Loughborough University

Renewable Energy Systems

23WSC303

Semester 1 2023 — 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 **3 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.

<u>Help during the exam</u>

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 SEVEN** questions.

All questions carry equal marks.

Use a **SEPARATE** answer book for **EACH** question.

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).

A range of formulae and tables likely to be of benefit in the solution of these questions is provided in the paper.

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1. Renewable Energy Systems, Economics and Policy

The chart below shows the annual Capacity Factor over a period of time for four major energy generation technologies in the UK power system.

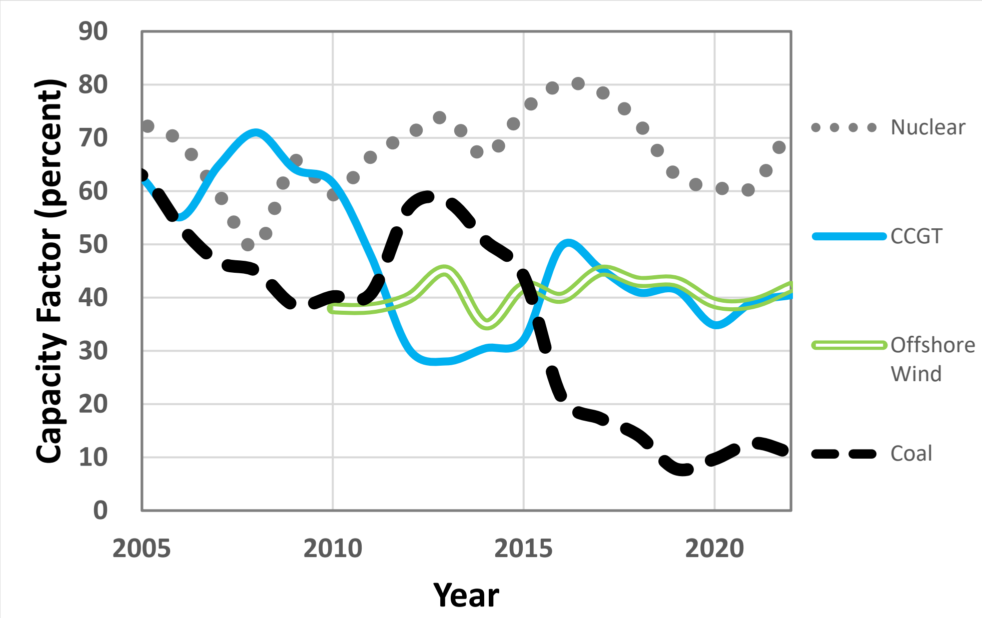

Figure 1 - Timeseries of the capacity factor of different generating technologies.

a) Give the general equation for the calculation of the capacity factor. [1 mark]

b) What are the key factors which predominantly influence the capacity factor of these technologies? [3 marks]

c) With particular reference to the curve for wind and coal over this period, explain the behaviour of capacity factors over this period and suggest reasons for this? Your answer should consider the role of the marginal cost of energy and other drivers. [3 marks]

d) The incomplete table below shows the energy generated (GWh) for each of the four technologies in **2020**. Read the Capacity Factor off the chart above to the nearest whole 5% and use this to calculate the available generating capacity of each technology in GW. [4 marks]

e) Calculate the total tonnes of carbon emitted in **2020** for each technology. [3 marks]

f) Derive the approximate grid carbon intensity in kG/MWh to the <u>nearest whole kilogram</u>. [1 mark]

See next page for table.

	Generated (GWh / year)	Carbon Intensity ($tCO2_{eq}$/MWh)	Capacity Factor	Generating Capacity (GW)	Emitted (t/year)
Nuclear	52596.0	0.02			
CCGT (Gas)	138064.5	0.4			
Offshore Wind	87660.0	0			
Coal	6574.5	1			

2. Solar Photovoltaics.

a) It is often said that "enough solar energy strikes the Earth each hour to meet our total energy demand of a whole year."

Human annual total energy demand	1.7×10^{14} kWh
Total power output of the Sun	3.86×10^{27} W
Sun-Earth distance	1.5×10^{8} km
Earth diameter	12800 km
Area of a circle	πr^2
Surface area of a sphere	$4\pi r^2$

Using the above information, show through calculation whether this is a reasonable claim. Check units and make sure to show all working and any sketches you use. *Hint: what is the irradiance [W/m^2] at the Sun-Earth distance?* [5 marks]

b) The datasheet of a solar PV module gives its physical dimensions as 2094 x 1134 mm and maximum power at Standard Test Conditions (STC) as 500 W. Given that STC irradiance is 1000 W/m^2, calculate the module efficiency under these conditions. [2 marks]

c) An array of 20 of these same modules is installed in a system with a grid-connected inverter in Ribnica, Slovenia. Over a year, the energy measured at the array output is 12760 kWh, and the energy measured at the inverter output is 12498 kWh.

