Loughborough University

RENEWABLE ENERGY SYSTEMS

22WSC303

Semester 1 2022 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.

You may use a calculator for this exam. 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).

RENEWABLE ENERGY SYSTEMS

(22WSC303)

January 2023 | 3 Hours

Answer **ALL SEVEN** questions.

All questions carry equal marks.

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

Any University-approved calculator is permitted.

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1. Renewable Energy Systems, Economics and Policy

a) Give a general equation for the capacity factor of an energy generation technology [1 mark]

b) A grid connected domestic PV System in France has an annual capacity factor of 15%. Over the course of a (non-leap) year the system generates 3287 kWh of electricity. What is the rated capacity, in kW, of the PV system? [3 marks]

c) The PV system exports two thirds of the energy it generates to the grid. The other third is consumed by domestic energy services. Exported energy earns 10c/kWh. The energy consumed avoids import costs of (i.e. earns) 30c/kWh. Calculate the effective annual income in Euros from the PV system. [3 marks]

d) The above PV system costs €900/kW rated capacity. The balance of system (inverter) costs €274. What is the simple payback period? [3 marks]

e) Give a general equation for the simple levelised cost of energy and explain why it is a useful economic parameter in the energy industry? [3 marks]

f) The PV system above has a lifetime of 25 years during which two replacement inverters are purchased. The system scrappage cost is €329. Calculate the total lifecycle costs and the simple levelized cost of energy in cents per kWh (to 1 decimal place). [2 marks]

2. Solar Photovoltaics

a) At solar noon on the autumnal equinox (21st Sept) in Loughborough, you measure the global horizontal irradiance to be 577 Wm^{-2} and calculate the horizontal irradiance outside the Earth's atmosphere to be 816 Wm^{-2}.

Calculate the clearness index and show by empirical model that the horizontal beam and diffuse components of irradiance are 442 Wm^{-2} and 135 Wm^{-2}, respectively. [3 marks]

b) At this time, the solar angle of incidence to a PV array installed at a tilt angle of 45° and facing South is 8.0°. Show that the total in-plane irradiance is 888 Wm^{-2} and explain why it is higher than the global horizontal irradiance measurement. [4 marks]

c) The PV array has a total area of 100 m^2 and an STC (datasheet) power rating of 18 kWp but is generating 14.1 kW at the time mentioned above.

Calculate the system power output that you would expect from only irradiance considerations and then suggest reason(s) for the difference between that and the observed output. [4 marks]

d) Calculate the system operational efficiency at that specific time and explain what measured data and processing chain would be needed to calculate the annual system efficiency. [4 marks]

You may find some of the following formulae useful for question 2:

$$\delta(°) = 23.45 \sin\left(\frac{360}{365} \times (\mathrm{DoY} + 284)\right)$$

$$\omega = 15 \times (T_{solar} - 12)$$

$$\sin h = \sin\delta \sin\Phi + \cos\delta \cos\Phi \cos\omega$$

$$\cos\gamma_S = \frac{\sin h \sin\Phi - \sin\delta}{\cos h \cos\Phi}$$

$$\cos\theta = \sin\delta \sin\Phi \cos\alpha - \sin\delta \cos\Phi \sin\alpha \cos\beta + \cos\delta \cos\Phi \cos\alpha \cos\omega + \cos\delta \sin\Phi \sin\alpha \cos\beta \cos\omega + \cos\delta \sin\alpha \sin\omega \sin\beta$$

$$G_{ET,h} = 1367 \times \left(1 + 0.033 \cos\frac{360 \times DoY}{365}\right) \times \sin h$$

$$k_T = \frac{G_h}{G_{ET,h}}$$

$$\Psi = \begin{cases} 1 - 0.09k_T \; for \; k_T \le 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4 \; for \; 0.22 < k_T < 0.8 \\ 0.165 \; for \; k_T \ge 0.8 \end{cases}$$

$$G_{b,h} = G_h(1 - \Psi),\; G_{d,h} = G_h - G_{b,h}$$

$$G_{b,i} = G_{b,h}\frac{\cos\theta}{\sin h},\; G_{d,i} = \frac{1}{2}G_{d,h}(1 + \cos\alpha)$$

