University of Colorado
Boulder

Photovoltaic Power Electronics
ECEA 5716 Open-Loop Photovoltaic Power Electronics
Laboratory
Direct Energy Transfer System

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Measurement Equipment:

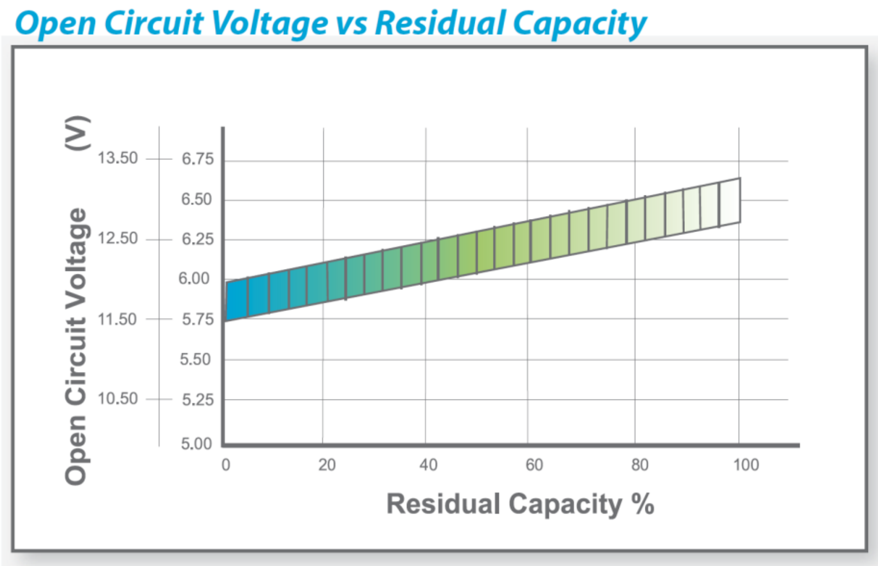
- FLUKE 179 TRUE RMS MULTIMETER (Calibrated by TRANSCAT on 06/15/2021)
- FLUKE 289 TRUE RMS MULTIMETER (Calibrated by TRANSCAT on 06/15/2021)

PV Characteristics and Direct Energy Transfer

1. *Battery V_{oc} recorded, and battery state of charge estimated*

- Reading = **12.685Vdc**

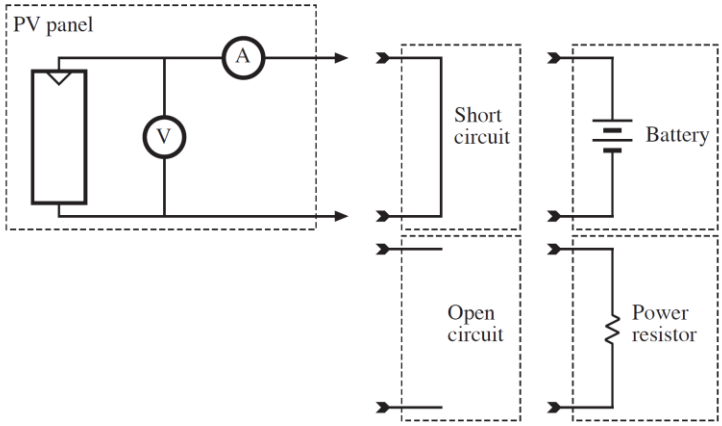
Based on given parameter from battery datasheet UB1250 [1]:



100% SOC ≈ 13.00Vdc
0% SOC ≈ 11.75Vdc

The estimated SOC is:

$$\frac{V - V_{0\%soc}}{V_{100\%soc} - V_{0\%soc}} = \frac{12.685 - 11.75}{13.00 - 11.75} \times 100\% = \mathbf{74.8\%}$$



