Loughborough University

ENERGY SYSTEMS ANALYSIS

24WSC804

Semester 1

In-Person Exam paper

This examination is to take place in-person at a central University venue under exam conditions. The standard length of time for this paper is **2 hours**.

You will not be able to leave the exam hall for the first 30 or final 15 minutes of your exam. Your invigilator will collect your exam paper when you have finished.

Help during the exam

Invigilators are not able to answer queries about the content of your exam paper. Instead, please make a note of your query in your answer script to be considered during the marking process.

If you feel unwell, please raise your hand so that an invigilator can assist you.

Answer **ALL FOUR** questions.

Questions carry the marks shown.

Use of a calculator is permitted - It must comply with the University's Calculator Policy for In-Person exams, in particular that it must not be able to transmit or receive information (e.g. mobile devices and smart watches are not allowed).

Each student may bring **ONE DOUBLE-SIDED HANDWRITTEN** A4 page into the exam.

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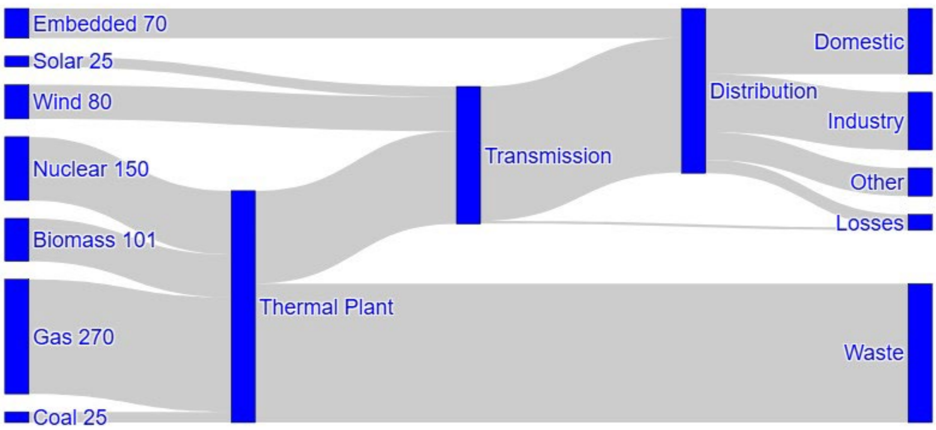
1. National Power System

a) It is often said that we do not use energy but rather the service that energy provides. Discuss this in terms of the provision of domestic lighting using LEDs, sketching a diagram of the architecture of the power system with primary sources, conversion technologies and carriers. [5 marks]

A national power grid has the energy generation portfolio has indicated on the left-hand-side of the Sankey diagram below. The renewable generation and primary energy consumption for a whole year is given by the numbers in units of TWh.

National Power System



The average fuel energy (enthalpy of combustion or fission) to power conversion efficiencies of four types of thermal plant are 30%, 35%, 48% and 35% for Nuclear, Biomass, Gas and Coal, respectively. Transmission losses are deemed to be 2% of the power entering the transmission network, and 8% of the power entering the distribution network

b) Calculate the following energy flows in units of TWh.

i. Thermal plant to Transmission
ii. Thermal plant to Waste
iii. Transmission to Distribution
iv. Transmission to Losses
v. Distribution to Losses
vi. Distribution to consumers (domestic, industry and other)

Show your woking out and clearly label each part of your answer. [9 marks]

c) The mass of CO_2 emitted per unit of enthalpy of combustion for gas and coal are 0.24 and 0.35 tonnes of CO_2 per MWh, respectively. Assuming no net Carbon emissions for biomass and nuclear, and similarly none for solar, wind and embedded energy technologies, calculate the yearly average carbon emissions in tonnes per MWh consumed. [5 marks]

d) The average capacity factors of wind and solar are 0.35 and 0.10, respectively. Calculate the installed capacity of wind and solar connected directly to the transmission network. [4 marks]

e) The switch to heat pumps for domestic heat puts another 30 TWh annual demand on the grid. If this were to be generated solely by wind, how much extra capacity of wind would we need to install if energy policy required a derating factor of 20%. Discuss this answer in relation to the concept of firm power and technologies required by the transition to a zero-carbon grid. [5 marks]

2. A UK energy firm is conducting a cradle-to-gate life cycle analysis (LCA) of two photovoltaic (PV) technologies: Silicon and Cadmium Telluride (CdTe) thin film solar cells. The purpose of this analysis is to assess the environmental impacts in terms of Carbon Emissions (Global Warming Potential, GWP) and Resource Depletion (RDP). This analysis focuses on resource extraction and manufacturing stages, adopting a cradle-to-gate approach, considering S1 (Materials), S2 (Process). The unit of analysis is per MWh generated, with the following assumptions:

UK Solar PV Capacity Factor: 11%

Technology Lifetime: Silica solar cells have a lifetime of 30 years, while CdTe solar cells have a lifetime of 25 years.

