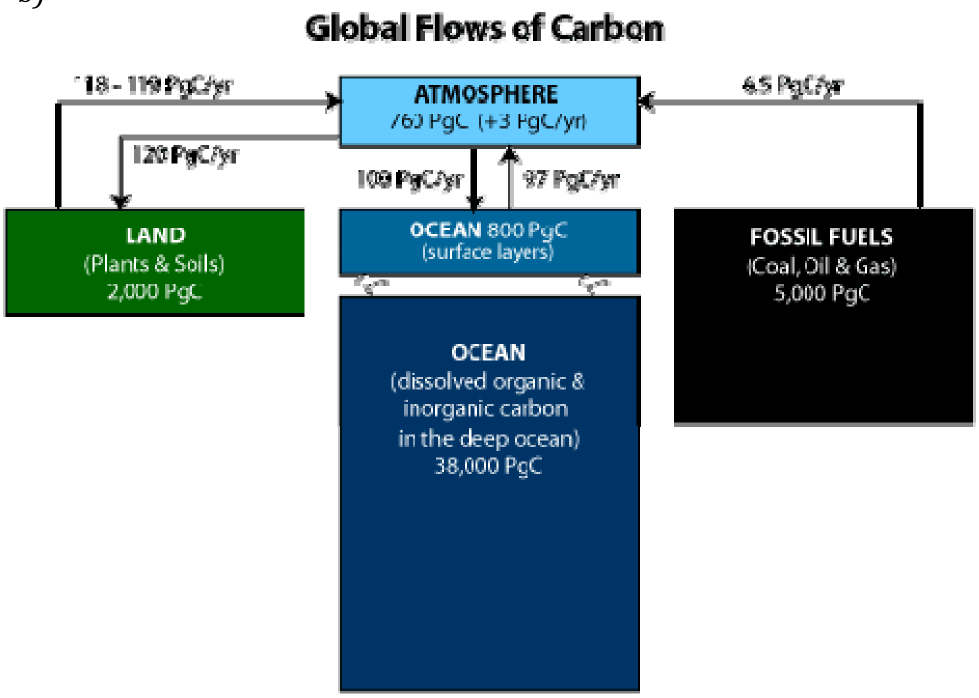
EXAM IN TFY 4300 Energy and environmental physics – suggested solution

Monday August 3rd 2009

Problem 1. The Greenhouse effect, the carbon cycle and fossil fuels (25%)

a) The Earth is covered by an atmosphere that contains various gases (H_2O, CO_2, O_3, CH_4 etc) that can absorb the long wavelength thermal radiation that is emitted from the surface of the Earth. The atmosphere heats up and emits thermal radiation both out in space and inwards to the surface of the Earth again. The atmosphere thus acts as the glass windows in a greenhouse, letting the short wavelength radiation from the sun in, while stopping thermal radiation from getting out from the hot inside. Without the atmosphere this radiation would escape into space and the surface of the Earth would be cooler. The gases that contribute the most to the natural greenhouse effect are water vapour and carbon dioxide. Without the atmosphere the temperature of the surface of the earth would be ca -20C.

b)



The carbon content is increasing in the atmosphere, oceans and the land, and decreasing in the fossil fuel reserves.

c) The fossil fuels are utilized (after some processing) in heat engines where they are combusted to give of their chemical energy as heat. The heat engine converts the heat into mechanical work that can be utilized directly in transportation (e.g. internal combustion engines, jet engines, steam engines) or the work can be fed into a generator that converts the mechanical energy into electric energy. The heat from the combustion of fossil fuels can also be utilized directly for e.g. cooking and space heating.

The problems related to the use of fossil fuels can be divided in three:

1) Fossil fuels are of limited availability, and that we are consuming the fossil fuels much faster than they are formed.
   Human activities today rely heavily on the utilization of fossil fuels. Actually, the industrial revolution and the development of modern society, is due to fossil fuel utilization. As the development level of a society increases, the amount of energy used per person will also increase. The proven reserves of fossil fuels will last between 40 and 200 years, if the consumption remains at the present level, and no new occurrences are proved. The fossil fuels are very unevenly distributed on Earth, and this have already led to political conflicts between countries and regions. In addition, as the population in the third world is increasing rapidly along with their development level, the total energy demand on Earth will increase the coming years.

