Examination Renewable Energy Sources (4P510)

Date: November 7, 2012
Time: 14.00 – 17.00 hours

Note: Different lecturers will correct the answers to the various problems for this examination.

Write down every answer on a different sheet of paper.

Please write on every sheet of paper you use the following:
1. the problem number;
2. your last name and initials;
3. your identity (student) number;
4. your email;
5. your department;

Should you write down answers to more than one problem on one piece of paper, then the first answer will be corrected and the other answers will be void.

The exam consists of 5 questions. For each question 20 points are available, the maximum score is 100 points.

The use of course books and notes is not allowed.
The use of simple calculators is allowed.

Good luck!

Problem 1 General introduction

For this problem, don't worry if you don't know the exact numbers. It's more about the order of magnitude which counts.

a) What was the average energy use of mankind in kW per capita through history, so ranging from the prehistoric man to the technological man. (4 points)

b) Given the total primary energy usage of 500 EJ in the year 2010, calculate the surface area needed in the Sahara desert to generate our electricity needs using PV or Concentrated Solar Power. Clearly state your assumptions. (4 points)

c) List different methods to reduce CO_2 emissions in order of importance. (4 points)

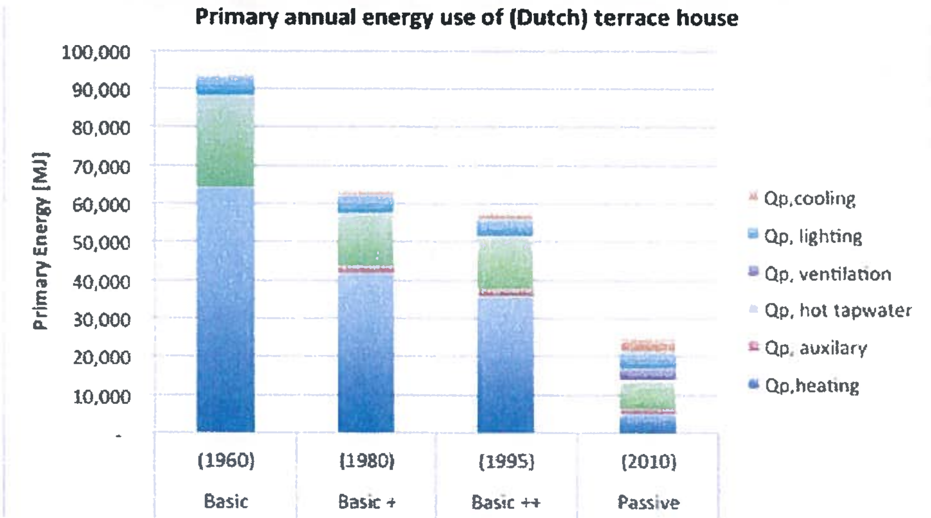
d) What are the 3 main key factors in an energy scenario determining the development of future global energy demand? Explain your answer. (4 points)

e) Explain the extra greenhouse effect. (4 points)

Problem 2 Renewables in the Built Environment

"Improvement of buildings through increased insulation and improved air tightness of the building envelope, can lead to a fast reduction of energy use, though it also will lead to a higher dependency on energy for proper functioning."

a. Comment on the mentioned reduction measures with reference to (some of) the values defined by B.E.S.E.L.F.



Problem 2 continues on next page

b. In the figure above there is a huge difference in the amount of energy needed for heating of a basic house in 1960 and after the renovation in 2010.
Give the measures (passive and active) that were used to realize this reduction.

c. Explain why insulation of the building envelope for small buildings (dwellings) is of greater importance than for large buildings.

d. For distribution networks the amount of heat transported is $q = f(\Phi_v, T_{sup}, T_{ret})$.
Give the equation and explain the relation of these variables with the load, the source and the distribution system.

Problem 3 Photovoltaic Conversion

a) Describe which phenomena take place when sunlight strikes on a crystalline silicon solar cell. In detail, answer the following questions and motivate your answers.

1. Which photons are responsible for carrier generation? (1 point)
2. Where are the carriers generated within the c-Si solar cell? (1 point)
3. Where does carrier separation occur? Explain this concept by making use of the band diagram of the p-n junction. (3 points)

b) According to the Shockley-Queisser limit, there is a maximum theoretical efficiency as function of the band gap of the semiconductor when using a single p-n junction.

