Formula Sheet

General Energy
- 1 kilocalorie = 4184 Joules
- Force = $F = m \cdot a$
- $1 \text{ N} = 1 \text{ kg} \cdot \text{m} \cdot \text{s}^{-2}$
- $1 \text{ W} = 1 \text{ J/s}$
- $1 \text{ J} = \text{kg} \cdot \text{m}^2 \cdot \text{s}^{-2} = N \cdot m$
- Potential Energy = $m \cdot g \cdot h$
  - $m =$ mass
  - $g = 9.8 \text{ m/s}^2$
  - $h =$ height
- Kinetic Energy = $KE = \frac{1}{2}mv^2$
- $1 \text{ kWh} = 3.6 \text{ MJ}$
- $1 \text{ Quad} = 293.083 \text{ TWh} = 1.055 \text{ EJ}$

Thermodynamics
- Entropy: $\Delta S = \frac{\Delta Q}{T}$
- Exergy: $E = W_{\text{max}} = Q \left( 1 - \frac{T_C}{T_H} \right)$

OTEC
- $\eta_{\text{max}} = \frac{W}{Q_h} = \text{work output [MW] } \div \text{ heat input [MW] }$
- $Q_h = m_{\text{warm-water}} \cdot c_p \cdot \Delta T$

Wind Energy
- kinetic energy per second: $P = \frac{1}{2} \rho AV_4$
- Betz limit = $16/27 = 0.593$

Heat Engines
- Carnot efficiency: $\eta_c = 1 - \frac{T_C}{T_H}$

Heat Pump
- $COP_{\text{heating}} = \frac{\Delta Q_{\text{hot}}}{\Delta W} \leq \frac{T_{\text{hot}}}{T_{\text{hot}} - T_{\text{cool}}}$
- $COP_{\text{cooling}} = \frac{\Delta Q_{\text{cool}}}{\Delta W} \leq \frac{T_{\text{cool}}}{T_{\text{hot}} - T_{\text{cool}}}$

Other
- $[\text{K}] = [\text{°C}] + 273.15$
- 1 metric tonne = 1000 kg = 1 m$^3$ H$_2$O
- Heat capacity of water = $c_p = 4.184 \frac{J}{g \text{°C}}$

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How to do this test:

- First take a few minutes to read all the questions and rank them in order of increasing difficulty.
- Then start by answering the easiest questions; leave the more difficult ones for the end.
- There are 10 questions. Please make sure that your copy of the exam has all of them.
- All questions are weighted equally, with points divided evenly among the subquestions.
- Do not spend more than typically ca. 15 minutes on a single question.
- Please do the test individually; do not communicate with your colleagues during the test.
- Please do not leave the examination room during the first hour after the start of the test.
- ONLY the formula sheet is allowed for reference during the exam.
- NO other Reference materials or hardware are allowed except pocket calculator
- If data is not given you are asked to assume reasonable values for the quantities involved.

**Question 1**

a) For a country trying to increase its amount of generation from renewables, why is geothermal interesting with regard to its contribution to an energy mix? In particular, what are three characteristics of geothermal energy that may cause people to choose it over other types of renewable energy technologies?

b) List four different forms of geothermal energy systems.

c) While there is considerable potential for geothermal energy, it still plays a very minor role in terms of electricity generation from renewables. What are some of the factors that are causing this and could limit further development?

**Question 2**

An article recently appeared titled *The 'Wind Tree’ that could heat your home*. This device is a large structure consisting of multiple vertical axis wind turbines. These turbines can harvest wind from any direction, and start generating electricity at lower wind speeds than with traditional wind turbines, thus making them ideal for urban environments.

From several sources, the following facts and assumptions have been compiled:

- Height: 11 meters tall
- 72 micro turbines, total capacity of 3.1 kW
- Total Cost: 29500 €
- Expected yearly electricity production: 3500 to 13500 kWh
- Expected lifetime: 25 years
- Weight: 5 tonnes (assume 4 tonnes for the steel structure)
- The manufacturing of steel requires an energy input of approximately 20 GJ/tonne
- Cost of electricity from the grid: 15 cents/kWh
a) Calculate the energy and economic payback times. Make sure to show your calculations. Assume the best case scenario of 13500 kWh generated per year. To simplify the calculations, as the production of steel is very energy intensive, we can assume that a suitable estimate of the energy payback time can be arrived at by only considering this.

b) What if we just grew an actual tree instead and burned it in a power plant after 25 years? How would the amount of electricity generated compare? To give the real tree a better chance, assume that the generation of the Wind Tree is at the lower range of the stated estimate (3500 kWh/year). Use the following assumptions:

- A 25 year old tree of equivalent size weighs about 350 kg
- Wood has an energy density of 15 MJ/kg
- A power plant can convert the energy in biomass into electricity with 35% efficiency

c) The article further states that “There is a very negative view of wind energy, people think it’s ugly and it ruins their landscapes. Then they see the wind tree and they think differently.” Discuss how this statement and the title of the article reflect the social challenges involved in creating a sustainable supply of energy.

