Solution

EXAM IN TFY 4300 Energy and environmental physics

Friday December 2nd 2005 Duration: 9-13

Problem 1 (5% + 5% = 10%)

a)

We can obtain information about prehistoric climates by measuring the isotope ratio of ^{16}O and ^{18}O in the ice on Greenland by using the small mass difference between ^{16}O and ^{18}O atoms resulting in a little mass difference of the corresponding water molecules H_2O. The point is that the lighter molecules evaporate more easily and the heavier molecules condense more easily. Thus, when the oceans evaporate, the heavier molecules will tend to fall down again as rain but the lighter molecules will remain somewhat longer in the air, reaching the arctic regions where they fall as ice and snow. The isotope ratio $^{16}O/^{18}O$ in the Greenland ice will depend on the temperature at the location of evaporation, on the precipitation during transport from the tropics to the arctic regions and finally on the air temperature in Greenland itself. One has obtained empirical relations to connect the isotope ratio with the temperature at Greenland. Therefore, accurate measurement of isotope ratios in old ice will show the temperature of the period when they were formed; its age of course should be estimated independently.

b)

The natural causes to climate change can be classified as follows

1) Variations in the local insolation (incoming solar radiation).

There are three physical phenomena determining the insolation, and these are called Milankovitch cycles after the astronomer that described them first. The first phenomenon is the eccentricity of the orbit of the earth around the Sun, which varies with a period of 100000 years, with the sun remaining in the focal point; the second factor is the tilt angle between the earth's axis and the normal on the orbital plane, which varies between 21.5 and 24.5° with a period of 41000 years. The last one is the precession of the earth's axis around the normal with a period of 26000 years. The physical origin of this last effect is due to the deviation of the earth from a sphere which may be represented by an extra 'belt' at the equator of a spherical earth; the moon is exerting a torque on this 'gyroscope' which causes the precession. The two other effects are due to more complicated gravitational interactions with the rest of the solar system.

2) Variations in the intensity of the solar radiation

The intensity of the solar radiation varies with the life cycle of the sun (its age) on a very long time scale (billions of years), and the intensity was weaker when the sun was young. On a much shorter time scale (tens/hundreds of years) the intensity varies due to fluctuations in the processes on the sun (i.e. sun spot activities).

3) Catastrophic events

Volcano eruptions, meteorite impacts etc can influence the climate by adding aerosols (ash and other small particles) leading to reduction of the insolation and thus a temperature decrease (global dimming/haze), and by adding greenhouse gasses (in particular CO_2 and sulphur rich gases) leading to a temperature increase (global warming).

Problem 2 (10% + 5% + 10% + 10% = 35%)

a)

The sun radiates like a black body and the total radiative power emitted is $P_{sun} = 4\pi r_s^2 \sigma T^4$.

Of this a fraction $\frac{\pi r_e^2}{4\pi d_{se}^2}$ reaches the Earth. Outside the atmosphere the total incoming solar radiation is thus $P_{in} = P_{sun} \cdot \frac{\pi r_e^2}{4\pi d_{se}^2}$, so per square meter just outside the atmosphere the incoming solar radiation per square meter is

$$S = P_{in} \cdot \frac{1}{\pi r_e^2} = 4\pi r_s^2 \sigma T^4 \frac{\pi r_e^2}{4\pi d_{se}^2} \cdot \frac{1}{\pi r_e^2} = \sigma T^4 \frac{r_s^2}{d_{se}^2}$$

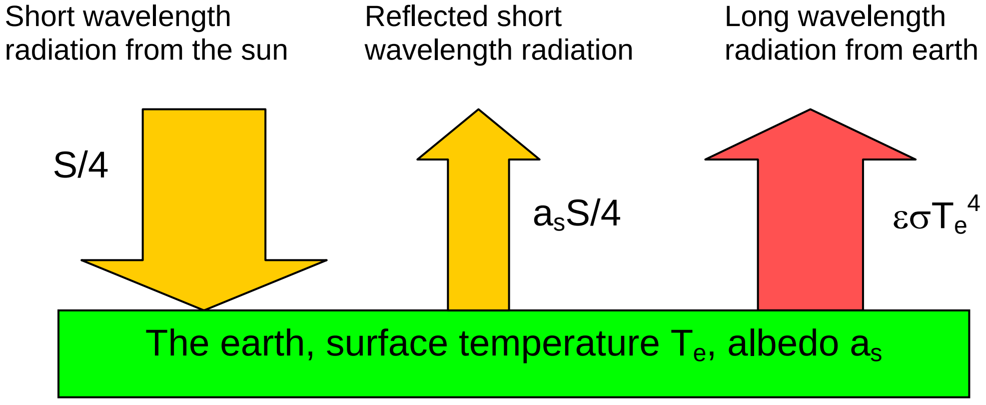
S is called the solar constant.

b)

The albedo is a dimensionless number giving the amount of incoming radiation (from any source) that is (diffusely) reflected from an object. In general it depends on the wavelength of the radiation, so that the same object, i.e. the atmosphere, can have different albedo for the short wavelength solar radiation and the long wavelength thermal radiation of the earth. In the short wavelength region, the surface of the earth has an albedo of ca $a_s = 0.11$, while viewed from space $a_s = 0.34$. The number $a_s = 0.11$ is an average over the earth's surface, where differences in vegetation and habitation give rise to rather differing albedos. For example fresh snow has and albedo of ca 0.85, deserts 0.30, vegetation 0.10-0.15 and dark soil 0.10. Clouds have an albedo between 0.4 and 0.9 depending on the type.

