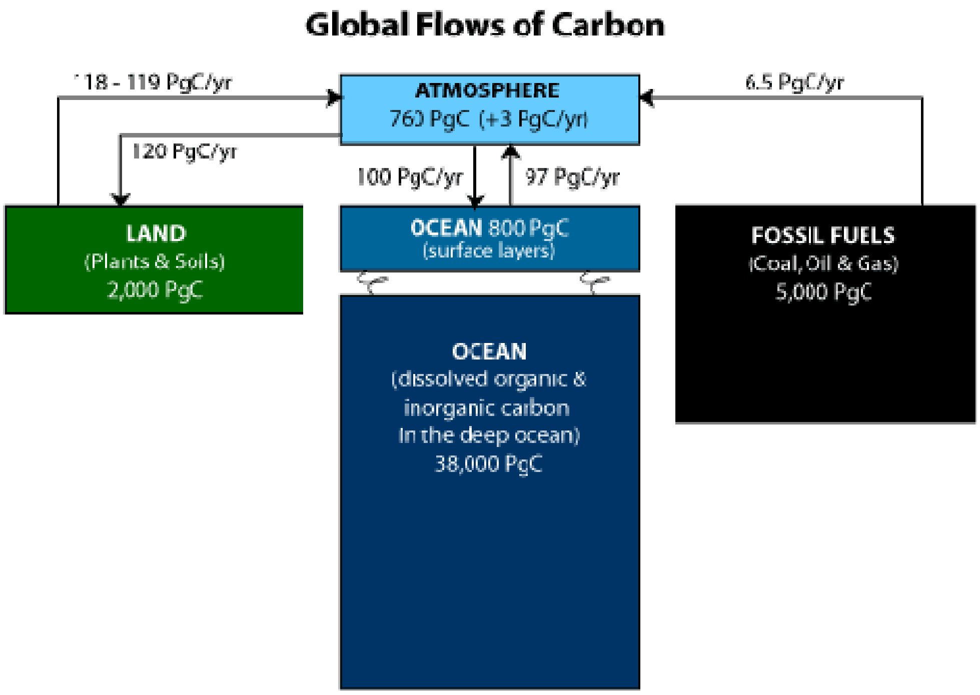
EXAM IN TFY 4300 Energy and environmental physics
Friday December 14th 2007

Problem 1. The Greenhouse effect, the carbon cycle and fossil fuels

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) <u>Fossil fuels are of limited availability, and that we are consuming the fossil fuels much faster than they are formed.</u>
   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) <u>Fossil fuels lead to emission of pollutants</u>
   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) <u>Fossil fuels lead to emission of green house gases.</u>

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 energy

a) The fission process involving ^{235}U and a slow neutron can be expressed as follows:

$$^{235}\mathrm{U} + \mathrm{n} \rightarrow {}^{236}\mathrm{U} \rightarrow X + Y + \upsilon \mathrm{n} + \text{energy}$$

A slow neutron is absorbed in ^{235}U and ^{236}U is formed. ^{236}U is unstable and fissions spontaneously into the fission products X and Y and ν fast neutrons. Many pairs of fission products X and Y can be produced. The fission products and the neutrons that are liberated have high kinetic energies, on the order of 165MeV and 5MeV, respectively. The rest of the liberated energy is emitted in several types of emissions. ν is 2 or 3 and 2.43 on average.

In total the amount of energy released in the process is ca 200MeV. The source for this energy is mass energy. One starts with a large nucleus that is fissioned into smaller fractions. The binding energy per nucleon is smaller for the products than for the starting nuclei, and thus the mass of the products is smaller than the mass of the starting nucleus. This mass difference is what is released in the fission or fusion process: $\Delta E = \Delta m\, c^2$. Although the mass difference is small, since the speed of light c is large, ΔE is substantial.

b) The ν fast (5MeV) neutrons are slowed down to thermal energies (0.025eV) by using a *moderator*. In the moderator (usually water or graphite) the neutrons collide with protons and thus loose half their kinetic energy in each collision since neutrons and protons have similar mass. During the slow-down process the neutrons can be absorbed/captured in the water, in the ^{238}U or in the reactor vessel, and the number of liberated neutrons per fission event reduces to the so-called *multiplication factor* k. If the reactor is of infinite size, no neutrons will be lost to the outside. In this case the multiplication factor is called k_∞, and it is always larger than k for a real-sized reactor. For a typical reactor k_∞ is in the order of 1.10 to 1.20. To maintain safe steady-state operation of the nuclear power plant the multiplication factor k should equal 1, i.e. the ν fast neutrons should (after moderation, absorption and/or escape) be reduced to one slow neutron. If there are excess neutrons (k>1) present in the reactor control rods that absorb neutrons are used, to reduce k to 1.

