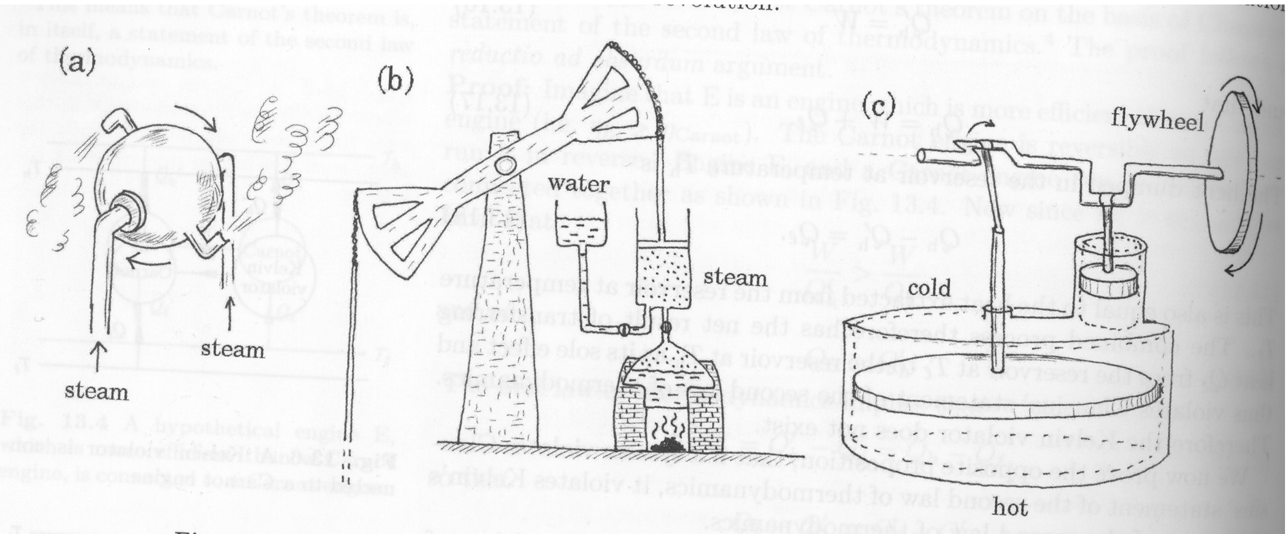


Fig. 13.8 Sketches of (a) Hero's engine, (b) Newcomen's engine and (c) Stirling's engine.

Figure 1: Engines and energy conversion

1 Energy consumption : some numbers.

- **Power** is rate of **energy** transfer.

$$\begin{aligned}
&\text{Power} \;=\; \frac{\text{Energy}}{\text{time}} \\
&P = E/t \\
&1\ Watt = 1\ W = 1 \text{ Joule per second } = 1\ J/s = 1\ Js^{-1} \\
&1\ KW = 10^3\ W \\
&1\ MW = 10^6\ W \\
&1\ GW = 10^9\ W \\
&1\ TW = 10^{12}\ W
\end{aligned} \qquad (1)$$

Exercise L1 : Show that

$$1 \text{ kilowatt-hour(kWh)} = 3.6 \times 10^6 J = 3.6\ MJ$$

- 1 Joule : Work done when force of 1N acts over 1 metre

$$Work\ done = Force \times distance \qquad (2)$$

- **Energy is conserved. It can be converted from one form to another, e.g mechanical , thermal, electrical** . (First Law of Thermodynamics)
- Basic engine designs to do useful work are illustrated in Fig. 1 from [2]

- : **Thermal energy** 1 calorie of heat is the amount needed to raise 1 gram of water 1 degree Centigrade.
  1 calorie (cal) = 4.184 J

  One kcal (often called Cal, or large Calorie in the context of food energy) is 1000 cal. 1 g of pure carbohydrate yields about 4 kcal of energy. Recommended intake for an adult is 2000-2500 kcal.

- A BTU (British Thermal Unit) is the amount of heat necessary to raise one pound of water by 1 degree Farenheit (F).
  1 British Thermal Unit (BTU) = 1055 J
  1 BTU = 252 cal = 1.055 kJ

- 1 UK gallon ($\approx 4.55\text{litre} = 4.55 \times 10^3 cm^3$) of oil : 40 kWh of energy.
  1 barrel = 36 UK gallons (42 US gallons).