If the measured in-plane irradiation over the same period is 1404 kWh/m^2, calculate the inverter efficiency and the total system operating efficiency for the year. [3 marks]

d) At STC, the same module type has an open-circuit voltage of 45.5 V and the voltage at maximum power point is 38.4 V. Given the Ribnica array is formed of 2 parallel connected strings of modules, sketch the power-voltage characteristics of 1 module, 1 string, and the full array (on the same axes, labelling the key points). [5 marks]

3. Wind Power

a) What is the maximum theoretical power a wind turbine can generate if it has a rotor diameter of 200m, and the wind speed is 12 m/s. [3 marks]

b) Draw a velocity triangle for the cross section of a wind turbine blade. On the diagram show the rotational speed, the incoming wind speed, relative wind speed, angle of attack and the lift and drag forces. With the aid of the diagram, explain why it is important to control the pitch of the blade in modern wind turbines under operating conditions. [8 marks]

c) Calculate the wind speed at a height of 90m above the ground under neutral stability. The speed at 20m above the ground is 15m/s, and the surface roughness length is 0.1. [4 marks]

Some equations and constants you may find useful:

$$U(z) = \frac{U_*}{k}\left[ln\left(\frac{z}{z_0}\right) + \Psi_s\left(\frac{z}{L_s}\right)\right],$$

$$U(z_h) = \frac{U_*}{k}\ln\left(\frac{z_h}{z_0}\right),$$

$$\ln(z_0) = \frac{U(z_1)\ln(z_2) - U(z_2)\ln(z_1)}{U(z_1) - U(z_2)},$$

$$Q(U > V) = \exp\left[-(V/C)^k\right],$$

$$P_w = \frac{1}{2}\rho A U_0^3$$

$$C_P = \frac{U_{rel}^2}{U_\infty^2}\lambda\sigma c_t = \frac{\Omega\frac{1}{2}\rho U_{rel}^2 cRc_tRN}{\frac{1}{2}\rho A U_\infty^3}$$

$$\rho_{air} = 1.224\ kg/m^3$$

4. Bioenergy

a) With the aid of diagrams, explain the differences between a closed cycle steam turbine system and a combined cycle gas turbine system. [8 marks]

b) Name the 3 stages involved in combustion of biomass, including the temperatures ranges of each stage. [3 marks]

c) Explain what a combined heat and power (CHP) system is and what advantages it has over standard systems. [4 marks]

5. Integration to the grid.

a) Integrating high levels of renewable energy generation into power grids will bring significant impacts to the conventional centralised power systems. Name THREE main impacts. [3 marks]

b) A grid-connected 3 kW PV system in a residential property in the UK is G98 compliant. In the event of a fault causing the distribution network frequency to drop to 48 Hz, describe the anticipated action of the PV system and the explain the reason and importance for this response. [3 marks]

c) Identify TWO energy storage technololigies suitable for power system power quality applications. [2 marks]

d) A power electronics converter is used to connect a PV panel to a 24V battery pack. The PV panel output voltage range is from 0 to 40 volts. [3 marks]

i. Which DC/DC converter should be selected for this PV battery system? A buck converter or a Boost converter?

ii. Calculate the duty cycle D for the selected DC/DC converter so that the PV panel output voltage is around the maximum power point of 35V.

Some equations you may find useful:

Buck Converter: $V_{out} = DV_{in}$

Boost Converter: $V_{out} = \frac{V_{in}}{1-D}$

e) An offshore wind farm is 100 km away from shore. Describe a typical power electronics system needed for integrating this offshore wind farm to the onshore power grid. [4 marks]

6. Future Energy Systems

a) Explain the difference between production-based emissions and consumption-based emissions and why these differ widely on a country-by-country basis. [2 marks]

b) Why are the marginal emissions of the UK energy system usually higher than the aggregate emissions? [2 marks]

c) GB has significantly reduced electricity-based emissions over the last two decades. How has it achieved this and what challenges does the approach have for the future? [2 marks]