Start with 1 slow (thermal) neutron, go via ν fast neutrons, end up with k slow ones:

$$1n_{slow} \xrightarrow{\text{decay of } ^{236}\text{U}} \nu n_{fast}$$

$$\xrightarrow{\text{capture in } ^{235}\text{U and } ^{238}\text{U}} \eta n_{fast}$$

$$\xrightarrow{\text{Moderation and absorption}} k_\infty n_{slow}$$

$$\xrightarrow{\text{Finite reactor size, control rods}} k n_{slow}$$

The ν fast neutrons must be slowed down because the fission cross-section for ^{235}U is much larger for slow neutrons than for fast neutrons, i.e. if the neutrons were not slowed down, it would not be absorbed by ^{235}U to cause a second fission process, and there would be no chain reaction. If there is no chain reaction neutrons would have to be supplied from an external source.

c) In a reactor a neutron reproduces itself in a time L: The neutrons will first slow down by collisions and then stay for some time with thermal energies in the moderator, before they are absorbed by the ^{235}U of one of the fuel rods. Then the neutrons immediately cause another fission process. L is typically 10^{-4}s

However, a small fraction of the neutrons result from the decay of the fission products and their "daughters", and these neutrons are called delayed neutrons. On average the delay time t_d is 9s for the decay of ^{236}U, and even though the fraction of delayed neutrons is small, the delayed neutrons significantly increase the reproduction time. With this increase, the operation of the reactor is much safer, since now the safety systems will have longer time to respond to a small increase in the multiplication factor k. Without the delayed neutrons one needs to react within a fraction of a second, while with the delayed neutrons, the reaction times increases to tens of seconds.

Problem 3. Bioenergy

a) 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. *Comment: for the grading of the exam full score was given for answers that only included agriculture, since the Norwegian translation was misleading.*

The advantages with energy farming and bioenergy 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 dangers 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

b)

The primary biofuels used today are wood, dung, plant residues, solid waste from various human activities, liquid fuels extracted directly from plants etc.

The secondary fuels used are gases (biogas/methane), liquids (oils, esters, biodiesel, ethanol, methanol, tar, pitch etc) and solids (charcoal). Of these methane has the highest energy density. (Hydrogen can also be produced as a secondary fuel, and has a higher energy density than methane, but I have not included this fact in the lectures.)

Problem 4. Energy supply

a)

Incident solar energy during one year on the area of 1km^2:

$$E_{in} = 4497 Wh/m^2/day \cdot 365 days \cdot 1km^2 = 1.6 TWh = 5.9 \cdot 10^{15} J$$

Cover 80% of the area with 15% efficient solar cells, then the amount of produced electricity is:

$$\underline{\underline{E_{PV}}} = 0.8 \cdot 0.15 \cdot 1.6 TWh = \underline{\underline{0.20 TWh}} = 0.20 \cdot 10^{12} \frac{J}{s} \times 3600 s \underline{\underline{= 7.1 \cdot 10^{14} J}}$$

b)

Energy input from the sunflowers:

$$E_{in} = 29 GJ/ha \cdot 1km^2 = 29/(100 \cdot 100) \cdot (1000 \cdot 1000) GJ = 2.9 \cdot 10^{12} J$$

$$= 8.1 \cdot 10^{-4} TWh$$

With a power plant efficiency of 20%, the amount of electric energy generated using the sunflowers as fuel is

$$\underline{\underline{E_{Out} = }} E_{in} \cdot \eta = 2.9 \cdot 10^{12} J \cdot 0.2 = \underline{\underline{5.8 \cdot 10^{11} J}} = 5.8 \cdot 10^{11} J / 3600 s \times h = \underline{\underline{1.6 \cdot 10^{-4} TWh}}$$

c)

$$E_{in} = 294 MW \cdot (3600 \cdot 24 \cdot 365) s = 9.27 \cdot 10^{15} J = 2.58 TWh$$

This means that the amount of electric energy generated using the geothermal heat as source is

$$\underline{\underline{E_{Out}}} = E_{in} \cdot \eta_{tot} = 9.27 \cdot 10^{15} J \cdot 6\% \cdot 90\% \underline{\underline{= 5.0 \cdot 10^{14} J = 0.14 TWh}}$$

d)

The available power is twice the power at the average wind speed since the power depends on the cube of the wind speed, thus the contributions at higher wind speeds is large.