If the earth warms up, this could lead to a melting of ice and snow, and thus a lowering of the albedo a_s. The increased temperature will also give rise to more water vapor and clouds in the atmosphere, and thus the albedo for the atmosphere a_a' will increase (for long wavelengths). Increased temperature may also lead to more CO_2 in the atmosphere, since the CO_2 uptake in the seas will be less efficient. This increase in CO_2 level may lead to an increased growth of plants which may change the albedo.

c) A simple model for the energy balance of the earth with no atmosphere is as follows, where the energy fluxes (energy per time and area unit) are drawn as arrows.



a_s is the albedo of the earth, σ the Stefan-Boltzman constant, ε is the emissivity of the earth for long wavelengths, and T_s the surface temperature of the earth.

The incoming solar radiation equals S/4 where S is the solar constant given in a). We use S/4 since the incoming radiation (the solar constant) is on a disc of area πr_e^2, and the energy from this incoming radiation is distributed of the whole surface of the earth with four times this area, $A_e = 4\pi r_e^2$.

From the model sketched above, we can set up the following expression for the energy flux balance (P is power):

$(P/A)_{in} = (P/A)_{out}$

$\Rightarrow S/4 = a_s\, S/4 + \varepsilon\sigma T_e^4$

We can solve this for T_e:

$T_e = [(1-a_s)S/4 \,*(1/\varepsilon\sigma)]^{1/4} = [(1-a_s)/(4\varepsilon\sigma)\ \ (\sigma T_{sun}^4\, r_s^2/\, d_{se}^2)\,]^{1/4}$

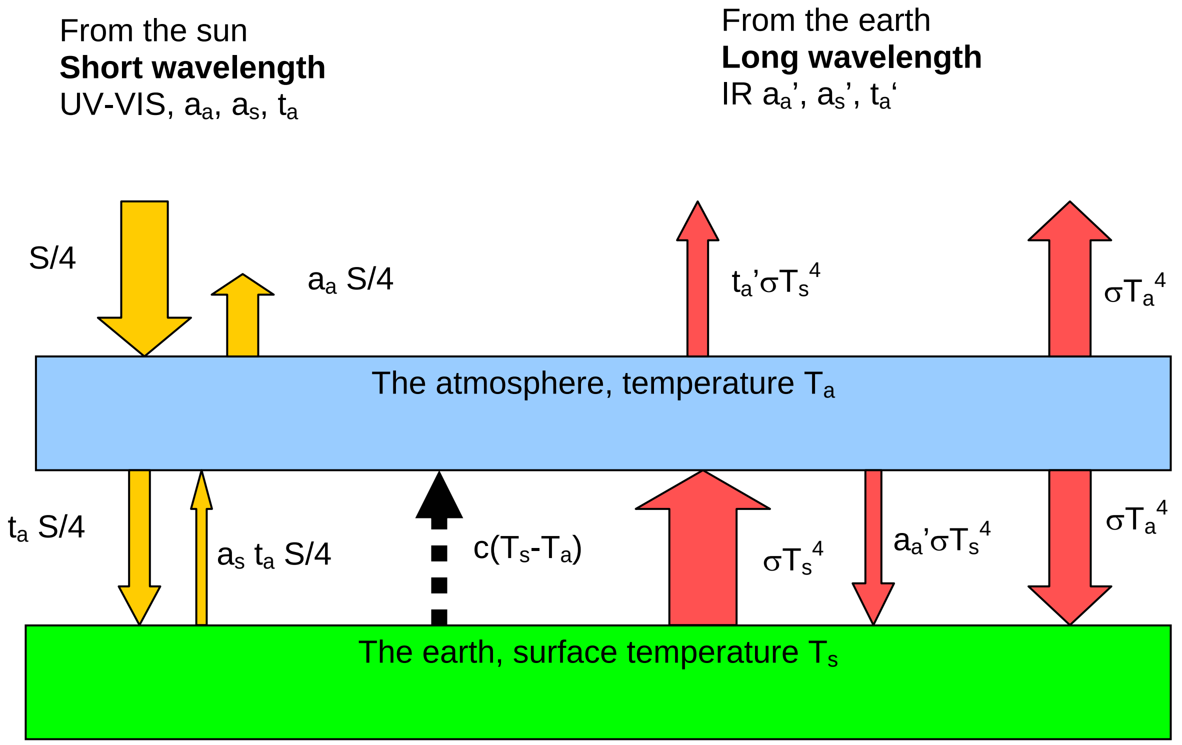
where the expression for S from 2a) is inserted.

Inserting the given numerical values, we get T_e = 253K.

Using this simple model of the earth without the atmosphere, the resulting temperature of the earth is found to be 253K = -20°C, which is 35°C below the actual average surface temperature. The deviation is explained by the natural green house effect: In the atmosphere of the earth there are gasses present (water vapour, CO_2 and others) that will absorb parts of the long wavelength (thermal) radiation emitted from the surface of the earth. In this way the temperature of the atmosphere increases and the amount of black body radiation emitted back to the surface of the earth increases. A fraction of the long wavelength radiation is thus re-emitted back to the surface and causes and temperature increase here. In addition, the atmosphere also reflects parts of the long wavelength radiation emitted from the surface of the earth.

d)

The simple model for the energy balance is as follows, where the energy fluxes (energy per time and area unit) are drawn as arrows.



