Fundamentals of Renewable Energy and Solar Photovoltaics

ELEC2005 Electrical and Electronic Systems - Week 11

Dr. Leonardo Callegaro

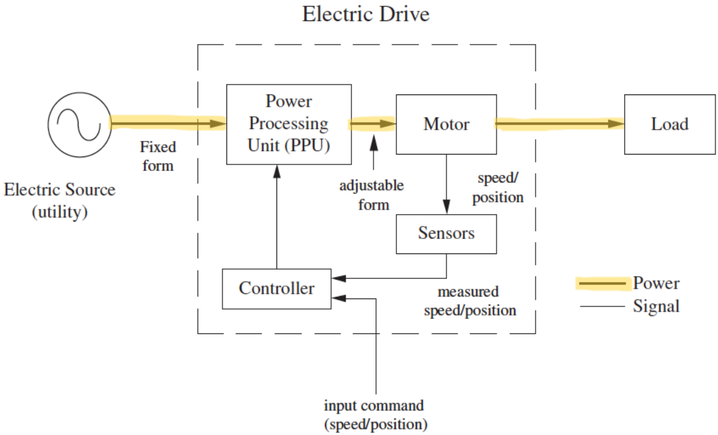
School of Engineering
Faculty of Science and Engineering

MACQUARIE University

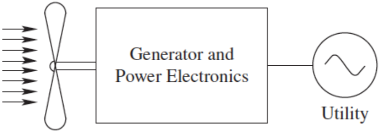
Table of Contents

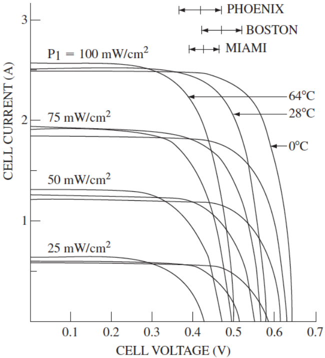
Introduction

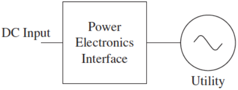
- Electric and electronics systems are fundamentals in renewable energy, residential, commercial, transportation and industrial applications
- Variable speed drives, are used to change the speed of electric motors, in HVAC, industry, wind power, electric transportation applications



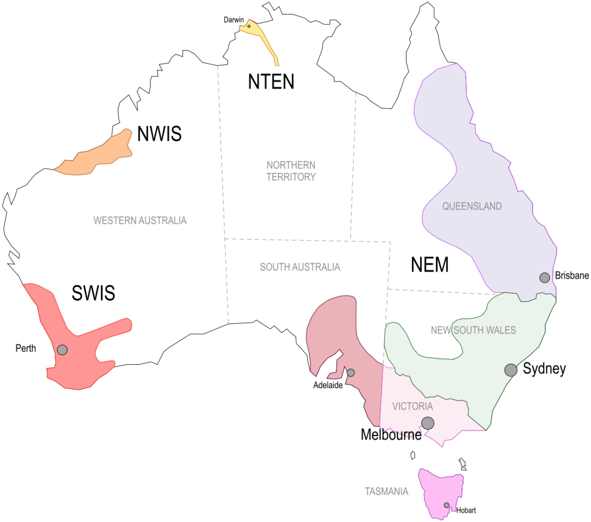
Renewable energy applications: wind and solar







Energy Markets in Australia

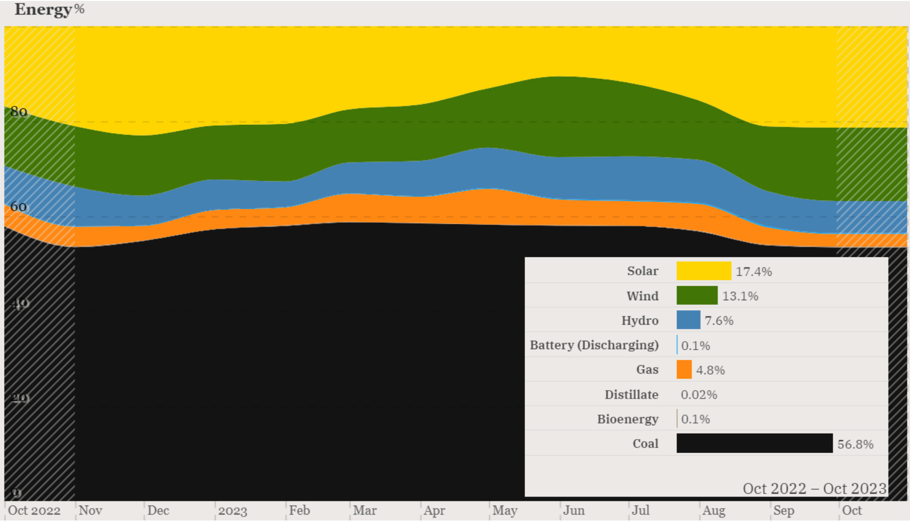


- Adjacent coloured areas are electrically interconnected
- Tasmania in connected to Victoria via an undersea dc cable
- Biggest electricity market are NEM (QLD, NSW, VIC, SA, TAS) and SWIS (WA)

figure source - Palmer G., "An input-output based net-energy assessment of an electricity supply industry", *Energy*, Vol. 141, 2017, pp. 1504-1516

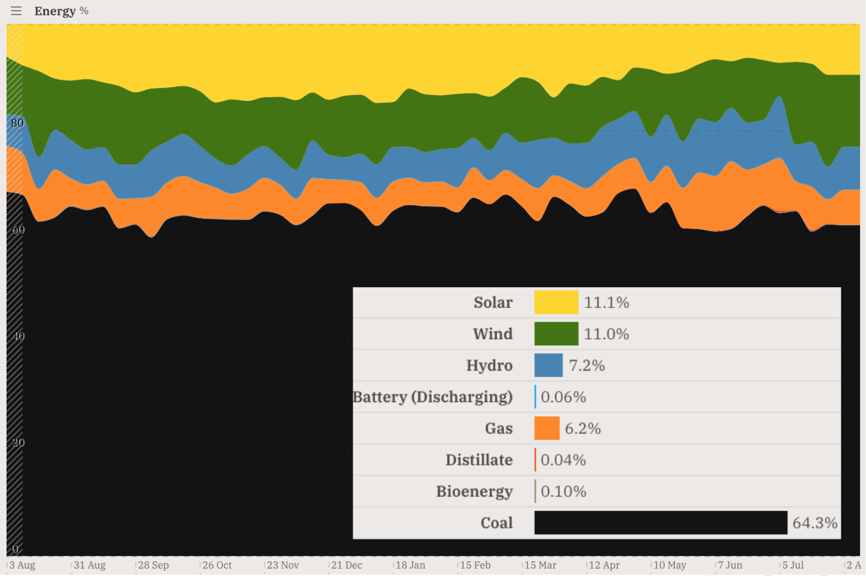
NEM (Eastern Australia) electricity generation