Wind power available from one turbine operating at the average wind speed:

$$P_T = \frac{1}{2} \rho A u_0^3 \cdot C_p = \frac{1}{2} \cdot 1.123 kg\ m^{-3} \cdot \pi \left(\frac{90}{2}\right)^2 m^2 \cdot 7^3 m^3 s^{-3} \cdot (0.59 \cdot 0.55) = 3.98 \cdot 10^5 W$$

The available power in the wind is twice this amount:

$$P_{Available} = 2 \cdot P_T = 7.95 \cdot 10^5 W$$

The amount of electric energy produced in one year is then

$$\underline{\underline{E}} = \eta_{generator} P_T \cdot \Delta t = 0.95 \cdot 7.95 \cdot 10^5 \cdot 3600 \cdot 24 \cdot 365 J \underline{\underline{= 2.38 \cdot 10^{13} J = 6.62 \cdot 10^{-3} TWh}}$$

Each turbine need an area of 500x500m^2, and this means one can place 4 turbines in the allotted area, so that the total amount of wind energy produced in an area of 1km2 is:

$$\underline{\underline{E_{4turbines}}} = 4 \cdot 6.62 \cdot 10^{-3} TWh \underline{\underline{= 2.7 \cdot 10^{-2} TWh = 9.5 \cdot 10^{13} J}}$$

e)

Technology	Advantage	Disadvantage
Solar cells	- solar energy distributed globally - Generates electricity directly (need no generator) - Existing technology - Flexible technology (stand-alone, grid connected) - Modular technology (easy to expand at a later stage) - Reliable - Easy to use - No noise or emissions - Prices are being reduced rapidly - Suitable for building integration	- Not a continuous energy source: Need energy storage - Still quite expensive, due to low conversion efficiency - Only utilizes < 15% of the solar energy; the rest is lost as heat to the environment. - Battery lifetime only 3-6 years - visual impact on nature
Biomass	- Biomass used as a fuel reduces the need for fossil fuels - Biomass is readily available and can be continuously produced - Carbon dioxide, which is released when biomass fuel burns is returned to the natural carbon cycle. - Biomass fuel from agricultural wastes may be a secondary product that adds value to an agricultural crop. - Ethanol blends can be used in all petrol engines without modifications.	- Increase in soil infertility and erosion. -Land used for energy crops may be in demand for other purposes - Compete with food production - Deforestation in some regions - Research is needed to reduce the costs of production of biomass-based fuels. - need labor and area for the processing of the sunflowers and for the heat power plant - some pollution and emissions possible
Geothermal	- Continuous source (can operate over 90% of the time) - Use energy from the Earth - Very low CO_2 emissions - Little pollution - Moderate maintenance requirements and costs - Large hot dry rock system/EGS potential, but technology not mature	- Surface disturbances - Changes in scenery, untidiness - Heat effects on the environment - Air pollution - Noise - Financial risk - Need to be near the consumers - Need more research and development for dry rock fracturing
Wind	- established industry - cheapest of the renewable energies at present - modular - large potential globally - no emissions	- not continuous, need energy storage - visual impact - noise - impact on wild-life/ecosystems

Recommendation to city council:
From the calculations above the solar cells gives the maximum amount of electric energy for the assumptions made, but is comparable with the geothermal electric energy delivered (70% of the solar cell output). Energy farming with sunflowers and wind turbines yields ca 0.1% and 13.4% of the solar cells yield, respectively. From the table above, we see that the disadvantages for the solar cells are acceptable. For geothermal energy, there is some financial risk that you avoid with the solar cells. <u>I therefore would recommend using solar cells for electricity generation.</u>

Validity of assumptions:

Solar cells
It may be difficult to evaluate if the assumption of the incoming solar energy of 4497Wh/m^2 per day is reasonable. But by making some (qualified) guesses we can try. The insolation in Southern Europe is ca 1700W/m^2 at maximum, but in general much lower (in the winter and at night). From fig 4.7 in T&W we know that on average the minimum insolation at mid-winter is around 1/3 of the maximum insolation. If we assume, as a first approximation, that the insolation varies linearly from mid-winter to mid-summer, then the average daily insolation is 1700x(1+ 1/3)/2= 1133 W/m^2. To end up with a daily average of 4497Wh/m^2, the sun has to shine with the average insolation 4497/1133 h = 4.0 hours per day which seems a bit low. *(Comment: The value 4497Wh/m^2 is taken from measured insolation data for Madrid, taking into account meteorological and topographical effects.)*

For the solar cells and efficiency of 15% is reasonable, however we did not included system losses that can amount to 20-25%, so that the real amount of electric energy is reduced. The output form the solar cells can be increased by choosing more efficient solar cells that currently are being developed. (Efficiencies are expected to be doubled or tripled over the next 15-20 years.) Horizontal mounting gives a lower insolation on the surface, and by mounting the solar arrays at an (fixed) optimum angle, the number of solar arrays than are needed to cover the 1km^2 area will be smaller (to absorb the same amount of solar radiation). A coverage of the area of 80% is maybe too low; one could imagine that all access to the solar cells is done from below, so there is no need for space between the solar arrays.

Sunflowers
It is hard to know if an energy yield of 29GJ/ha is reasonable, without prior knowledge. *(Comment: The listed yield is taken from literature and is in the lower end for dried crops and is similar to the yield of soya beans and rapeseed (20 and 30GJ/ha respectively). Other (dried) biomass can yield up to 200GJ/ha per harvest.)*

The stated efficiency of the power plant is reasonable; typical steam power plants have an efficiency of 17-20%.

Geothermal
On average the heat flux from the inner of the earth is 0.06W/m^2= 0.06MW/km^2, which is much lower than the stated 294MW/km^2, so one would first guess that the stated value is overestimated. However, for dry rock fracturing, the heat flow is <u>enhanced</u> by circulating water through the hot fractured rock, but the degree of enhancement is difficult to evaluate

without performing more detailed calculations. The heat extraction of 294MW/km^2 may therefore be reasonable. *(Comment: the stated heat extraction is calculated in example 15.1. in the textbook, and assumes a temperature gradient of 40C/km, so the heat extraction in Madrid, where there is no reason to assume this larger temperature gradient, is actually lower than 294MW/km^2.)*
At a depth of 7km the temperature would be 210K above surface temperature, assuming the thermal gradient for normal regions of 30°C/km, so it is reasonable to believe that the circulated water can be heated to 103°C and extracted.

The stated efficiency of the geothermal power plant is very low; typical steam power plants have an efficiency of 17-20%. The Carnot efficiency is $\eta = 1 - \frac{T_C}{T_H} = 1 - \frac{5+273}{103+273} = 26\%$, so if 6% is the correct efficiency, there must be large losses in the power plant. *(Comment: The energy content and the efficiency are taken form literature on real geothermal power plants working at the low temperature of 103°C , so the states efficiency is real.)*

Wind energy
The rotor area is acceptable, but 55% of the theoretical efficiency is a little less than what can be achieved. An average wind speed of 7m/s is a bit low; wind turbines of this large size normally have a cut-in speed of 5m/s, so this low average wind speed will mean that the wind turbines will not operate for long periods when the speed is too low. It may, however, be correct for Madrid that the average wind speed is 7m/s; that is impossible to say without prior knowledge. The same holds for the area needed for one turbine. *The average wind speed in Madrid is actually less than 7m/s. An area of 500x500m^2 for a single wind turbine seems a bit large, but is actually near the amount of space that is required.*

So, in conclusion all of the assumptions (than can be evaluated) are reasonable.

Obviously, all technologies listed can perform better, if better technology (or more energy dense biomaterial) is chosen, for example, more efficient solar cells or larger wind turbines. More importantly, the “waste” heat from the heat power plants fuelled by the sunflowers or geothermal heat should be utilized. The very low efficiency of the geothermal power plant means that 94% of the energy is “lost” as heat, and obviously this heat should be utilized, e.g. as process heat.