The physical quantities are as follows:

- S is the solar constant
- T_s is the temperature of the surface of the earth
- T_a is the temperature of the atmosphere
- t_a is the transmittance of the atmosphere in for short wavelengths
- t_a‘ is the transmittance of the atmosphere in for long wavelengths
- a_a is the albedo of the atmosphere in for short wavelengths
- a_a‘ is the albedo of the atmosphere in for long wavelengths
- a_s is the albedo of the surface of the earth for short wavelengths
- c is a proportionality constant taking care of the heat exchange between the earth and the atmosphere, other than radiation.

First we look at the energy fluxes in and out of the atmosphere, and set up an equation for the energy balance (energy in = energy out):

$$\frac{S}{4}+t_a a_s\frac{S}{4}+\sigma T_s^{\,4}+c(T_s-T_a)=t_a\frac{S}{4}+a_a\frac{S}{4}+t_a^{'}\sigma T_s^{\,4}+a_a^{'}\sigma T_s^{\,4}+2\sigma T_a^{\,4}$$

$$\Leftrightarrow -(1-a_a-t_a+a_s t_a)\frac{S}{4}-c(T_s-T_a)-\sigma T_s^{\,4}(1-t_a^{'}-a_a^{'})+2\sigma T_a^{\,4}=0 \quad (1)$$

Similarly we get for the surface:

$$t_a\frac{S}{4}+\sigma T_a^{\,4}+a_a^{'}\sigma T_s^{\,4}=t_a a_s\frac{S}{4}+\sigma T_s^{\,4}+c(T_s-T_a)$$

$$\Leftrightarrow (-t_a)(1-a_s)\frac{S}{4}+c(T_s-T_a)+\sigma T_s^{\,4}(1-a_a^{'})-\sigma T_a^{\,4}=0 \quad (2)$$

A global warming can change the values for the albedos and the transmittances of the earth and the atmosphere. After making estimates of how these values change, the new values can be inserted in the equations above, and the effect on the temperature of the earth (and the atmosphere can be calculated).

Problem 3 (15% + 10% = 25%)

a)

Solar energy in the form of solar radiation can be utilized in mainly three different ways to cover the energy needs of a house:

1) For water heating
2) For space heating or cooling
3) For cooking
4) For electricity production

1) Water heating

For water heating one can choose between active and passive/static water heating. In both cases, a solar collector that absorbs as much of the solar radiation as possible, while keeping the heat losses to a minimum, is required. Depending on the budget of the house owner various designs of flat plate solar collectors can be chosen. In the simplest case the solar water heater consists of an open water-filled container on the ground, or on the roof of the house. If the container is not properly thermally insulated on the bottom there will be conductive heat losses through the bottom. Also heat losses due to evaporation and convection are large. Lastly water has quite low absorbance of solar radiation, so little heat is absorbed. This simple water heater can be greatly improved by containing the water in a black rubber bag; then the evaporation losses can be eliminated and the absorbance can be much closer to 1, so we both gain more power, while reducing the losses. The temperature of the water can now reach, typically 40°C. But still convective heat losses (both free and forced by the wind) can be large. These convective losses can be reduced by putting the bag in a glass shelter, eliminating much of the forced convection heat loss. The bag will be at a high temperature (up to 95°C), while the glass is heated only by radiative and free convective losses from the bag, and thus be at a much lower temperature (typ. 40°C), reducing the total heat loss. The convection losses inside the shelter can be further reduced by introducing a second layer of glazing and/or by evacuation. If there is no air in the shelter there will be no convective heat loss from the bag to the glass at all.

If the budget allows for it, an active solar water system can be installed. In these kinds of systems, the water is allowed to circulate through the solar collector, and is then transported (in well insulated pipes) to a hot water storage system. The water can be transported by free circulation (i.e. in a thermosyphon) or forced circulation (by using pumps). Water can now be extracted from the storage system to supply hot water (to the bathroom and kitchen), or to supply space heating. Used for space heating, the water flows in pipes to radiators, or the water pipes are integrated in the floor. In general the active solar water heating systems with a storage system are more energy effective than the static systems, since the heat can be transported away and used before it is lost. A static system will not store more heat energy after the maximum temperature of the system is reached, since after that (in equilibrium) the losses balance the incoming heat. Also with a separate storage, more water may be heated and thus more heat can be stored.

In general the solar collector surface should have a high absorbance for the solar radiation, while the emittance for the thermal (long wavelength) radiation should be small. In this manner the amount of absorbed heat can high, while the radiative heat loss can be small. A surface with these absobance/emittance properties is called a selective surface. Certain semiconductors have suitable bandgap to be used as a selective surface, but since they are rather expensive, have low thermal conductivity and are not very robust, they are usually used in combination with metals.

2) Space heating and cooling

A solar collector can also be used to heat air, but then air instead of water is heated (and circulated). For space heating we also distinguish between active and passive systems, where the “active” term is used to indicate that the air is heated on the exterior, and then transported inside. In passive systems the heat is absorbed and stored in the room where it is needed. As for water heating the amount of heat absorbed should be maximized while the amount of heat loss should be minimized. For a passive system, the amount of absorbed solar heat is maximized by having large areas of a black surface that will be irradiated by the sun during the day. It is important to have windows with a high transmittance for the solar radiation. The emittance for the thermal radiation should be as small as possible. In addition the thermal heat losses due to conduction through the floor, walls and ceiling should be minimized by proper insulation. Heat losses through the windows can be minimized by using double (or triple) glazing and by covering the windows by curtains after sunset. The areas of the windows should be as large as possible, to harvest as much solar radiation as possible. For the heat storage, the black surface should be covering an object (i.e. a wall) with high heat capacity; i.e. a massive, thick concrete wall with high specific heat, and low thermal conductivity. In this manner a lot of thermal heat can be stored, and be radiated back afterwards. One drawback with using large windows is that the house can get too hot during the day, especially during summer. This can be solved by shading (roof overhangs), or by building a so-called storage wall, with openings over and under it, on the sunny side of the building. Air will circulate past this wall forced, or freely and transport the heat away. During summer the wall will be shaded and can be cooled by air circulating from the cool side of the house.

