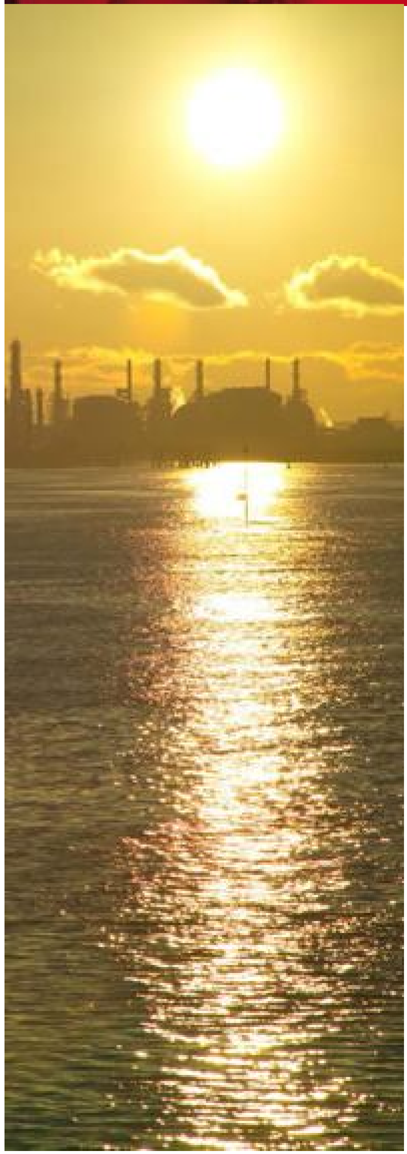


Photovoltaic Systems Engineering

Ali Karimpour

Associate Professor

Ferdowsi University of Mashhad

Reference for this lecture:

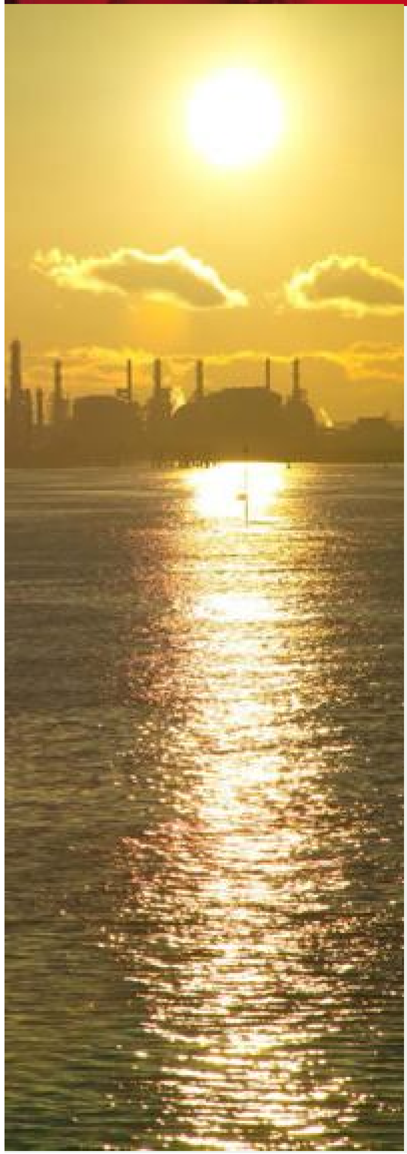
Photovoltaic Systems Engineering Third Edition CRC

Roger Messenger, Jerry Ventre

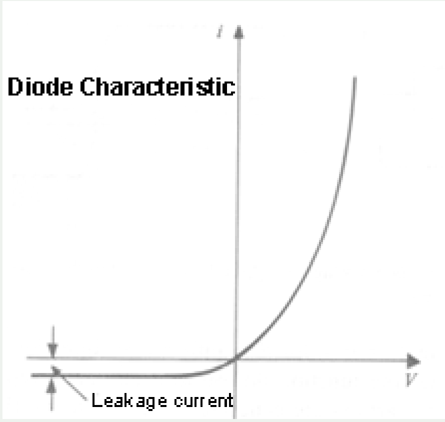
Lecture 6

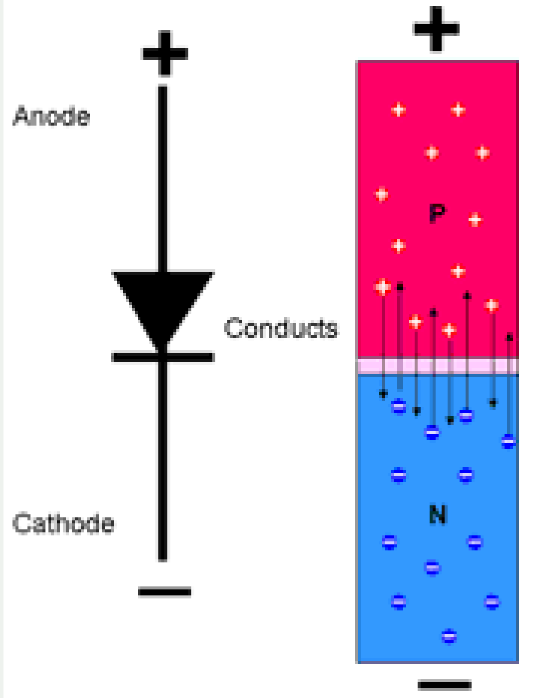
The PV Cell Model

Diode



P-N junction in forward biased





$$I_d = I_0\left(e^{\frac{qV}{kT}} - 1\right)$$

I_o is the reverse saturation current (A), V is the voltage across the diode (V)

q is the electron charge (1.602×10^{-19} C),

T is the junction temperature in *Kelvin* (K).

k is the Boltzmann's constant (1.381×10^{-23} J/K),

Solar cell

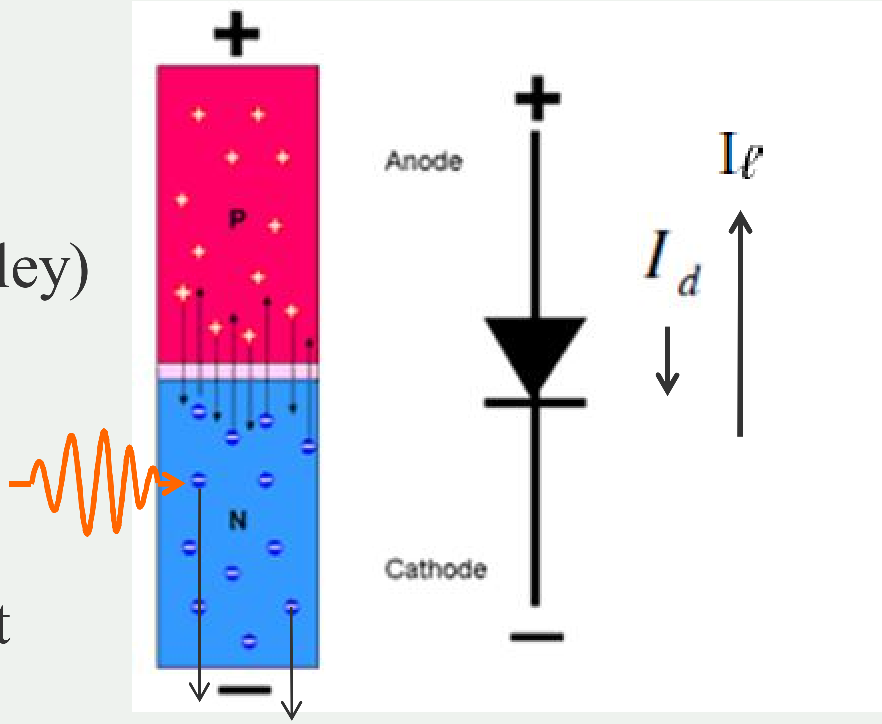
$$I_d = I_0\left(e^{\frac{qV}{kT}} - 1\right)$$

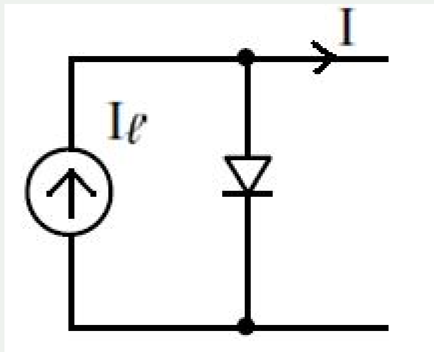
Diode current (Shockley)

$$I_l$$

Component of current due to photons

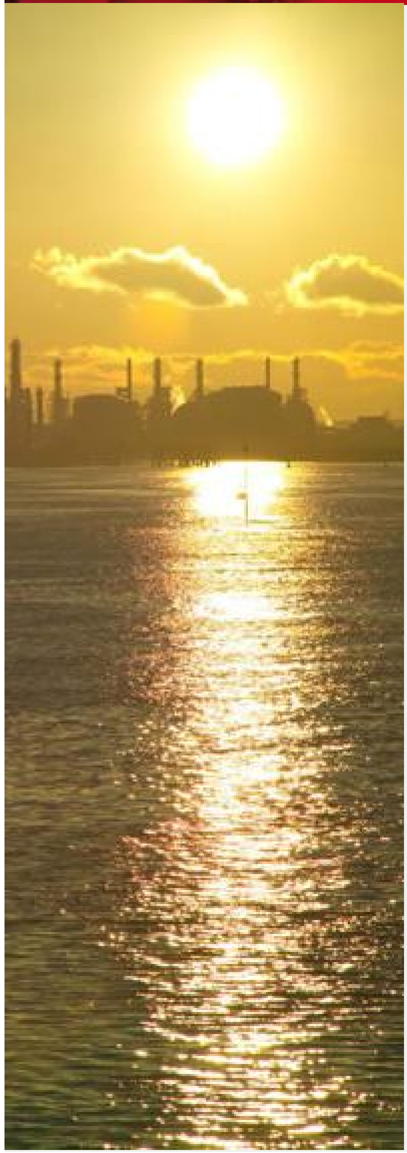
$$I = I_l - I_0\left(e^{\frac{qV}{kT}} - 1\right)$$

