SOLAR POWER
22WSP033

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).

SOLAR POWER

(22WSP033)

January 2023 | 3 Hours

Answer **ALL FOUR** questions.

All questions carry equal marks.

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

Any University-approved calculator is permitted.

Exam begins on Page 2.

1.

a) Irradiance data can be collected on-site or can be obtained from a range of off-site sources. Which sensor types are most commonly used? Give an advantage and a disadvantage of each. Why might alternative off-site sources be used instead? [7 marks]

b) Zermatt, Switzerland (Lat. 46°N, Long. 7.75°E) is situated in a deep, steep-sided valley running approximately North-South. Temperatures range from well below 0°C in winter up to 20°C in summer, with monthly precipitation being a relatively consistent 40-60mm all year round. A client in Zermatt is looking for advice regarding the installation of a rooftop photovoltaic array. The roof is tilted at an angle of 27.5°, and faces 47° East of South. If the global horizontal irradiance is 602 W/m^2 on the 17th of March (DoY 76) at 2pm Solar Time, calculate the total irradiance incident on the roof. Explain why this site might not give the ideal performance for the client's array. [15 marks]

c) The optimum tilt angle for a solar collector tends towards horizontal (0 degrees) the higher the proportion of diffuse light there is in the incident spectrum. Explain why. [3 marks]

Formulæ you might find helpful for question 1:

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

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

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

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

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

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

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

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

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

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

2.

a) Draw a band energy diagram of a solar cell. On your diagram indicate the n and p type sides, the Fermi level position, the conduction band and valence bands, the built-in voltage, and the width of the depletion region. [6 marks]

b) Calculate the built-in voltage of a Si solar cell, at 20°C, if the doping density of the n type side of the p-n junction is $5\text{x}10^{17}/\text{cm}^3$ and the doping density of the p type side is $3\text{x}10^{15}/\text{cm}^3$. The density of states in the conduction band of Si is $2.86\text{x}10^{19}/\text{cm}^3$ and the density of states in the valence band is $2.66\text{x}10^{19}/\text{cm}^3$. [8 marks]

c) Explain how the open circuit voltage, Voc, of a solar cell is affected by the doping density on the n and p type side, and for a fixed doping density and material band gap, explain how the Voc could be improved. [5 marks]

d) Show that the Fermi level, E_F, of an intrinsic semi-conductor is given by the expression $E_F = \frac{(E_C+E_V)}{2} + \frac{kT}{2}ln\left(\frac{N_V}{N_C}\right)$. [6 marks]

The following equations and constants are provided for you for question 2:

$$n_i^2 = N_C N_V e^{\left(\frac{-E_g}{kT}\right)},\ \ n = N_C e^{\left(\frac{-(E_C-E_F)}{kT}\right)},\ \ p = N_V e^{\left(\frac{-(E_F-E_V)}{kT}\right)},$$

$$V_{bi} = \frac{kT}{q}ln\left(\frac{N_D N_A}{n_i^2}\right),\ \ I = I_L - I_0\left(e^{\left(\frac{qV}{kT}\right)} - 1\right)$$

$k = 1.38\text{x}10^{-23}$ J/K or $8.62\text{x}10^{-5}$ eV/K

$q = 1.60\text{x}10^{-19}$ C

3.

a) Why is the cost of electricity from building-mounted PV systems generally higher than from ground-mounted systems? [6 marks]

b) Two PV module types are in stock at your PV module supplier, with the following specifications:

	Module A (thin-film)	Module B (crystalline silicon)
Length [m]	2.0	1.7
Width [m]	1.2	1.1
Weight [kg]	34.0	20.8
STC P_{MAX} [W]	485	430
STC V_{MP} [V]	194	30.0
STC I_{MP} [A]	2.5	10.7
TC V [%/°C]	-0.30	-0.30

Calculate the STC efficiencies of module types A and B. [3 marks]

c) You have been offered a good price on a particular inverter. The expected range of PV module operating temperature at the site of intended use is 20 to 65 °C. For each type of module, what number of modules per string should be used to ensure the inverter always operates within its maximum power point tracking window of 580 to 800 V? [10 marks]

d) You have been asked by a potential client to specify a PV system for a warehouse building with a pitched roof (i.e.: not flat).

Nearby to the building are two others, both with existing PV systems that have been operating for over a year. One system is of module type A and the other of type B.

The roof of each of the three buildings is oriented in a different direction and has different incline angle.

There is also a nearby UK Met Office weather station with irradiance measurements available.

Describe how you would decide on which type of module to use, based on some metric of the existing systems: You should define the metric, explain what steps are needed to reach a decision, and note any limitations in the method. [6 marks]

4.

a) What methods could be used to reduce the top loss in a flat-plate solar thermal collector? [2 marks]

b) A flat-plate solar thermal collector has been installed on a roof with a tilt angle of 22°. Assuming an absorber plate temperature of 80°C, a cover temperature of 18.5°C, an ambient temperature of 15°C and a sky temperature of 3.2°C, calculate the top loss coefficient. Assume that the thermal conductivity of air is 0.028 $Wm^{-1}K^{-1}$, the kinematic viscosity of air is $1.9x10^{-5}$ m^2s^{-1}, the wind-driven convection coefficient is 4.73 $Wm^{-2}K^{-1}$, the cover plate has an emissivity of 89% and the absorber plate has an emissivity of 7%. The Stefan-Boltzmann constant is $5.67x10^{-8}$ $W.m^{-2}K^{-4}$ [9 marks]

c) Explain how the use of solar thermal technologies for both residential and industrial heat production purposes can be beneficial, both at an individual level and from a national perspective. What are the downsides to these technologies? [10 marks]

d) The most common types of passive building heat control involve some form of shading device. Give an example of a fixed shading system and a manually controlled system, and describe how they work. [4 marks]

Formulæ you might find helpful for question 4:

$$h_c = \left(0.06 - 0.017\left(\frac{s}{90}\right)\right)\lambda_{air}\left(\frac{g\Delta T}{\overline{T}\nu^2}\right)^{1/3}$$

$$h_r = \frac{\sigma(T_p + T_c)(T_c^2 + T_p^2)}{\frac{1}{\epsilon_p} + \frac{1}{\epsilon_c} - 1}$$

$$h_r = \epsilon_c\sigma(T_c + T_{sky})(T_c^2 + T_{sky}^2) \times \frac{T_c - T_{sky}}{T_c - T_a}$$

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