Question 3

a) Given the information in the table below, at which electricity price do the Biomass and Gas plant recover their costs? Make sure to show your calculations.

<table>
<thead>
<tr>
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<th>Biomass plant</th>
<th>Gas plant</th>
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<tbody>
<tr>
<td>Capacity (MW)</td>
<td>250</td>
<td>400</td>
</tr>
<tr>
<td>Capital cost per year (€/year)</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>Fuel efficiency %</td>
<td>40%</td>
<td>55%</td>
</tr>
<tr>
<td>Average operational hours (hours/year)</td>
<td>8000</td>
<td>4000</td>
</tr>
<tr>
<td>Fuel prices</td>
<td>40 €/ton</td>
<td>0.3 €/m³</td>
</tr>
<tr>
<td>Energy content of fuels</td>
<td>8000 kWh/ton</td>
<td>10 kWh/m³</td>
</tr>
</tbody>
</table>

b) Why does bidding at variable costs maximize cash flow for power producers?

c) Describe the difference between a CO₂ tax and a cap and trade system. Give advantages and disadvantages of both.

Question 4

a) A hot topic right now is whether electric vehicles are “greener” than vehicles that run on petrol. Why is it difficult to calculate the lifetime CO₂ emissions of an electric vehicle, i.e. what are the aspects of the system that must be taken into account?

b) What are the differences between the traditional power system that has been in place for over a century, and the type of power system that is starting to emerge currently? In particular consider the nature of generation, the types of infrastructures, and the type of grid management involved.

c) Rank the list below in terms of the availability of generation by fuel type (i.e. the amount of a year that a power plant using that fuel is operating at full capacity). For technologies where availability may vary considerably, discuss which factors influence this variability.

- Biomass
- Coal

- Geothermal
- Hydro
- Natural Gas
- Nuclear
- Offshore Wind
- Onshore Wind
- Solar

**Question 5**

a) Draw and explain what is shown in a **Load Duration Curve**. Specifically, what can one see on the horizontal axis from left to right, and what is shown on the vertical axis? Identify which parts of the chart (likely) relate to different types of power plants.

b) How would a **Price Duration Curve** be influenced by a greater increase in the amount of renewable energy generation?

c) What is the **Merit Order**? Specifically, how is the ranking of power plants determined, and where are particular types of power plants often found in this order?

**Question 6**

a) List three aspects of fuels cells that make them attractive as a means of converting fuels into electricity

b) Why would it be useful to combine a fuel cell with a Carnot Engine?

c) One strategy for transitioning towards more sustainable energy systems involves thinking about ways in which we can integrate systems to solve multiple problems at the same time. List and describe four of seven integration options discussed for energy systems by Dr. Hemmes.

**Question 7**

Consider an OTEC system with the following values:

- 28°C on the surface of the water
- 24°C at seawater outlet in the heat exchanger
- 5°C at a depth of 1 km, from which cold water is drawn into the system
- \( m_{\text{warm\_water}} = 1050\, \text{kg/s} \)
- \( m_{\text{cold\_water}} = 950\, \text{kg/s} \)

a) What is the maximum efficiency of this process, and how does it compare to traditional fossil fuel power plants?

b) Why is the efficiency of the OTEC process not as much as a concern as it would be with traditional fossil fuel power plants?

c) Calculate the amount of electricity produced assuming the maximum efficiency.

d) List four types of applications that could be coupled with an OTEC system, and describe briefly how they fit into the system.
Question 8

a) Photovoltaic cells are not able to convert all of the light that shines on them into electricity. Name three factors that must be addressed when trying to increase the efficiency of photovoltaic cells.

b) A recent study argued that more people should be facing their PV systems west, instead of south. What is a situation in which this might make sense given that the PV system would produce less power than if it were facing south?

c) Aside from efficiency, what are other factors that can (and should) influence where and how much of certain PV technologies are installed?

Question 9

a) What is the definition of 1st and 2nd generation biofuels? Why is there a distinction between these two?

b) What are the opportunities and barriers for both 1st and 2nd generation biofuels?

c) List five different conversion techniques for producing energy from biomass. Which of these are commonly used with existing thermal power plants?

Question 10

a) What are the general differences between electricity generation from fossil fuels and renewables? Specifically mention aspects related to their material use and life cycle.

b) Why does demand response seem increasingly necessary, and what are the different options for achieving it? How does it relate to a mix of fossil and renewable generation?

c) What are some of the challenges of implementing demand response? In particular list social, economic, and technical issues.