		Open Circuit		Short Circuit		Load = 30 Ω		Load = 15 Ω		Load = 60 Ω		Load = 7.5 Ω		Load = Battery	
						Acutal = 30.12 Ω		Acutal = 15.23 Ω		Acutal = 59.65 Ω		Acutal = 7.62 Ω			
Date	Time	V	I	V	I	V	I	V	I	V	I	V	I	V	I
09/06/2021	12:00	21.3000	0.0000	0.0000	0.6980	17.3200	0.5795	10.2800	0.6896	18.9900	0.3189	5.2250	0.6927	16.2000	0.6516
09/06/2021	12:00	21.0800	0.0000	0.0000	0.7000	17.3600	0.5811	10.1300	0.6797	19.0000	0.3191	5.2570	0.6953	16.2900	0.6498
09/06/2021	12:00	20.4800	0.0000	0.0000	0.7120	17.4200	0.5835	10.0800	0.6752	19.0100	0.3193	5.3800	0.7140	16.4000	0.6456
09/06/2021	12:15	20.2200	0.0000	0.0000	0.7025	17.4300	0.5837	10.0000	0.6710	19.0000	0.3194	5.3710	0.7064	16.5000	0.6432
09/06/2021	12:30	20.4000	0.0000	0.0000	0.7189	17.5000	0.5840	10.3300	0.6874	18.8500	0.3163	5.4300	0.7138	16.7000	0.6420
09/06/2021	12:30	20.4900	0.0000	0.0000	0.6945	17.5300	0.5858	10.4600	0.6923	18.8500	0.3164	5.3880	0.7086	16.2000	0.6405
09/06/2021	12:30	20.5500	0.0000	0.0000	0.6980	17.6000	0.5874	10.5000	0.6954	18.8400	0.3161	5.4200	0.7120	16.3000	0.6380
09/06/2021	12:45	20.3000	0.0000	0.0000	0.7300	17.2200	0.5750	10.4600	0.6957	18.8400	0.3160	5.4250	0.7136	16.4000	0.6369
09/06/2021	12:45	20.2400	0.0000	0.0000	0.7180	17.2500	0.5762	10.4800	0.6976	18.8400	0.3163	5.4250	0.7136	16.5000	0.6356
09/06/2021	12:45	20.2000	0.0000	0.0000	0.7175	17.2800	0.5769	10.5000	0.6996	18.8400	0.3164	5.4250	0.7136	16.6000	0.6343
Average		20.5260	0.0000	0.0000	0.7089	17.3910	0.5813	10.3220	0.6884	18.9060	0.3174	5.3746	0.7084	16.4090	0.6418

Q2-5 are based on the data acquired above.