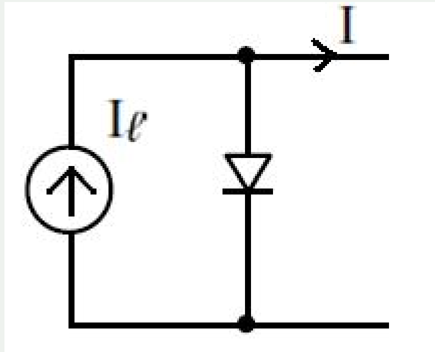


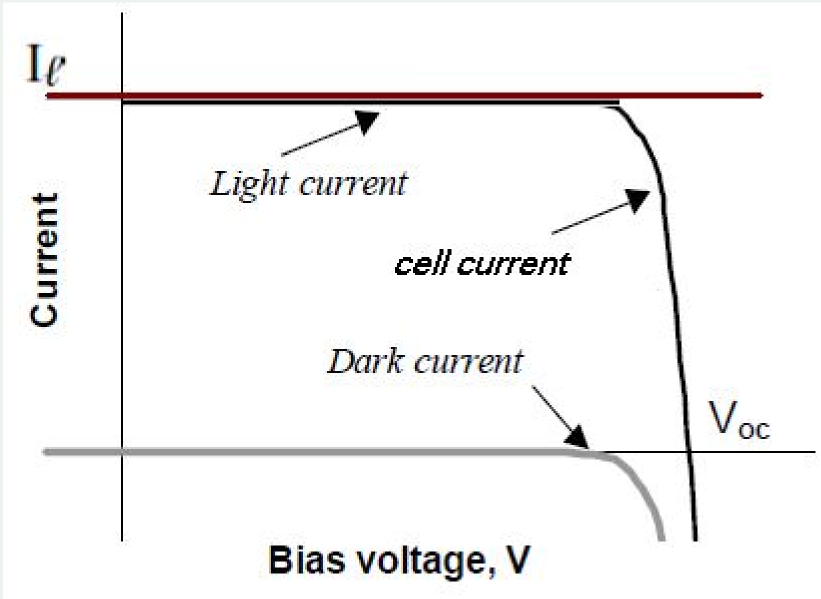


Solar cell

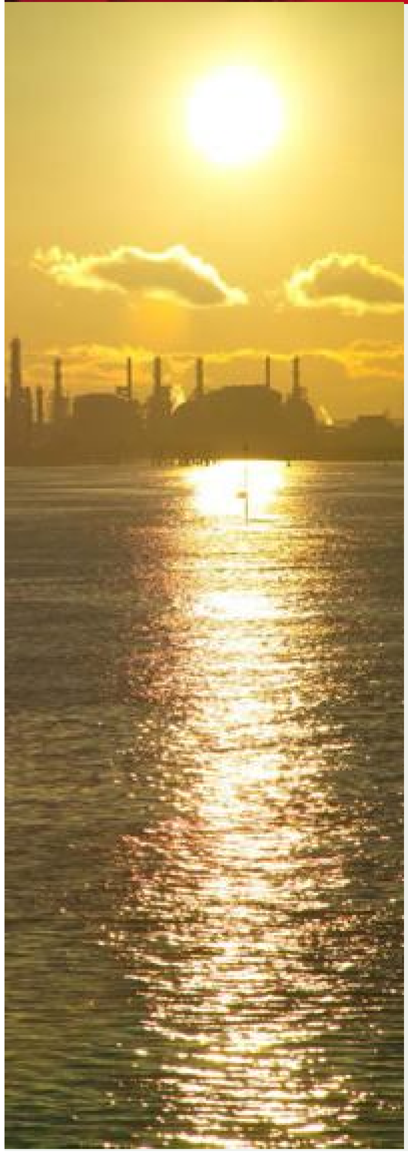
$$I = I_l - I_0\left(e^{\frac{qV}{kT}} - 1\right)$$







I-V characteristics of PV



V-I equation:

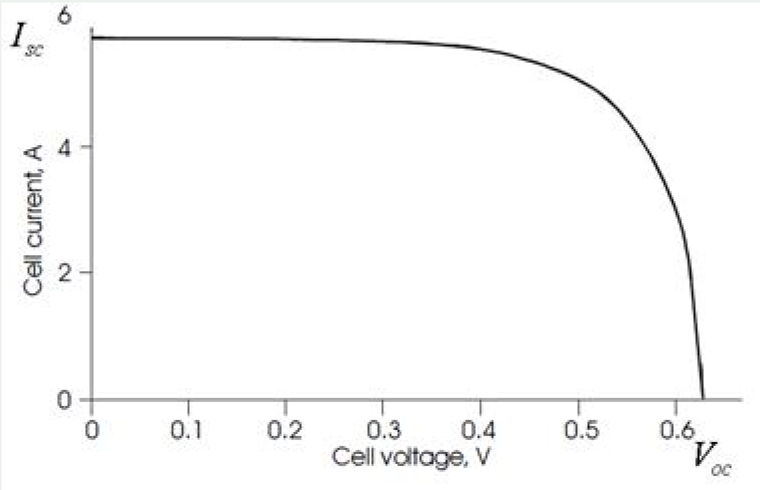
$$I = I_l - I_0\left(e^{\frac{qV}{kT}} - 1\right)$$

Open circuit voltage:

$$V_{oc} = \frac{kT}{q}\ln\frac{I_l + I_0}{I_0} \approx \frac{kT}{q}\ln\frac{I_l}{I_0}$$

Short circuit current:

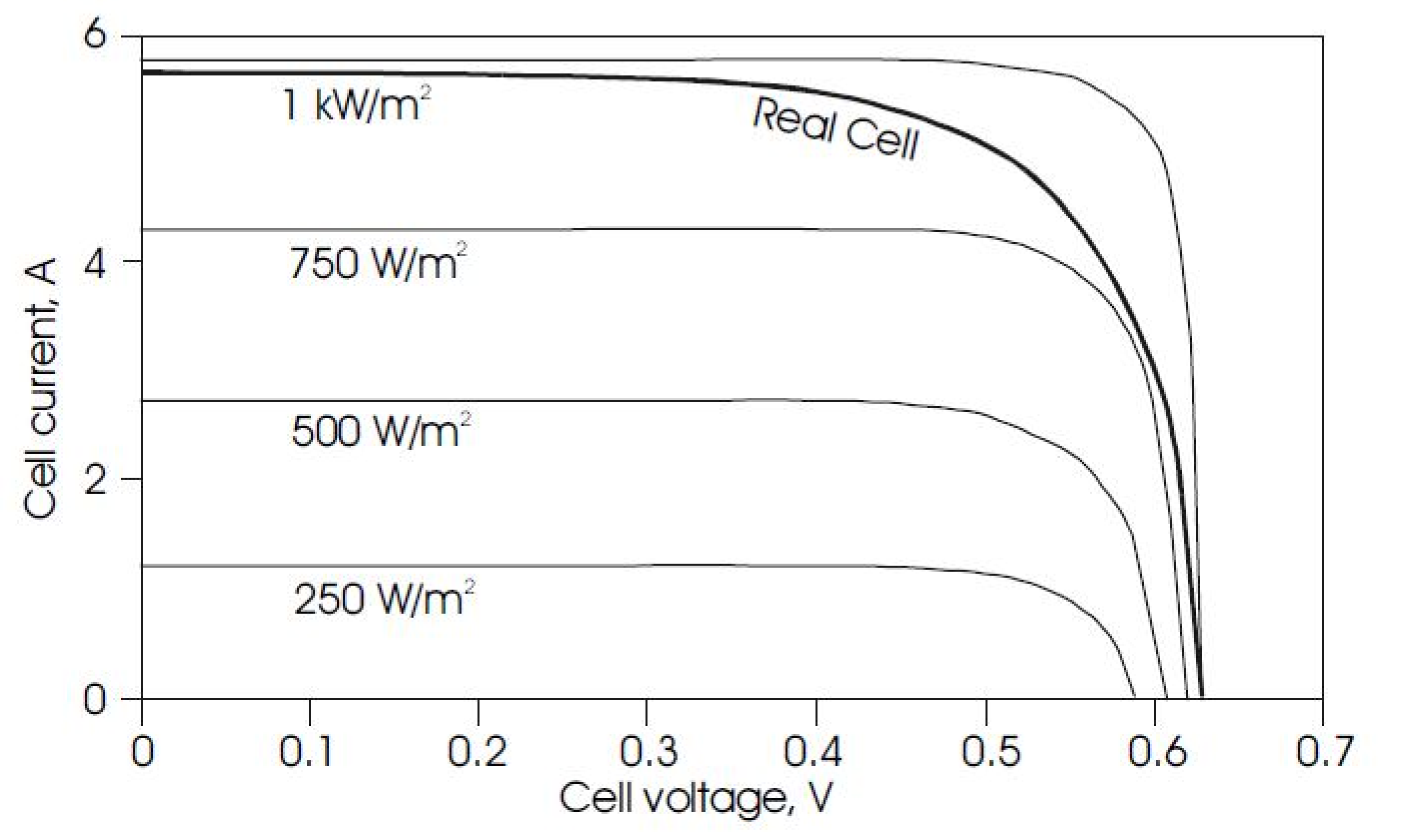
$$I_{sc} = I_l$$



I-V characteristics of PV

I-V characteristics of real and ideal PV cells under different illumination levels.