3. Wind Power

a) A 3 bladed wind turbine has a 100m blade length and generates a maximum power of 9MW at a wind speed of 10m/s. Calculate the power coefficient of this turbine. [2 marks]

b) Under the same conditions described in a) (100m blade length, and wind speed of 10m/s), calculate the theoretical maximum power that a wind turbine could generate? Name the law which governs this theoretical maximum. [2 marks]

c) Draw a typical cross section of a blade aerofoil and label the key positions of the aerofoil. [5 marks]

d) Draw a velocity triangle to illustrate the concept of the angle of attack for a wind turbine blade. Show how it relates to the relative wind speed, the blade pitch angle, and the rotational speed of the rotor. Using this diagram, explain why is very important to control the blade pitch angle when the turbine experiences a turbulent wind condition. [6 marks]

Some equations you may find useful for question 3:

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

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

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

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

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

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

4. Biomass

a) What are the three main stages of combustion? [3 marks]

b) What is the difference between an open cycle and close cycle steam turbine system, and why is the use of one preferable over the other? [3 marks]

c) Draw a schematic of a combined cycle gas turbine system. What is the advantage of this system compared to a standard gas or steam turbine system? [9 marks]

5. Integration

a) Integrating high levels of variable renewable energy generations into power grids will bring significant impacts to the conventional centralised power grids. Explain why it could reduce the power system mechanical rotational inertia. [4 marks]

b) Explain why all new/modified generation units wishing to access the power grid need to be grid connection code compliant. [3 marks]

c) Energy storage has been widely used in renewable energy integrated power systems. List THREE energy storage applications categories based on the length of discharge, and name ONE suitable energy storage technology for each category. [3 marks]

d) List TWO main functions of grid-tie PV inverters. [2 marks]

e) Compared to doubly fed induction generator (DFIG) based wind turbine system, describe TWO main advantages and ONE disadvantage of fully rated converter-based wind turbine systems. [3 marks]

6. Future Energy Systems

a) A hydrogen car has a 0.12m^3 compressed hydrogen tank at 350 bar. The hydrogen added to the tank has been generated by electrolysis using wind power. The electrolysis process is 75% efficient and each kg of hydrogen requires 5 kWhkg^{-1} for compression and transport. How many kWh of wind electricity were required to fill the tank? Assume that hydrogen at 350 bar has density 26.1 kgm^{-3} and the higher heating value of hydrogen is 39.4 kWhkg^{-1}. [3 marks]

b) If the fuel cell is 65% efficient and the electric motor for the car is 98% efficient what amount of energy is available to drive the car? [1 mark]

Table 1 gives the dispatch of the grid at a particular time.

Plant	Wind	Hydro	Other	CCGT
Emissions (g/kWh)	0	0	300	394
Generation (MW)	8500	2000	2000	12500
Installed Capacity (MW)	12000	2000	3000	20000
Marginal cost (£/MWh)	0	0	70	45

Table 1: Dispatch and plant information.

c) An EV is charged during this period. Given that the battery efficiency is 90% and the EV uses 0.3 kWh per km, what are the emissions of the EV in grams of CO_2 per km? State any assumptions you make and give reasons! [3 marks]

d) Comment on the relative energy use of batteries for electric cars compared to Hydrogen. [1 mark]

e) List THREE challenges with using Hydrogen as an alternative fuel for boilers compared to natural gas in a net zero future energy system. [3 marks]

f) One alternative to hydrogen for heating is to use heat pumps, give TWO potential advantages of each technology. [4 marks]

7. Energy and Buildings (Some useful equations for Q7 on Page 7)

a) What are the major challenges for the UK to accelerate towards Net Zero Carbon in the building sector? [5 marks]

b) A typical English house usually consumes 290.0 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.

Assume the floor area of your house is 155m^2. Your Ground Source Heat Pump (GSHP) will be installed at 2 meter depth below the ground level. Consider the soil condition is dry clay soil. During the operation of GSHP, the average temperature drop of the ground loop will be maintained to be 8.5°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 install air source heat pump rather than ground source heat pump. From an 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]

	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

Table 2: The physical properties for a range of soil conditions in the UK

Some 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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