5.6 Recreate the spreadsheet that was started in Example 5.4 for a 72-cell, 233-W PV module for which the equivalent circuit of each cell has both series (0.001Ω) and parallel resistances (10.0Ω).

a. From your spreadsheet, what is the current, voltage and power delivered when the diode voltage \( V_d \) is 0.4 V?

b. Plot the entire I-V curve for this module.

From CKT model below:

\[
I = I_{sc} - I_0 \left( e^{\frac{38.9 V_d}{10}} - 1 \right) - \frac{V_d}{R_p}
\]

\[V_d = I R_s + V \]

\[\Rightarrow V = V_d - IR_s\]

For \( V_d = -4V \):

\[I = 6.0 \times 10^{-11} \left( e^{\frac{38.9 \times (-4)}{10}} - 1 \right) - \frac{-4}{10}\]

\[= 5.9597 \text{ A} \text{ns.}\]

\[V = 72 \left( 4 - 5.959 \times 1001 \right) \]

\[= 72 \left( 4 - 0.00595 \right) \]

\[= 28.37 \text{ V} \text{ns.}\]

\[P = V I = 169.062 \text{ W} \text{ns.}\]
PART Q

1. Characteristic: PV Module with 72 series connected cells

Module Voltage mapped to $V_d$ (1 cell)

VALUES OF $V_d$

Module Voltage (V)

Module Voltage mapped to $V_d$ (1 cell)

Module Power (W)

MAX POWER POINT: 169 W
5.7 Consider how you might make a simple, cheap pyranometer out of a single small (e.g. 1 cm²) PV cell along with a precision load resistor. If the PV cell has the following I-V curve and the goal is for the digital multimeter (DMM, with infinite input resistance), when set on its millivolt dc- scale, to give you direct readings of insolation.

![I-V Curve Diagram]

Figure P5.7

a. Find the load resistance that the pyranometer needs if the goal is to have the output of the DMM on a millivolt (mV) scale provide insolation readings directly in Btu/ft²-h (Full sun = 1 kW/m² = 317 Btu/ft²-h = 317 mV).

Sketch the I-V curve with your load resistance superimposed onto it. Show the PV-curve at both 1-sun and 1/2-sun insolation.

b. Suppose you want the mV reading to be W/m². What resistance would work (but only for modest values of insolation). Draw an I-V curve with this resistor on it and make a crude estimate of the range of insulations for which it would be relatively accurate.

\[
I = I_{sc} - I_0 (e^{-\frac{V}{0.4}} - 1)
\]

a) \[V_R = 317 \text{ mV} = IR\]

\[R = \frac{317}{0.4} = 792.5 \text{ \Omega} \quad \text{ANS.}\]

b) \[V_R = 1000 \text{ mV} \leq IR\]

\[R = \frac{1000}{0.4} = 250 \text{ \Omega} \quad \text{ANS.}\]
0. THE 1/2 SUN CURVE WILL BE SHIFTED TO 1/2 THE 1 SUN CURVE VALUES AS $I_{sc}$ IS DIRECTLY PROPORTIONAL TO ILLUMINATION.

0. THE LOAD RESISTANCE IS SET BY 2 POINTS:

- Origin \( V = 0 \) \( I = 0 \)

- \( V = 0.2 \) \( I = \frac{0.2V}{7.93} = 0.025A \)

0. THE LOAD RESISTANCE CURVE DOES NOT APPROACH THE KNEE OF THE PV CURVE.

- NO ISSUES OF LINEARITY.

(b) CONT.

- AGAIN THE 1/2 SUN CURVE IS SHIFTED 1/2 1 SUN VALUES.
- LOAD RESISTANCE CURVE SET @ ORIGIN AND

\[ V = 0.5 \Rightarrow I = \frac{0.5}{25} = 0.02 \]

- NOTE THIS METER IMPLEMENTATION IS LINEAR TO N 500 W/m² BEYOND THAT NON-LINEARITIES PRECLUDE ACCURATE READINGS.
5.8 A 4-module array has two south-facing modules in series exposed to 1000 W/m² of insolation, and two west-facing modules exposed to 500 W/m². The 1-sun I-V curve for a single module with its maximum power point at 4A, 40V is shown below.

![Diagram of module connections]

**Figure P5.8**

Draw the I-V curve for the 4-module array under these conditions. What is the output power (W) at the array’s MPP?

- **Original curve is for 1 south-facing.**
- Duplicate original curve and add its voltage to the original curve.
- The 1st west-facing panel will have the original curve scaled by 1/2.
- Duplicate 1st west curve and add voltage to 1st west curve.
- Add 2 west curve current to the pair of south-facing panels. The result is in red.