- *World Energy consumption* (2001) :
  403.9 Quad $= 403.9 \times 10^{15}$ BTU
  World Energy consumption (2010 : est.) : 470.8 Quad

  Exercise L2 Express these numbers in terms of power consumed in Watts ?

  Solar power incident on Earth is $1kWm^{-2}$ or a $100mWcm^{-2}$.

  Exercise L3 Which is greater the rate of energy consumption or the amount of solar energy incident on the Earth ? Radius of Earth is $6.4 \times 10^3 km$

- An instructive calulation of the amount of coal needed to power a lightbulb for year is given here [8]. The amount of CO_2 and pollutants, including radioactive ones !! is also discussed.

- A good discussion of the numbers around energy consumption is given in MacKay's book [9] in the section "the balance-sheet" of Chapter 1-Numbers not adjectives.

- **Electrical Energy**

  Potential difference : V
  Current I :
  Related by $V = IR$ for a resistor.
  Electrical power $P = IV$.
  Can be used to calculate the energy output of a battery or energy dissipated in a resistor.

- *Exercise L4 : Internet research :* Average consumption of energy in household. Typical devices.

- Cost of energy $14p$ per KWh.

1.1 Summary of key points

Definitions of Energy, Power, Force ; Formulae for mechanical and electrical energy ; understanding the quantitative translation between different forms of energy.

2 Dimensional Analysis

Dimensional Analysis as a useful way to understand formulae. Fundamental quantities M, L, T.

$$\begin{aligned} \text{Velocity or speed } &: [v] = LT^{-1} \\ \text{Acceleration } &: [a] = LT^{-2} \\ \text{Force } &: [F] = MLT^{-2} \\ \text{Energy } &: [E] = [Fx] = ML^2T^{-2} \end{aligned} \tag{3}$$

The energy of a photon is given by

$$E = hf \tag{4}$$

Exercise What are the dimensions of Planck's constant h ? Show that the de Broglie momentum-wavelength relation is consistent with the dimensions of h, p, λ

Exercise Check that Einstein's famous equation is consistent with dimensional analysis.

Exercise Work through Ex. 1.1 and 1.2 of AJ.

3 First and Second Law of Thermodynamics

- Applications : Maximum efficiency of Power plants.

  Reference : AJ Chapter 2.

- First Law of Thermodynamics :

  $$Q - W = \Delta U \tag{5}$$

  where Q is heat input to the system, W is the work done by the system, and ΔU is the change in internal energy.

- Second Law of Thermodynamics : No system operating in a closed cycle can convert all the heat absorbed from a heat reservoir into the same amount of work. The maximum possible efficiency is

  $$\eta_C = 1 - \frac{T_2}{T_1} \tag{6}$$

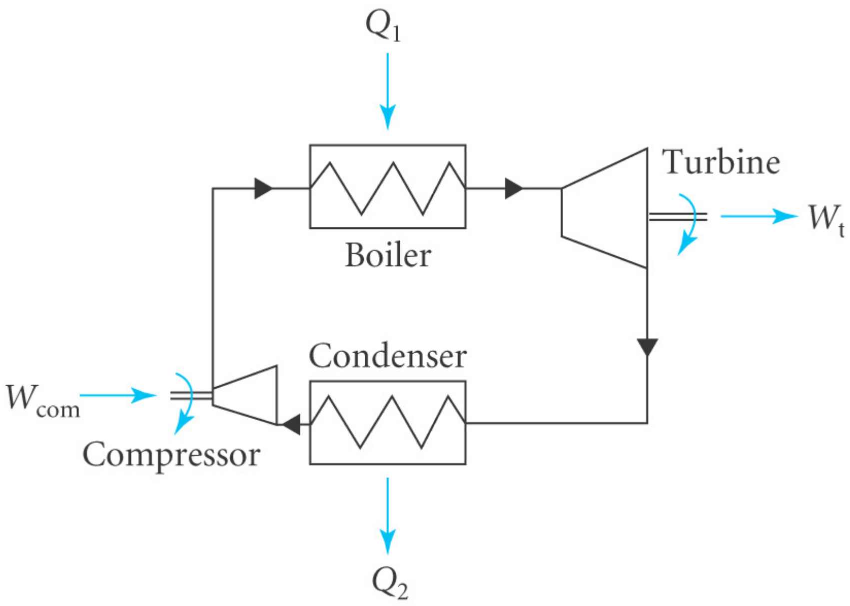


Figure 2: Cycles and Power Plants

where

$$\eta = \frac{W_t - W_{com}}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1} \tag{7}$$

3. Other equivalent formulations of the second Law :

(3A) No process is possible whose result is the sole transfer of heat from a colder to a hotter body.