Oct 2022-Oct 2023 (source: opennem.org.au)



NEM (Eastern Australia) electricity generation

Aug 2020-Aug 2021



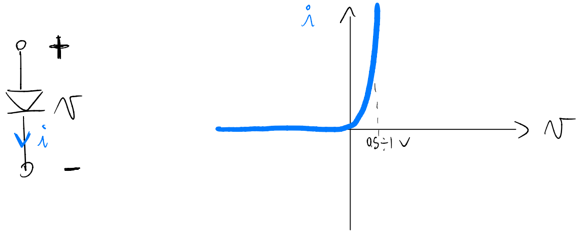
- Renewables (Wind, Solar, Hydro) contributed to more than 35% of all electricity generated in Australia (NEM system, Oct 2022-23)
- Proportion electricity generated from renewables is set to increase steeply
- Australian Energy Market Operator declared to be working on a grid capable to handle 100% renewable energy penetration by 2025[1]
- In this scenario *solar photovoltaic (PV) energy* is going to be one of the major sources of electricity in Australia

[1] source: www.pv-magazine-australia.com, July 2021

1. Renewable energy
2. Photovoltaic energy fundamentals
   - Solar cell basics
   - PV cells, modules, arrays
   - PV cell detailed equivalent circuit
   - Impact of partial shading
   - Function of bypass diodes and blocking diodes
3. Peak power operation and efficiency
4. PV power conversion system

Solar cell fundamentals

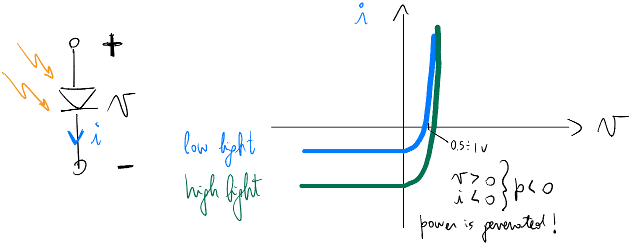
Photovoltaic cells energy conversion: `https://youtu.be/xKxrkht7CpY`



$$i = I_0(e^x - 1)$$

note that $x \propto v$

($\propto$: "is proportional to")

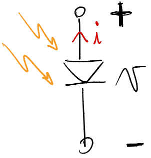


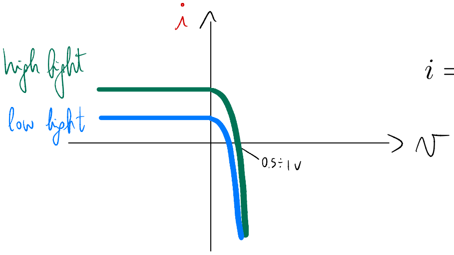
$$i = I_0(e^x - 1) - \underbrace{\text{const.}}_{I_{sc}}$$

Note that, in these figures, the *load* convention is used

Solar cell basic equivalent circuit

Using the *generator* convention

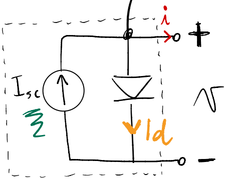


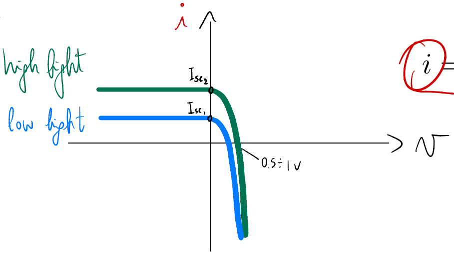


$$i = -I_0(e^x - 1) + I_{sc}$$

KCL $+I_{sc} - I_d - i = 0$

$i = I_{sc} - I_d$

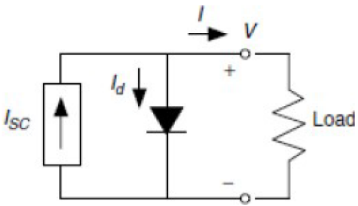


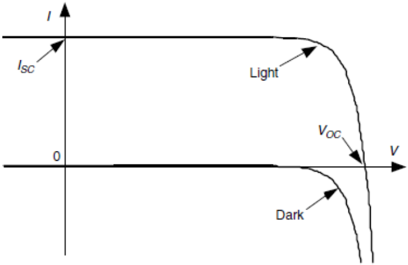


$$i = I_{sc} - \overbrace{I_0(e^x - 1)}^{I_d}$$

Solar cell equations

Simple current generator with anti-parallel diode model





$$I = I_{\rm sc} - I_{\rm d}$$

$$\boxed{I = I_{\rm sc} - I_0 \left(e^{\frac{q\,V}{k\,T}} - 1 \right)}$$

$q = 1.6022 \times 10^{-19}$ C: electron charge

$k = 1.38 \times 10^{-23}$ J/K: Boltzmann const

$V_T = \dfrac{k\,T}{q}$ V: thermal voltage

T : temperature, in K

at $25\,°$C
($T = 273.15 + 25 = 298.15\,$K)

$$\boxed{I = I_{\rm sc} - I_0 \left(e^{38.9\,V} - 1 \right)}$$

Solar cell equations (cont'd)