$$I_l(G) = (G / G_0) I_l(G_0),\ \ G_0 = 1\ \text{kW/m}^2 \text{ at AM}1.5$$

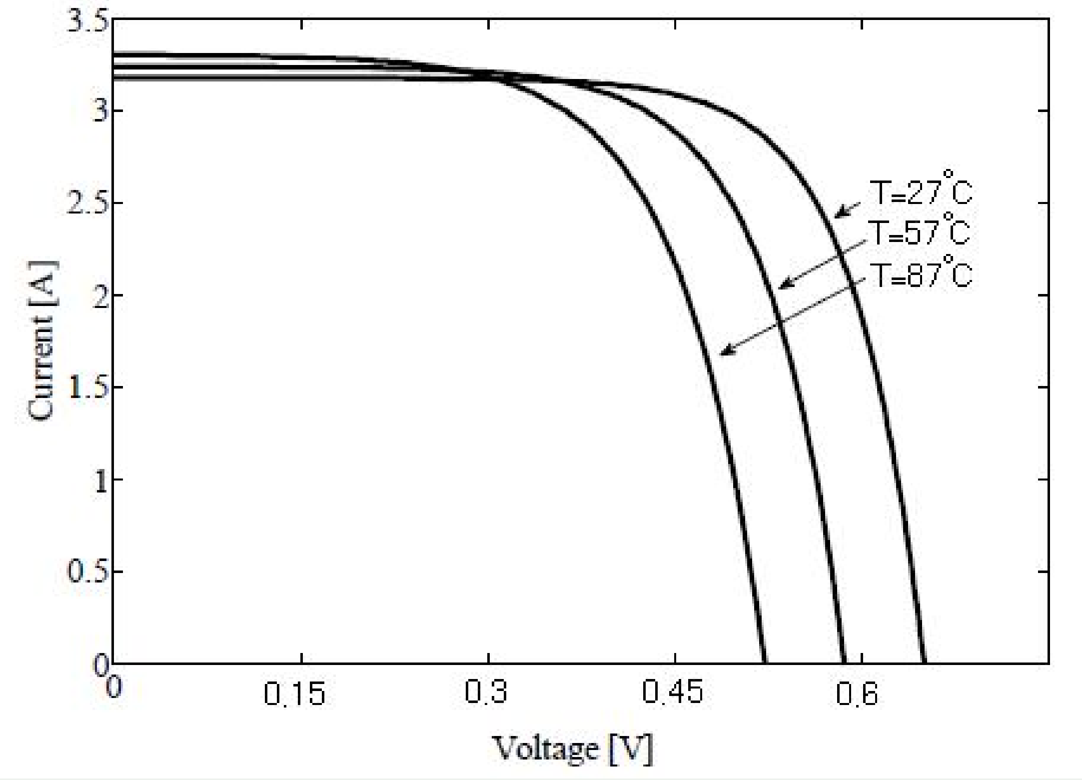


I-V characteristics of PV

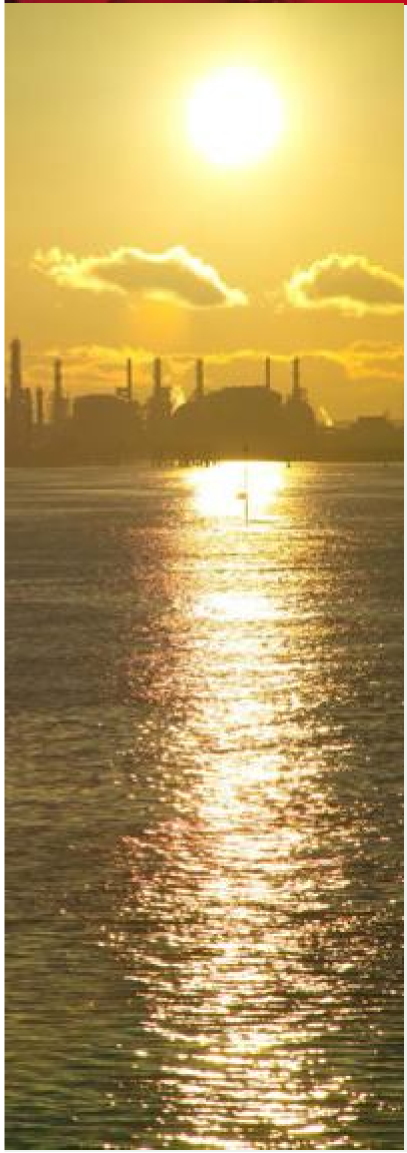
I-V characteristics of PV cells under different temperature.

V_{oc} of silicon PV cell decrease by 2.3 mV/ °C

Cell power decrease 0.5%/°C



I-V characteristics of PV



NOCT: Nominal Operating Cell Temperature

It is the cell temperature at an ambient temperature 20°C, at AM 1.5 irradiance conditions, G=0.8 kW/m^2 and a wind speed less than 1 m/s.

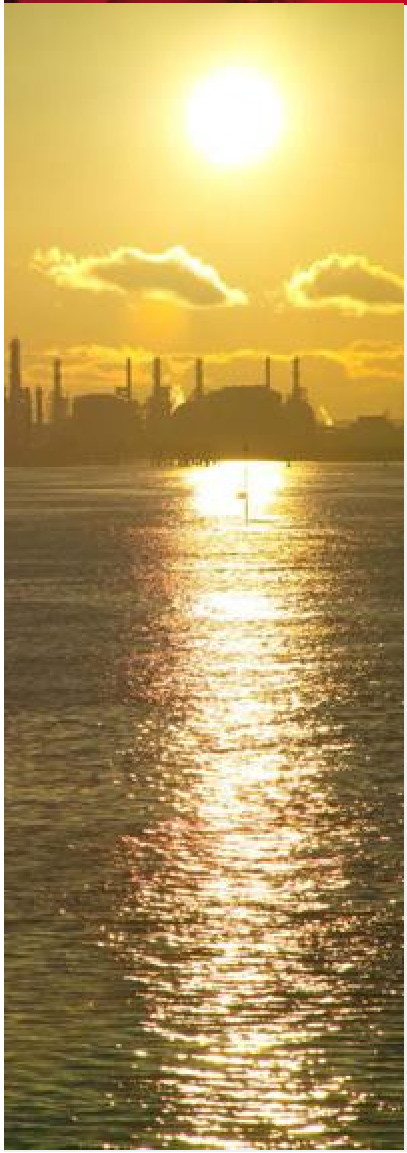
$$T_C = T_A + \left(\frac{\mathrm{NOCT} - 20}{0.8} \right) G$$

Now suppose a cell has NOCT equal to 40 to V_{oc}=19.4 (36 cell in series) and ambient temperature rises 30°C and G increases to 1 kW/m^2.