(3B) No process is possible whose sole result is the complete conversion of heat into work.

The following formulation relies on the idea that physical systems (in thermal equilibrium) have an additional property called *entropy* denoted by S along with other properties like pressure, temperature, volume etc. S can be thought as a measure of "degree of disorder".

(3C) The entropy of the universe can only increase :

$$(\Delta S)_{\text{Universe}} \geq 0 \tag{8}$$

4. Relation between entropy and heat for reversible processes :

$$dQ = TdS \tag{9}$$

- For relation between cycle and power plant see 2 and also sections 2.3 and 2.4 of [AJ]

5. The "energy crisis" is not a depletion of energy resources. It is a depletion of "available energy" or "useful energy".

Thermodynamic potentials, such as the enthalpy (H) or Gibbs free energy (G)

$$\begin{aligned} H &= U + pV \\ G &= U + pV - TS \end{aligned} \tag{10}$$

quantify the amount of useful energy. When a chemical reaction at fixed temperature and pressure produces heat energy, the amount of available energy can be obtained from the change in free energy of the chemical constituents. Whether a reaction is energetically allowed or not is determined by the change in Gibbs free energy.

See Blundell and Blundell section 16.5, which expresses the second law of thermodynamics

$$dS_{tot} \geq 0 \tag{11}$$

in terms of the availability $A = U + p_0 V - T_0 S$ as

$$dA \leq 0 \tag{12}$$

The relation between dA and variations dH (for fixed pressure, thermally isolated system) and dG (for fixed pressure and temperature) are also explained.

As a result, one talks about the "enthalpy of combustion" which is the thermal energy available from the burning of chemical compounds, when the reactants and products are at the same pressure. For combustion at constant volume the heat produced is a change of internal energy (rather than enthalpy). *Further reading :* If you are interested in seeing some worked examples which develop these concepts, you may consult Chapter 13 of [10], especially Examples 13.6, 13.7. Example 13.10 also illustrates, with numbers, how typical combustion processes relevant to energy consumption result in an increase of entropy.

6. Note that one of the most fundamental laws of physics, the second law of thermodynamics, is a *universal* fact about the efficiency of conversion of heat to work.

Generally,

$$\begin{aligned} \text{Efficiency} &= \frac{\text{Useful energy output}}{\text{total energy input}} \\ &= \frac{\text{Useful Power output}}{\text{total Power input}} \end{aligned} \tag{13}$$

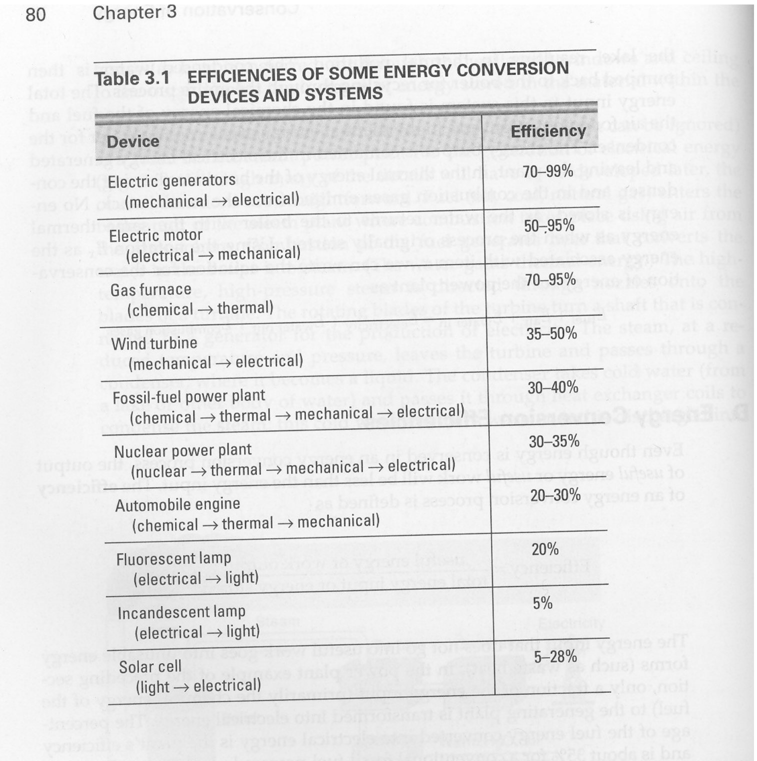
Examples : Typical light bulb has 5% efficiency of conversion of electrical energy to light energy. The best electrical motors have 95% efficiency for electrical to mechanical.