Simple current generator with anti-parallel diode model

$$I = I_{sc} - I_0 \left(e^{\frac{q\,V}{k\,T}} - 1 \right)$$

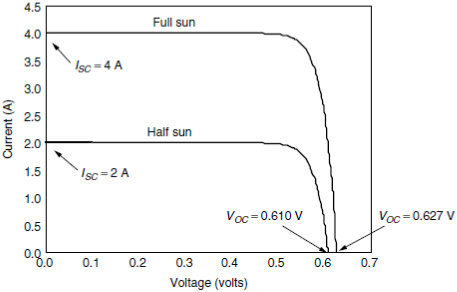
for $I = 0$, $V = V_{oc}$

$$\boxed{V_{oc} = \frac{k\,T}{q} \ln \left(\frac{I_{sc}}{I_0} + 1 \right)}$$

at $25\,^\circ$C, for $I = 0$

$$0 = I_{sc} - I_0 \left(e^{38.9\,V_{oc}} - 1 \right)$$

$$\boxed{V_{oc} = 0.0257 \ln \left(\frac{I_{sc}}{I_0} + 1 \right)}$$

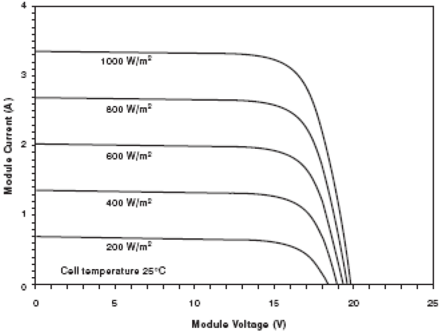


- I_{sc} varies proportionally with irradiation
- V_{oc} varies logarithmically with irradiation (i.e. does not change that much)

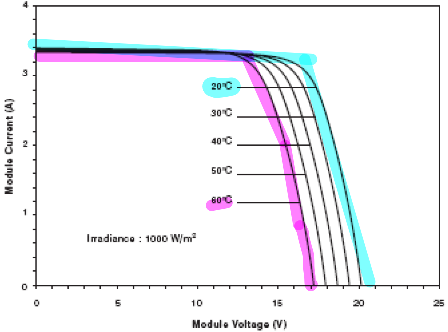
Impact of solar irradiance and temperature

Note: the area under the *i-v* curve is the power generated

irradiation change



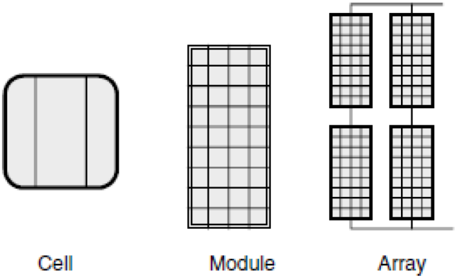
temperature change



higher irradiation $\rightarrow$ *higher* power

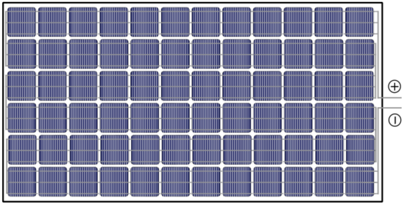
higher temperature $\rightarrow$ *lower* power

From cells, to module, to arrays



Typical indicative values

- cell: $0.6\,\mathrm{V}$ $5\,\mathrm{A}$
- module: $30\,\mathrm{V}$ $5\,\mathrm{A}$
- array: $400\,\mathrm{V}$ $10\,\mathrm{A}$

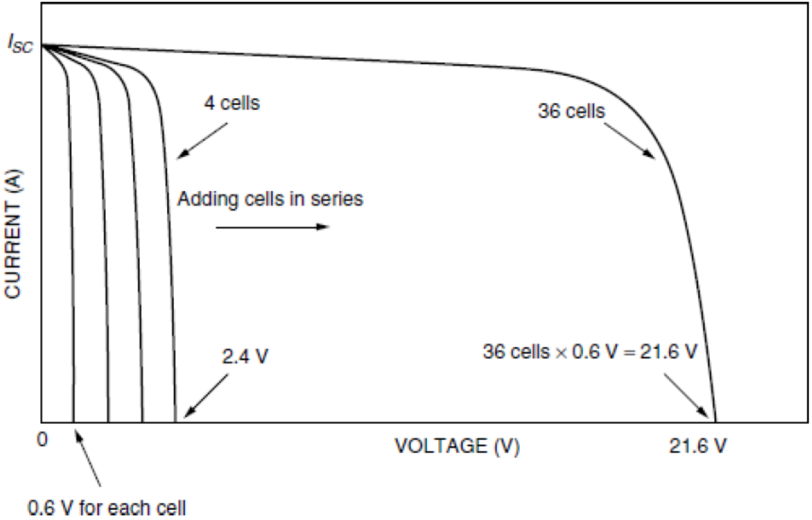


Cells	P_{MAX}	V_{MPP}	I_{MPP}	V_{OC}	I_{SC}	Efficiency
72	340 Wp	37.9 V	8.97 A	47.3 V	9.35 A	17.5%
60	280 Wp	31.4 V	8.91 A	39.3 V	9.38 A	17.1%
36	170 Wp	19.2 V	8.85 A	23.4 V	9.35 A	17%

source: www.pveducation.org

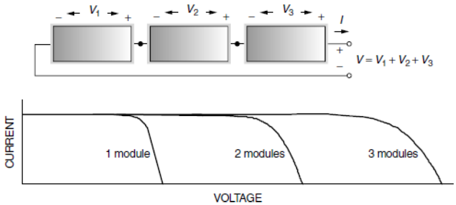
i-v characteristic of series/parallel connected cells

Series connections of PV cells:

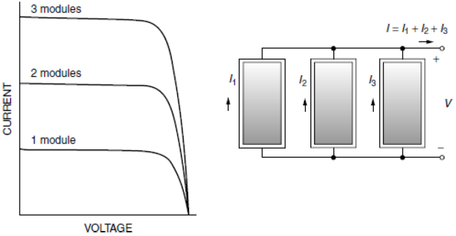


i-v characteristic of series/parallel connected modules

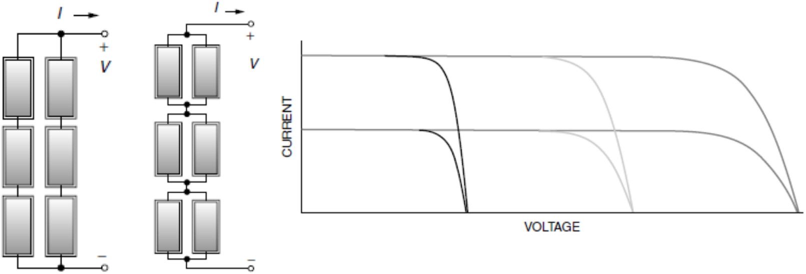
series: v add $\forall\ i$



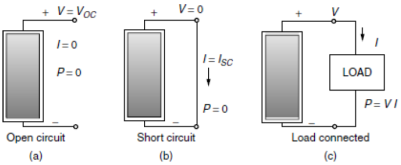
parallel: i add $\forall\ v$



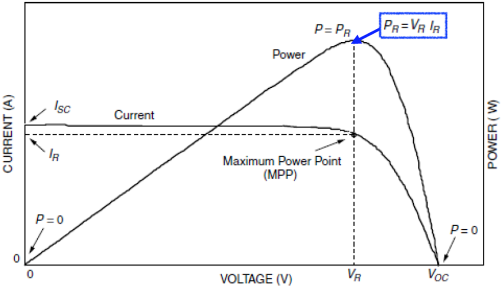
series/parallel v add in series, i add in parallel



p-v and i-v curve: power delivered by a PV module

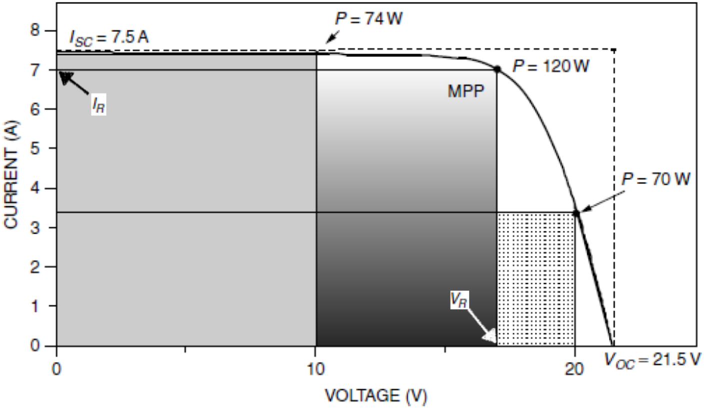


at open-circuit (a) and short-circuit (b) the PV module delivers no power



The PV module delivers the maximum power only at one operating point (MPP) $V = V_{\mathrm{R}}$, $I = I_{\mathrm{R}}$

Fill factor



$$FF = \frac{V_R I_R}{V_{oc} I_{sc}} = \frac{120}{21.5 * 7.5} = 0.74$$

(in this example)

- FF is the ratio between the maximum area fitting under the i-v curve and the $V_{oc}I_{sc}$ area
- $FF = 70 - 75\%$ for cristalline Silicon (cSi) $FF = 50 - 60\%$ for amorphous and multicristalline Silicon PV modules

Typical PV module specifications

Manufacturer	Kyocera	Sharp	BP	Uni-Solar	Shell
Model	KC-120-1	NE-Q5E2U	2150S	US-64	ST40
Material	Multicrystal	Polycrystal	Monocrystal	Triple junction a-Si	CIS-thin film
Number of cells n	36	72	72		42
Rated Power $P_{DC,STC}$ (W)	120	165	150	64	40
Voltage at max power (V)	16.9	34.6	34	16.5	16.6
Current at rated power (A)	7.1	4.77	4.45	3.88	2.41
Open-circuit voltage V_{OC} (V)	21.5	43.1	42.8	23.8	23.3
Short-circuit current I_{SC} (A)	7.45	5.46	4.75	4.80	2.68
Length (mm/in.)	1425/56.1	1575/62.05	1587/62.5	1366/53.78	1293/50.9
Width (mm/in.)	652/25.7	826/32.44	790/31.1	741/29.18	329/12.9
Depth (mm/in.)	52/2.0	46/1.81	50/1.97	31.8/1.25	54/2.1
Weight (kg/lb)	11.9/26.3	17/37.5	15.4/34	9.2/20.2	14.8/32.6
Module efficiency	12.9%	12.7%	12.0%	6.3%	9.4%

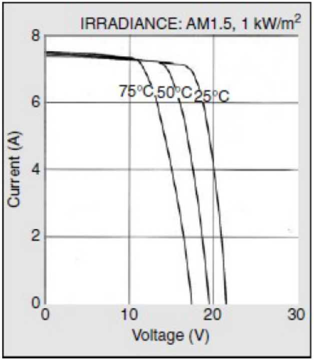
Specs at Standard Test Conditions (STC):

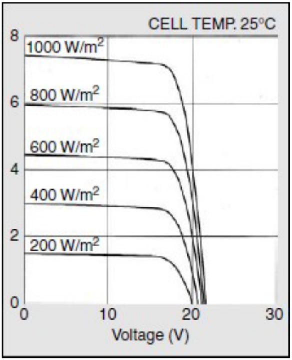
- Cell temp. $25\,^{\circ}\mathrm{C}$
- Solar irradiation $1000\,\frac{\mathrm{W}}{\mathrm{m}^2}$
- Air mass 1.5 (relates to sunlight inclination)

- Rated power is the power at MPP
- Today's commercial PV modules have efficiencies $\eta \approx 20\,\%$
- Area A $[\mathrm{m}^2]$ $\rightarrow$ number of hours n_h at $1\,\frac{\mathrm{kW}}{\mathrm{m}^2}$ $\rightarrow P_\mathrm{Sun} = A \times n_\mathrm{h}$ [kW]
- $P_\mathrm{pv} = P_\mathrm{Sun} \times \frac{\eta}{100}$ [kW] $\rightarrow$ num. of PV modules $= P_\mathrm{pv}/P_\mathrm{module}$

PV module data

Typical curves found in a PV module datasheet ($120\,\mathrm{W}$ Kyocera KC120-1)



