EXAM IN FY 2290 Energy resources **SUGGESTED SOLUTUION**
Wednesday May 27th 2009

PROBLEM 1: POLLUTION (30%)

a) *(10%) What pollutants are related to electricity generation in power plants? What are the major concerns related to these pollutants?*

Key words:

- Coal fired power plants: SO_2, particles, CO, and NO_x, CO_2. The first two are the most important. (In general >50% of CO emission is more related to motor vehicles.)
- gas and oil fired power plants; same as coal fired, but much less SO_2 and particles.
- biomass power plants: particles, CO, and NO_x, (possibly CO_2)
- geothermal power plants: possibly emission of CO_2 and other gasses trapped underground; depends on geothermal source
- nuclear power plants: radioactive material.

Major concerns:

- SO_2 combined with particles and moisture: classic smog
- SO_2 and NO_x: contributes to acid rain
- NO, NO_2 and CO: poisonous
- CO_2: greenhouse gas → global warming
- radioactive materials: harmful for living organisms

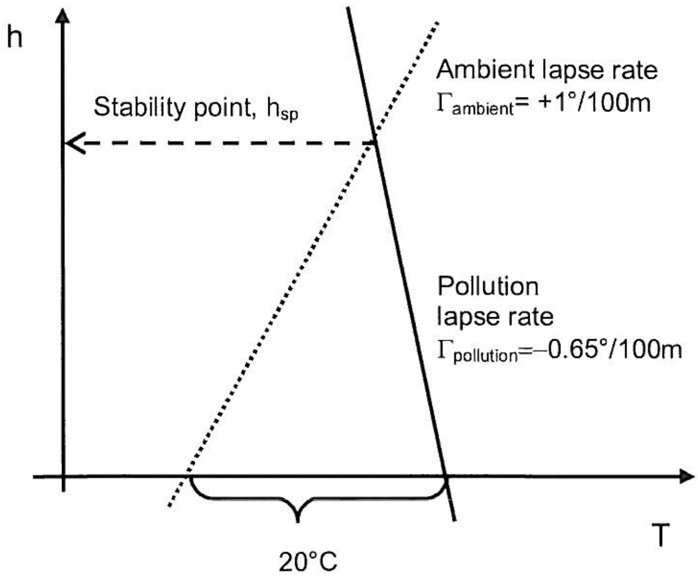
b) *(10%) What determines whether an emission of pollution will rise and be diluted or not? Describe how situations where the pollution is prevented from rising occur.*

If pollution rises or not depends on the lapse rate of the pollution, relative to the lapse rate of the environment. The best case is when the pollution will cool slower than the environment, so that it will always stay warmer, and continue rising until it reaches the upper troposphere.

Pollution is prevented from rising, if it is colder than the environment, i.e. if it cools faster that the environment, or if the environment does not cool with altitude, but warms up. The case where the temperature of the environment increases with altitude is called thermal inversion, since this situation is the inverse of the normal temperature decrease with altitude. Thermal inversion can occur during night if there are no clouds, and the ground will get colder than the air just above, due to radiative cooling. In this case there will be thermal inversion near the ground, until the sun starts heating the ground and the air near it. Thermal inversion can also occur if a high pressure area subsides towards the earth and the air in the high pressure region gets compressed as it subsides (due to the pressure increase). In this case there will be a layer of thermal inversion at a certain altitude in the troposphere, where the air is warmer than the air nearer to the ground.

c) *(10%) As a result of thermal inversion the temperature in the surroundings increases with 1°C per 100m above the ground. If pollution (with temperature 20°C above the ambient) is emitted at ground level, to what altitude will the pollution rise, when the lapse rate of the pollution is –0.65°C/100m?*

The situation is as shown in the figure below:

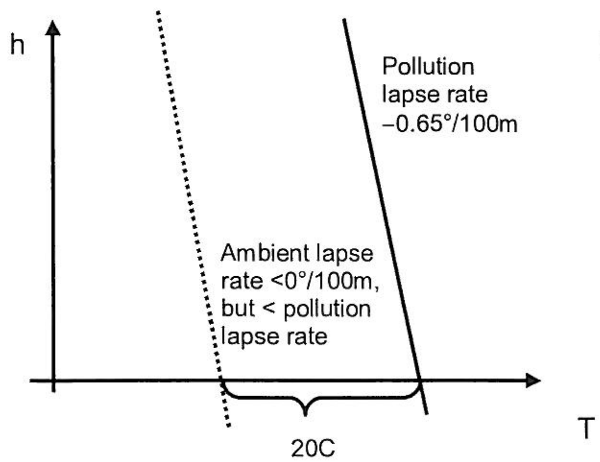


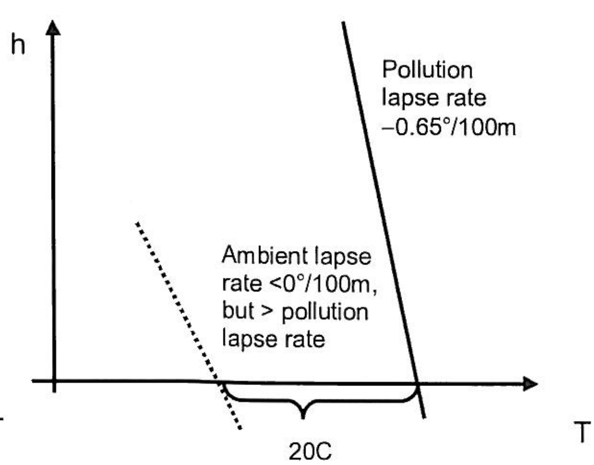
The pollution will start with a temperature 20C above the ambient, and will cool at a rate 0.0065C/m. The ambient air will increase in temperature by 0.01°/m. The pollution will rise until it reaches the stability point, where it has reached the same temperature as the ambient, and thus will stop rising. This correspond to the altitude

$$h_{sp} = \frac{\Delta T}{\left|\Gamma_{pollution}\right| + \Gamma_{ambient}} = \frac{20}{0.01 + 0.0065} m = 1212m$$

How high will the pollution rise if the ambient has a normal temperature profile? (Numerical answer not needed.)

If the ambient has the normal temperature profile with decreasing temperature with altitude, as sketched below. The pollution might be cooled down to the ambient temperature before the pollution reaches the Straosphere, but that depends on how large the lapse rate of the pollution is compared to that of the ambient. If the ambient cools much faster than the pollution, then the pollution will reach the Startosphere, where there is a thermal inversion. If the ambient cools at a rate comparable to the pollution, then probably the pollution reaches a stagnation level high up in the troposphere .





In the case to the left, the pollution might reach a stagnation level, but in the case to the right, the pollution will always be warmer than the ambient in the troposphere, and rise till the top.

PROBLEM 2: BIOENERGY (15%)

a) (10%) What is bioenergy? Mention both sources/types and usage.

By bioenergy we mean energy from biological (organic) materials. Examples of such materials are wood, waste and biofuels, such as biogas, biodiesel or ethanol. The energy stored in these materials originates in photosynthesis, where photon energy is absorbed and stored as chemical energy in carbohydrates. Biomaterials can be classified by how it is produced as being either thermochemical, biochemical or agrochemical. The feedstock to the processing can be

- Wood and wood waste from forestry.
- Agricultural crops and their waste by-products and animal waste from agriculture.
- Aquatic plants and algae.
- Products or waste from aquaculture
- Waste (or products) from industrial or social activities that produce organic waste, such as municipal solid waste, waste from food processing and urban refuse.

The biomass can be processed into solids, liquids or gases that are more suitable for handling and transportation.

The use of biofuels and biomaterials is in general the same as for fossil fuels: it can be combusted to give heat that can be utilized directly (e.g. for space heating, cooking or water heating), or the heat can be fed into a heat engine to generate work that can be utilized e.g. for transportation, or to generate electricity via a generator/dynamo.

b) (5%) List at least three positive and three problematic sides with bioenergy production (energy farming).

