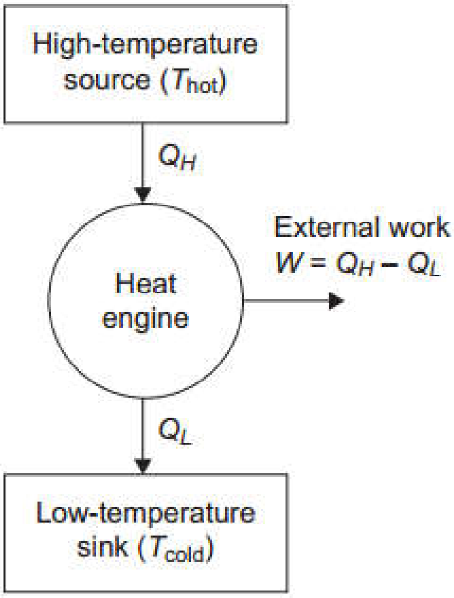


FIG 1.2 Schematic diagram of an ideal heat engine.

If it is assumed that no energy is stored, then by applying the first law of thermodynamics it is possible to write down an energy balance for the system:

$$W = Q_H - Q_L \tag{1.11}$$

where *W* is the mechanical work produced by the engine (J), *QH* is the heat absorbed from the high-temperature ' source ' (J), and *QL* is the heat rejected to the low temperature ' sink ' (J).

Similarly, the efficiency, η, of the heat engine can be expressed thus:

$$\eta = \frac{work\ output}{work\ input} = \frac{W}{Q_H} \tag{1.12}$$

$$= 1 - \frac{Q_L}{Q_H}$$

Because the respective heat flows are proportional to the absolute temperature of the hot 'source' and the cold 'sink', it is possible to express the efficiency of an ideal heat engine as:

$$\eta = 1 - \frac{T_L}{T_H} \qquad 1.13$$

Given that the second law of thermodynamics dictates that heat must flow from hot to cold, it can be seen from Eqn 1.13 that if no temperature difference exists between the hot ‘ source ’ and the cold ‘ sink ’ , then heat cannot flow and the efficiency of the engine must therefore be zero.

Conversely, if a large temperature difference exists between the hot ‘source’ and the cold ‘sink’, then the heat flow will be much greater, with the result that the efficiency of the cycle will be high.

So all-embracing is the second law of thermodynamics that it can be used to explain how the communities and ecosystems on Earth behave when they consume energy.

If environmental pollution is low and only renewable energy sources are used, then the Earth should remain relatively stable, allowing a low-entropy ecosystem to survive and prosper. If, however, fossil fuels, such as petroleum, coal and natural gas, are consumed, then ‘concentrated energy’ from the sun, laid down in biomass hundreds of thousands of years ago, is suddenly released into the atmosphere. In thermodynamic terms, the energy trapped in fossil fuels is in a highly ordered low-entropy form. When burnt, this highly ordered energy is dispersed into the environment raising its entropy, which is exactly what the second law of thermodynamics predicts. So as more and more non-renewable fossil fuels are consumed the *Second Law* tells us that entropy-related problems, such as pollution and global warming, will inevitably increase.

It is impossible to ‘buck’ the second law of thermodynamics – entropy will always increase in the end! Even nuclear power, which some think might solve the Earth’s energy crisis, conforms to the second law of thermodynamics. While nuclear power offers almost unimaginable amounts of energy from very small masses of uranium, the *Second Law* tells us that once this highly ordered energy is consumed it will inevitably be dispersed into the environment raising its overall entropy. This increase in entropy may, in part, explain why the safe disposal of nuclear waste has proven to be a considerable problem.