2) Fossil fuels lead to emission of pollutants
   The burning of fossil fuels can lead to emissions of several pollutants: carbon monoxide (CO), nitrogen oxides (NOx), sulphur dioxide (SO_2), particulates and hydrocarbons. CO is emitted as a result of incomplete combustion, when there is an insufficient amount of oxygen present. A prime source of CO is the gasoline-fuelled, spark-ignited internal combustion engine. Nitrogen oxide (NO) is formed whenever a nitrogen-oxygen mixture (such as air) is heated to over 1100C. The major sources for NO_x are transportation, electric utilities and other stationary fuel combustion processes. In addition to the toxicity of NOx, NOx play an important role in the formation of acid rain. Sulphur dioxide (SO_2) is released from fossil fuels when the fuels are burnt. The major source for SO_2 emissions are not vehicles, but electric utilities that burn coal or oil to produce electricity. Almost all fossil fuels contain sulphur, in general between 0.5 to a few weight-percent. It is difficult to separate the effects of SO_2 from those of H_2SO_4 (sulphuric acid) that contributes to acid rain. Particulates from man made sources are only 1/14 of the amount from natural sources (volcanoes, forest fires, dust etc), but since the man-made are emitted where the population density is high they tent to have more far-ranging consequences. The largest man-made contribution is fly ash from coal combustion. One of the main threats to health of the particulates results from their deposition in the lungs. In addition to their effects on human health, particulates in the atmosphere can scatter and absorb an appreciable amount of sunlight. Hydrocarbons are an important ingredient in the formation of photochemical smog, and are emitted to the atmosphere in many different ways, for example from automobile exhaust and partially unburned gasoline.

3) Fossil fuels lead to emission of green house gases.

The production of CO_2 is an inherent consequence of burning fossil fuels. CO_2 and methane (CH_4) are considered to be the two gases that contribute the most to the green house effect on earth.

We will have coal for 200 years, oil for ca 40 years and gas for 66 years. If the ultimate reserves are included coal will last 850 years, oil 124 years, gas 100 years and uranium 118 years (if we don't use breeder reactors).

Problem 2. Nuclear fusion (25%)

a) In a fusion process two small nuclei are brought together to form a larger nucleus. The mass of the large nucleus is smaller than the mass of the starting nuclei, and this manifests it self in a larger binding energy per nucleon. This difference in mass (or binding energy) is released in the fusion process and given to the large nucleus, and any accompanying neutrons that are released, as kinetic energy. The kinetic energy is then transferred to a heat transfer medium/coolant (typically molten lithium) that heats up and takes the heat out of the fusion region. Via a heat exchanger the heat is then used to produce steam in a secondary loop. The steam is fed to a heat engine power plant, where a turbine converts the heat in the steam to mechanical energy (when the steam is allowed to expand through the turbine) and a generator converts the mechanical energy to electricity.

b) The amount of energy released is on the order of a few to a few tens of MeV. This is ten to fifty times less than the amount that is typically released in a fission process, which amounts to ca 200MeV. In the combustion of fossil fuels the amount of energy released is on the order of eV, i.e. a factor 10^{-7} less than in fusion.

c) Examples of possible processes fusion processes are

$$^{2}\mathrm{D} + {}^{3}\mathrm{T} \rightarrow {}^{4}\mathrm{He} + \mathrm{n} + 17.6\mathrm{MeV}$$

$$^{2}\mathrm{D} + {}^{2}\mathrm{D} \rightarrow {}^{3}\mathrm{He} + \mathrm{n} + 3.27\mathrm{MeV}$$

$$^{2}\mathrm{D} + {}^{2}\mathrm{D} \rightarrow {}^{3}\mathrm{T} + {}^{1}\mathrm{H} + 4.03\mathrm{MeV}$$

$$^{2}\mathrm{D} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + 18.3\mathrm{MeV}$$

where ^{2}D=^{2}H are deuterium nuclei, ^{3}T=^{3}H are tritium nuclei, ^{1}H hydrogen nuclei, ^{4}He and ^{3}He helium nuclei and n are neutrons. The amount of mass energy released as kinetic energy is also stated. The mostly looked into is the fusion of deuterium and tritium.

d) The challenges in utilizing fusion for electricity generation are related to achieving high enough temperatures for the nuclei in the fuel to overcome the repulsive Coulomb barrier. The amount of mass energy released in the fusion reactor must be larger than the energy lost from the reactor plus the energy required to heat the fuel in the reactor.

e) Fusion reactors that have been tried out are the Tokamak and the laser fusion reactor.

In the Tokamak a (toroidal) magnetic field is used to contain the plasma and the plasma is heated by setting up a current through it by induction, like in a transformer, see figure on the right. The plasma acts as the secondary winding in the transformer. The plasma will be shaped as a torus by use of magnets.

Another fusion reactor design is the laser fusion reactor, where pellets of fuel are dropped into the reactor and illuminated by several precisely timed and focussed laser beams that converge inside the reactor, as shown in the figure on the right. The fuel is heated to the required level and confined to achieve the required density by the laser beams.