Positive sides with energy farming is that

1) it can reduce the CO_2 emissions, if biofuels replaces the use of fossil fuels. This will only be the case if the raw materials for the biofuels are produced at the same rate as the fuels are combusted (meaning that the same amount of CO_2 is captured in the photosynthesis process as is released in the combustion), and if the energy farming does not cause deforestation.
2) it has a huge potential world wide, and especially in tropical third world countries
3) it can solve the problem of increasing amount of waste from human activities, and even use it for something useful.
4) it can also boost economies and give added value to existing activities, such as farming or food processing.

Problematic sides with energy farming is that

1) it can lead to food shortage and hunger, if food plants are used as feedstock for biofuels
2) it may lead to soil infertility and erosion
3) it can lead to conflicts between local farmers and multinational companies, concerning limited resources such as land and water, and may lead to pollution locally.
4) it can also lead to unwanted genetic engineering

PROBLEM 3: CAR TRANSPORT (15%)

a) *(10%) What forces work on a can that accelerates in an up-hill slope? Draw a figure and indicate the forces, and write down expressions for the different forces.*

The forces that work on the car accelerating up-hill are as follows:

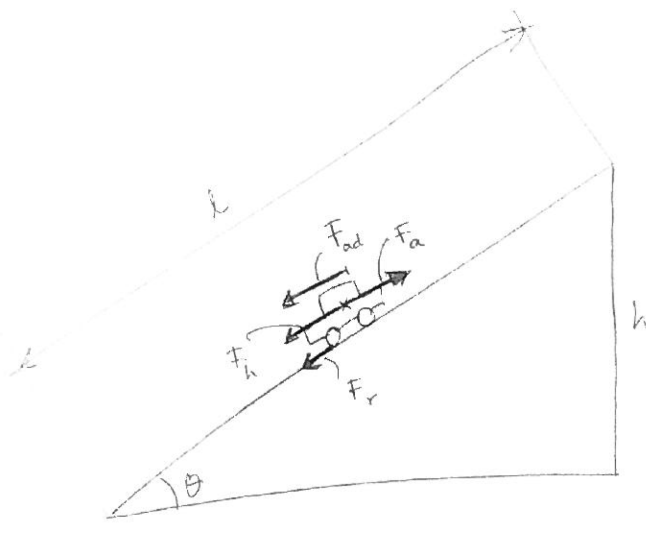
- From the acceleration there is a force working in the same direction as the car is moving, i.e. forwards, up-hill, parallel to the slope. This force is called F_a and can be expressed as
  $$F_a = ma = m\frac{\Delta v}{\Delta t}$$
  where m is the mass of the car and a is the acceleration. The more the car accelerates the stronger the force is.

- From gravity there is a "hill climbing force" F_h that works in the opposite direction as the car is moving, e.g. backwards and opposite to F_a. F_h can be expressed as
  $$F_h = mg\alpha$$
  where g is the gravitational acceleration, and α the slope of the hill as indicated in the figure below. (α=h/l)

- From deformation of the wheels and the road (friction) there will be a backwards force F_r due to rolling resistance, that can be expressed as
  $$F_r = k_r \cdot m \cdot g \cdot \cos\theta$$
  where k_r is a frictional coefficient (not the same as for static friction) and θ the angle the hill makes with respect to the horizontal axis.

- From air resistance there will be a backwards working force F_{ad} that can be expressed as
  $$F_{ad} = \frac{1}{2} \cdot A_f \cdot C_D \cdot \rho \cdot v^2$$
  where A_f is the cross-sectional area of the car seen from the front, C_D a drag coefficient that depends on the shape of the car and v the velocity of the car.

The forces are indicated in the figure below.



$\sin\theta = \frac{h}{l} = \alpha$

b) *(5%) What is the link between fuel usage and the forces that work on the car? How can the fuel consumption be reduced?*

The amount of fuel that a car has to use to move forwards depends on the sizes of the forces working on the car. In general the total forces amounts to

$$F_{tot} = F_a + F_h + F_r + F_{ad}$$

If all these forces are constant, then the energy that is needed equals
$E_{tot} = F_{tot} \cdot l$,
where l is the distance the car travels. This energy has to be supplied from the engine, and the engine must be supplied energy from the fuel. Thus the larger the forces the more energy is needed.