A mechanical device capable of space cooling based on solar radiation is the absorption refrigerator. In this device solar heat is used to increase the pressure of the refrigerant. This amount of heat is normally supplied by electricity to a compressor. These devices are not very efficient.

3) Cooking
Using concentrator systems one can achieve much higher temperatures than with the solar collectors described so far. In theory the maximum temperature that can be achieved for a parabolic trough concentrator is nearly 1160C, while in practice one achieves ca 970K. For a parabolic bowl one can reach much higher temperatures; up to 3000K in practice. Concentrator systems require direct sunlight to be able to focus it to one spot, so while non-concentrating systems also work well for diffuse light, the concentrator systems do not. To exploit as much of the direct radiation as possible, the concentrator should track the motion of the sun over the sky. This requires quite advanced technological solutions, and can make concentrator systems expensive. Simpler systems may, however, be designed and these can be used for combined heating and cooking purposes in a house. For this to be a reasonable thing to include in a house, it should be located at a place with climatic conditions that give a lot of direct solar radiation most of the year. For these simpler systems temperatures of up to 700K are feasible.

4) Electricity production
Due to the high temperatures reached in the concentrator systems, these can be combined with heat engines and generators to generate electricity. Since the temperature is increased, the thermal efficiency of the heat engines increases. Currently scientists are developing different systems for electricity production based on solar heat, and the larger solar power plants are not suitable to combine for electricity production for a single house. Smaller systems, with a Stirling engine attached to the concentrator (the heliostat) can be envisaged as stand-alone systems. These systems for solar thermal electricity generation can have efficiencies of more than 30%.

A direct way if producing electricity, to cover parts of the energy needs in a house, is to utilise solar cells. These convert the solar radiation (below a certain wavelength determined by the bandgap of the semiconductor) to direct current electricity. Each absorbed photon excites an electron from the valence band to the conduction band, and generates thus what is called an electron-hole pair. A photogenerated current is created flowing out of the terminals/electrodes of the solar cell, and this current can be used immediately, stored in a battery, or fed into the electricity grid. Another option is to use the solar cell to produce hydrogen for energy storage, but this is relevant only if the hydrogen society becomes a reality. A typical silicon solar cell produces 3A and a voltage of 0.6-0.7V. This voltage is too low for most applications, so the cells need to be connected in series into a module to add up to a usable voltage (often 15V). Then the modules can be connected in parallel into an array to increase the total current delivered.

Over-all considerations

For all solar energy devices mentioned, it is important that the device is oriented so that maximum amount of solar radiation falls onto it. The device should face the sun, with an angle relative to the horizontal axis equal to the latitude, i.e. 64° here in Trondheim. On the parts of the walls and roof facing the sun should we should use the various devices according to our needs (and budget). In general it is better to utilise the solar heat directly, instead of using electricity to generate heat and hot water (to keep the electricity usage at a minimum).

A system combining solar heat for both water and space heating will probably be an advantage. If the budget allows it, an active solar water heating system with hot water storage will be better, since more heat can be harvested. For such a house we need to construct it with water pipes (and a pumping system), and can easily include heat exchangers to capture waste heat leaving for the sewage, to reduce the total heat loss from the house.

The amount of windows for passive space heating will depend where the house is situated: too large windows might be a problem in very sunny locations, where maybe cooling is more important than heating. In hot locations, absorption refrigerators or maybe even heat pumps (for cooling) powered by solar electricity, may be installed.

Solar cells may be integrated in all surfaces (roofs, windows, walls), but with lower electricity production in those positions where the insolation is small, due to the not optimum orientation. A stand-alone concentrator system with a Stirling engine or for combined heating/cooking could be placed next to the house (so far away that it does not shade).

b) Solar heating og a room

i. The total absorbed power is $P = \tau\alpha G A_a$

ii. The general expression for the heat loss from the room is $P_{loss} = \Delta T/R = (T_r - T_a)/R$

iii. Heat loss mechanisms

The solar radiation heats up the concrete structure by radiation through the window. This heat is lost via the following heat transport mechanisms:

From the concrete structure (assuming that the concrete is warmer than the other parts of the room and the ambient):

- The heat is conducted to other parts of the house that it is attached to; to the floor, and maybe to the walls and the ceiling/roof
- The heat is also transported by free convection of the air in the room and to other parts of the house
- Finally the heat is lost by radiation from the hot concrete structure to the cooler surroundings inside and outside

From the walls and the roof

- If the walls and roof have high thermal conductivity, they will in general be warmer than the outside. Then heat can be lost in the form of free and forced (if there is wind outside) convection and radiation
- In the house is well insulated, then the resistance of heat transport for the walls and the roof is very high, and the temperature drop over them is large, and the outside temperature of the walls and the roof is the same as the ambient. Then there will be no heat transport from the walls and the roof to the ambient.

From the floor

- If the floor is not well insulated, heat can be transported from the floor to the ground by conduction.

Heat can be transported through the windows by

- Conduction and radiation. In addition there is always a thin insulating layer of air next to the window where heat is transferred by convection.
- If there is a second glazing and the spacing between then two glass sheets is small enough, then the convective heat loss between them can be minimized, and increase the total thermal resistance of the window. A curtain can have the same effect, and reduce the heat loss.

iv. General expression for the irradiance G that is needed to keep a given temperature T_r in the room.