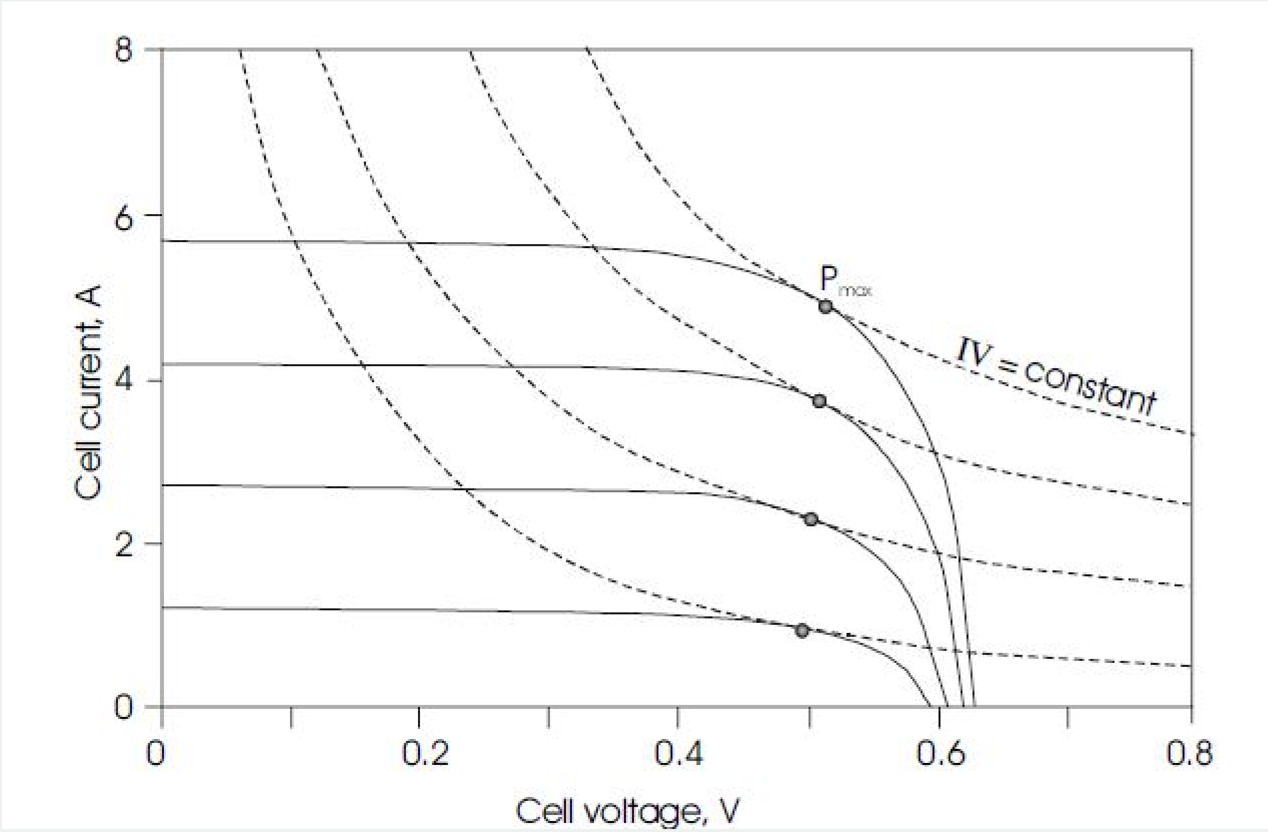
$$T_C = 30 + \left(\frac{40 - 20}{0.8} \right) 1 = 55^\circ$$

Now V_{oc}=19.4-(55-40)*36*2.3*10^{-3}=18.16 so 6% decrease.

I-V characteristics of PV

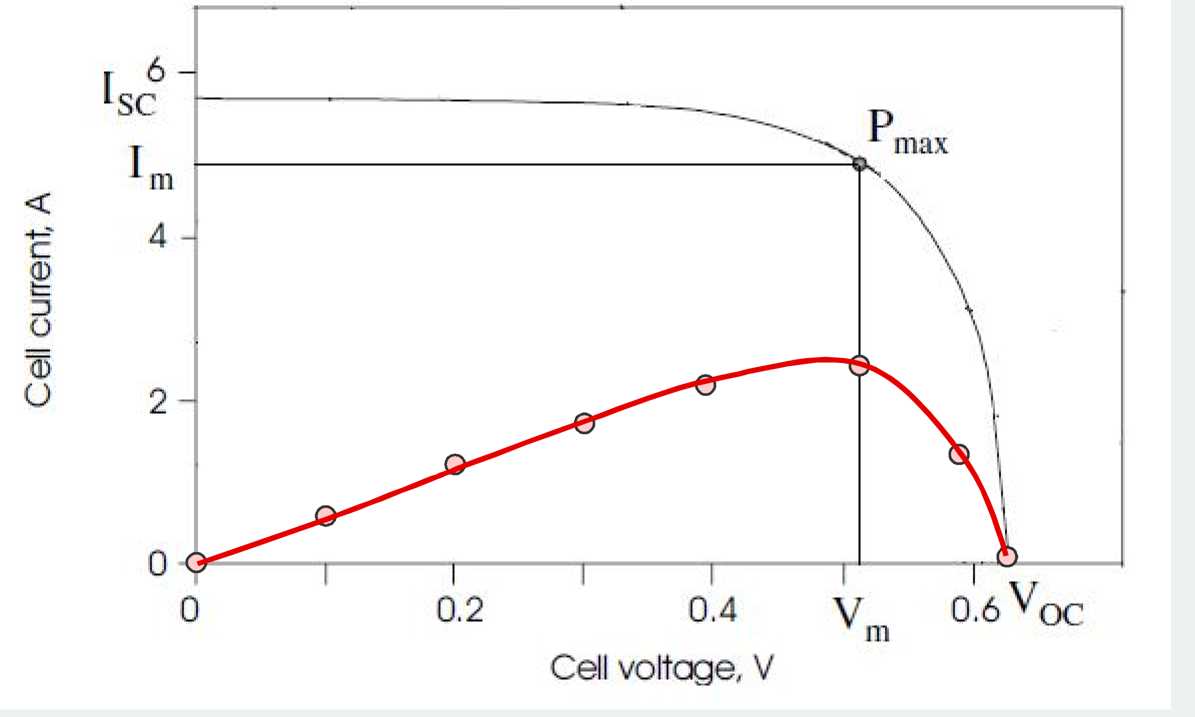


Maximum power of a PV cell



I-V characteristics of PV

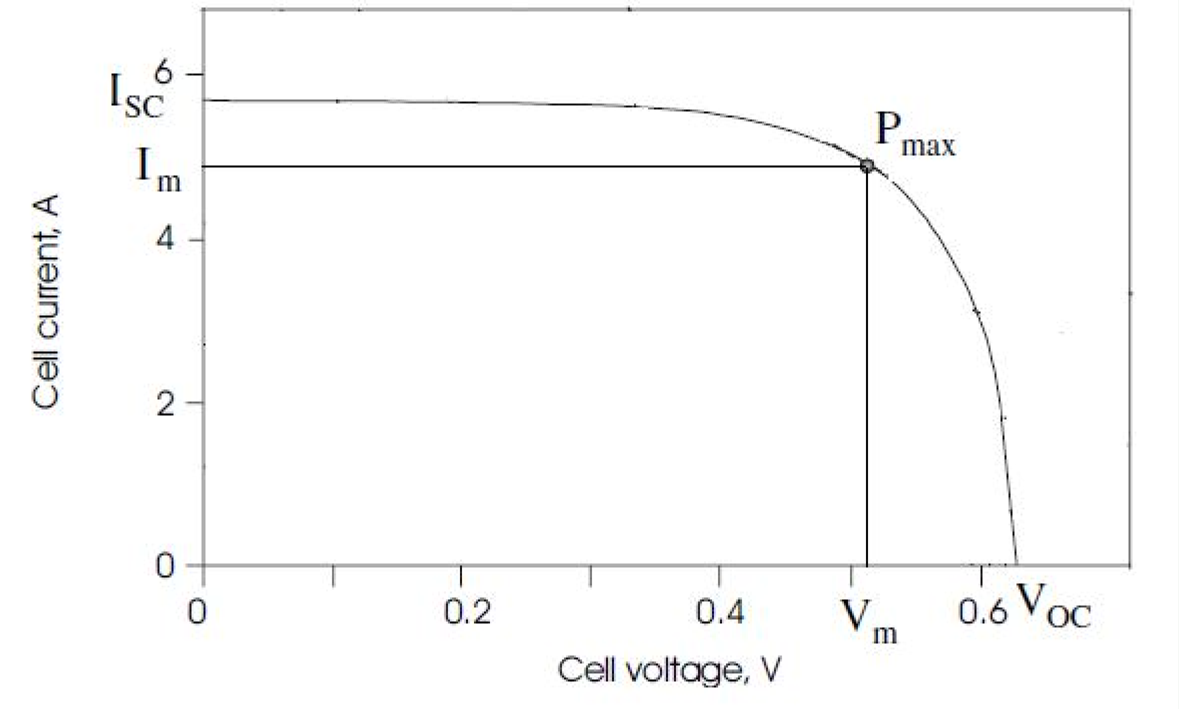
Power



$$P = V\left(I_l - I_0 (e^{\frac{qV}{kT}} - 1) \right)$$

I-V characteristics of PV

Fill factor



$$P_{max} = I_m V_m = FF I_{SC} V_{OC},$$

$$I = I_l - I_0\left(e^{\frac{qV}{kT}} - 1\right)$$

$$\text{if } \begin{cases} V_{OC} = 0.596\,\mathrm{V} \\ I_{SC} = 2\,A \end{cases}$$