For both reactor designs the fuel is deuterium (^{2}H) and tritium (^{3}H). There is a lot of deuterium on earth since one out of 6700 hydrogen atoms in sea water is deuterium, but there is little tritium, since tritium's half life is on the order of 10 years (12.3 years). Tritium can, however, easily be generated by bombarding lithium with neutrons, in the following process: $^{6}\mathrm{Li} + \mathrm{n} \rightarrow {}^{4}\mathrm{He} + {}^{3}\mathrm{H}$. If you then cover the fusion reactor by a mantel of lithium, the neutrons released in the fusion process can generate tritium in this mantle. The lithium also heats up as it is bombarded by the high energy neutrons, and will act as a coolant, transporting the energy released in the fusion process to the (steam turbine) power plant via a heat exchanger. The tritium is them separated from the lithium and the lithium is fed back to the mantle, while the tritium is prepared into new fuel.

Problem 3. Electricity supply (50%)

a) An expression for the power delivered by the turbine is

$P_T = \frac{1}{2} C_p \rho A u_0^3 = C_p P_0$, where P_0 is the (available) power in the wind.

$C_p = 4a(1-a)^2$ tells us how much of the incoming power in the wind P_0 that can be extracted by a wind turbine. The maximum for C_p is reached for a=1/3 and equals C_p^{max}= 0.59.

C_p can not be 100% since that would imply that all the power is taken out of the wind, and the wind speed at the down-steam side u_2 would equal zero and the air at the down-stream side will not have any energy to move away from the turbine region.

A wind mill of diameter 80m has an area of A= π 40^2 m^2= 5024 m^2, and can collect wind energy over this area.

The energy in the wind with speed u_0, through a cross-section A is

$$P_T = \frac{1}{2} \rho A u_0^3 \cdot C_p$$

The air density is taken to be ρ = 1.2 kgm^{-3}, and C_p is said to be 50% of the maximum value of 59%, i.e. C_p =0.50 x 0.59 = 0.295.

Thus for an (average) wind speed of 8 m/s

$$P_{T,avg} = \frac{1}{2} \rho A u_0^3 \cdot C_p = \frac{1}{2} 1.2 kgm^{-3} \cdot 5024 m^2 \cdot 8^3 m^3 s^{-3} \cdot 0.295 = 0.46 MW$$

The rule of thumb for estimating wind turbine power says that the available power equals twice the power achieved for the average wind speed at the location in question, so that

$$P_T = 2 \cdot P_{T,avg} = 0.91 MW$$

To get the amount of electric energy (in Wh) generated in one year, we multiply with the generator efficiency (95%) and the number of hours in one year:

In one year one turbine will produce

$$E_T = 2 \cdot P_{T,avg} = 0.91 \cdot 10^6 \cdot 0.95 \cdot (24 \cdot 365) Wh = 7.6 \cdot 10^9 Wh = 7.6 \cdot 10^{-3} TWh$$

To find how many turbines are needed to supply 27.5TWh, we divide 27.5TWh by the amount of energy generated by one turbine, i.e. 7.6 10^{-3} TWh:

$$\underline{\underline{N_{turbines}}} = \frac{110 TWh}{7.6 \cdot 10^{-3} TWh} = \underline{\underline{3627}}$$

b) In a solar cell solar radiation is converted to electric energy by absorption of photons in a semiconductor. Only photons with energy larger than the bandgap can be absorbed; the rest are transmitted. In the absorption process an electron is excited from a state in the valence band (where the electron takes part in the bonding of the semiconductor) to a state in the conduction band (where the electron is able to conduct a current through the semiconductor). The empty state left behind in the valence band will also contribute to the photo-generated current, so each absorbed photon will create one electron-hole pair. To reduce the recombination of the electrons and holes, a built in electric field is formed by making a pn-junction in the solar cell. The electrons and holes will move in opposite directions in this built-in electric field since they have opposite charge. (The electrons move from the p-side to the n-side.) Outside the pn-junction, the electrons and holes will move to the external contacts on the solar cell. At the contact on the n-side of the solar cell pn-junction, the electrons will have a higher (electrostatic) potential energy than (the holes) on the p-side, and this potential difference gives rise to the voltage over the solar cell (called the photo-voltage). This voltage forces the photogenerated electrons (on the n-side) out of the cell and through the load where they give up their energy, before they return into the solar cell at the p-side, at the lower potential energy. In summary: electrons inside the solar cell get an increased potential energy by the absorption of photons, and this increased potential energy (which is partially lost inside the solar cell) gives rise to a voltage over the cell and a current (made up by the photogenerated electrons) will flow out of the cell and through the external circuit.