The general expression is:

$$mc\frac{dT_r}{dt} = \tau\alpha GA + P_{boost} - \frac{(T_r - T_a)}{R}$$

In steady state $\frac{dT_r}{dt} = 0$ and with the solar energy as the only energy source $P_{boost} = 0$, so the equation simplifies to

$$0 = \tau\alpha GA - \frac{(T_r - T_a)}{R}$$

that can be solved for G:

$$G = \frac{(T_r - T_a)}{R\tau\alpha A}$$

<u>Problem 4 (30%)</u> Answer <u>three</u> of the following five problems.

a) Ozone

Ozone (O_3) forms a thin layer in the stratosphere, with a maximum concentration between 20 and 26 km above the earth's surface. That ozone forms a very thin shield indeed is probably best demonstrated by the fact that the amount of O_3 in the atmosphere corresponds to a layer of 0.3 cm at standard temperature and pressure.

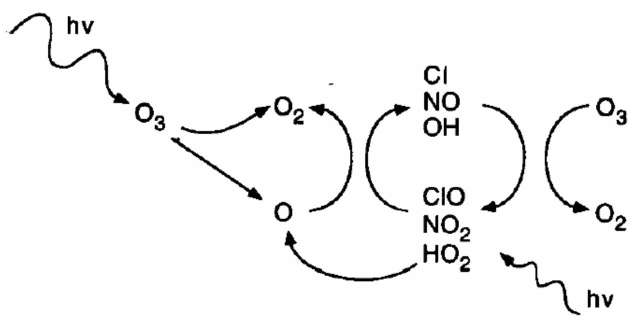
The atmospheric ozone absorbs essentially all the radiation below a wavelength of 295 nm, due to a strong optical transition at about 255 nm, which extends into the mid-UV region. The crux of the ozone problem is that a small variation only in the ozone concentration will lead to changes in both the amount of UV light at a particular wavelength and the transmission of shorter wavelength radiation. Since the action spectrum for damage to living cells or tissue is an exponentially increasing function (with decreasing wavelength) the amount of damage may dramatically increase, even with a relatively small decrease in the amount of ozone. It is predicted that a 10% ozone depletion will result in a 45% increase in damage from UV-B radiation. These alarming numbers illustrate the necessity to monitor accurately the structure of the ozone layer and to quantify the effects of increased UV on living organisms. The ozone layer therefore effectively acts as an UV-filter protecting life on earth from cell damage.

The efficiency of O_3 formation and destruction by UV light is sensitive to a large number of factors, amongst which are the availability of O_2, changes in stratospheric temperature, chemicals and dust from volcanic eruptions. Especially chemicals and dust can be a result of human activities. Ozone is permanently being formed and broken down in the stratosphere and only a very small fraction of the formed ozone escapes down to the troposphere. There are basically two pathways for the destruction and the reformation of ozone:

$$O + O_3 \longrightarrow 2O_2$$

$$O_3 + O_3 \longrightarrow 3O_2$$

These reactions are the net result of a complex set of reactions catalysed by various gases and radicals, for example atomic chlorine Cl, nitric oxide NO and hydroxyl radicals OH; the pathway along which they operate is as follows:



Look for example at the Cl radical. It strips off an O atom from O_3 (right-hand side), forming ClO; then loses an O atom to a free O atom and returns to the radical Cl state again. The net effect is $O + O_3 \rightarrow 2O_2$.

The free radicals NO, Cl and OH are produced partly by human activities: The OH radical is a product of the breakdown of H_2O vapour, for instance produced in the exhaust of supersonic aeroplanes. Although part of the Cl radical may be formed from HCl released by volcanoes, the major input of Cl into the stratosphere originates from chlorofluorocarbons (CFCs), which are used as foam-blowing agents, refrigerants and propellants.

CFCs are extremely stable in the troposphere. However, a small fraction may escape into the stratosphere, eventually reaching the upper stratosphere where they may be decomposed under the influence of UV light, thereby producing Cl and ClO.

N_2O is partly of anthropogenic origin and is released from soils and waters where it has been formed as a fertilizer waste product. Like the CFCs, the N_2O released at the earth's surface may eventually be photodecomposed and NO is formed. These radicals, together with the OH radical, remove some 99% of the stratospheric ozone.

At ground level ozone is not a good thing, since ozone is a strongly reactive and poisonous gas, and is harmful for humans, animals and plants.

b) Energy fuel, use and future

In 2003 the energy "consumption" was 4.4 10^{20}J. Of this approximately 80% was from fossil fuels in the EU, and approximately 37% in Norway.

If we use energy sources at the same rate as today we have

1) coal for ca 200 years (850 years*)
2) Oil for ca 40 years (124 years*)
3) Gas for ca 66 years (100 years*) and
4) Uranium for ca 68 years (118 years*)

(* = if we include the ultimate reserves)

In sea water there is 1 deuterium atom per 6700 hydrogen atoms, and from the huge amounts of water on earth, one has calculated that there is enough deuterium for 10^9 years, supplying all the energy needed on earth. If fusion on earth is realised, the deuterium will represent an infinite energy source in practice.