1. Explain the presence of the maximum as function of the band gap. (2 points)
2. According to the above-mentioned limit, the c-Si solar cell should have an efficiency of 25%. The commercial solar cells, however, are characterized by efficiency values well below 25%. Explain in detail the main loss mechanisms occurring in a commercial solar cell. (3 points)

c) Answer the following subquestions:

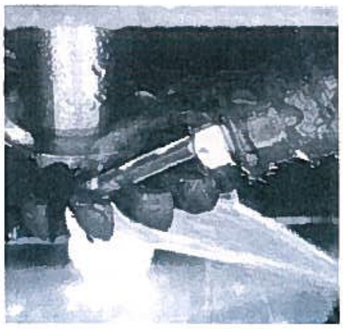
1. Draw the diagram of the power-voltage (PV) characteristics of a solar cell and indicate where the maximum power point (P_{mp}) is located. (1 point)
2. Calculate the P_{mp} for a solar cell characterized by a fill factor (FF) of 0.70, a short circuit current (I_{SC}) of 35 mA/cm^2 and an open circuit voltage (V_{OC}) of 600 mV. (2 points)
3. Define the standard test conditions and calculate the electrical efficiency of this solar cell.(2 points)

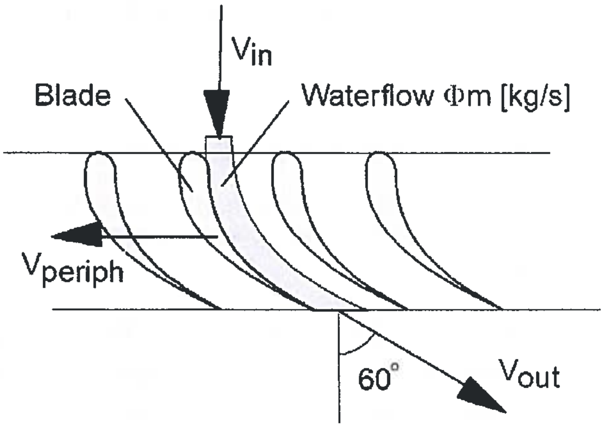
d) Make an accurate sketch of a grid-connected PV system and describe the function of its components. (5points)

Next problem on next page

Problem 4 Hydropower

Shown is a Turgo turbine. The picture left gives an impression of the flow path from the nozzle, through the turbine rotor. As can be seen, the turbine to some extent looks like the Pelton turbine. Picture right schematically gives the flow path, with velocities V_{in} and V_{out}, relative to a frame of reference that moves with the rotor (peripheral speed V_{periph}).





Give the most precise answer 1, 2 or 3, and motivate your answer.

a) The Turgo turbine is an example of what kind of turbine?

1. An impulse turbine;
2. A reaction turbine;
3. Both an impulse and a reaction turbine.

b) Given the velocity diagram (figure right), the runner inlet velocity V_{in} (relative to the moving frame) essentially is, in the absence of fluid friction, in magnitude:

1. equal to the outlet velocity V_{out};
2. Higher than the outlet velocity V_{out};
3. Lower than the outlet velocity V_{out}.

c) On the basis of the velocity diagram, the circumferential impulse F [N] of the water jet, driving the runner is equal to:

1. Φ_m [(sin 60) V_{out} - V_{in}];
2. Φ_m (tan 60) V_{out};
3. Φ_m (sin 60) V_{out}.

Problem 4 continues on next page

d) The velocity diagram (inlet and outlet velocities relative to the moving frame of reference), indicates that the turbine operates:

1. At adequate rotational speed;
2. Rotates much too slow;
3. Rotates much too fast.

e) Given the size of the turbine runner (relative to the jet diameter) and the velocity diagram, the Turgo Turbine is especially suited for applications, characterised by:

1. High dimensionless speed Ω and large dimensionless diameter Δ
2. Low dimensionless speed Ω and large dimensionless diameter Δ
3. Low dimensionless speed Ω and small dimensionless diameter Δ