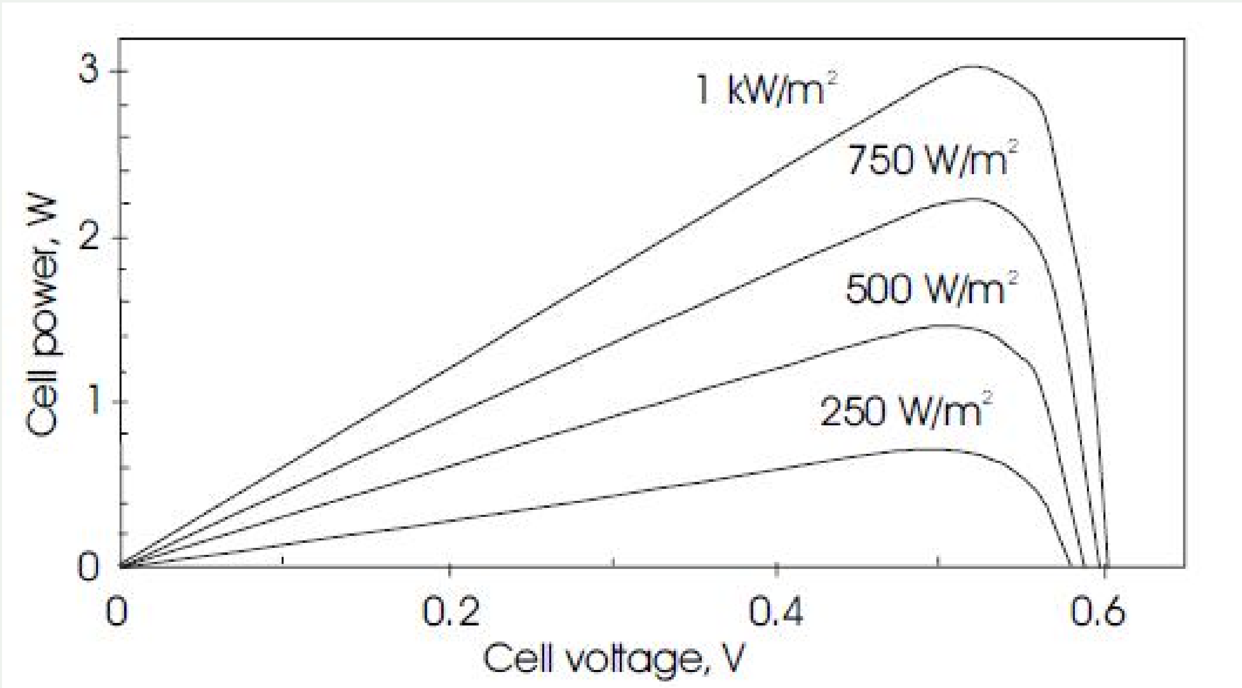
$FF = 0.83$

Real Cell

0.5 - 0.82

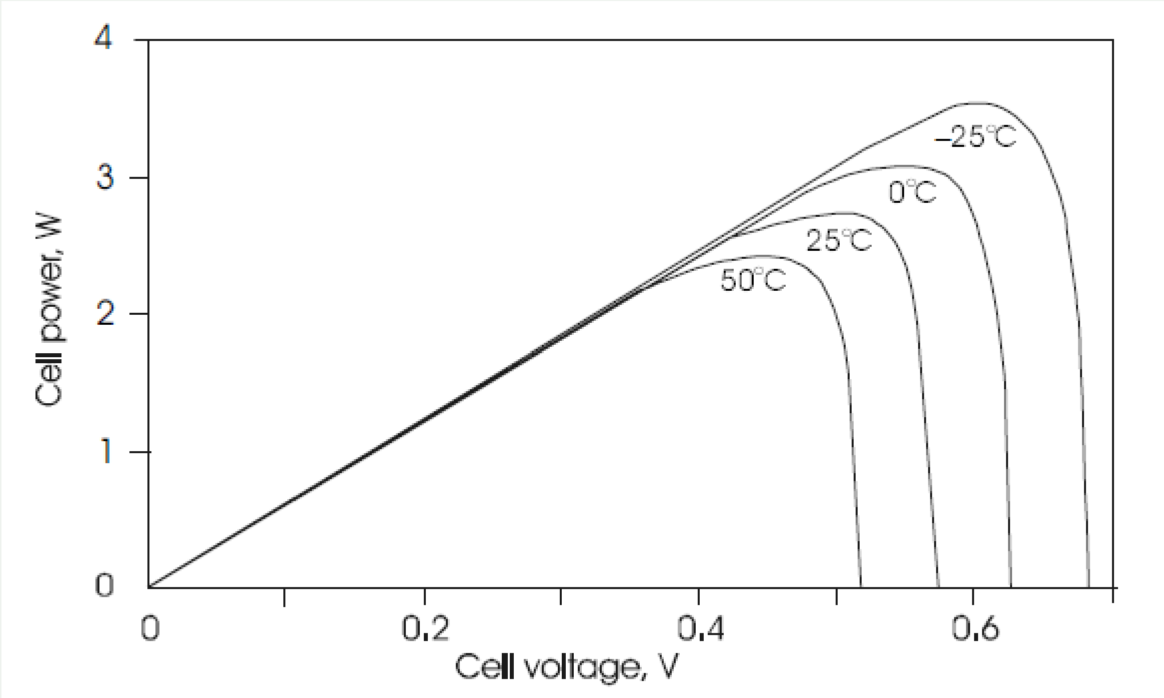
I-V characteristics of PV

Power versus voltage for a PV cell for 4 illumination levels



I-V characteristics of PV

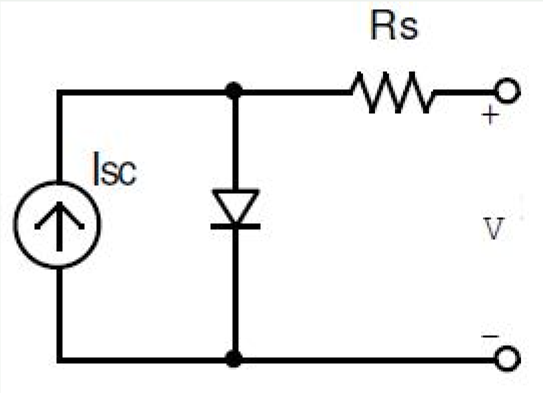
Temperature dependence of the power vs. voltage curve for a PV cell



Cell power decrease 0.5%/°C

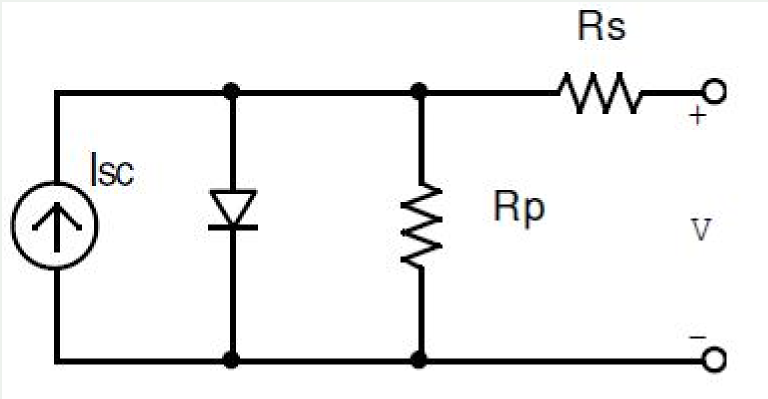
I-V characteristics of PV

PV Conventional Model



R_s : Semiconductor material, the metal grid, collecting bus.

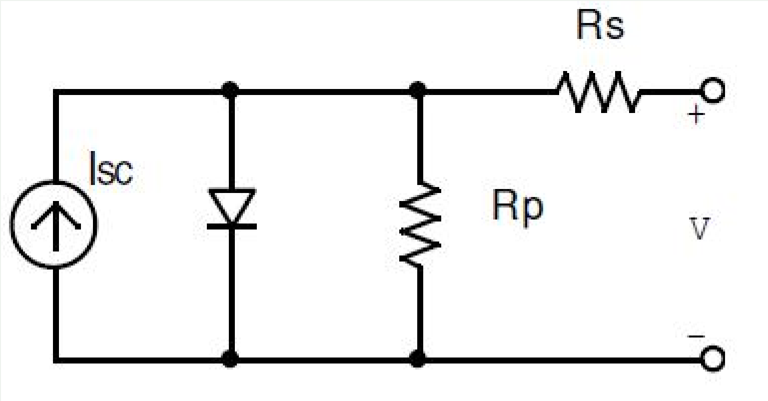
The more accurate model



R_p : Small leakage of current through a resistive path in parallel with the intrinsic device.