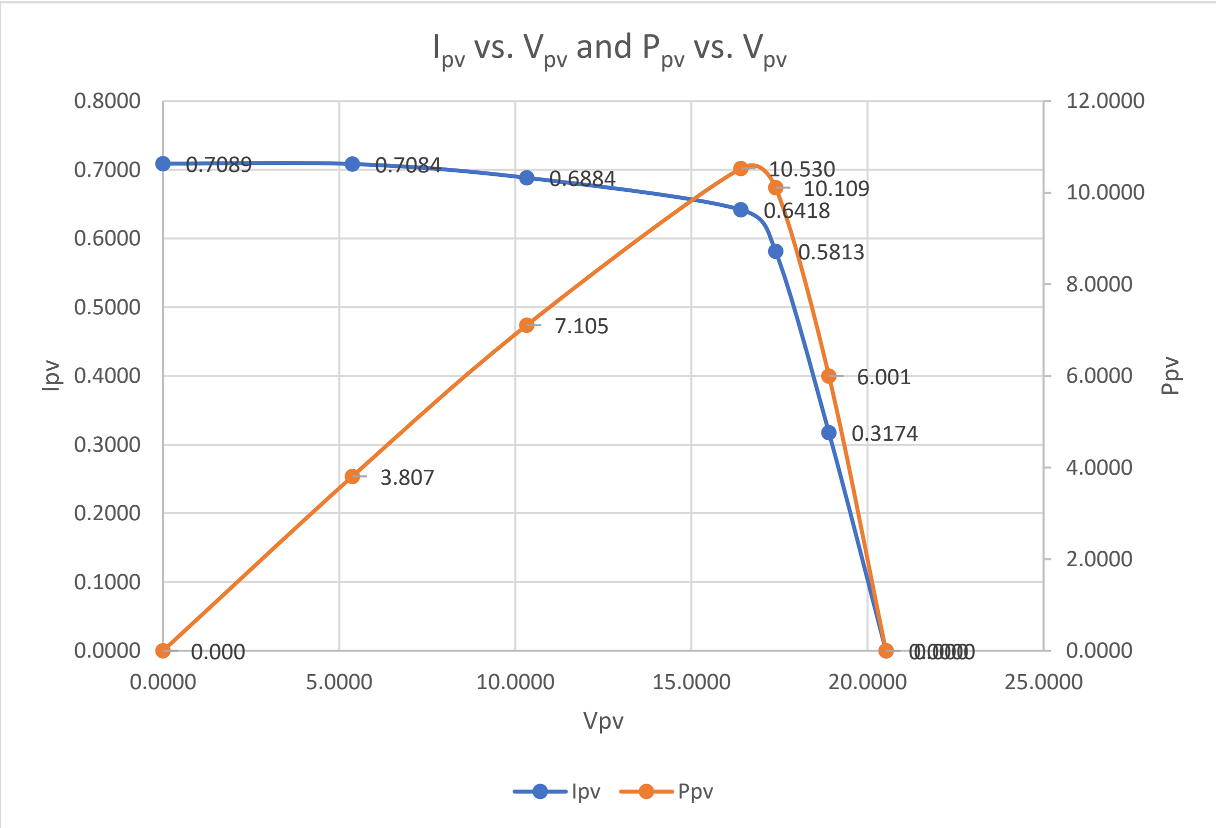
2. PV panel V_{oc}
   - Reading(average) = **20.5260Vdc**

3. PV panel I_{sc}
   - Reading(average) = **0.7089Adc**

4. Collection of PV panel I_{pv} vs. V_{pv} data at six points: open circuit, short circuit, with resistive loads of 15Ω; 30Ω; 60Ω, and with direct connection to battery.
   - 15Ω Reading(average)
     - **10.3220Vdc**
     - **0.6884Adc**
   - 30Ω Reading(average)
     - **17.3910Vdc**
     - **0.5813Adc**
   - 60Ω Reading(average)
     - **18.9060Vdc**
     - **0.3174Adc**
   - Battery Direct Connect Reading(average)
     - **16.4090Vdc**
     - **0.6418Adc**

5. Plot of PV panel experimental data: I_{pv} vs. V_{pv} and P_{pv} vs. V_{pv}.

V_{pv}	I_{pv}	P_{pv}
0.0000	0.7089	0.0000
5.3746	0.7084	3.8071
10.3220	0.6884	7.1051
16.4090	0.6418	10.5305
17.3910	0.5813	10.1096
18.9060	0.3174	6.0011
20.5260	0.0000	0.0000



6. Battery charging current when PV panel is partially shaded.

		Load = Battery (Shaded)	
Date	Time	V	I
09/06/2021	13:00	13.3300	0.0129
09/06/2021	13:00	13.2400	0.0129
09/06/2021	13:00	13.1800	0.0144
09/06/2021	13:00	13.1500	0.0144
Average		13.2250	0.0137

- Battery Direct Connect with Partially Shaded Reading(average)
    - **13.2250Vdc**
    - **0.0137Adc**
    - When the cell is shaded, the cell become simple diode, because there is lack of bypass diodes, all current generated by other cells will be flowing back and drop on the shaded cells. And the drop of the Voltage measured also proof that.

7. Comparison of measured plots vs. data sheet, including I_{sc}; V_{oc}, and P_{mp}. Briefly discuss potential reasons for any discrepancies.