For a multi-step process, the *overall efficiency* is a product of efficiencies

$$\eta = \eta_1 \eta_2 \eta_3 \tag{14}$$

for a 3-step process.

Go back to the earlier discussion of the power in dams to see another example of efficiency. Section 3D of [3] gives a useful discussion of efficiencies with examples. The figures Fig. 3 and Fig. 4 are from that section.



80 Chapter 3

Table 3.1 EFFICIENCIES OF SOME ENERGY CONVERSION DEVICES AND SYSTEMS

Device	Efficiency
Electric generators (mechanical → electrical)	70–99%
Electric motor (electrical → mechanical)	50–95%
Gas furnace (chemical → thermal)	70–95%
Wind turbine (mechanical → electrical)	35–50%
Fossil-fuel power plant (chemical → thermal → mechanical → electrical)	30–40%
Nuclear power plant (nuclear → thermal → mechanical → electrical)	30–35%
Automobile engine (chemical → thermal → mechanical)	20–30%
Fluorescent lamp (electrical → light)	20%
Incandescent lamp (electrical → light)	5%
Solar cell (light → electrical)	5–28%

Figure 3: Typical efficiencies of energy conversions

4 Power stations : Hydro , Fossil Fuels – Physics + Numbers

- Mechanical energy : Force.

$$W = Fs \tag{15}$$

Kinetic energy of motion

$$K = \frac{1}{2}mv^2 \tag{16}$$

Potential Energy : Gravitational.

$$P = mgh \tag{17}$$

- *Applications :*

Hydroelectric power.
Exercise L4 Power produced by a Hydro power station. Discuss Example 4.1 of [1].