The amount of solar electricity generated by the solar cells can be expressed as

$$E_{PV} = E_{in} \cdot \eta_{PV} \cdot A_{PV}$$

where E_{in} is the incoming solar energy, η_{PV} the solar cell efficiency, typically 15% and A_{PV} is the area of the solar cells, that we want to calculate. To generate 27.5TWh the area needed is found by setting $E_{PV} = 27.5TWh$ and solving for A_{PV}:

$$A_{PV} = \frac{E_{PV}}{E_{in} \cdot \eta_{PV}} = \frac{27.5TWh}{900kWh/m^2 \cdot 0.15} = 2.04 \cdot 10^8 m^2 = 204km^2$$

For a solar cell with an efficiency of 20%:

$$A_{PV} = \frac{E_{PV}}{E_{in} \cdot \eta_{PV}} = \frac{27.5TWh}{900kWh/m^2 \cdot 0.20} = 1.53 \cdot 10^8 m^2 = 153km^2$$

c) By energy farming we mean the production of fuels or energy as a main or subsidiary product of agriculture (fields), sivilculture (forests), aquaculture (fresh and sea water), and also industrial or social activities that produce organic waste residues, e.g. food processing, urban refuse. The main purpose of the activity may be to produce energy, but more commonly it is found best to integrate the energy and biofuel production with crop or other biomass material products.

The advantages with energy farming are

- bioenergy can be CO_2-neutral if new plants are grown at the same rate as they are harvested
- bioenergy can reduce the total CO_2-emission by replacing fossil fuels
- the potential for bioenergy is largest in the third world countries
- the biomass and biofuels have a large variety of uses
- energy farming can be linked with existing farming activities, in an economically advantageous way
- energy farming can be good for the environment, since waste, residue and by-products are utilized and not discarded to the environment
- energy farming encourages rural development and diversifies the (local) economy

and problems are as follows:

- energy farming may lead to soil infertility and erosion
- it may compete with food production

- transport of bulky biomass to a processing factory
- genetic engineering might be a problem
- energy farming may lead to pollution if processes are not properly controlled
- large scale energy farming may be socially disruptive
- foreign capital may have other priorities than local authorities

The amount of bioenergy produced per forest area is given in GJ/ha and we need to convert this to TWh/km^2. 1J equals 3600Wh, 1TWh= 10^{12}Wh, and 1ha=10^4m^2=10^{10}km^2, so that

$$E/A = 100GJ/ha = 100\cdot 10^9 \cdot \frac{1}{3600} \cdot Wh/ha = 2.8\cdot 10^7 Wh/ha = 2.8\cdot 10^7 Wh/10^4 m^2$$
$$= 2.8\cdot 10^3 Wh/m^2 = 2.8\cdot 10^9 Wh/km^2 = 2.8\cdot 10^{-3} TWh/km^2$$

For a steam turbine power plant with efficiency η_{steam}, the electric energy E_{el} generated from an incoming amount of bioenergy of E_{in} (assuming that all the energy in the bio mass is transferred to the steam boiler) can be expressed as

$$E_{el} = E_{in} \cdot \eta_{steam}$$

For a forest of area A_{forest} the total energy produced is $E_{in} = E/A \cdot A_{forest}$, we insert this in the expression for E_{el}, solve for A_{forest} and find:

$$E_{el} = E_{in} \cdot \eta_{steam} = E/A \cdot A_{forest} \cdot \eta_{steam} \Leftrightarrow A_{forest} = \frac{E_{el}}{E/A \cdot \eta_{steam}}$$

The amount of electric energy we want to generate equals 27.5TWh, so that

$$A_{forest} = \frac{E_{el}}{E/A \cdot \eta_{steam}} = \frac{27.5TWh}{2.8\cdot 10^{-3} TWh/km^2 \cdot 0.36} = 2.8\cdot 10^4 km^2$$

d) The typical efficiency is 30-40%. (World average is 31%, and the world record is approaching 50%.)

Using an efficiency of $\eta_{coal} = 36\%$, the amount of thermal power E_{th} from the burning of the coal should equal $E_{th} = \frac{E_{el}}{\eta_{coal}}$, where E_{el} is the amount of electric energy to be generated, i.e. $E_{th} = \frac{E_{el}}{\eta_{coal}} = \frac{17.5TWh}{0.36} = 76.4TWh$.

The advantages for coal fired power plants

- compared to wind and solar cells is that electricity can be generated continuously, that the cost of the electricity is low and that the technology is established
- and compared with bioenergy the advantages are that the energy density is higher, so that less amount of fuel is needed to generate the same amount of electricity.