Energy, Work, and Power

Introduction

Although commonly used interchangeably, these concepts actually have different meanings. The first two (energy and work) are so closely related that he distinction is small enough to be ignored most of the time in this class. However the distinction between these two and power is very important, and must be understood.

Commonly the terms 'energy' and 'power' are used interchangeably. When we refer to the production of electricity from the nucleus of the atom we commonly refer to it as 'nuclear power'. But if we want to be precise we should refer to it as 'nuclear energy'. It is electrical energy that is being produced, electrical power is really telling us the rate at which it is being produced (see later for definitions). In principle we can produce an enormous amount of energy, with very little power, providing we produce it for a long time. The reverse is also true, the production of even a small amount of energy if done rapidly enough can correspond to very high power level.

So which concept is more important, energy or power? The real answer is that they are both important, they tell us different things. Both power stations and weapons need energy in order to work, in comparable amounts. The difference between them lies in their power levels. The weapons is much more powerful, even for the case of low energy (small scale) weapons.

Energy

Loosely defined, energy is the ability to act, the ability to do something. Without energy you are inactive, and remain so until it is provided. The energy itself can come in many different forms, including

- Kinetic energy, the energy associated with motion
- Gravitational Energy, associated with height
- Elastic energy, the energy of a spring or other elastic object
- Chemical energy, commonly found in fuels, for example, wood, coal, oil, food, etc
- Light
- Sound
- Heat
- Nuclear Energy
- etc

For example

- Gasoline provides chemical energy to make your car go.
- Food provides chemical energy to allow you to function

- Electricity provides the electrical energy to operate TV sets, computers, microwave ovens, electric chairs, etc
- Oil, Gas, or coal fired power stations use chemical energy to produce electricity
- Nuclear power stations use nuclear energy to produce electricity
- Solar panels use light to produce electricity
- etc

In all these cases one (sometimes more) form of energy is used to do work ('something'), and one (usually more) form of energy is produced. We can write symbolically

initial energy → work → final energy

However, note that the conceptual idea of energy as “the ability to do something” does not necessarily mean something useful. For example, in an accident the kinetic energy of the cars can be used to severely injure, or even kill, riders and pedestrians as well as damaging the vehicles. The energy of warm tropical waters can cause hurricanes which are tremendously damaging when they reach land, and the energy we absorb from the Sun can cause lethal skin cancer (see section on health hazards).

Principle of Conservation of Energy

The most fundamental law in all of science is the Principle of Conservation of Energy which states that when we do work we convert energy from one form to another (or possible more than one form), but that the total energy must remain a constant. To date no violation of this law has been found. In the first example above we take chemical energy stored in the gasoline, and through the process of doing work we turn it into the kinetic energy of the car, gravitational potential energy (if we drive uphill), electrical energy to operate the electronics, light (particularly at night), sound (especially if your exhaust isn't in good shape, and quite a lot of heat. In the end the total amount of all these energies put together must equal the total energy extracted from the gasoline.

In the case of nuclear processes (radioactivity and nuclear reactions) we have to also regard mass as having an equivalent energy. It is possible to transform mass (as one form of energy) into electricity (a different form of energy) but in the end the total (equivalent) energy has to remain unchanged. We will encounter this equivalence between mass and energy first when looking at the structure of the atomic nucleus, and then later in radioactivity and nuclear reactions.

Power

The concept of power is fundamentally different to that of energy. Whereas energy tells you the total amount of work you can do, power tells you how fast you do that work. As a definition

Power = Energy / Time

For example, a 50 W light bulb and a 100 W light bulb might each perform the task of converting 500 J of electrical energy into 500 J of light and heat combined. However the 100 W bulb, with a higher power rating will do so in only 5 hours whereas the 50 W light bulb will take 10 hours to do the same task.

Supposing I ask you "Which device converts more nuclear energy, a nuclear power station or a nuclear bomb?" It might well be the power station, although it will take a long time, maybe 30 years. But if I ask "Which has the higher power rating?" then the answer is clearly the bomb, since it will only take a fraction of a second to convert roughly the same amount of energy.

Units

You will find many different units for both energy (or work) and power. In this class we shall principally use the following

- for energy, the standard scientific unit is the Joule (J for short)
- for energy, at the atomic or nuclear level the unit of electron volt (eV for short) is more appropriate. You can convert back and forth using the relationship 1 eV = 1.6×10^{-19} J.
- For power, the standard scientific unit is the Watt (W for short). From the definition of power (see above) it follows that 1 W = 1 J/s.