The power output is given by

$$P = \eta\rho g h Q \tag{18}$$

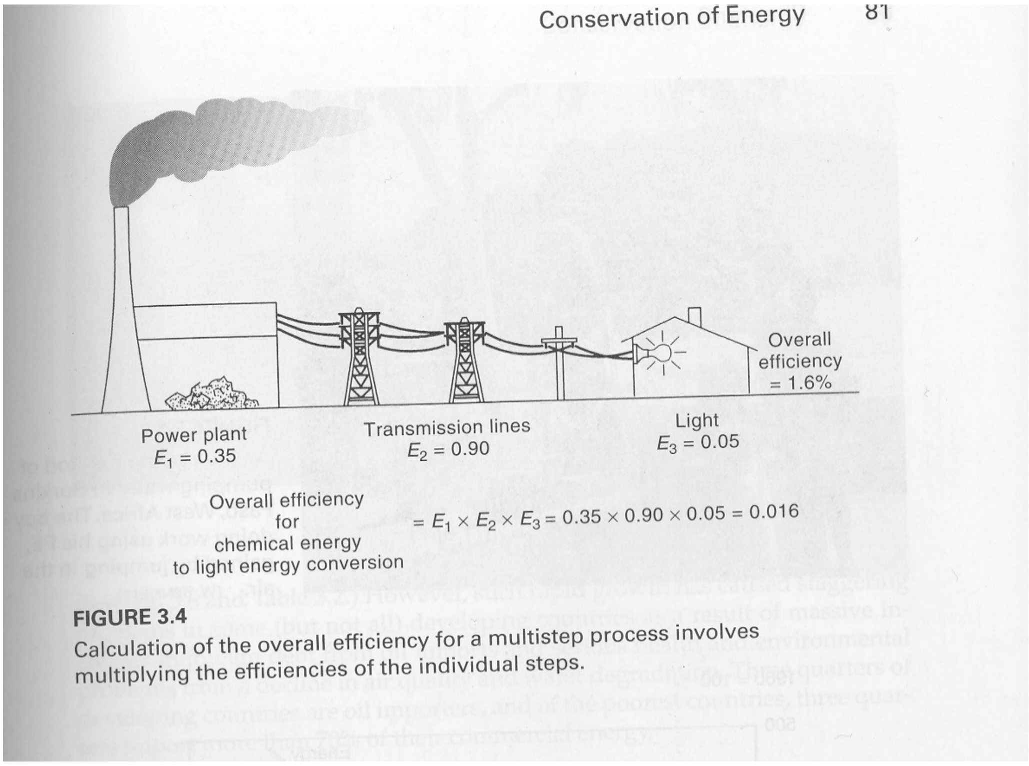


FIGURE 3.4
Calculation of the overall efficiency for a multistep process involves multiplying the efficiencies of the individual steps.

Figure 4: Overall efficiency

where η is the efficiency, ρ is the density, g the acceleration due to gravity, h the difference in height between the surface of the water and the reservoir, called the *head* .

- Data on a hydro power station in Guangdong, China gives $Q = 202.4m3s^{-1}$, $h = 5.7m$, power output $10.42MW$.

  Exercise L4.1 Calculate the efficiency.

  Typical eficiencies for various methods of power conversion from [6]

- Temperature and random kinetic energy. An ideal gas at temperature T has randomly moving particles.

$$\frac{1}{2}k_BT = \frac{1}{2}m < v_x^2 >= \frac{1}{2}m < v_y^2 >= \frac{1}{2}m < v_z^2 > \tag{19}$$

  $\frac{1}{2}k_BT$ per degree of freedom. Here k_B is a fundamental constant of nature called the Boltzmann constant.