Problem 5 Hydrogen Technology

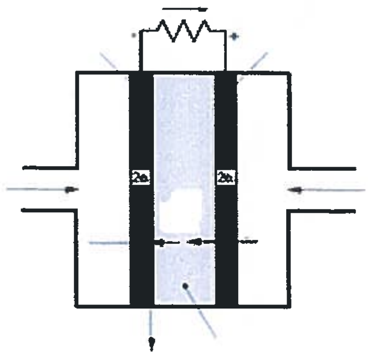
Hydrogen plays already an important role in the production of clean transportation fuels. It might become an efficient energy carrier in the future facilitating a shift to a sustainable low carbon society.

a) Name at least three fossil resources for the production of H_2?
Which is predominant and what process is used to produce hydrogen from this feedstock.
Why is this process not regarded as a sustainable production process for hydrogen?

b) Mention at least three other ways to make H_2 in a (more) sustainable manner and discuss briefly the main aspects.

Fuel cells are efficient devices for the conversion of chemical energy in electricity.

c) Give a schematic representation of a fuel cell and give the two electrochemical half reactions occurring in a hydrogen fuel cell (indicate: cathode, anode, electron flow, electrolyte, reactants (fuel, air), products).



d) What is the difference between a proton exchange membrane fuel cell and a solid oxide fuel cell in terms of the electrolyte? What does this mean for the operating temperatures of the two types of cells?

Problem 5 continues on next page

Instead of hydrogen, methanol (CH_3OH) is another type of fuel which can be used to drive a direct methanol fuel cell. The overall reaction in this fuel cell is:

$$CH_3OH + 3/2\ O_2 \rightarrow 2\ H_2O + CO_2$$

Given the following Gibbs free and standard enthalpies of formation:

Compound	ΔG_f° (kJ/mol)	ΔH_f° (kJ/mol)
CH_3OH (l)	-163	-238
H_2O (l)	-237	-286
CO_2 (g)	-394	-394

Note the following:

- Gibbs free energies and standard enthalpies of formation of the elements are zero;
- Faraday's constant, F = 96485 C/mol.

e) Compute the Gibbs free and standard enthalpy changes for the overall oxidation of methanol.

f) Compute the maximum efficiency of a direct methanol fuel cell.

g) Calculate the open circuit potential.

Problem 1 General introduction

a) What was the average energy use of mankind in kW per capita through history, so ranging from the prehistoric man to the technological man.

			Average power consumption (kW/capita)
Prehistoric man		1 million years before Christ	0.2
Neanderthal man	Primitive hunter	100,000 years before Christ	0.25
Homo Sapiens	Primitive farmer	5,000 years before Christ	0.50
Medieval man	Developed farmer	1,400 years after Christ	1.75
Industrial man		Great Britain 1875	3.7
Technological man		US 1971	11.1

b) Given the total primary energy usage of 500 EJ in the year 2010, calculate the surface area needed in the Sahara desert to generate our electricity needs using PV or Concentrated Solar Power. Clearly state your assumptions. (4 points)

20% electricity so 100 EJ per year. Assume the following:

- 30% efficiency for the plant;
- 75 % reduction due to day-night effect, summer-winter effect, clear skies versus cloudy days;
- 25% occupancy of space;
- 50% transport losses to other continents

This leads to a total efficiency of 1% so 10 MW/km^2, 30.10^{13} J/(km^2.year). Per year we need 100.10^{18} J. This leads to a total area of around 0.3.10^6 km^2, which is around 550x550 km.

c) List different methods to reduce CO2 emissions in order of importance.

Measure	**CO_2 emissions reduction [GtC]**
Improved resource efficiency (energy and materials)	200 – 600
Reduced carbon intensity	
• renewable energy sources	200 - 600
• nuclear fission	100 - 300
• shift from coal to natural gas	0 - 200
• CO_2 capture and sequestration *)	100 - 300
Reforestation	50 - 100

d) What are the 3 main key factors in an energy scenario determining the development of future global energy demand? Explain your answer.
   - Population development: the number of people consuming energy or using energy services.
   - Economic development, for which Gross Domestic Product (GDP) is the most commonly used indicator. In general, an increase in GDP triggers an increase in energy demand.
   - Energy intensity: how much energy is required to produce a unit of GDP.

e) Explain the extra greenhouse effect.
   The extra greenhouse effect is the effect caused by the increase of the concentration of greenhouse gases over time. These concentrations are not only increased by the burning of fossil fuels but by other activities as well like biological decomposition processes under swampy conditions or wet growing of rice (these 2 examples are just named to show that changes in concentration of greenhouse gases are not solely related to the burning of fossil fuels).