Other units that you might find are

- for energy, the British Thermal Unit (BTU). 1 BTU = 1024 J
- for electrical energy the kiloWatt hour (kWh). 1 kWh = 3,600,000 J = 3.6 MJ
- for power, the horse power (h.p.) 1 h.p. = 747 W
- for nuclear weapons, the energy is commonly measured in relation to the energy released by one ton of TNT (a chemical explosive). 1 ton TNT is equivalent to 4.184 GJ (4.184×10^9 J)

Typical values

The range of possible energies and power levels is very wide, from those that require very little energy to those that use large amounts of energy, from those that convert energy rapidly, to those which are more sedate. Some typical values are:

Energy type	**Typical Energy (in J)**	**Typical Energy (in eV)**
Chemical reaction (per molecule)	0.000000000000000001 J (10^{-18} J)	2 to 5 eV
Nuclear reaction (per nucleus)	0.0000000000001 J (10^{-12} J)	1,000,000 to 200,000,000 eV (1 to 200 MeV)

AA alkaline battery	4 J
12 V car battery	7,500 J
Car (2000 lbs) at freeway speeds	200,000 J
Stick of dynamite	2,000,000 J (2 MJ)
Used by 100 W bulb left on for 8 hours	3,000,000 J (3 MJ)
Food intake per person (2000 Cal)	8,000,000 J (8 MJ)
1 gallon of gasoline	125,000,000 J (125 MJ)
Hiroshima bomb	10^{17} J
Modern Thermonuclear bomb	10^{20} J
US Energy consumption	10^{20} J
Received by Earth from Sun per year	6 x10^{24} J
Total output of Sun per year	2 x 10^{34} J

Energy type	**Typical power level (in W)**
Human being (radiated energy)	100 W
1 h.p. electric motor	750 W
Automobile engine (135 h.p.)	100,000 W
Electric power plant	200,000,000 W (200 MW)
Total output of Sun	4 x 10^{26} W

US energy production and consumption

According to the Department of Energy, the current annual energy consumption in the United States is about 100 quadrillion BTU's, or about 10^{20} J[(1)]. Of this total about 40% is in the form of electrical energy, and of that 40% about one fifth comes from nuclear power. That means that the nuclear power industry contributes about 8% of the total energy used in the United States, or about 8 x 10^{18} J annually.

Examples

1. A typical TV set (when turned on) consumes electrical energy at a rate of about 75 W. If it is turned on for 4 hours during the evening, what is the total amount of electrical

1 http://www.eia.doe.gov/aer/pdf/pecss_diagram.pdf

energy is consumed? What is this in kWh? If the utility company charges 12 ¢ per kWh, how much does your evening's viewing cost you?

1. 4 hours = 4 * 60 * 60 seconds = 14,400 s
2. Energy = power * time = 75 W * 14,400 s = 1.08×10^6 J
3. Energy = 1.08×10^6 J / 3.6×10^6 J/kWh = 0.3 kWh
4. Cost = 0.3 kWh * 12 ¢ / kWh = 3.6 ¢.

2. The energy intake by an adult human by way of food (but excluding heat received from the environment) is about 8 MJ in a day. What is the average power?
   1. The total energy is 8×10^6 J in one day.
   2. There are 24 * 60 * 60 = 86,400 seconds in one day.
   3. Power = Energy / Time = 8×10^6 J / 86,400 s = 93 W.

3. Using the figure above for the annual production of energy from nuclear power, what is the average rate at which this energy is produced?
   1. The total energy is 8×10^{18} J in one year.
   2. There are 365 * 24 * 60 * 60 = 3.15×10^7 seconds in one year.
   3. Power = Energy / Time = 8×10^{18} J / 3.15×10^7 s = 2.5×10^{11} W = 25,000 MW.

4. A typical nuclear power station is rated at 250 MW, and has an operating life expectancy of 30 years. What is the total amount of electrical energy that is produced during its operation. Compare this with the energy released by the bomb dropped on Hiroshima.
   1. There are 365 * 24 * 60 * 60 = 3.15×10^7 seconds in one year.
   2. In 30 years there are 30 * 3.15×10^7 s = 9.5×10^8 s.
   3. Energy = 250×10^6 W * 9.5×10^8 s = 2.4×10^{17} J.
   4. From the table above the energy released by the bomb dropped on Hiroshima was about 10^{17} J. We can see that the energy produced by the power station exceeds the energy released by the weapon. The devastation of Hiroshima is a consequence of releasing the energy very rapidly, in less than a second. The power level of the bomb is orders of magnitude larger than that of the power station.