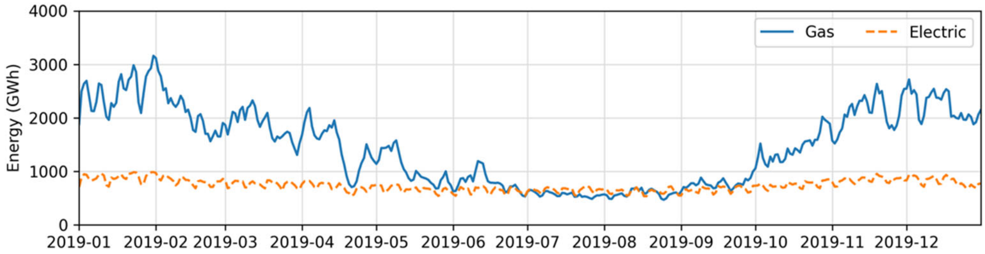

Figure 2 shows timeseries of the daily gas demand (excluding power generation) and the daily electricity demand for the UK in 2019.

d) Briefly explain 3 reasons why the provision of net zero heat is challenging in the UK. You may wish to refer to **Figure 2**. [3 marks]

e) Assume the average capacity factor for offshore wind in the UK is 40%. Estimate what level of wind generation (in GW) would be required to provide an equivalent amount of heat to the total annual heat demand using heat pumps. Explain your reasoning and state any assumptions. You may wish to refer to **Figure 2**. [3 marks]

f) Considering a 100L hot water tank is a 'large' tank of water, explain whether hot water tanks in households are a good option for storing heat in future? You may wish to refer to **Figure 2** and assume that there are approximately 20 million gas-connected households in the UK. The heat capacity of water is $4200\ \mathrm{Jkg^{-1}K^{-1}}$. [3 marks]

7. Energy in Buildings.

a) List five strategies for the UK to reduce the energy consumption and carbon footprint from building sector. [5 marks]

b) A typical English house usually consumes 296.2 $Wh/m^2/y$ of energy just for space heating purpose, which is equivalent to $35W/m^2$. In order to save energy bills, you decide to change the existing Combi-boiler of your house into a Ground Source Heat Pump, with COP equal to 3.5.

Assume the floor area of your house is $155m^2$. Your Ground Source Heat Pump (GSHP) will be installed at 1.8 meter depth below the ground level. Consider the soil condition around your house is clay soil with 50% saturation (**see Table 1 on page 8**). During the operation of GSHP, the average temperature drop of the ground loop will be maintained at 8°C.

i. What would be the area of the soil that needs to be occupied for installing such GSHP? [6 marks]

ii. Your neighbour suggests you to install air source heat pump rather than ground source heat pump. From efficiency point of view, using the scientific reason, explain to your neighbour why you choose to have a GSHP? (which one is generally having higher efficiency, ground source heat pump or air source heat pump? And why?) [4 marks]

Table 1 - The physical properties for a range of soil conditions in the UK

	thermal conductivity κ (W/m/K)	heat capacity C_V (MJ/m^3/K)	length-scale z_0 (m)	flux $A\sqrt{C_V \kappa \omega}$ (W/m^2)
Air	0.02	0.0012		
Water	0.57	4.18	1.2	5.7
Solid granite	2.1	2.3	3.0	8.1
Concrete	1.28	1.94	2.6	5.8
Sandy soil				
dry	0.30	1.28	1.5	2.3
50% saturated	1.80	2.12	2.9	7.2
100% saturated	2.20	2.96	2.7	9.5
Clay soil				
dry	0.25	1.42	1.3	2.2
50% saturated	1.18	2.25	2.3	6.0
100% saturated	1.58	3.10	2.3	8.2
Peat soil				
dry	0.06	0.58	1.0	0.7
50% saturated	0.29	2.31	1.1	3.0
100% saturated	0.50	4.02	1.1	5.3

Equations you may find useful for question 7:

1. Heat transfer rate Q through the building envelope layer: Q=U*A*ΔT

   Where U - U value of the building envelope layer (W/m^{2}K)

   ΔT - Temperature difference (◦C)

2. The U value of a series building components (1, 2,….n) can be calculated as:

$$U = \frac{1}{R_1 + R_2 + \cdots \ldots + R_n}$$

3. The efficiency of a heat engine: $\boldsymbol{\varepsilon} = \frac{T_2}{T_1 - T_2} = \frac{1}{\frac{T_1}{T_2} - 1}$

4. The COP of a heat pump: $COP = \frac{Q_H}{W_{net,in}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1-(Q_L/Q_H)}$

5. Average heat flux q_s that can be extracted from soil $q_s = \kappa \frac{\Delta T}{h}$

   Where, ΔT is the temperature difference of the soil;

   h is the depth between the soil level and the surface of the soil, meter

   κ is the thermal conductivity of the soil, W/mK

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