Based on given parameter from Solar Panel datasheet SLP010-12U [2]:

Electrical Characteristics	SLP010-12U
Produc code	010011201B
Maximum power (Pmax)	10W
Voltage at Pmax (Vmp)	17.0V
Current at Pmax (Imp)	0.58A
Open-circuit voltage (Voc)	21.6V
Short-circuit current (Isc)	0.68A
Temperature coefficient of Voc	-(80±10)mV/°C
Temperature coefficient of Isc	(0.065±0.015)%/ °C
Temperature coefficient of power	-(0.5±0.05)%/ °C
NOCT (Air 20°C; Sun 0.8kW/m² wind 1m/s)	47±2°C
Operating temperature	-40°C to 85°C
Maximum system voltage	1000V DC
Power tolerance	± 5%

	From Datasheet	Obtained Data	Δ
V_{oc} (V)	21.6	20.5260	1.074
I_{sc} (A)	0.68	0.7089	0.0289
P_{mp} (W)	10	10.53	0.53

- Couple of factors that would contribute the variances from Datasheet:
    - Manufacturing defects
    - Raw materials tolerances
    - Geometry location on where the data are obtained
    - Real time Solar Irradiance

8. Compute the PV panel efficiency, based on your measured data and the panel outside dimensions listed on the datasheet.

Panel Dimension = 0.302 x 0.357 = 0.107814m^2
Assuming we have 1000W/m^2 irradiance at the time of measure.

The efficiency of the Panel:

$$\frac{Measured\ Pmp/Panel\ Dimension}{1000W/m^2} = \frac{\eta}{100\%}$$

$$\frac{10.53}{0.107814 \times 1000} = \frac{\eta}{100\%}$$

$$\eta \approx \mathbf{9.77\%}$$

9. Estimate the increase in power with which the battery could be charge if maximum power point tracking were used, rather than the direct energy transfer approach used in this experiment.

- **Coincidently, Battery direct energy transfer on this measurement (10.53W) is closed to the Power Peak which is around 11W, once SEPIC converter is installed in between it will ensure average 11W power delivery.**

PV Panel Equivalent Circuit Model

10. Sketch the equivalent circuit model you developed for your PV panel, and give numerical values for the four cell parameters: gain k_i of current source modeling solar irradiance, diode I_{D0}, shunt resistance R_p, series resistance R_s.

- For k_i

$$I_0 = k_i(irradiance)$$

Assuming $I_0 = I_{sc} = 0.7089A$
Assuming irradiance at the moment of measurement is $1000W/m^2$

$$0.7089 = k_i(1000)$$
$$k_i = \mathbf{708.9 \times 10^{-6}}$$

- For I_{D0}

$$I_D = I_{D0}(e^{\lambda V_D} - 1)$$

When Open Circuit, all I_0 generate goes into Diode Current I_D,
For Individual cell $V_D = V_{oc}/36 = 20.5260/36 = 0.570$
$\lambda = (26mV)^{-1}$

$$I_{D0} = \frac{I_{sc}}{(e^{\lambda V_D} - 1)} = \frac{0.7089}{(e^{\frac{0.57}{0.026}} - 1)} = \mathbf{213.557 \times 10^{-12}}$$

- For R_s (per cell)

R_s can be estimated by taking the 1/slope of V_{oc} side:

$$R_s \approx \left| \frac{\frac{V_{oc} - V_{(\text{Load}=60\Omega)}}{36}}{I_{oc} - I_{(\text{Load}=60\Omega)}} \right| \approx \left| \frac{\frac{20.526 - 18.906}{36}}{0 - 0.3174} \right| \approx \mathbf{0.14\Omega}$$

- For R_p (per cell)