Problem 2 Built environment

a. Main answer (80%):
   Basic: human health & comfort, a good indoor air quality requires mechanical ventilation, without this a good IAQ cannot be guaranteed.
   Additional:
   Ecological: Requires a reliable energy source, if renewables are used back-up (storage) might be necessary.
   Strategic: Robust to rises in market price of energy, low demand feasible to become self-supplying.
   Economical: (Gas) infrastructure might become uneconomical, (same investment, lower consumption).
   Local: No direct link.
   Functional: It will require higher maintenance.
b. Passive: increase of insulation; air tight construction, improved glazing
   Active: condensing boilers, hp, ventilation with heat recovery
c. When building get larger the required m^2 of façade per m^2 of floor space decreases, so the heat loss per m^2 of floor space reduces.
d. See syllabus

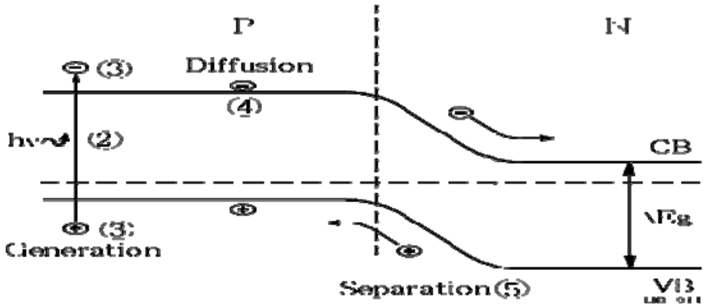
Problem 3 Photovoltaics

Problem 3 Photovoltaic conversion

3. 1 Describe which phenomena take place when sunlight strikes on a crystalline silicon solar cell. In detail, answer the following questions and motivate your answers.

a) Which photons are responsible for carrier generation? (1 point)
b) Where are the carriers generated within the c-Si solar cell? (1 point)
c) Where does carrier separation occur? Explain this concept by making use of the band diagram of the p-n junction. (3 points)

a) Photons having an energy equal or above the band gap of c-Si (1.1 eV) can generate carriers.
b) Photo-generation of electron-hole pairs principally occurs in the thick p-doped Si wafer since this is much thicker (in the order of hundreds of um) with respect to the n-type Si (in the order of tens of nm).
c) Carrier separation occurs at the p-n junction where charges are separated because of the electric field developed at the junction region.



3.2 According to the Shockley-Queisser limit, there is a maximum theoretical efficiency as function of the band gap of the semiconductor when using a single p-n junction.

a) Explain the presence of the maximum as function of the band gap. (2 points)
b) According to the above-mentioned limit, the c-Si solar cell should have an efficiency of 25%. The commercial solar cells, however, are characterized by efficiency values well below 25%. Explain in detail the main loss mechanisms occurring in a commercial solar cell. (3 points)

The maximum develops as it follows: for value of band bap below 1.4 eV the efficiency increases as there is a positive effect on the V_{OC} since the efficiency is directly proportional to V_{OC} (and the Is decreases as the band gap increases). As the band gap increases, the no of absorbed photons decreases and the efficiency drops.

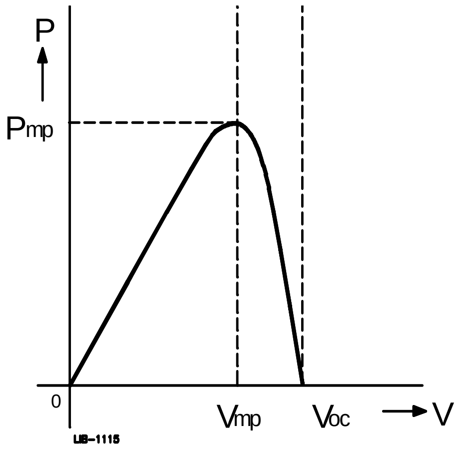
$$V_{oc} = \frac{kT}{q}\ln\left(1+\frac{I_{ph}}{I_s}\right)$$

The mismatch between the theoretical value and the value for a commercial solar cell is due to several loss mechanisms. These are the spectral mismatch, contact shadowing and reflection loss, fundamental generation and recombination.