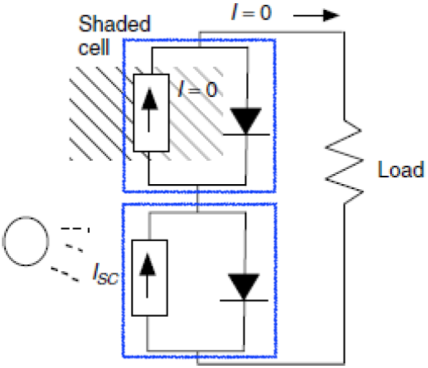


- curves at different irradiance & cell temperature
- cell temperature not to be confused with ambient temperature
- NOCT (datasheet) cell temperature at $T_{\mathrm{amb}} = 20\,°\mathrm{C}$ and $S = 0.8\,\frac{\mathrm{kW}}{\mathrm{m}^2}$

$$T_{\mathrm{cell}}[°\mathrm{C}] = T_{\mathrm{amb}} + \left(\frac{NOCT - 20\,°\mathrm{C}}{0.8}\right) S, \qquad S \text{ in } \frac{\mathrm{kW}}{\mathrm{m}^2}$$

PV cell/module detailed equivalent circuit

Consider the ideal single diode model for each cell, and two cells connected in series, where one is partially shaded.



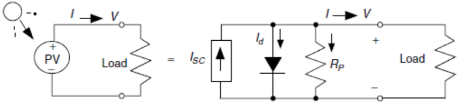
According to the diagram using ideal PV cell equivalent

- the shaded cell produces no current
- the shaded cell is a reverse biased diode, blocking the flow of current to the load
- the load current is null, $I = 0$

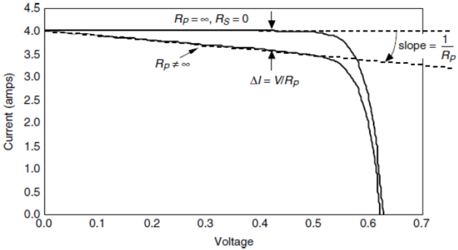
With non-uniform irradiation:

a more detailed model is needed to explain what happens in practice, because in reality $I > 0$

Inclusion of parallel resistance R_p

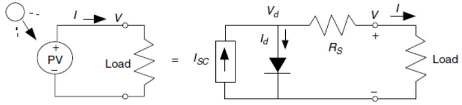


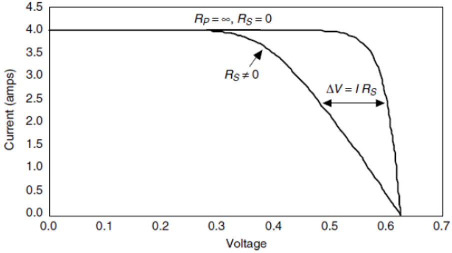
$$I = I_\mathrm{sc} - I_\mathrm{d} - \frac{V}{R_\mathrm{p}}$$



- the higher the voltage V, the higher the current though R_p (less current goes to the load)
- this "current drop" (decrease in load current) as the load voltage rises is represented by an horizontal slope in the *i*-*v* curve
- for a large cell, typical $V_\mathrm{oc} = 0.6\,\mathrm{V}$, $I_\mathrm{sc} = 7\,\mathrm{A}$, $R_\mathrm{p} = 9\,\Omega$

Inclusion of series resistance R_s (assuming $R_\mathrm{p} = \infty$)

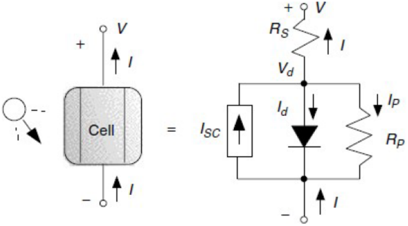




$$I = I_\mathrm{sc} - I_\mathrm{d} = I_\mathrm{sc} - I_0\left(e^{\frac{q\,V_\mathrm{d}}{k\,T}} - 1\right)$$
$$= I_\mathrm{sc} - I_0\left(e^{\frac{q\,(V + R_\mathrm{s} I)}{k\,T}} - 1\right)$$

- the higher the load current, I, the higher the voltage drop, ΔV, on R_s
- this voltage drop as the current rises is represented by a vertical slope in the *i*-*v* curve
- for a large cell, typical $V_\mathrm{oc} = 0.6\,\mathrm{V}$, $I_\mathrm{sc} = 7\,\mathrm{A}$, $R_\mathrm{s} = 1 \times 10^{-3}\,\Omega$
- inclusion of R_s causes an "algebraic loop", where the PV cell output, I, depends on itself! In fact $I = f\,(V, I)$

Inclusion of R_s and R_p: PV module i-v curve



$$I = I_{sc} - \overbrace{I_0\left(e^{\frac{q\,V_d}{k\,T}} - 1\right)}^{I_d} - \overbrace{\frac{V_d}{R_p}}^{I_p}$$

$$\boxed{= I_{sc} - I_0\left(e^{\frac{q\,(V+R_sI)}{k\,T}} - 1\right) - \frac{V + R_sI}{R_p}}$$

At $25\,°$C:

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

$$V = V_d - R_s I$$

PV module with n-cells in series:

$$V_{module} = n\left(V_d - R_s I\right)$$

Number of cells, $n = 36$

Parallel resistance/cell R_P (ohms) $= 6.6$

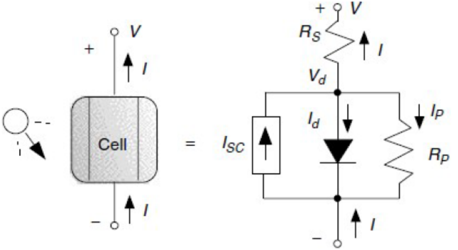
Series resistance/cell R_S (ohms) $= 0.005$

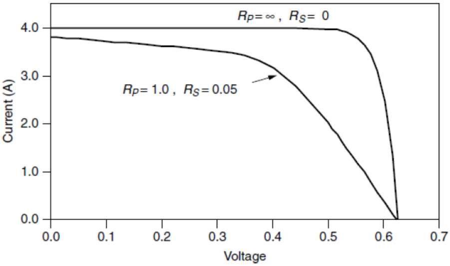
Reverse saturation current I_0 (A) $= 6.00$E-10