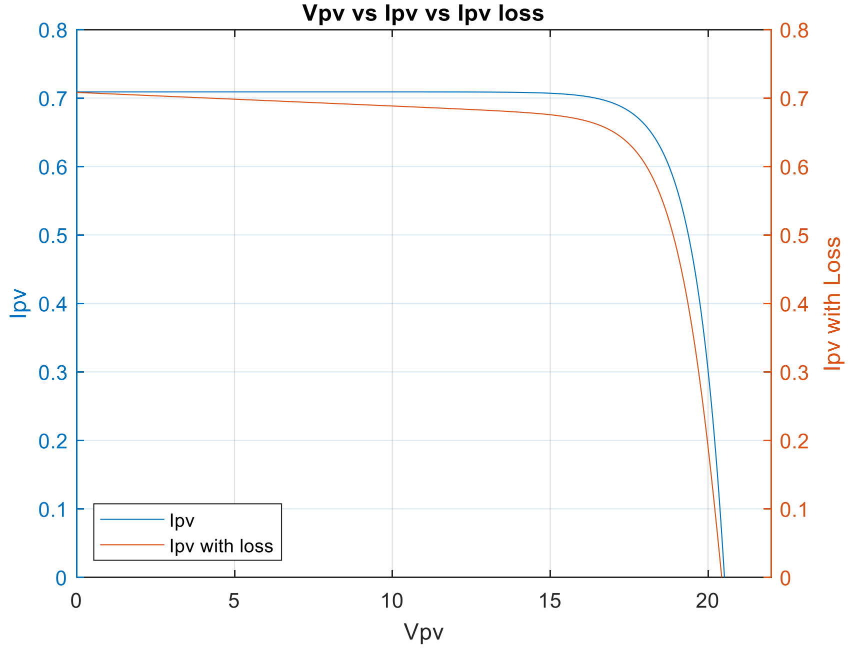
R_p can be obtained by taking the 1/slope of I_{sc} side:

$$R_p \approx \left| \frac{\frac{V_{(\text{Load}=15\Omega)} - V_{sc}}{36}}{I_{(\text{Load}=15\Omega)} - I_{sc}} \right| \approx \left| \frac{\frac{10.322 - 0}{36}}{0.6884 - 0.7089} \right| \approx \mathbf{14\Omega}$$

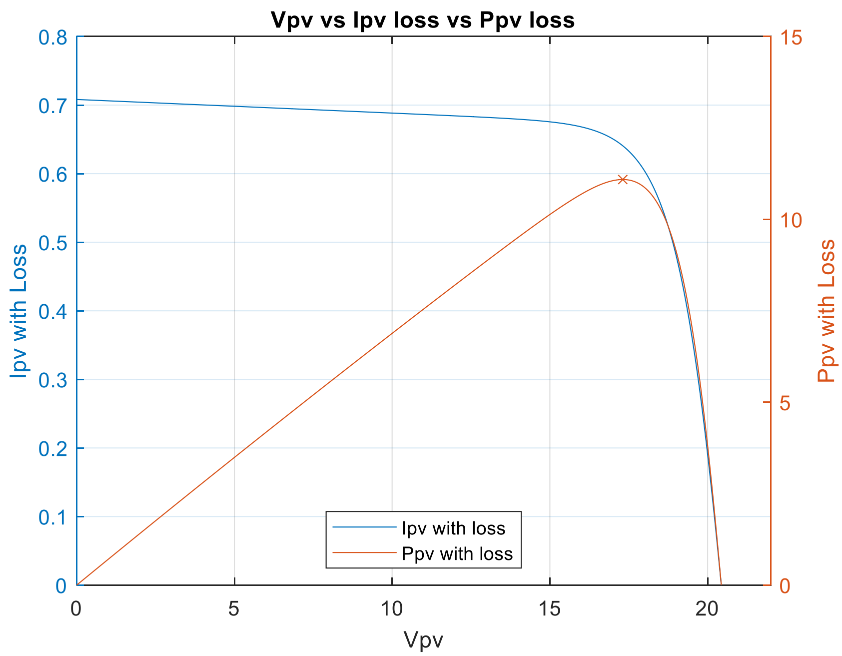
Exact formula:

$$I_{cell} = I_0 - I_{D0}\left(e^{\lambda(V_{cell} + I_{cell}R_s)} - 1\right) - \left(\frac{V_{cell} + I_{cell}R_s}{R_p}\right)$$

11. Provide a screen capture of your simulation model (LTspice or MATLAB) and its I_{pv} vs. V_{pv} plot for your PV panel at a solar irradiance of 1000W/m^2.