In addition to the forces mentioned in a) there are losses in the engine it self (due to laws of thermodynamics and to friction), and losses due to friction in the drive train.

The fuel consumption can be reduced in the forces are reduced, and by looking at the expressions in a) we see that reducing the mass m, the acceleration a, the frictional coefficient, the velocity v, the drag coefficient C_D and the cross-sectional area A_f, the forces and thus the fuel consumption can be reduced. In addition the fuel consumption can be reduced by using a more efficient engine and a car with as little friction as possible in the engine and the drive train.

PROBLEM 4: ENERGY SUPPLY IN THE FAROE ISLANDS (40%)

a) *(15%) Which of the sources wind energy, wave energy or PV should be selected, for maximum generation of electricity? Calculate how much electricity can be generated from the energy sources, using the assumptions listed below. Give the answers in TWh and J.*

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

$$P_T = \frac{1}{2}\rho A u_0^3 \cdot C_p = \frac{1}{2} \cdot 1.1 kg\, m^{-3} \cdot \pi \left(\frac{100}{2}\right)^2 m^2 \cdot 6^3 m^3 s^{-3} \cdot (0.59 \cdot 0.60) = 3.3 \cdot 10^5 W$$

The available power in the wind is twice this amount (from the rule of thumb):

$$P_{Available} = 2 \cdot P_T = 6.6 \cdot 10^5 W$$

The amount of electric energy produced in one year is then

$$\underline{\underline{E_{1turbine}}} = \eta_{generator} P_T \cdot \Delta t = 0.95 \cdot 6.6 \cdot 10^5 \cdot 3600 \cdot 24 \cdot 365.25 J = \underline{\underline{2.0 \cdot 10^{13} J = 5.5 \cdot 10^{-3} TWh}}$$

$$\underline{\underline{E_{200turbines}}} = 200 \cdot 5.5 \cdot 10^{-3} TWh = \underline{\underline{1.1 TWh = 4.0 \cdot 10^{15} J}}$$

Incident solar energy during one year on the area of 25km^2:

$$E_{in} = 1000 kWh/m^2 \cdot 25 \cdot (1000m)^2 = 25 TWh = 9.0 \cdot 10^{16} J$$

The amount of electricity produced by the solar cells is:

$$\underline{\underline{E_{PV}}} = 0.15 \cdot 25 TWh = \underline{\underline{3.8 TWh}} = 3.8 \cdot 10^{12} \frac{J}{s} \times 3600 s = \underline{\underline{1.4 \cdot 10^{16} J}}$$

The amount of electricity produced by the wave energy technology is:

$$P_{Available} = 110 \cdot 1000m \cdot 60kW / m = 6.6 \cdot 10^9 W$$

$$\underline{\underline{E_{wave}}} = \eta \cdot P_{Avaiable} \cdot \Delta t = 0.2 \cdot 6.6 \cdot 10^9 \cdot 3600 \cdot 24 \cdot 365.25J = \underline{\underline{4.2 \cdot 10^{16} J = 11.6TWh}}$$

Energy technology	**TWh**	**J**
Wave	11.6	$4.2\ 10^{16}$
PV	3.8	$1.4\ 10^{16}$
Wind	1.1	$0.4\ 10^{16}$

Based on the given assumptions, all three energy sources generate more electricity than the domestic electricity consumption, so all can be used for export of electricity. Wave energy technology will supply the most excess electricity, and wind the least.

b) *(5%) Which of the available technologies will be the most reliable in terms of continuous electricity generation and in terms of minimization of running costs? State the reasons for your answers.*

Since the Faroe Islands are quite far north (60.4°N), it is probable that there are many more hours with wind and than with solar radiation. Waves are generated by the winds, so wave energy should be as available as the wind energy. Neither of the three will be able of generating electricity continuously, so energy storage will be needed, but it is more probable that there will be wind and waves during the whole year (although less in summer), while solar radiation will be limited in the winter when the energy need is largest.