$$k_B = 1.3806503 \times 10^{-23} m^2 kg s^{-2} K^{-1} \tag{20}$$

- Conservation of Energy

$$E_{before} = E_{after} \tag{21}$$

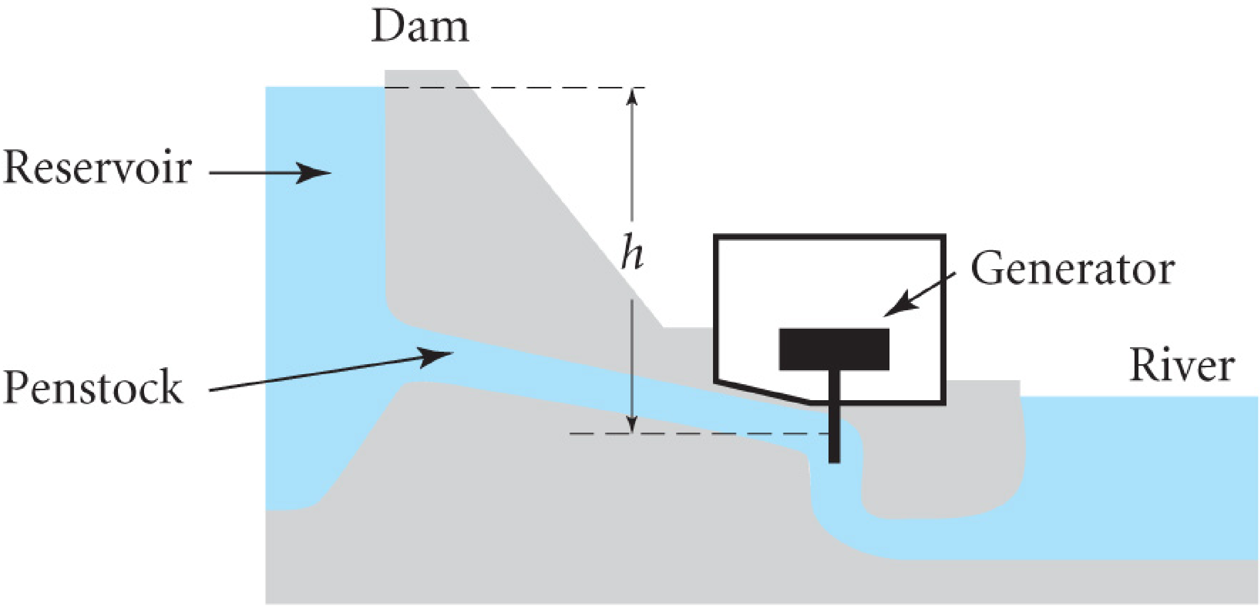


Figure 5: Hydro-electric plant

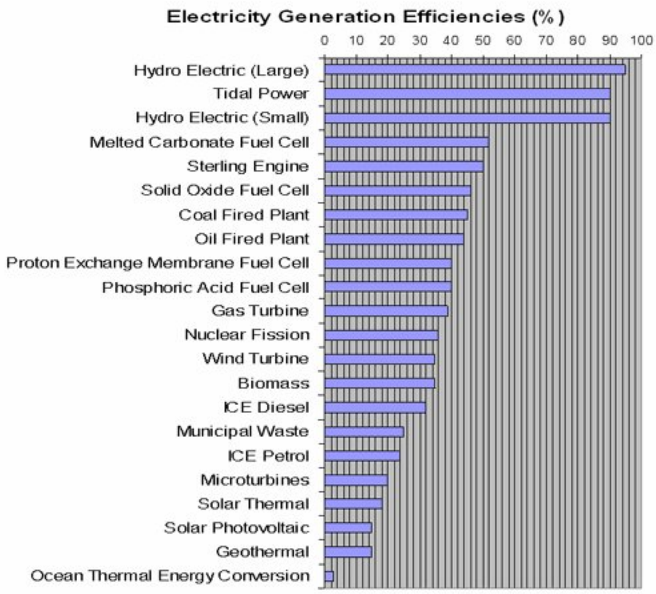


Figure 6: Efficiencies of Power sources

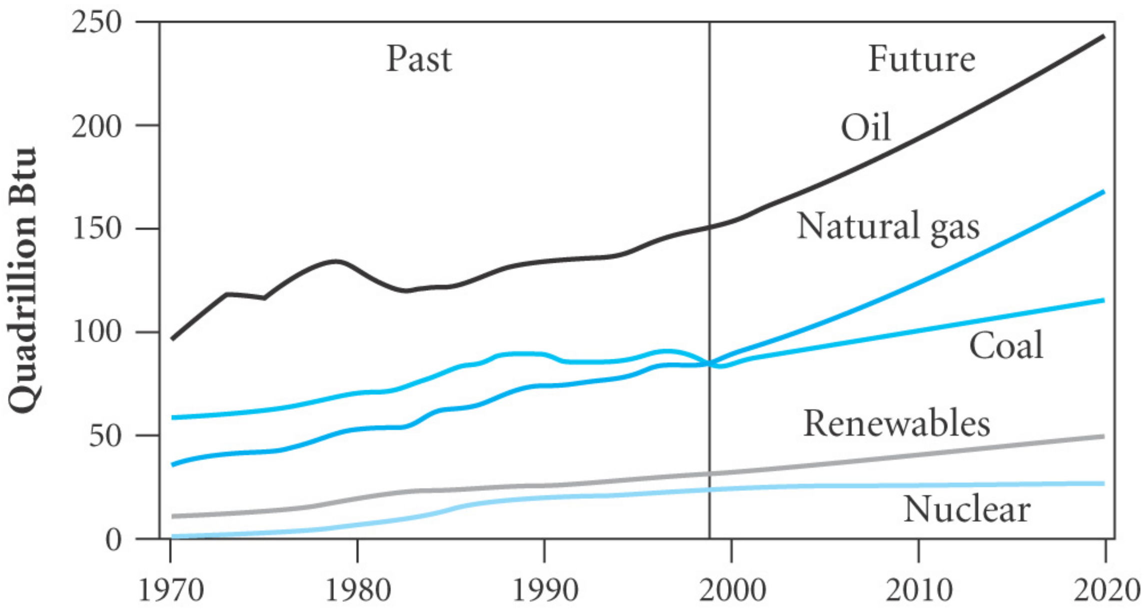


Figure 7: trends in Energy consumption

- Usefulness of a form of energy. (Later entropy etc.) – see chapter 2 of AJ.
- Fossil Fuels v/s Renewable energy sources. Coal, Gas, Oil, v/s Wind, Wave, Solar, Nuclear.
- Fossil-fuel power stations burn coal, oil or natural gas. Carbon combines with oxygen to form CO_2 e.g

$$\begin{aligned} CH_4 + 2O_2 &\rightarrow CO_2 + 2H_2O \\ C_5H_{12} + 8O_2 &\rightarrow 5CO_2 + 6H_2O \end{aligned} \tag{22}$$