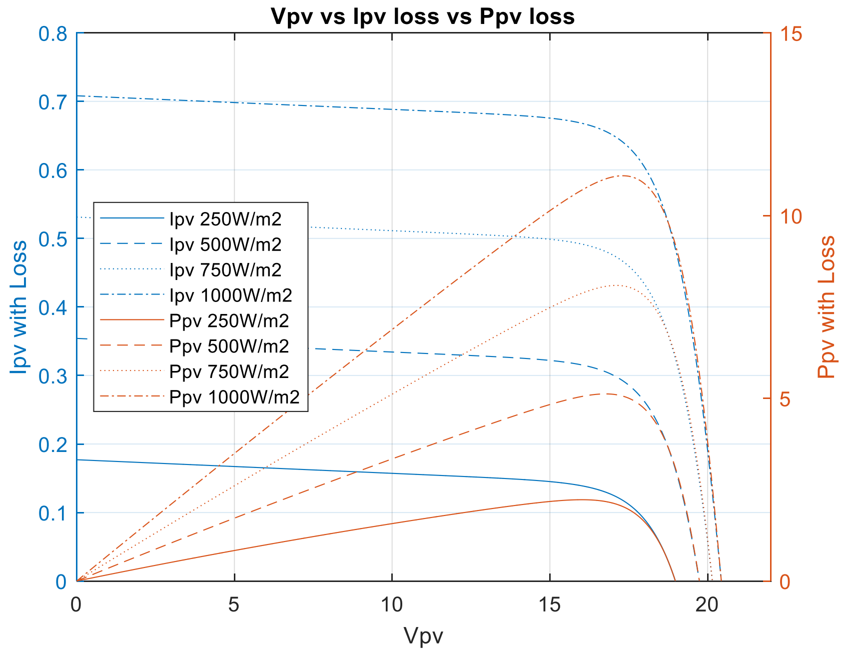


12. What values of I_{sc}; V_{oc}, and P_{mp} does your simulation model predict? Compare with the data sheet specifications, and briefly discuss any discrepancies.



I_{sc} = 0.7089A
V_{oc} = 20.5208V
P_{mp} = 11.0889W at 17.31V
Slope is close to what monitored, P_{mp} is close to what datasheet provided (17W), there are slight variance on V_{oc} Due to imperfect model.

13. Using your simulation model, predict the I_{pv} vs. V_{pv} characteristics of your panel for solar irradiances of 250W/m^2, 500W/m^2, 750W/m^2, and 1000W/m^2. Overlay these plots on the same graph.



Preliminary Converter Specification

14. Specify converter input range: voltage and current.

$$V_{inmax} = V_{ocmax} \times 1.2 = 21.6 \times 1.2 = 25.92 \approx \boldsymbol{26V}$$
$$I_{inmax} = I_{scmax} \times 1.2 = 0.73 \times 1.2 = 0.876 \approx \boldsymbol{0.9A}$$

- Input Voltage Range ≈ **10V - 26V**
- Input Current Ragne ≈ **0A – 1A**

15. Specify converter output range: voltage and current.

Assuming we can get close to 100% efficiency from Solar Panel and neglect losses of Converter, Total Output ≈ 10W

- Max Output Voltage to achieve 100% SOC of Battery ≈ **13.5V**
- Max Output Current ≈ 10W / 13.5V ≈ 0.741A ≈ **0.8A**

16. Preliminary choice of converter switching frequency.

- $\boldsymbol{f_s} = \boldsymbol{250kHz}$

17. Preliminary estimate of converter peak efficiency for V_{pv} = 17V, V_{batt} = 12V, and 0 ≤ P_{pv} ≤ 10W.

- $\boldsymbol{Estimated\ Efficiency} \approx \mathbf{90\%}$

18. Brief explanation of approach for preventing reverse power flow.

- Based on the Circuit of SEPIC converter, **Diode D_1 inherently prevent reverse power flow.**