Two of these effects should be explained in detail.

3.3 Answer the following subquestions:

a) Draw the diagram of the power-voltage (PV) characteristics of a solar cell and indicate where the maximum power point (Pmp) is located. (1 pt)
b) Calculate the Pmp for a solar cell characterized by a fill factor (FF) of 0.70, a short circuit current (ISC) of 35 mA/cm2 and an open circuit voltage (VOC) of 600 mV. (2 points)
c) Define the standard test conditions and calculate the electrical efficiency of this solar cell (2 points).

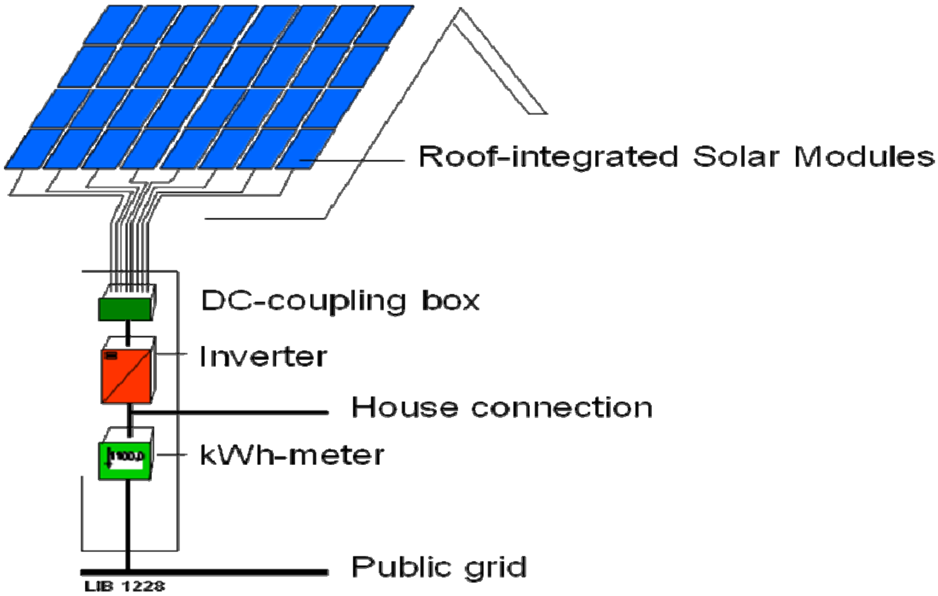


$$P_{mp} = I_{mp}V_{mp} = FFI_{sc}V_{oc} = 0.70 * 0.60V * 35mA/cm^2 = 14.7mW/cm^2$$

The standard test conditions are 1000W/m2 of irradiance, solar spectrum AM 1.5 and cell temperature of 25 deg. The efficiency is then 14.7%:

$$\eta = \frac{P_{mp}}{P_{opt}} = \frac{147W/m2}{1000W/m2} = 0.147$$

3.4 Make an accurate sketch of a grid-connected PV system and describe the function of its several components. (5points)



- PV module in strings and arrays
- DC coupling box: separators, fuses, overvoltage protection, DC-switch
- Inverter: the output voltage is chosen according to the load requirement: 220-230V single phase for domestic appliance and 415V three phase for large area building

Problem 4 Hydropower

1) Like the Pelton, with a free water jet hitting curved blades, the Turgo is:

   a) An impulse turbine

2) As there is no change of pressure, no change of velocity (Bernouilli). Inlet velocity:

   a) Equals outlet velocity.

3) The circumferential impulse F [N] of the water jet, driving the runner is equal to:

   c) Φ_m (sin 60) V_{out}

4) When in the velocity diagram the peripheral speed is added (in vector sense) to the outlet velocity, the absolute outlet velocity is vertical (downward) and in magnitude minimal. The turbine operates:

   a) At adequate rotational speed

5) Like the Pelton turbine, the rotor is big with respect to size of the nozzle and water flux. Also, the peripheral speed is in the same order of magnitude as inlet (and outlet velocity; hence a relatively slow runner (again, as the Pelton).
   The Turgo Turbine is especially suited for applications, characterised by:

   b) Low dimensionless speed Ω and large dimensionless diameter Δ

Problem 5 Hydrogen technology

Hydrogen plays already an important role in the production of clean transportation fuels. It might become an efficient energy carrier in the future facilitating a shift to a sustainable low carbon society.

a. What is currently the main route for H_2 production? Why is this process not regarded as a sustainable production process for hydrogen?