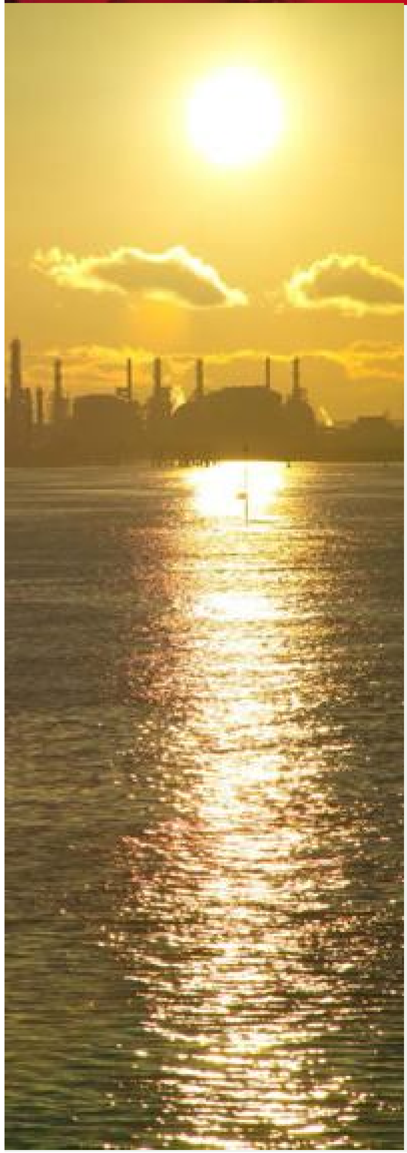
I-V characteristics of PV

Deriving equivalent circuit parameters

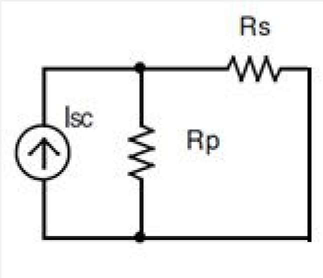


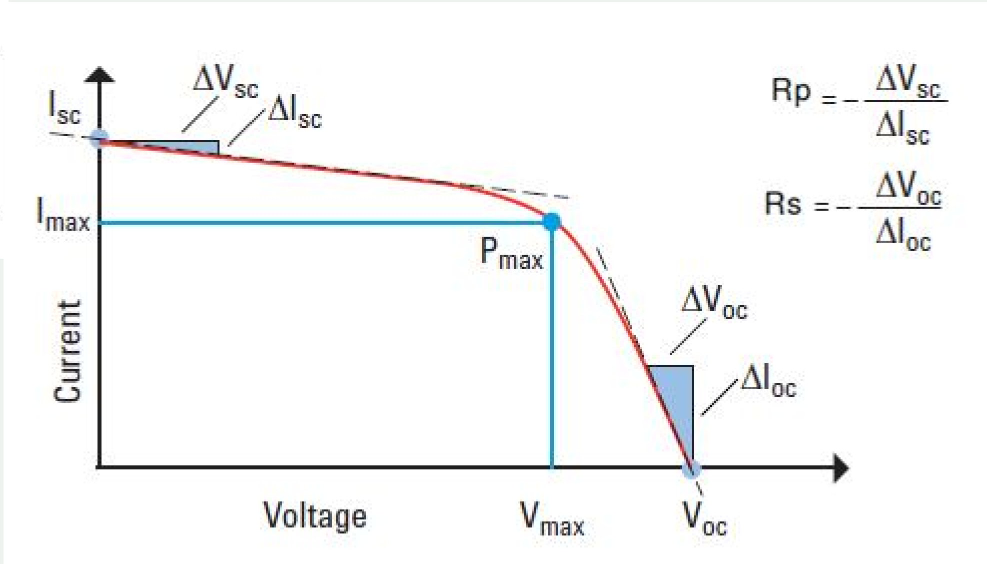
$I_{SC} = ?$ Let V = 0 then measure I_{SC}

