HW 1

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Problem 1

The energy of a photon can be quantified as:

$$E = \frac{hc}{\lambda},$$

where, E, h, c and λ are energy, Planck's constant, speed of light and wavelength respectively. To create electron-hole pairs, the following condition needs to be satisfied:

$$E \geq E_{gap}, \tag{1}$$

where E_{gap} is the band gap energy of the material in which the electron-hole pairs are required to be created. From (1),

$$\begin{aligned} \frac{hc}{\lambda} &\geq E_{gap} \\ \implies \lambda &\leq \frac{hc}{E_{gap}}. \end{aligned} \tag{2}$$

Plugging in the values of $E_{gap} = 1.42\ eV,\ h = 6.63 \times 10^{-34}\ m^2kg/s$ and $c = 3 \times 10^8\ m/s$ in (2),

$$\begin{aligned} \lambda &\leq \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{1.42 \times 1.6 \times 10^{-19}}\ m \\ &= 0.875\ \mu m. \end{aligned}$$

Therefore, a photon can have a maximum wavelength of 0.875 μm to create electron-hole pairs in Gallium Arsenide.

Problem 2.1

The system needs to deliver 4000 kWhr/yr energy. Now, Las Vegas receives 6.4 kWhr/m^{2}day of average insolation. It can be interpreted as 6.4 hr/day of 1kW/m^2 solar irradiation. Therefore, the AC rated power (kW) of the system should be

$$\begin{aligned} P_{ac} &= \frac{4000}{365 \times 6.4} \\ &= 1.71. \end{aligned}$$

Problem 2.2

We know that,

$$P_{ac} = P_{dc,stc} \left[1 - ((T - 25)l_t)\right](1 - l_d)(1 - l_m)\eta_{inv}, \tag{3}$$

where, $P_{dc,stc}, T, l_t, l_d, l_m$ and η_{inv} are DC power (kW) at STC (standard test condition), cell temperature, percentage drop in voltage/°C, percentage loss due to dirt, percentage loss due to cell condition mismatch and inverter efficiency respectively.

Plugging in the values of $P_{ac} = 1.71$ kW$, T = 45$°C$, l_t = 0.0036, l_d = 0.03, l_m = 0.03, \eta_{inv} = 0.92$, we get

$$\begin{aligned} P_{dc,stc} &= \frac{1.71}{0.928 \times 0.97 \times 0.97 \times 0.92} \\ &= 2.13. \end{aligned}$$

Problem 2.3

Let $A \in \mathbb{R}$ denote the required area (m^2)of the system. We previously calculated the DC power, $P_{dc,stc}$ kW, under STC. This power has to come from a system with A m^2 area with 1 kW/m^2 irradiation. If the PV module efficiency is 13%, then,

$$\begin{aligned} P_{dc,stc} &= A \times 0.13 \\ \implies A &= \frac{2.13}{0.13} \\ \implies A &= 16.38. \end{aligned}$$

Problem 2.4

DC output power of the system is $P_{ac}/\eta_{inv} = 1.86$ kW. Therefore, total capital cost (\$) of installation is $C = 6 \times 1860 = 11160$.

Interest rate, d is 0.06 and duration of investment is $n = 30$ years.

The renewable energy credit pays the owner \$0.05/kWhr generated. In the question, it is not clear that if this payment is done upfront or annual. Here I assume that the payment of credit is annual. Let $A \in \mathbb{R}$ denote the annual installment for the loan. Therefore, the net present value of the system is

$$\begin{aligned} C &= A\frac{(1+d)^n - 1}{d(1+d)^n} \\ \implies A &= C\frac{d(1+d)^n}{(1+d)^n - 1} \\ \implies A &= \frac{(11160)(0.06)(1.06)^{30}}{(1.06)^{30} - 1} \\ \implies A &= 810.76. \end{aligned}$$

Annual energy yield is 4000 kWhr. Therefore, considering the renewable energy credit, the cost of electricity should be

$$\text{cost of electricity (\$/kWhr)} = \frac{810.76}{4000} - 0.05 = 0.153.$$

Problem 3.1

Absolute value of the slope of I-V curve near the open circuit voltage is approximately equal to $\frac{1}{R_s}$. From the given graph, we can calculate the slope and find

$$\begin{aligned} \frac{1}{R_s} &= \frac{1.4 - 1.0}{0.58 - 0.56} \\ \implies R_s &= 0.05\ \Omega. \end{aligned}$$

Problem 3.2

The absolute value of the slope of I-V curve near the short circuit current is approximately equal to $\frac{1}{R_p}$. From the given graph,

$$\begin{aligned} \frac{1}{R_p} &= 0 \\ \implies R_p &= \infty\ \Omega. \end{aligned}$$

Problem 3.3

From the graph, approximately it looks maximum power point, for the curve labeled as $R_s = 0$ is near $V =$ 0.56 V and $I = 3.8$ A. Therefore, the maximum power that can be delivered is $P_{max} = (0.56)(3.8) = 2.13$ W.