Short-circuit current at 1-sun (A) $= 3.4$

V_d	$I = I_{SC} - I_0\left(e^{38.9V_d} - 1\right) - \frac{V_d}{R_p}$	$V_{module} = n(V_d - I R_S)$	P (watts) $= V_{module} I$
0.49	3.21	17.06	54.80
0.50	3.16	17.43	55.02
0.51	3.07	17.81	54.75
0.52	2.96	18.19	53.76
0.53	2.78	18.58	51.65
0.54	2.52	18.99	47.89
0.55	2.14	19.41	41.59

Inclusion of R_s and R_p: PV module i-v curve

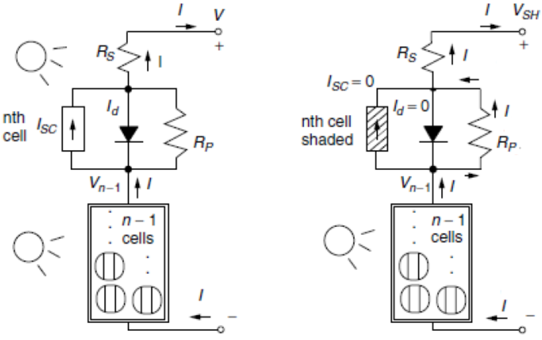




$$I = I_{sc} - I_0 \left(e^{\frac{q\,(V + R_s I)}{k\,T}} - 1 \right) - \frac{V + R_s I}{R_p}$$

- note the different curve when R_s and R_p are considered
- it is desired to have high R_p and low R_s for better performance

Impact of shading (using non-ideal PV cell circuit)



(a) All cells in the sun
(b) Top cell shaded

Fig. (a): all cells in full sun

- all PV cells produce I
- PV module voltage V

Fig. (b): one cell is shaded

- cells in full sun produce I
- shaded cell produces no current $I_{\text{sc}} = 0$
- shaded cell diode reverse biased
- PV module voltage $V_{\text{SH}} < V$

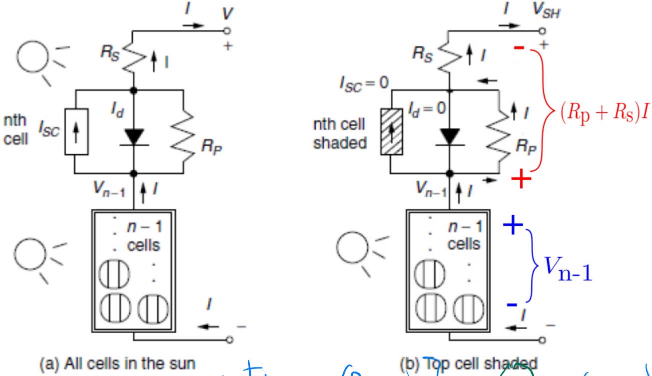
In full sun: PV module voltage is V

With one shaded cell: PV module voltage is $V_{\text{SH}} < V$

$V - V_{\text{SH}} = \Delta V$: PV module voltage reduction due to shading on one cell

Impact of shading (using non-ideal PV cell circuit)

Full sun to (one cell) shaded PV module voltage reduction ΔV



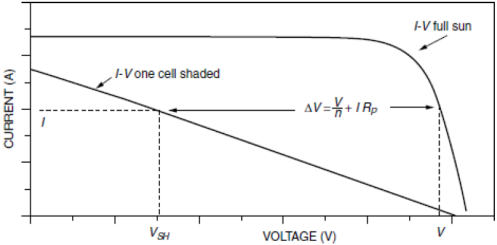
- *n-1* cells in full sun: generator $V_{n-1} = V\left(\frac{n-1}{n}\right)$
- n-th shaded cell: $R_p + R_s$ load resistor (with $R_p >> R_s$)
- shaded cell absorbs power $R_p I^2$
- shaded cell heats up/damage (hot spot) because of power absorption

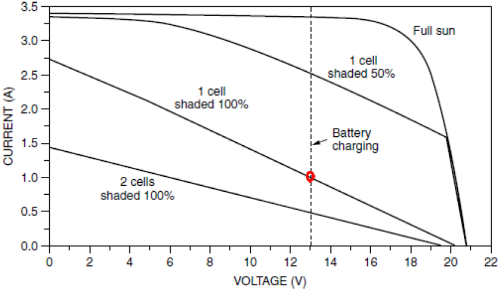
$$V - V_{SH} = V - \left[V_{n-1} - (R_p + R_s)I\right] = V - V_{n-1} + (R_p + R_s)I$$

$$\Delta V = V - V_{SH} = V - V\left(\frac{n-1}{n}\right) + (R_p + R_s)I$$

$$= \frac{V}{n} + (R_p + R_s)I \approx \frac{V}{n} + R_p I$$

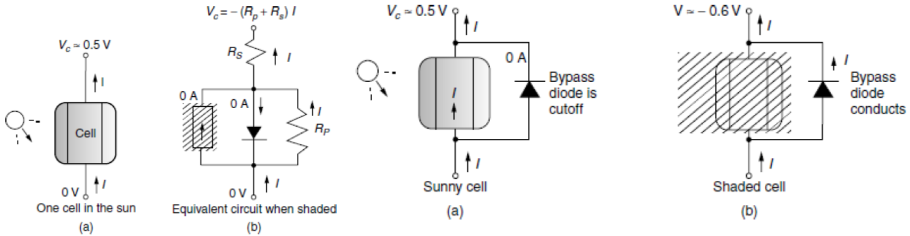
Examples of shading effects





- note large voltage drop due to shading
- shading significantly reduces available PV power

Shading effects mitigation: bypass diodes



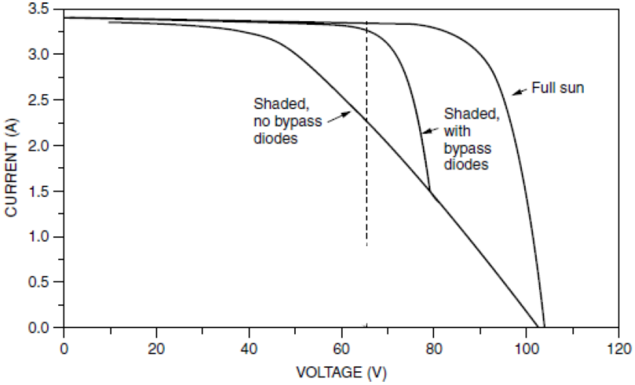
Without bypass diode:

- current flows through $R_\mathrm{p} + R_\mathrm{s}$
- shaded cell causes large voltage reduction
- shaded cell voltage $(R_\mathrm{s} + R_\mathrm{p})I$ is large

With bypass diode:

- current flow is diverted through BP-diode
- shaded cell causes small voltage reduction
- shaded cell voltage is small (typ. 0.5-1V)

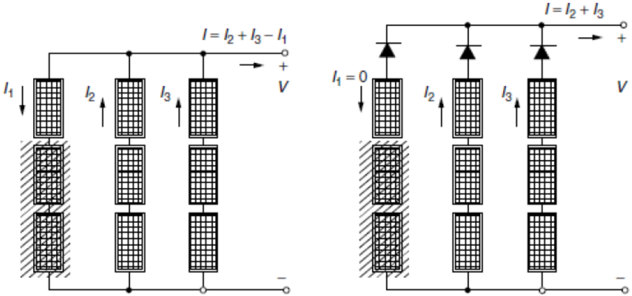
Impact of bypass diode



- it is impractical to use one bypass diode per cell in a PV module
- e.g. modules with 72 cells in series may use 3 bypass diodes (one every 24 cells)
- the graph shows the benefit of having bypass diodes inserted

Blocking diodes

Are placed at the end of each PV string to avoid current in the opposite direction in strings which have shaded PV modules



Without blocking diodes

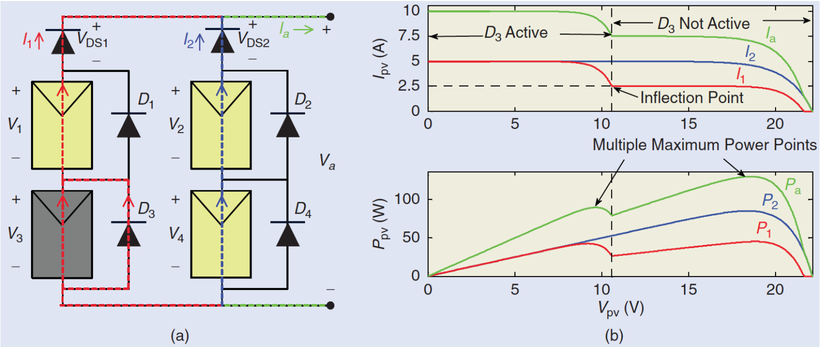
(a)

With blocking diodes

(b)

Shaded PV strings characteristic in practice

- in practice, PV strings have bypass diodes and blocking diodes
- a partially shaded PV string *i*-*v* and *p*-*v* characteristic looks like this:

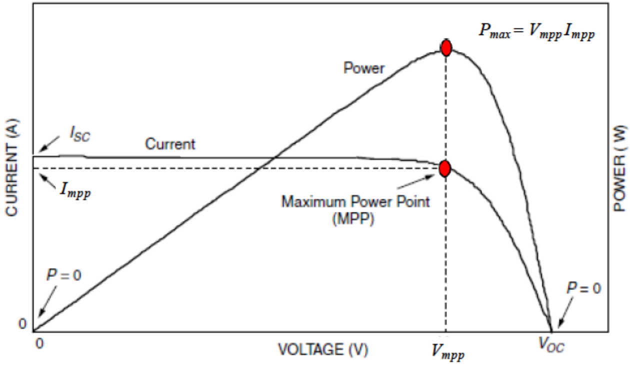


- there are multiple power peaks in the *p*-*v* curve
- special controls needed to extract maximum PV power (thesis topic)

figure from: Romero-Cadaval, E., et al. (2013). "Grid-Connected Photovoltaic Generation Plants: Components and Operation." *IEEE Industrial Electronics Magazine* 7(3): 6-20

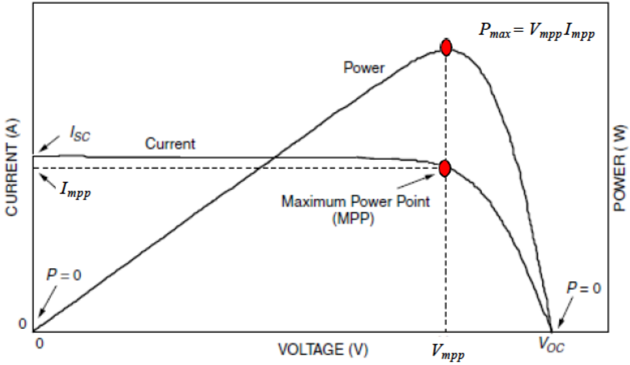
Peak power operation

- It is desirable to operate the PV array at the maximum power point



- the maximum power is extracted by the PV module as long as it operates at V_{mpp}

Efficiency

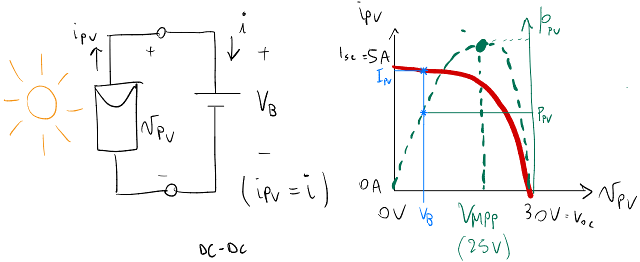


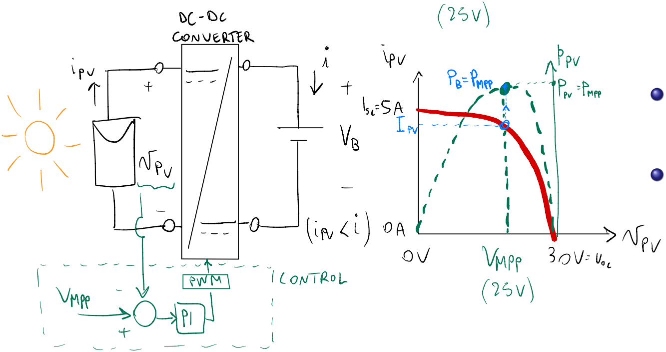
$$\eta = \frac{V_{\mathrm{mpp}} \times I_{\mathrm{mpp}}\ [\mathrm{W}]}{1000\,[\mathrm{W/m^2}] \times \text{Area}\ [\mathrm{m^2}]}, \text{typical} < 20\% \text{ for commercial modules}$$

Area of the PV module is found in the PV module datasheet

Peak power operation: what if the load does not allow it?