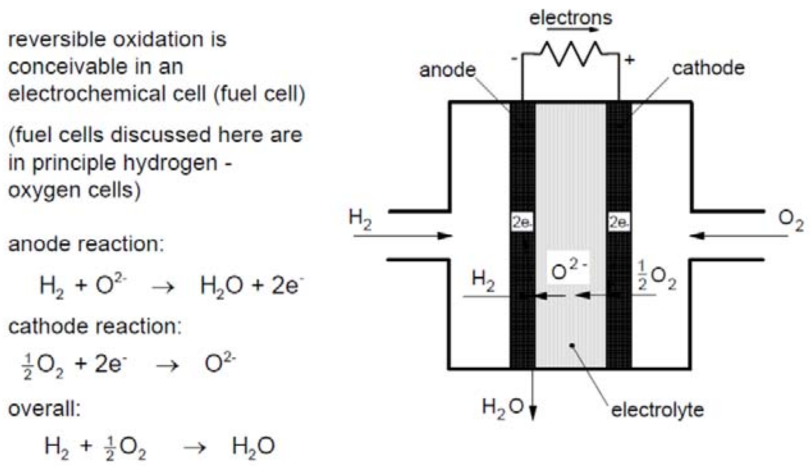
   Steam reforming of CH_4, gasification of oil and coal

   Not *sustainable* because it makes use of *finite* fossil resources, predominantly *natural gas* but also oil and coal, leading to *undesired CO_2 emissions*.

b. Mention at least three other ways to make H_2 in a (more) sustainable manner and discuss briefly the main aspects.
   1. Pre- or post-combustion CO_2 capture during steam reforming or other methods to gasify fossil resources; adequate solution for the medium term if combined with CO_2 sequestration
   2. Gasification of biomass; partly carbon neutral
   3. Hydrogen by electrolysis with electricity from renewable energy resources such as wind, solar, hydro power; efficiencies of electrolyzers & their costs are important challenges.
   4. Direct photocatalytic water splitting with solar light; very challenging

Fuel cells are efficient devices for the conversion of chemical energy in electricity.

c. Give a schematic representation of a fuel cell and give the two electrochemical halfreactions of a hydrogen fuel cell.



Note that for a PEMFC not O2- but H+ is being transferred from anode to cathode through the electrolyte. Both answers are correct.

d. What is the difference between a proton exchange membrane fuel cell and a solid oxide fuel cell in terms of the electrolyte? What does this mean for the operating temperatures of the two types of cells?

Proton exchange membrane: transport of H^+ (protons) through sulfonic acid resin at relatively low temperatures (80-120 ˚C)

Solid oxide fuel cell: transport of O^{2-} anions through oxide material at relatively high temperature (> 600 ˚C)

Instead of hydrogen, methanol (CH_3OH) is another type of fuel which can be used to drive a direct methanol fuel cell. The overall reaction in this fuel cell is $CH_3OH + 3/2\ O_2 \rightarrow 2\ H_2O + CO_2$

Given the following Gibbs free and standard enthalpies of formation:

Compound	$\Delta G_f°$ (kJ/mol)	$\Delta H_f°$ (kJ/mol)
CH_3OH (l)	-163	-238
H_2O (l)	-237	-286
CO_2 (g)	-394	-394

N.B.: - the Gibbs free energies and standard enthalpies of formation of the elements are zero

- Faraday's constant, F = 96485 C/mol

e. Compute the Gibbs free and standard enthalpy changes for the overall electrochemical reaction.

$\Delta G_r = \{2\times(-237) + (-394)\} - \{(-163) + 3/2 \times (0)\} = -705$ kJ/mol

$\Delta H_r = \{2\times(-286) + (-394)\} - \{(-238) + 3/2 \times (0)\} = -728$ kJ/mol

f. Compute the maximum efficiency of a direct methanol fuel.

$\eta_{max} = \Delta G_r / \Delta H_r = 705/728 \times 100\% = 97\%$

g. Calculate the open circuit potential.

$E_0 = \Delta G_r/NF = 705000 / (6 \times 96493) = 1.22$ V