Energy usage is strongly connected to technological development. With the industrial revolution the energy usage increased (from 8MJ per person per day in the stone-age) to more than 400MJ. Today people in the developed (industrialised) countries are using more than 1100MJ per person per day. In the third world countries the energy usage is only a fraction of the usage in the developed countries, and also amount of energy in the form of electricity is only ¼ of the electricity usage in the developed countries. As the countries are developing the energy usage globally will increase, and the part that is in the form of electric energy will increase from today's global average level. This increase in demand will be rapid, as the developing countries are those with the largest population growth as well. It is a challenge to meet this energy demand, and to meet it without increasing the emissions of green house gasses, especially CO_2 from the burning of fossil fuels which still is the cheapest option for most countries.

c) Nuclear power

Fission nuclear plants are using and creating radioactive material during operation. The dominant process used in fission power plants if fission initiated by slow neutrons to ^{235}U, in the process shown below:

$$^{235}\mathrm{U} + \mathrm{n}\ (\mathrm{slow}) \longrightarrow {}^{236}\mathrm{U} \longrightarrow X + Y + \upsilon\mathrm{n}\ (\mathrm{fast})$$

Many of the radioactive materials have very long half-life times, and thus special measures need to be taken to avoid emission of these into nature. The safety of a fission nuclear power plant can be classified as being either active, passive or inherent. An active safety system requires an outside interference by human beings, and is thus not a good solution. The two worst accidents related to fission power plants (Chernobyl and Three Mile island) were initiated by misjudgement by plant operators.

A passive safety system operates automatically, and will depend on the reactor design. The worst thing that can happen under operation of a fission reactor is that the temperature rises, for example by loss of cooling. A passive safety measure would be to design a reactor such that it has a negative temperature coefficient dk/dT around the operational parameters. (k is the number of slow neutrons created per incoming slow neutron to ^{235}U, and should be 1 for a controlled chain reaction.) With a negative dk/dT, the number of fission reactions will down, and hopefully the reactor will cool down. Another passive safety measure is called the Doppler effect, and is based on the fact that the absorption lines for ^{238}U broaden as the temperature rises. Thus the absorption of neutrons in ^{238}U will increase and fewer will be available for fission of ^{235}U, reducing the reactivity. Most fission power plants utilize these two passive safety measures, except the Chernobyl type.

The best safety system for a fission power plant would be based on inherent safety. For such a safety system the reactor should shut down because of physical principles when the temperature gets too high. Also, after the reactor has shut down, the decay heat of the many radioactive nuclides in the reactor should be transported away by virtue of physical principles. Up till now no fission power plants using inherent safety has been built, but ABB in Sweden has designed one: the PIUS. In the PIUS the reactor is embedded in a pool of cold water with a high concentration of boron. Boron has a very high cross-section for neutron absorption over a wide range of energies, and thus the water with boron would immediately shut down the reactor if it entered it. The construction of the PIUS is such that the boron-water is allowed to enter immediately if the cooling water gets too warm. The same water will then circulate for a long time, taking up the decay heat for a reasonably long time.

The high-temperature gas cooled reactor (HTGR) also is a promising reactor type when it comes to safety, since the radioactive fuel is encapsulated in materials (ceramics) that are supposed to withstand very high temperatures. So in case there was an accident the radioactive material would not leak out.

In addition to emission/leakage of radioactive material a safety issue connected with fission power plants is that some of these materials (^{235}U and Pu) can be used to make nuclear bombs.

For fusion light nucleons such as deuterium ^{2}D and tritium ^{3}T and helium ^{4}He are the fuels. Of these tritium is the most radioactive, but is has a short half life time. Only a small amount of tritium is present during the fusion processes, but there may be more radioactive material in the reactor vessel. Tritium is very small and will leak out very easily. The total activity of the tritium present would be 1016 Bq, a few orders of magnitude lower than the activity in a nuclear fission power plant. The radiation of the walls in the fusion reactor with neutrons leads to radioactivity there, typically the same amount as in a fission plant. The main difference is however, that a fusion power plant can not melt down: The plasma needed for the fusion processes will immediately collapse if anything goes wrong, and the fusion will stop. For some fusion reactions, neutrons are not formed, and thus the dangers associated with neutron irradiation will be eliminated.

Since tritium is the most dangerous material emitted from a fusion power plant, one has studied the consequences of the daily routine emissions. For people living around the reactor the dose would be less than the agreed limits, and also in case of an accident that releases 200g tritium, the dose 1km away from the plant would equal the admissible dose for a radiological worker, so it is acceptable.

Thus in total the fusion power plants can be regarded as much safer when it comes to safety, since very little radioactive material is involved and since the fusion will shut down by it self if something goes wrong.

For fusion power plants, the main problem is that very high temperatures, on the order of 10^8K, are needed to get the fusion process going. At these temperatures the fuels (deuterium, tritium, helium) are in the plasma state; an electrically neutral mixture of electrons and ionized atoms (the nuclei). The challenge is to achieve this temperature and to contain the plasma: if the ions and electrons were allowed to hit the reactor walls, alien nuclei would enter the plasma and stop any fusion reactions taking place. Also the plasma would cool if it was allowed to hit the walls. Therefore one tries to confine the plasma using magnetic fields. This is the confinement method that has been studied the most. Two other strategies to achieve fusion on earth are based on inertial confinement instead of magnetic, namely laser implosion and particle beam fusion.