The inventories have been developed from industry LCA databases and calculated per kW of standardised generating capacity

a) Calculate the lifetime generation per MW installed capacity for each technology. [2 marks]

b) Define the primary goal of this LCA study. [2 marks]

c) Describe the scope of the analysis, including the system boundaries (included and excluded stages) and the functional unit used. [4 marks]

d) Conduct an inventory analysis using the data in the following inventory tables for each material for S-1 and S-2 lifecycle stages. Using these, calculate the total cradle to gate GWP and RDP for each technology. Express this global warming and resource depletion impacts per MWh generation. [6 marks]

Inventory for Si

Stage	Material/Process	GWP Factor (kg CO_{2eq} per kg)	RDP Factor (kg_{sb} per kg)	Quantity Used (kg per kWp)
S1	Quartz	0.9	0.1	500
S1	Aluminium	8	0.5	100
S1	Rare-earth elements	20	2	2
S2	Silica processing	2.5	0.3	300
S2	Cell assembly	0.6	0.05	200

Inventory for CdTe

Stage	Material/Process	GWP Factor (kg CO_2-eq per kg)	RDP Factor (kgsb per kg)	Quantity Used (kg per kWp)
S1	Cadmium	4.2	0.8	100
S1	Tellurium	3	0.4	80
S1	Rare-earth elements	20	2	2
S2	Cadmium processing	3.5	0.7	100
S2	Tellurium processing	3	0.4	80
S2	Manufacture	0.7	0.05	120

e) Explain which material could be excluded from a comparative analysis and why this might be a valid option. [2 marks]

f) Critique the benefits and limitations of this cradle-to-gate approach in capturing the environmental impacts of these solar technologies. Suggest changes to the scope that could improve the comprehensiveness of this LCA. [6 marks]

3.

a) Give two definitions of the Second Law Efficiency. [2 marks]

b) Does the geographical location of an energy system affect its exergy? Explain your answer [2 marks]

c) Consider two heat pumps with different COPs. Will the one with a higher COP have the higher Second Law efficiency? Briefly explain your answer [2 marks]

d) You are tasked with determining the work potential of a new concentrated solar-thermal power system. What properties of the solar receiver would you require to define the maximum work potential of the system? [2 marks]

e) What final state will maximise the work output of a device? [2 marks]

f) Steel cylindrical rods (ρ=7833 kg.m^{-3}, c_p=0.465 kJ.Kg^{-1}.°C^{-1}), with a diameter of 100mm are heat treated by drawing them through a 2m long oven at a rate of 20mm.s^{-1}. The oven is maintained at a temperature of 800°C. The rods enter at a temperature of 30°C and leave at a temperature of 600°C. The ambient temperature is 25°C. Determine:

   i. The rate of heat transfer to the rods in the oven [kW] [3 marks]

   ii. The rate of exergy destruction associated with this heat transfer process. [6 marks]

4. A shipbuilding company is looking to improve the efficiency of one its vessels by utilising the heat rejected from the main propulsion engines. The vessel currently uses a Diesel engine to drive electrical generators. The electricity from these generators is used to drive an electrical motor which ultimately drives the propellor. One proposal is to use the hot exhaust gases to produce steam which could drive a turbine, producing additional electricity.

The hot exhaust gases leave the internal combustion engine at 450°C and 150 kPa at a rate of 1.2 kg.s^{-1} . The exhaust system has a diameter of 125mm. The exhaust gas may be considered and ideal gas with ρ = 0.508 kg.m^{-3}, c_p = 1.15 kg.kg^{-1}.K^{-1} and R = 0.265 kg.kg^{-1}.K^{-1}

Ambient conditions are 20°C and 100 kPa.

a) What is the flow exergy of the exhaust gas leaving the system? [kJ.kg^{-1}] [5 marks]

b) It is proposed that an insulated counterflow heat exchanger is used in the exhaust system produced superheated steam at 350°C and 7 MPa. The design specification says that water would enter the heat exchanger at the ambient temperature of 20°C, and the exhaust gases leave the heat exchanger at 250°C. Neglecting velocity and pressure drop in the heat exchanger, determine:

i. The rate of steam production [kg/s] [4 marks]

ii. The rate of exergy destruction in the heat exchanger [kW] [8 marks]

iii. The second law efficiency of the heat exchanger [2 marks]

c) The steam from the heat exchanger would be used to drive a steam turbine. It is expected that steam would enter the turbine at 7MPa and 350°C and leave as a saturated vapour at 50 kPa, determine:

i. The reversible power output of the turbine [kW] [5 marks]

ii. A specification sheet for the turbine suggests that it may lose heat at a rate of 5 kW. Determine the rate of exergy destruction. [kW] [4 marks]

iii. The second law efficiency of the turbine. [2 marks]

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