Solar Power

23WSP033

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 FOUR** 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. Solar Resource.

a) Geostationary satellites can be used to obtain solar irradiance data with high temporal resolution, but their spatial resolution reduces considerably with increased distance from the equator. What causes this? [4 marks]

b) A client has recently taken on management of a newly installed solar farm, and has a small budget for installation of on-site irradiance measurement devices. What type of sensor would you recommend that they use, and why? What might the disadvantages of using this sensor type be? [5 marks]

c) Galway (Lat. 53.28°N, Long. 9.05°W) is a small city in the West of Ireland. A client in Galway is looking for advice regarding the installation of a rooftop photovoltaic array. The building has two useable roof areas, A and B, both facing 12° West of South. Area A is at an angle of 28.75°. If the global horizontal irradiance is 516 W/m^2 on the 30th of April (DoY 120) at 11am Solar Time, calculate the incident irradiance. Roof area B is considerably steeper, at 73°. Which roof section is more likely to receive higher annual irradiation, and why? How would you expand your calculation to demonstrate this? [13 marks]

d) Due to the slightly elliptical nature of the Earth's orbit, the solar constant actually varies approximately sinusoidally across the year. What other effects might cause variations in the amount of solar energy reaching the top of the atmosphere, and over what approximate timescales might these effects occur? [3 marks]

Formulæ you might find helpful:

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

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

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

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

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

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

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

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

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

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

2. PV Devices.

a) Explain what is meant by the “intrinsic carrier concentration” of a semiconductor? Considering two solar cells, each with different band gaps, but identical n and p type doping density, explain qualitatively the influence the intrinsic carrier concentration has on the maximum voltage possible in each solar cell. [6 marks]

b) At 300K, a silicon wafer has a relative Fermi level position 0.25eV above the valence band. The density of states in the conduction band is $2.86\text{x}10^{19}/\text{cm}^3$, and the density of states in the valence band is $2.66\text{x}10^{19}/\text{cm}^3$.

i. What element could be used as a dopant to obtain this Fermi level position? [1 mark]

ii. Calculate the impurity concentration required to obtain this Fermi level position. [2 marks]

iii. Assuming complete ionisation at 300K, where will the relative Fermi level position lie if $5\text{x}10^{15}/\text{cm}^3$ phosphorous atoms are added to the same wafer. [6 marks]

c) Draw a diagram of a direct and an in-direct band gap semi-conductor, highlighting the differences between the two. Give an example of each and indicate the band gap of each. [6 marks]

d) Explain in qualitative terms what happens to a solar cell when the temperature or the irradiance intensity changes. What are the consequences for its efficiency? [4 marks]

The following equations and constants are provided for you:

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

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

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

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

3. PV Systems

a) Consider the differences in design of a PV system to be added to an existing residential building (with a grid connection), and a large-scale, ground-mounted solar farm. For each case:

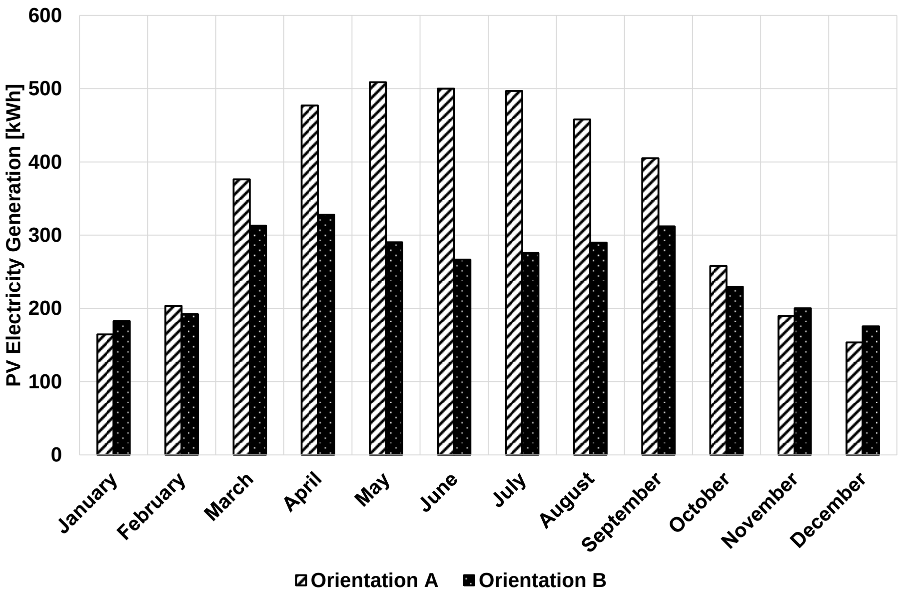
What are likely to be the main requirements of the system owners?

What metrics (indicators) would you suggest for evaluating designs?

What are the main design constraints to be considered?

How might the configuration of the modules and other system components be different? [14 marks]

b) A 4 kW_P PV system is being designed for an existing house in Loughborough, UK (latitude 52.8°). The array could be mounted on a south-facing roof section with an angle to the horizontal of 40 degrees, or to a south-facing vertical wall. The figure below shows the modelled electricity generation for both orientations:



Which orientation is which? Explain how you determined your answer. [3 marks]

c) For the same building, a West-facing roof section also at 40 degrees is another option. Show with a sketch graph how you expect the monthly generation to look compared to the other orientations above, and add a comment why. What would be a difference in generation from the other orientations that you will ***not*** be able to see in these graphs? [3 marks]

d) The module datasheet contains the following information:

Length [mm]	2094
Width [mm]	1134
Weight [kg]	26.0
STC P_{MAX} [W]	500
STC V_{MP} [V]	38.4
STC I_{MP} [A]	13.0

The 4 kW_P system is installed and generates 3055 kWh of electricity in the first year. The corresponding in-plane irradiation is 879 kWh/m^2.

Calculate the annual Performance Ratio for the system. [5 marks]

4. Solar Thermal Systems.

a) Explain the mechanism by which a solar selective coating can reduce thermal losses from the absorber plate. [4 marks]

b) A flat-plate solar thermal collector has been installed on a roof with a tilt angle of 47°. Assuming an absorber plate temperature of 62°C, a cover temperature of 11°C, an ambient temperature of 2°C and a sky temperature of -7.9°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 1.9×10^{-5} m^2s^{-1}, the wind-driven convection coefficient is 0.95 $Wm^{-2}K^{-1}$, the cover plate has an emissivity of 93% and the absorber plate has an emissivity of 6.5%. [9 marks]

c) Passive solar design involves construction of buildings and building elements in order to provide control over the amount of solar radiation coming into a building, thereby increasing control over the internal temperature. Give four examples of building elements designed to control or exploit incoming solar radiation, and explain how they might be beneficial to the end-user. [8 marks]

d) The temperatures which a non-concentrated solar thermal system can reach are relatively modest, normally within the range used for domestic hot water. Industrial processes often require much higher temperatures, which require the use of solar concentrators. What is the theoretical maximum temperature that can be achieved through the use of solar concentration, and why? Why is it very unlikely that such a temperature would be achieved in reality? [4 marks]

Formulæ you might find helpful:

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

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

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

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