  55 MJ of heat per Kg of methane. The atomic masses of H , C , O are in the proportion 1 : 12 : 16, so the burning of 16 kg of methane releases $44kg$ of carbon dioxide. $72kg$ of pentane (C_5H_{12}) releases $220kg$ of carbon dioxide.

- The heat is used to boil water. Steam runs turbines. The rotation of turbines runs generators which produce electricity (see Fig. 2). We will come back to power stations in relation to thermodynamics in section 3.

5 Energy Scenario

Patterns of global energy consumption. Future extrapolations (scenarios).

- Largest component of our energy consumption comes from oil. Oil was formed by geological processes that take millions of years. Once used up, the source is effectively irreplaceable. It is a non-renewable resource.

- See http://en.wikipedia.org/wiki/Electricity_generation for breakdown of energy production by source.

- Before the beginning of oil wells (1859), there were about 2 trillion barrels of oil scattered around the world. By 2006 we have used up 0.96 trillion. We are near halfway point.

- Production in many oil fields, countries has peaked. The US peaked in 1970.

  Hubbert in 1956 plotted graphs for the power output from a number of states in the US. He noted an initial phase of very rapid, almost exponential growth, followed by a peak and then a rapid decline. He predicted, correctly ! , that US oil production would peak in early seventies.

  Such curves have been plotted for several oil fields, countries and a similar pattern observed. One speaks of Hubbert peak, peak oil. A function often used in modelling these curves is

  $$P = \frac{2P_m}{(1 + cosh[b(t - t_M)]} \tag{23}$$

  P is the oil production at time t, P_M is peak production, b is a parameter that controls the slope, t_M the year of the maximum. The area under the curve is $U = \frac{4P_M}{b}$. U is called the "estimated ultimate recovery, " the total amount of oil we expect to recover over time.

  Further reading [4, 5]

- We are very close to the peak of oil production. Exploration becomes more expensive.

  Exactly how close we are to t_M is a matter of some debate. The paper [4] estimates between 2009-2020.

- An estimate for the length of time that oil supplies will last, assuming production levels stay at 2002 values, is

  Oil : 40 years
  Gas : 70 yrs
  Coal : 250 years

- Some experts predict that peak coal will be reached by 2050. See for example [7]. So the figure of 250 years may be giving a false sense of security.

- Traditional useful forms of Energy are running out ! And production levels are likely to decline significantly within our life-time.

6 Greenhouse effect and Global Warming

- Burning of fossil fuels produces CO_2, which is a greenhouse gas. It conributes to warming of the atmosphere through the greenhouse effect.

- In a simple model to understand the greenhouse effect :

  Without atmosphere : $-19C$ – Earth emits energy at the same rate as it receives from the sun.

  Atmosphere absorbs solar energy. Heats up. Radiates energy in IR to ground and out. Earth receives more energy. Warms up further. Radiates more as temperatire rises. At equilibrium, rate of emission from ground equals total received from Sun + atmosphere. Net effect around $35C$. This is the *greenhouse effect* .

  Main greenhouse gas IPCC estimates that between 1990 and 2100, temperatures will rise $1.4 - 5.8C$ due to CO_2 emissions from fossil fuel emissions.

  Further Reading : 1.3 of [AJ]
  Box 2.1 for a more technical approach.

References

[1] Andrews and Jelley, “Energy science : principles, technologies and impacts,” Oxford.

[2] Blundell and Blundell, Concepts in Thermal Energy, Oxford.

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[5] WikiPedia : http://en.wikipedia.org/wiki/Peak_oil

[6] http://www.mpoweruk.com/hydro_power.htm

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