The Lawson criterion is concerned with the energy balance of the fusion power plant, and must be fulfilled for sustainable fusion to occur. If the fusion processes produce enough thermal energy, then a fraction of this energy can be used to balance the losses from the plasma due to collisions (mainly between the electrons and the nuclei) and due to the Bremsstrahlung that occurs when charged particles meet. If enough energy is supplied, then the product of the density of the plasma (the number of ions per m^3) and its confinement time (lifetime) will be larger than a lower limit, and the fusion process will be self-sustained. The relevant power flows used to derive the Lawson criterion are shown in the drawing below

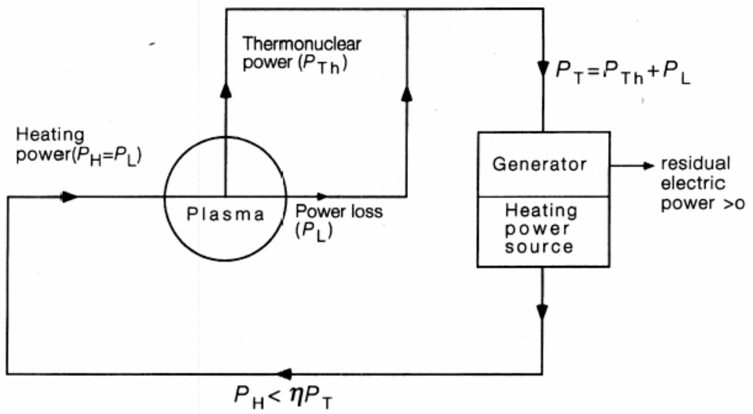


Figure 4.43 Power flows in deriving the Lawson criterion. (Reproduced by permission of Oxford University Press from [32], Fig. 1.4.1, p. 9)

Here P_L is the power loss, P_{th} is the thermal power produced by the fusion and η the efficiency of the heat power station:

$$P_L = \alpha n^2 \sqrt{kT} + 3n\frac{kT}{\tau_E}$$

$$P_{th} = \langle \sigma u \rangle E \frac{n^2}{4}$$

$$P_T = P_L + P_{th}$$

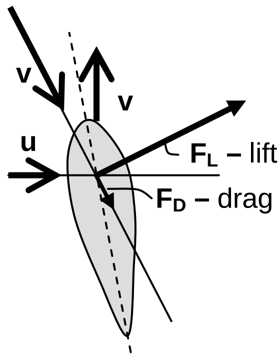
$$\eta P_T > P_L$$

$$P_{th} > (1-\eta)\frac{P_L}{\eta}$$

d) *Wind* energy
Wind is the kinetic energy of the atmosphere, and it is caused by air movement in response to temperature and pressure differences at different locations on the earth. These temperature and pressure differences are created by differences in the incoming solar radiation. So the source for the wind energy is the solar energy.

The energy in the wind can be converted to mechanical and electrical energy by use of a wind turbine. In a wind turbine, the (linear) movement of the wind makes it rotate. This rotational movement is mechanical energy and it can be converted to electrical energy in a generator (dynamo).

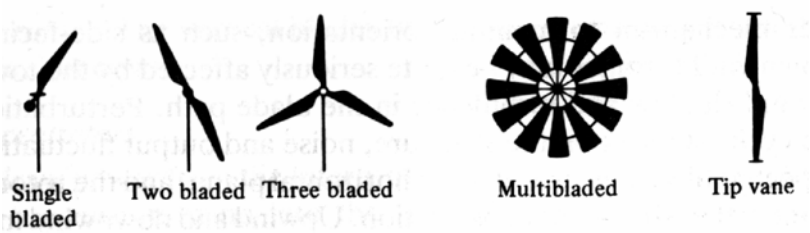
In the figure on the right the forces acting on a blade in a wind turbine are indicated. $\mathbf{u_o}$ is the wind direction, **v** the direction the blade moves and $\mathbf{v_r}$ the relative wind on the blade. Both the lift force $\mathbf{F_L}$ (that is normal to the relative wind direction on the blade) and the drag force $\mathbf{F_D}$ (in line with the relative wind direction, v_r) can be the one that makes the turbine rotate.



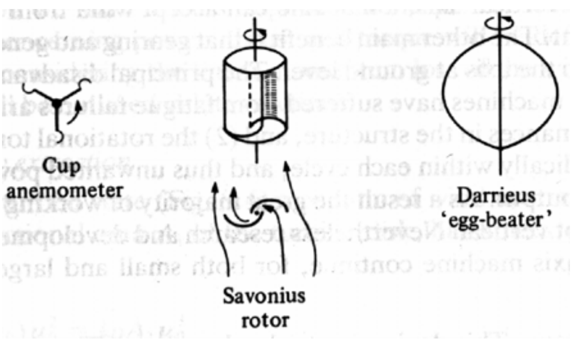
In general wind turbines are classified by

- The orientation of the rotational axis (vertical or horizontal)
- If it is the lift force or the drag force that is the dominant
- The solidity (i.e. the number of blades)
- The application area (mechanical or electrical)
- If the frequency is kept constant or is allowed to vary with the wind
- Generator coupling; direct or indirect via an energy storage

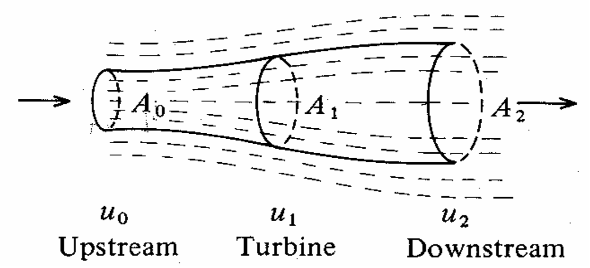
The most common wind turbine for electricity generation is a 3-bladed, horizontal axis turbine, where the lift force is much larger than the drag. For vertical axis turbines, the drag force is normally the largest, and the one utilized. Examples for the vertical axis machines are the cup anemometer, the Savonious rotor, the Musgrove rotor and the Evans rotor. The main advantage for a vertical axis machine is that it can accept wind from any direction without adjustment. Also the gearing and generators can be placed on ground level. The main disadvantages are 1) they are more prone to fatigue failure arising from the natural resonances in the structure, 2) the power produced has periodic features arising from the fact that the rotational torque is not constant during one cycle. As a result of these disadvantages most working machine are horizontal axis. Some horizontal axis machines are shown below



and here are some vertical axis machines to the right:



The power produced in a (horizontal axis) wind turbine equals $P_T = C_p A\rho u_0^3/2$, where A is the area the turbine intercepts the wind, ρ the density, and u_0 the wind speed. As an approximation the air density is taken to be constant, which is not completely correct. C_p is a coefficient indicating how much of the power in the wind ($P_0=A\rho u_0^3/2$) can be extracted. C_p has a maximal value of 16/27 =59% (the Betz criterion), and C_p is generally lower (typically 40% or less). The Betz criterion is derived by considering an expanding air stream through the turbine, and deriving expressions for the force on the turbine using the Bernoulli equation.



An expression for the force on the turbine obtained by considering the change in momentum in the air from upstream to downstream is $F_A = \rho A_1 u_1(u_0-u_2)$, and by considering the pressure change and using the Bernoulli equation we get $F_A = A_1\ \rho(u_0^2-u_2^2)/2$. From these two expressions for the force, one finds that $u_1= (u_0 + u_2)/2$. Now, the power captured by the turbine can be expressed as $P_T = u_1F_A$.
By inserting for u_1 and F_A, and introducing $a=(u_0-u_1)/u_0$, we get

$$P_T = [4a(1-a)^2]P_0\ (= C_p\, P_0)$$

which has a maximum for a=1/3, finally giving $C_p(max) =[4a(1-a)^2]_{a=1/3} = 16/27$.

A windmill used for water pumping should be able to operate at low wind speeds, and thus it should have a high solidity (i.e. many blades). This makes it easy to start, but it reaches maximum power for moderate wind speeds. A windmill used for electricity production should rotate at an appropriate speed, so as to generate 50Hz (or 60Hz). The wind mill should be able to utilize also strong winds, so it can produce much electric power.

We can not extract 100% of the power in the wind, since this means extracting all the wind out of the air. The air needs to keep a minimum of energy to be able to move away from the turbine.

e) Biomass energy

Bio energy is the chemical energy stored in biological materials (plants, animals and their waste), and that is produced initially through the photosynthesis.

In the photosynthesis process, CO_2 and H_2O react assisted by the absorption of a photon. The products are oxygen, water and carbohydrates:

$$CO_2 + 2H_2\dot{O} \xrightarrow{light} \dot{O}_2 + \left[CH_2O\right] + H_2O$$

The amount of energy available in the biomass can be given as a function of the amount of carbon in the material and the reduction level: When the biomass is converted back to CO_2 and H_2O, 459kJ per mole carbon per reduction level, is released.

The reduction level can be obtained from the formula R=(c+0.25 h - 0.5 o)/c where c, h and o is the number of carbon, hydrogen and oxygen atoms, respectively.
Methane CH_4 has a reduction level of R = (1+0.25x4-0.5x0)/1 = 2, while carbohydrate CH_2O has R = (1+ 0.25x2-0.5x1)/1 = 1. Thus, methane has twice as much bio energy per mole as carbohydrates.

Bio energy is considered a clean renewable energy source, since the CO_2 that is emitted during conversion of the bio mass, enters the natural CO_2 cycle, and is easily taken up in growing plants. So, provided that we grow as much bio mass as we convert, the net CO_2 emission is zero.

Many different types of biofuels are used today. They can be classified as follows

- primary
  - crops such as wood and other plants,
  - crop residues such as rice husk and bagasse, peat
- secondary
  - biofuels produced
    - thermochemically (i.e. by pyrolysis)
    - biochemically (i.e. alcoholic fermentation, anaerobic digestion or biophotolysis)
    - agrochemically (i.e. by fuel extraction)

The thermochemically processes can be i.e. pyrolysis, where the biomass is heated either in absence of air or by partial combustion. The products are extremely varied, consisting of gases, vapors, liquids, oils and solid char.

The alcoholic fermentation results in ethanol that may be used in place of refined petrol. Conventional fermentation has sugars as feedstock. Up to 96% ethanol can be produced by distillation. In anaerob digestion certain organisms produce CH_4 and CO_2, in the absence of oxygen. The mix of CH_4, CO_2 and trace gases is called biogas fuel. In biophotolysis water is split into oxygen and hydrogen by the action of light.

In agrochemical fuel extraction, liquid or solid fuels are obtained directly from living or freshly cut plants. Examples are oils from seeds, nuts, olives, eucalyptus leaves, stems, tapped exudates such as rubber latex and turpetine and oleoresins from pine trees.

The biofuel with highest energy density is methane: 55MJ/kg.

However, normally the methane is mixed with CO_2 to give biogass which has 28MJ/kg. Ethanol is the biofuel with the highest energy content for the as-produced fuel.

Biofuels can be used for various energy needs:

- it can supply heat for domestic uses (heating and cooking)
- it can supply process heat for industrial applications
- it can be used for transportation (ethanol or gasohol (10% ethanol+90% petrol) can be used in cars; for ethanol use the engine must be modified, for gasohol not, or hydrogen for fuel cell cars)
- biomass can also be used to supply heat for heat power stations producing electricity
- methanol and hydrogen can be used to power fuel cells to produce electricity