**Estimate max power point.** \[ P = VI \]

\[ 78.6 \times 46.8 \]

\[ \Rightarrow 3.6 \approx 480 \text{ mpp} \] Ans.
5.9 A 200-W c-Si PV module has NOCT = 45°C and a temperature coefficient for rated power of -0.5%/°C.

a. At 1-sun of irradiation while the ambient is 25°C, estimate the cell temperature and output power.

b. Suppose the module is rigged with a heat exchanger that can cool the module while simultaneously providing solar water heating. How much power would be delivered if the module temperature is now 35°C? What % improvement is that?

c. Suppose ambient is the same temperature, but now insolation drops to 0.8 kW/m². What % improvement in power output would the heat exchanger provide if it still maintains the cell temperature at 35°C?

![Diagram of a solar panel with a heat exchanger and cooling water at 35°C.](image)

**Figure P 5.9**

\[ T_{\text{cell}} = T_{\text{amb}} + \left( \frac{\text{NOCT} - 20^\circ}{8} \right) \times 5 \]

\[ = 25^\circ + \left( \frac{45 - 20}{8} \right) \times 5 \]

\[ = 56.25^\circ \text{C} \quad \text{Ans.} \]

\[ P_{\text{max}} = 200 \left[ 1 - \frac{T_{\text{TEMPhoot}}}{T_{\text{CELL}} - T_{\text{AMB}}} \right] \]

\[ = 200 \left[ 1 - \frac{590}{56.25 - 25} \right] \]

\[ = 200 \left[ 1 - \frac{31.25}{31.25} \right] \% \]

\[ = 168 \text{ W} \quad \text{Ans.} \]

\[ P_{\text{max}} = 200 \left[ 1 - \frac{\text{NOCT} - 20}{25} \right] \]

\[ = 200 \left[ 1 - \frac{45 - 20}{25} \right] \% \]

\[ = 190 \text{ W} \quad \text{Ans.} \]

\[ \% \text{ improvement} = \frac{190 - 168}{168} \Rightarrow 13.7\% \text{ improvement} \quad \text{Ans.} \]
(c) Insolation drops to \(\frac{0.8 \text{ kW}}{\text{m}^2}\)

\[
T_{\text{cell}} = T_{\text{amb}} + \left(\frac{\text{NOC} - 25^\circ}{0.6}\right) \frac{\text{insolation}}{\text{insolation}}
\]

\[
= 25 + \left(\frac{45-25}{0.6}\right) \times 8 = 50^\circ \text{C}
\]

\[
P_{\text{max}} = 200 \text{ W} \times 0.8 \left[1 - \frac{57^\circ}{50^\circ} (50-25)^\circ\right]
\]

\[
= 200 \times [0.8 \times 0.875]\]

\[
= 140 \text{ W}
\]

W/ Cooling via Heat Exchanger

\[
P_{\text{max}} = 200 \times 0.8 \left[1 - \frac{57^\circ}{50^\circ} (40-25)^\circ\right]
\]

\[
= 200 \times 0.8 \times 0.925 = 148 \text{ W}
\]

\[
\frac{148 - 140}{140} \geq 5.71\%
\]

Improvement.

Note: Improvement declines as Insolation declines.
5.10 Consider this very simple model for cells wired in series within a PV module. Those cells that are exposed to full sun deliver 0.5 V; those that are completely shaded act like 5-Ω resistors. For a module containing 40 such cells, an idealized I-V curve with all cells in full sun is as follows.

![Graph showing I-V curve and shaded cells.]

**Figure P 5.10**

**a.** Draw the PV I-V curves that will result when one cell is shaded and when two cells are shaded (no battery load).

**b.** If you are charging an idealized 12-V battery (vertical I-V curve), compare the current delivered under these three circumstances (full sun and both shaded circumstances).

\[ I_{\text{shaded}} = \frac{19.5}{5} = 3.9 \text{ A} = I_{\text{oc}} \]

\[ I_{\text{unshaded}} = 4 \text{ A} \]

\[ I_{\text{shaded}} = \frac{(19.5 - 12)}{5} = 1.5 \text{ A} \text{ (Ans)} \]

\[ I_{\text{shaded}} = \frac{(19 - 12)}{10} = 0.7 \text{ A} \]
5.11 An idealized 1-sun I-V curve for a single 80-W module is shown below. For two such modules wired in series, draw the resulting I-V curve if the modules are exposed to only 1/2 sun, and one cell, in one of the modules, is shaded. Assume the shaded cell has an equivalent parallel resistance of 10 Ω.

**Figure P 5.11**

Sketch the resulting I-V curve. How much power would be generated at the maximum power point?

\[ \text{V}_{\text{cell}} = 40 - IR_p = \]

\[ \text{V}_{\text{cell}} = 40 - 1 \times 10 \text{Ω} = 30 \text{V} \]

**Figure P 5.11**

\[ \text{MPP} = 1.7 \text{A} = 60 \text{W} \text{ (near knee of the curve)} \]