SOLAR POWER

21WSP033

January 2022 (1b) Exam paper

This is a (1b) online examination, meaning you have a total of **3 hours plus an additional 30 minutes** to complete and submit this paper. The additional 30 minutes are for downloading the paper and uploading your answers when you have finished. If you have extra time or rest breaks as part of a Reasonable Adjustment, you will have further additional time as indicated on your exam timetable.

It is your responsibility to submit your work by the deadline for this examination. You must make sure you leave yourself enough time to do so.

It is also your responsibility to check that you have submitted the correct file.

Exam Help
If you are experiencing difficulties in accessing or uploading files during the exam period you should contact the exam helpdesk. For urgent queries please call **01509 222900**.
For other queries email examhelp@lboro.ac.uk

You may handwrite and/or word process your answers, as you see fit.

You may use any calculator (not just those on the University's approved list).

Loughborough University

SOLAR POWER
(21WSP033)

January 2022 3 Hours

Answer **ALL FOUR** questions.

All questions carry equal marks.

1.

a) The optimum tilt angle for a solar collector to intercept the maximum irradiation across the year is often given as the angle of latitude minus 15 degrees. Why might the optimum tilt angle have a lower value than the latitude, and is the optimum tilt angle less than the latitude angle at all latitudes? [4 marks]

b) The operator of a small solar farm needs access to annual solar irradiance data for the location in order to assess the farm's performance but does not have an irradiance sensor installed and has a very limited budget. What data sources would you suggest they use, and why? If the budget allowed for the installation of a single photovoltaic sensor, what should its orientation be and why? [5 marks]

c) Consider two geographically disparate rural locations: one at a moderately high altitude in a mountainous area in North Africa, and another in a relatively flat area of farmland near sea-level in northern Europe. Which of the two would you expect to receive a higher level of annual irradiation, and why? Why might this location actually receive a lower level of irradiation? [4 marks]

d) The owner of a house in Stirling, Scotland (56.12 °N, 3.94 °W) wants to install a solar thermal hot water panel. The roof area to be used faces due South and has a tilt angle of 31.5 °. Calculate the total irradiance incident on the roof on the 6th of July (day 187) at 2pm solar time, assuming a global horizontal irradiance value of 346 W/m^2. The angle of incidence is 27.5 °. How might you find the average irradiance incident on this roof for the whole day, and what additional information would you need? [10 marks]

e) If a day is defined as a period of time in which the sun is continuously above the horizon, which location or locations would you expect to have the longest day? What is the reason for this? [2 marks]

Formulae you might find helpful:

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

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

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

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

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

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

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

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

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

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

2.

a) Explain the differences between a direct and an indirect band gap semi-conductor. Give an example of both and explain their advantages or disadvantages. You may draw a diagram to explain your answers. [6 marks]

b) Calculate the intrinsic carrier concentration in gallium arsenide at 20°C. The density of states in the valence band is 7.0x10^{18}/cm^3 and the density of states in the conduction band is 4.7x10^{17}/cm^3. Qualitatively explain why the intrinsic carrier concentration in gallium arsenide is higher or lower than it is in silicon. [7 marks]

c) Explain what determines the maximum open circuit voltage, Voc, which can be obtained by a solar cell. You may use diagrams or refer to equations to explain your answer. [7 marks]

d) Explain qualitatively what happens to a solar cell when the temperature or the irradiance intensity changes. What are the consequences for the resulting efficiency? [5 marks]

The following equations and constants are provided for you:

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

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

k = 1.38x10^{-23}J/K or 8.62x10^{-5} eV/K

q = 1.60x10^{-19} C

3. You have been approached to design a solar PV system in the South-West of England. The client has an outbuilding which they would like to use for a home-based side-business (polishing decorative glass pellets).

This is not the client's main source of income, and they are happy to have the equipment run intermittently throughout the year, with no specific timing requirements.

The client has specified that the maximum possible electricity be produced over the year, provided the cost per kWh over a 10-year operational period is no greater than 0.10 £/kWh.

The building has a South-West facing roof, with a tilt angle of 30 degrees from the horizontal. It is rectangular, 12 m wide by 6 m tall (up the slope of the roof), and is the only area available for placing solar modules. Modules may be installed on the roof up to 0.2 m from each edge.

The building has no grid connection, and the client cannot gain permission to install one.

a) Suggest two other possible constraints that would need to be verified to undertake the design process. [2 marks]

b) Your PV module supplier has two types in stock, with the following specifications:

	Module A ("premium")	Module B ("standard")
Length [m]	2.1	1.7
Width [m]	1.0	0.95
STC P_{MAX} [W]	440	290
Cost per W_P [£]	0.7	0.5

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

c) Show that the maximum installable capacity on this roof is 11.00 kW_P for module A and 10.44 kW_P for module B. [9 marks]

d) The UK Government "Standard Assessment Procedure for Energy Rating of Dwellings" (SAP) contains a simple model for expected PV system annual energy yield:

$$0.8 \times kW_P \times S \times Z_{PV}$$

Where kW_P is the system installed capacity,

S is the annual in-plane solar irradiation, calculated within the SAP method as 1189 kWh/m^2 per year for the given roof orientation and location,

and Z_{PV} is a shading impact modifier (in this case equal to 1, for no shading).

Calculate the annual Specific Energy Yield that the SAP method assumes for any system on this roof, and also the absolute annual energy yield for the module A and module B systems (for the system capacities stated in part c). [4 marks]

e) In addition to the scaling module costs given above, you have a fixed combined cost of Balance-of-System components, installation, legal compliance and insurance, and profit margin of £4000, whichever module type and system size is installed.

To save time here in the exam, consider only a simple cost-of-electricity calculation to determine whether the client's requirements can be met (i.e., no need to consider change in currency value over time). State the assumptions you are forced to make in reaching your conclusion. [7 marks]

4.

a) Despite having a reasonable solar resource, the use of solar thermal collectors in the UK is relatively low and is considerably less than other European countries at equivalent latitudes. Explain how increasing the use of solar thermal energy for space and water heating could be beneficial, both in the UK and more generally. What are the potential disadvantages of the use of solar thermal for these purposes? [8 marks]

b) A flat-plate solar thermal collector has been installed on a roof with a tilt angle of 32.7 °. Assuming an absorber plate temperature of 68 °C, a cover temperature of 11.3 °C, an ambient temperature of 5 °C and a sky temperature of -7.2 °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 1.76 $Wm^{-2}K^{-1}$, the cover plate has an emissivity of 96% and the absorber plate has an emissivity of 5%. [9 marks]

c) Coating the absorber plate in a flat-plate collector with a selective surface material is one method which can be used to reduce the top loss coefficient. How do these materials help to reduce the top loss without reducing the amount of sunlight absorbed? What other method could be used to reduce the top loss coefficient? [3 marks]

d) Describe how brise soleil (sun breakers) can be used to regulate a building's solar gain. What aspect of a building's design might make the use of brise soleil desirable in a relatively cold climate such as the UK? [3 marks]

e) When calculating a building's heat load, why are the presence and activities of any occupants ignored? When selecting the boiler size, why is it recommended that the heat load value be increased by 15%? [2 marks]

Formulae you might find helpful:

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

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

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

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