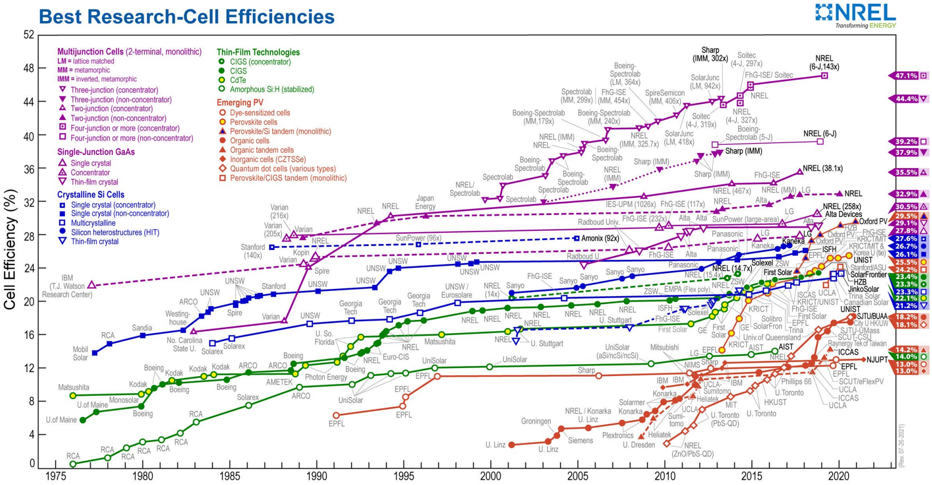
dc-dc converter with MPPT control ensures PV module works at MPP





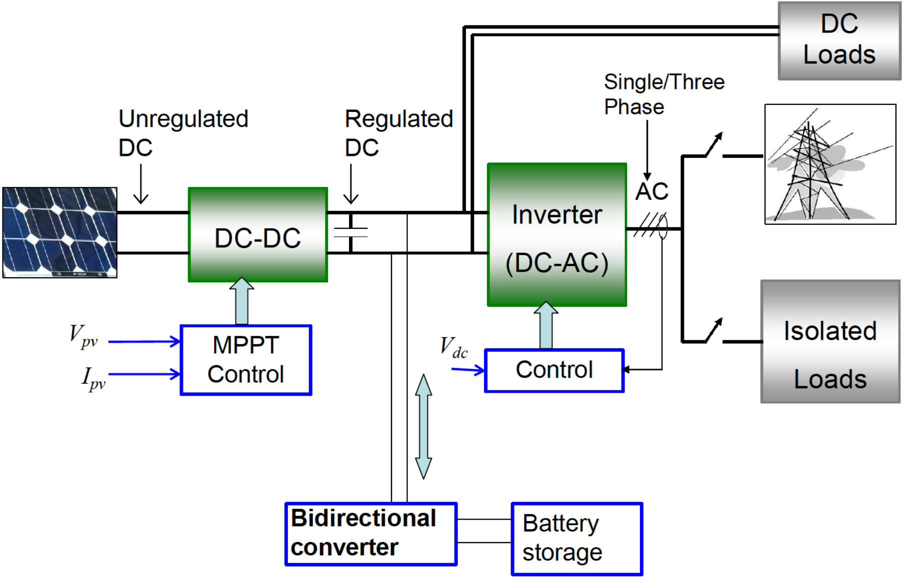
- Battery voltage V_B = PV voltage
- Low power delivered to battery $P_B < P_{mpp}$
- Battery voltage $V_B \neq$ PV voltage
- Max power delivered to battery $P_B = P_{mpp}$

PV cell efficiency progress in time



www.nrel.gov, accessed Aug. 2021

Typical PV power conversion system structure



Typical PV power conversion system components

- dc-dc converter: extracts maximum power from PV array and boosts PV string voltage to match inverter input voltage
- dc-ac converter: converts dc voltage/current into ac form (compatible with the grid)
- bidirectional converter/battery: supply load when there is no sun, and absorb power when PV power exceeds the load demand
- converters are studied in ELCT3005 Power Electronics
- PV power plants are considered in ELCT4004 Power Systems Analysis, ELCT4001 Smart Power Grids

Readings

From *Masters (2004), Renewable and Efficient Electric Power Systems*

- Chapter 8: Photovoltaic Materials and Electrical Characteristics (link)
    - 8.1: Introduction
    - 8.2: Basic Semiconductor Physics
        - 8.2.5: The p-n Junction Diode
    - 8.3: A Generic Photovoltaic Cell
        - 8.3.1: The Simplest Equivalent Circuit for a Photovoltaic Cell
        - 8.3.2: A More Accurate Equivalent Circuit for a PV Cell
    - 8.4: From Cells to Modules to Arrays
        - 8.4.1: From Cells to a Module
        - 8.4.2: From Modules to Arrays
    - 8.5: The PV I–V Curve Under Standard Test Conditions (STC)
    - 8.6: Impacts of Temperature and Insolation on I–V Curves
    - 8.7: Shading Impacts on I – V Curves
        - 8.7.1: Physics of Shading
        - 8.7.2: Bypass Diodes for Shade Mitigation
        - 8.7.3: Blocking Diodes

References

- Masters, Chapter 8: Photovoltaic Materials and Electrical Characteristics, in *Renewable and Efficient Electric Power Systems*, Wiley, 2004
- Mohan N., *Power Electronics: A First Course*, Wiley, 2011
- ELCT2005 S2 2020 lecture slides courtesy of Dr Binesh Puthen Veettil
- UNLV, Prof. Baghzouz EE 446/646 PV Devices III lecture
  - http://www.egr.unlv.edu/~eebag/Photovoltaic%20Devices%20III.pdf, accessed Aug 2021