In terms of minimization of the running costs, PV is better than the other two, since it has no moving parts. The only maintenance needed will be that of the batteries and control electronics, plus cleaning of the solar cell surfaces. Since wind turbines is a mature technology compared to wave technology, the running costs will probably be less for wind than wave energy.

c) *(5%) Why is it correct to say that electric energy is consumed while energy is conserved?*

Electric energy is of high quality and 100% exergy. When electricity is utilised, e.g. for electronic appliances etc, the electric energy is eventually (via other energy forms such as electromagnetic or mechanical and via processes like absorption, deformation and friction) converted to heat which is only <u>partly</u> exergy. All the available energy in the electric energy is converted to heat energy, so <u>energy</u> is conserved. The amount of exergy B in an amount Q of heat depends on the temperature of the heat (T_H) compared to the surroundings (T_0):

$$B = Q\left(1 - \frac{T_0}{T_H}\right)$$

thus, only if the temperature of the heat is larger than the temperature of the surroundings, the heat will have any exergy. When electricity is used, all the electric energy (finally) ends up as heat at the temperature of the surroundings, and the heat available has zero exergy, according to the expression above. Thus, when electric energy is utilized the amount of energy is conserved, but the amount of exergy is reduced; the electricity (or exergy) is consumed. (This is one way of formulating the second law of thermodynamics.)

d) *(5%) How can the energy be transported to the main land? List advantages and disadvantages for the different ways.*

The energy can be transported either as electricity directly in transmission lines, or one could use the electricity to produce hydrogen by electrolysis of water, and then transport the hydrogen. In theory one could store the electricity in batteries or in fly wheels, and then transport these to the main land.

The electricity generated by solar cells is direct current (DC), while wind and wave power can deliver alternating current (AC) directly. For transportation of electricity in transmission lines it is better to use AC since it makes possible to change the voltage at different points in the system. The electricity should be transported with high voltage (several hundred thousands of volts) to minimize the losses while for the end use in electric appliances etc. the voltage is much lower (ca 220V).

	Advantages	Disadvantages
Electricity	- Established technology - Need not transform to other form of energy	- Long transmission lines on the sea floor are expensive
Hydrogen	- Hydrogen has the highest energy density per kg (compared to batteries and flywheel) - Hydrogen can be used to generate electricity in a fuel cell or burned in a combustion engine	- Less developed technology - Need to transport the hydrogen - Hydrogen is more explosive than other fuels - Energy losses in the hydrogen production and conversion back to electricity
Batteries	- Existing technology	- Low energy density - Energy losses in the charging of the battery and in the extraction of electricity from the battery - Need to transport the batteries
Fly wheels	- High energy density	- Less developed technology - Need to transport the flywheels

e) *(5%) How can the population on the Faroe Island supply heat from renewable sources for space heating? What is the most important advantage and disadvantage for the various alternatives?*

For space heating the population on the Faroe Islands can supply heat from the following renewable energy sources:

- use electricity from a renewable energy source (wind, waves, hydropower etc)
    - most important advantage: 100% efficiency in converting electricity to heat
    - most important disadvantage: use exergy to generate anergy
- heat pumps
    - most important advantage: uses little electricity to generate a lot of heat with no emissions

    - most important disadvantage: needs electricity
- geothermal heat (dry hot rock/EGS; the Faroe Islands do not have hot spots and must use the normal temperature gradient)
    - most important advantage: continuous
    - most important disadvantage: EGS is not a mature technology
- active or passive solar heating
    - most important advantage: existing technology for both active and passive systems
    - most important disadvantage: not continuous and out of phase with demand
- bioenergy (wood, waste)
    - most important advantage: continuous
    - most important disadvantage: limited potential at the Faroe Islands

f) (5%) How can they supply renewable energy for transportation? What is the most important advantage and disadvantage for the various alternatives?

For transportation the population on the Faroe Islands can supply renewable energy from the following sources:

- biofuels (ethanol, methanol, biogas, biodiesel)
    - most important advantage: compatible with present engines and infrastructure
    - most important disadvantage: the potential on the Faroe Islands may be small due to the climate
- electricity
    - most important advantage: no emissions
    - disadvantage: not compatible with present engines and infrastructure

- hydrogen
    - most important advantage: no emissions
    - most important disadvantage: not compatible with present engines and infrastructure