I-V characteristics of PV



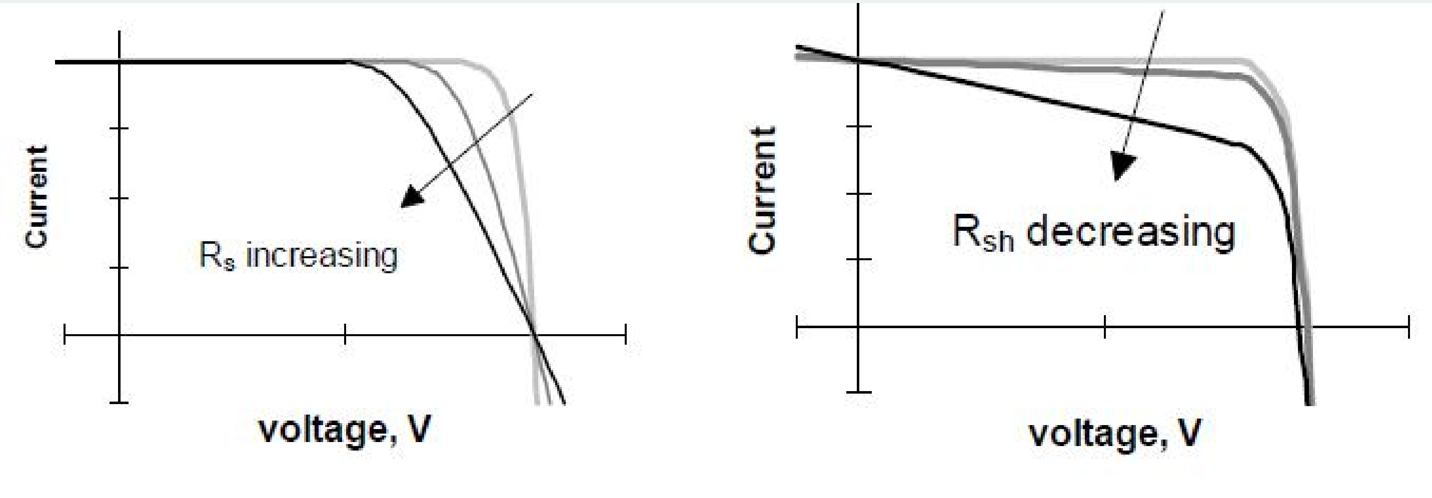
Deriving equivalent circuit parameters



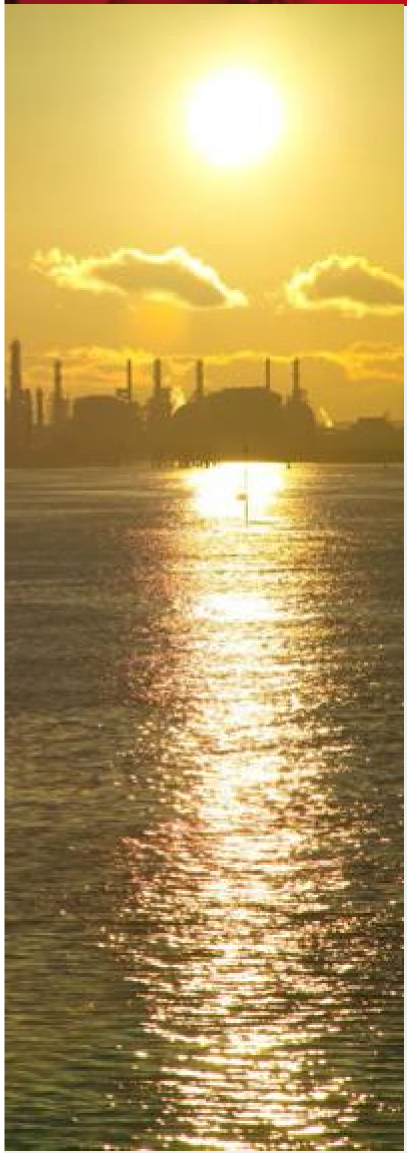


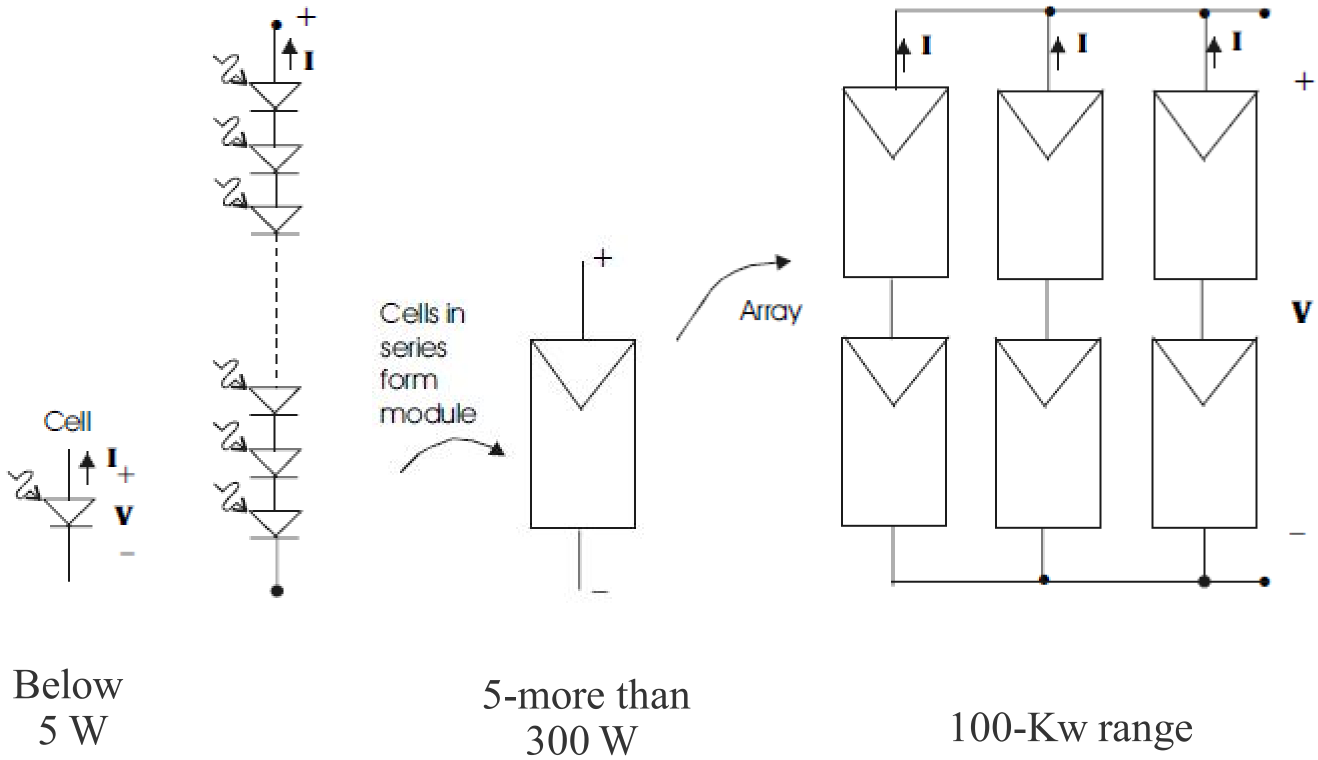
I-V characteristics of PV

Changing parameters in a pv cell



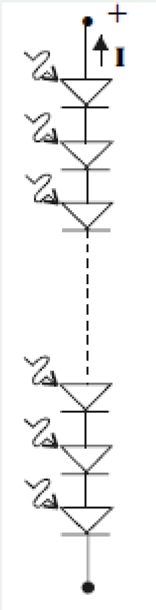
Cell, Module and Array

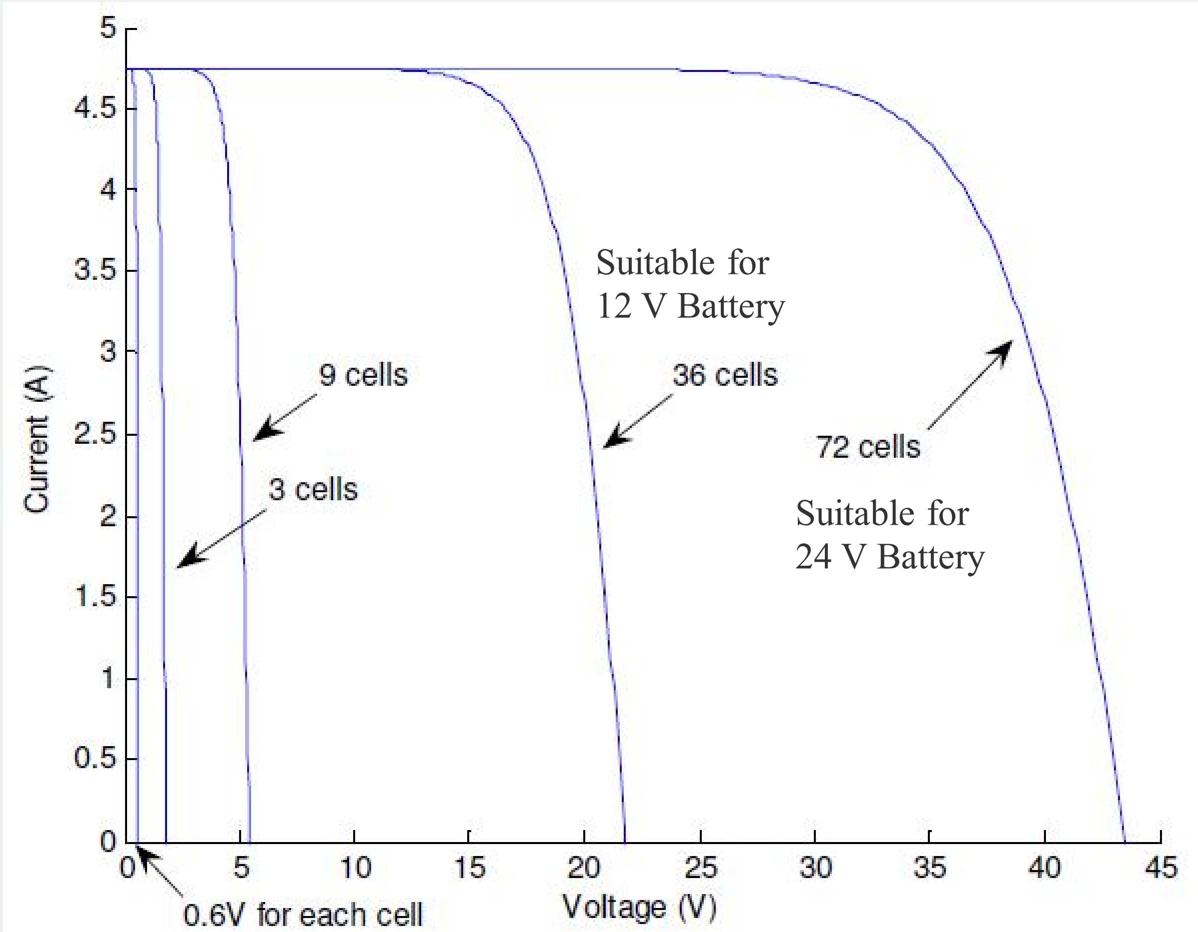




Cell, Module and Array