Problem 3.4

In case of 5 parallel strings of 10 series connected cells, the open circuit voltage would be $0.63 \times 10 = 6.3$ V and short circuit current would be $4 \times 5 = 20$ A. As for the curve labeled with $R_s = 0$ is having approximately very large parallel resistance ($R_p \leftarrow \infty$), as estimated before, and series resistance $R_s = 0\ \Omega$, as indicated in the given graph. Therefore, we can assume that there will not be significant effect on the slope of the I-V curve near open circuit as well as short circuit condition. An approximate I-V curve for the series-parallel combination is shown in Fig. 1.

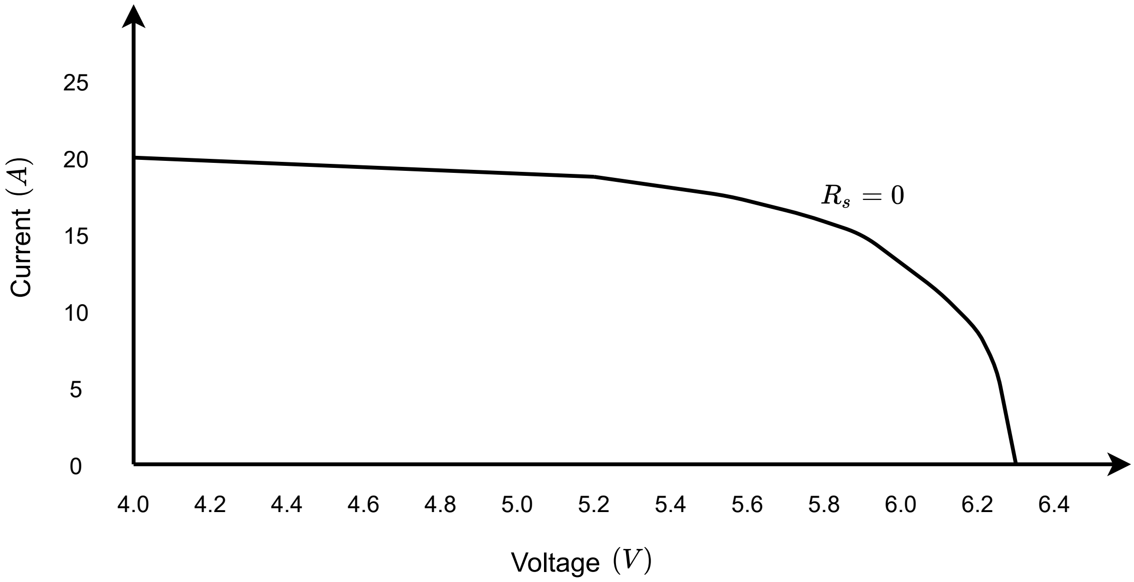

Figure 1: I-V curve of 5 parallel strings each with 10 series-connected PV cells

Problem 4

The maximum power point corresponds to 40 V and 5 A. We need to provide power to a 12 V battery. Therefore, for maximum power point operation of the PV resource, we need to step down the input voltage, $V_{in} = 40\ V$ to output voltage, $V_{out} = 12\ V$. Thus, we may use a buck converter to accomplish this. The input output voltage of a buck converter is related as follows:

$$V_{out} = DV_{in},$$

where, $D \in [0, 1] \in \mathbb{R}$ is the duty cycle of the buck converter. Plugging in the values of V_{in} and V_{out}, we find that $D = 0.3$.

Problem 5

Let $S \in \mathbb{N}$ and $P \in \mathbb{N}$ denote the number of PV modules connected in series and parallel respectively. Our objective is to deliver maximum power to the inverter. Let $V_{oc}, I_{sc}, V_{mppt}, I_{mppt}$ denote the PV modules's open circuit voltage, short-circuit current, voltage at maximum power and current at maximum power respectively and let $V_{inv}^{max}, V_{inv,mppt}^{max}, V_{inv,mppt}^{min}, I_{inv}^{max}$ denote the inverter maximum input voltage, MPPT (maximum power point tracker) voltage range maximum value, MPPT voltage range minimum value and maximum input current. In this question,

$$\begin{aligned} V_{oc} &= 43.40\ V \\ I_{sc} &= 4.80\ A \\ V_{mppt} &= 34\ V \\ I_{mppt} &= 4.40\ A \end{aligned}$$

$$
\begin{aligned}
V_{inv}^{max} &= 600\ V \\
V_{inv,mppt}^{max} &= 550\ V \\
V_{inv,mppt}^{min} &= 250\ V \\
I_{inv}^{max} &= 11\ A.
\end{aligned} \tag{4}
$$

For maximum power point operation of the PV module, we need to ensure the following:

$$
\begin{aligned}
SV_{oc} &\leq V_{inv}^{max} \\
V_{inv,mppt}^{min} \leq SV_{mppt} &\leq V_{inv,mppt}^{max} \\
PI_{mppt} &\leq I_{inv}^{max}.
\end{aligned}
$$

Plugging in the values from (4),

$$
\begin{aligned}
S &\leq 13 \\
8 \leq S &\leq 16 \\
P &\leq 2.
\end{aligned}
$$

Therefore, from the given combinations, I would choose $(8\ S, 2\ P)$ (choice no. 2 in question).