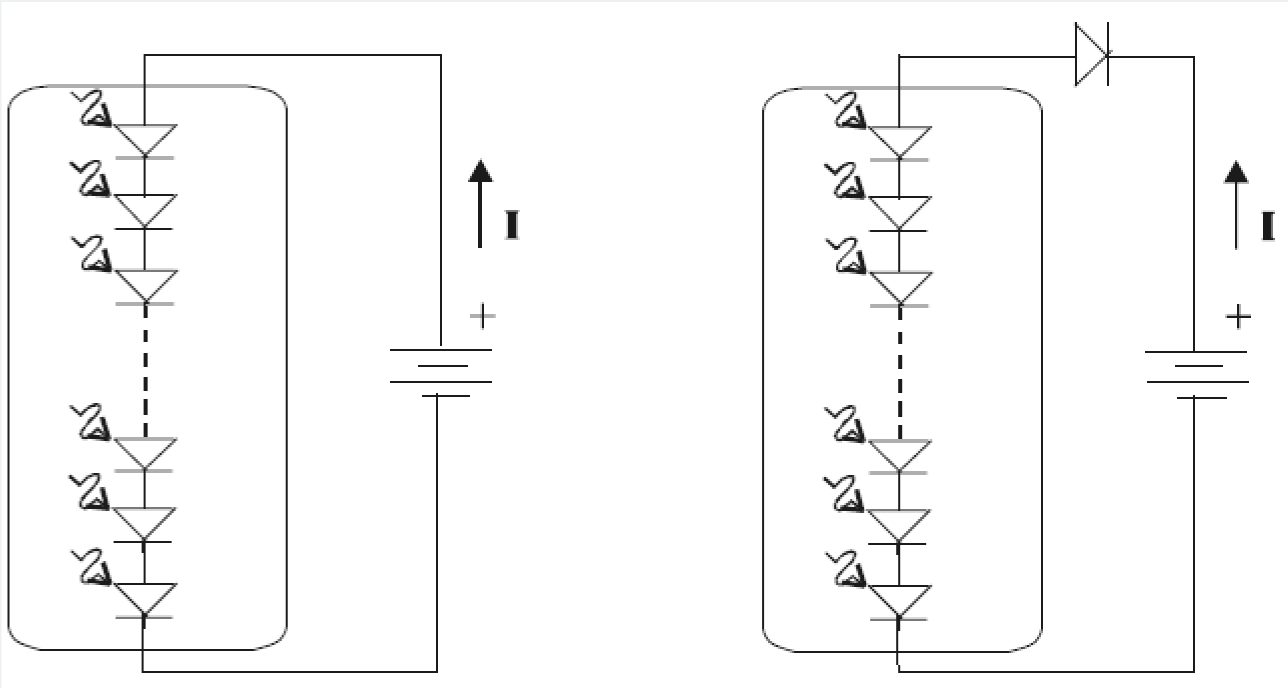
Making a module





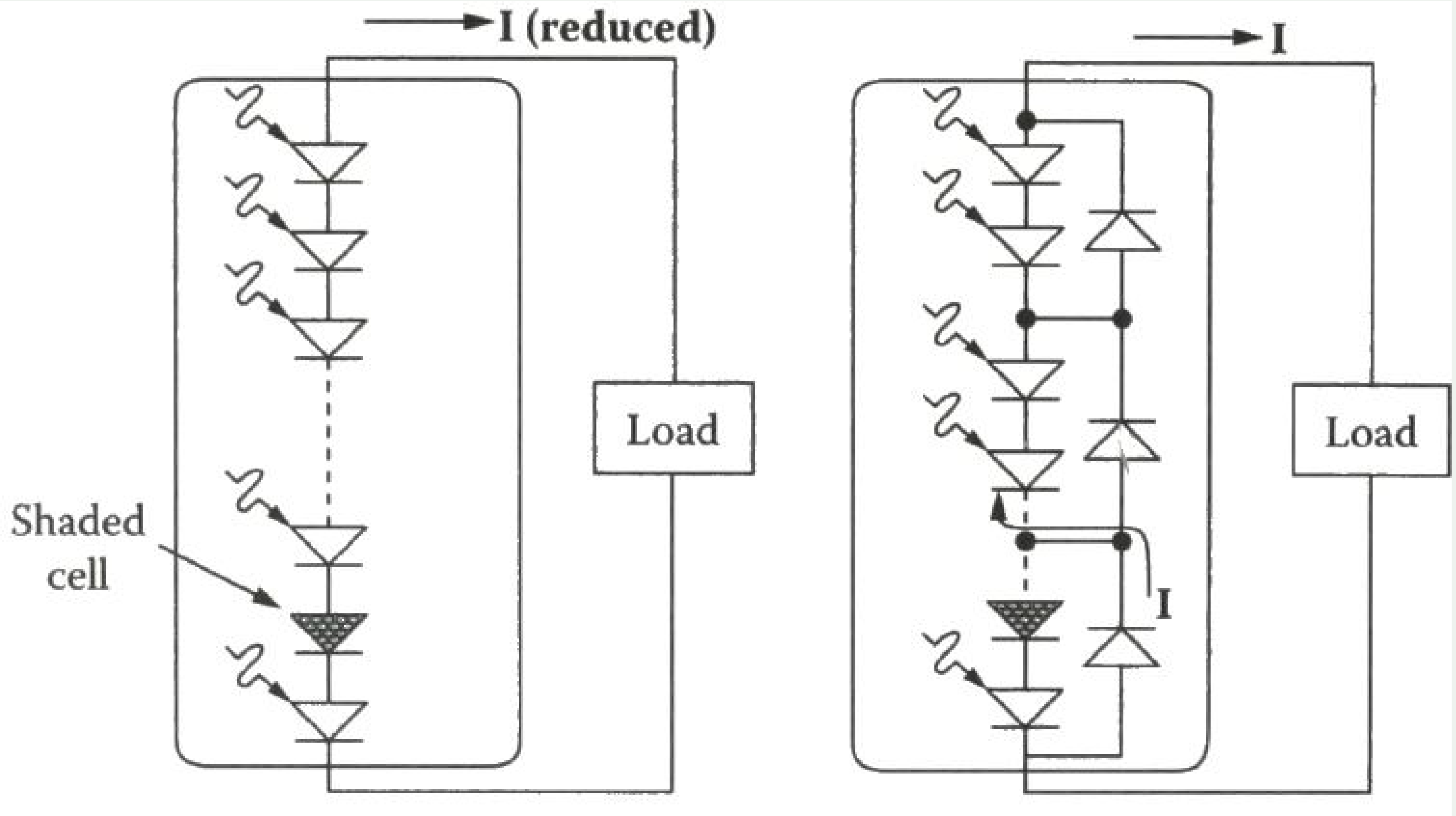
Cell, Module and Array

Blocking diode

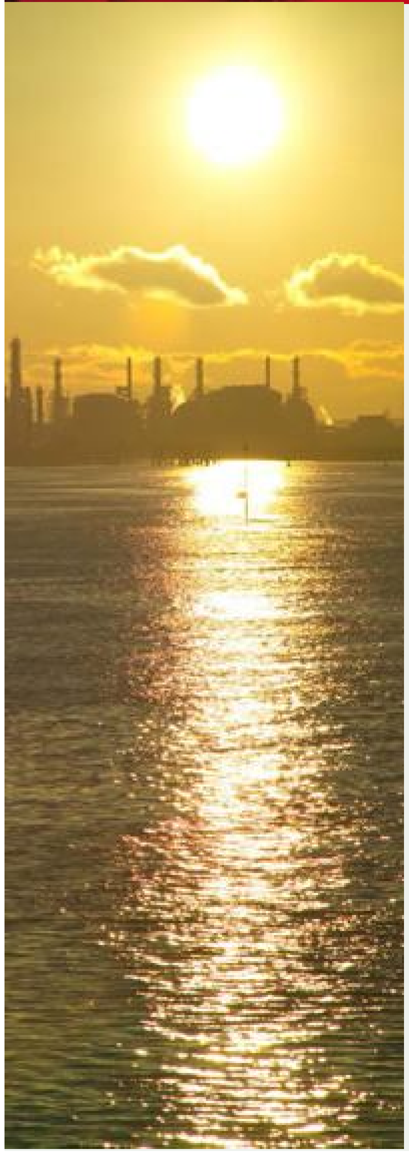


Cell, Module and Array

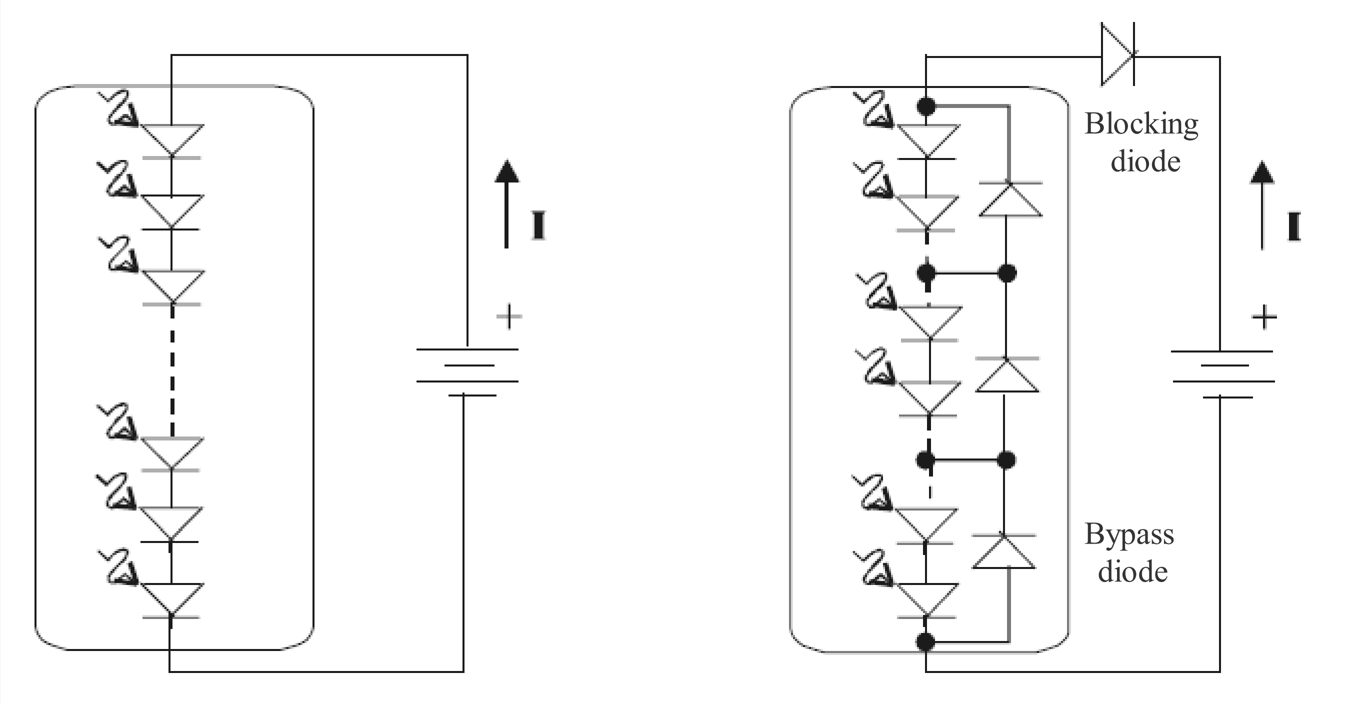
Bypass diode



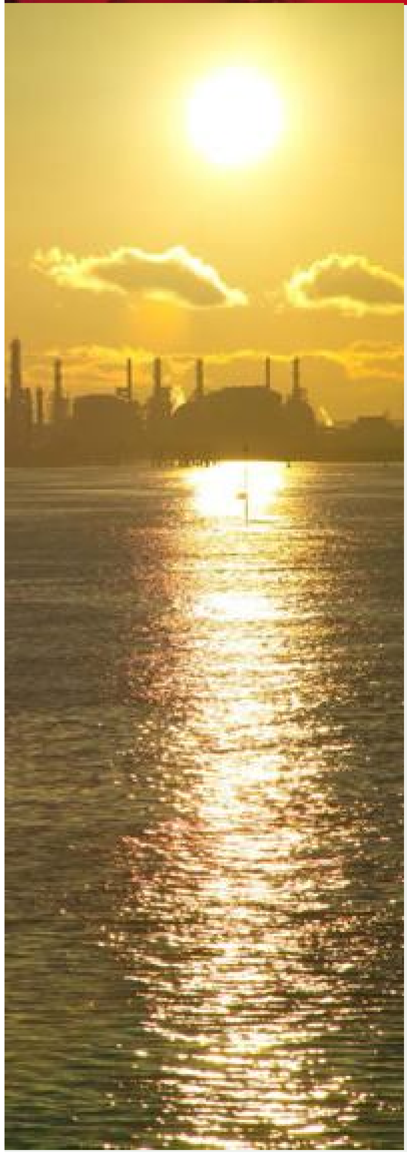
Cell, Module and Array



Combine bypass diode and blocking diode



Data sheet of NU-U235F1(Sharp solar electricity)



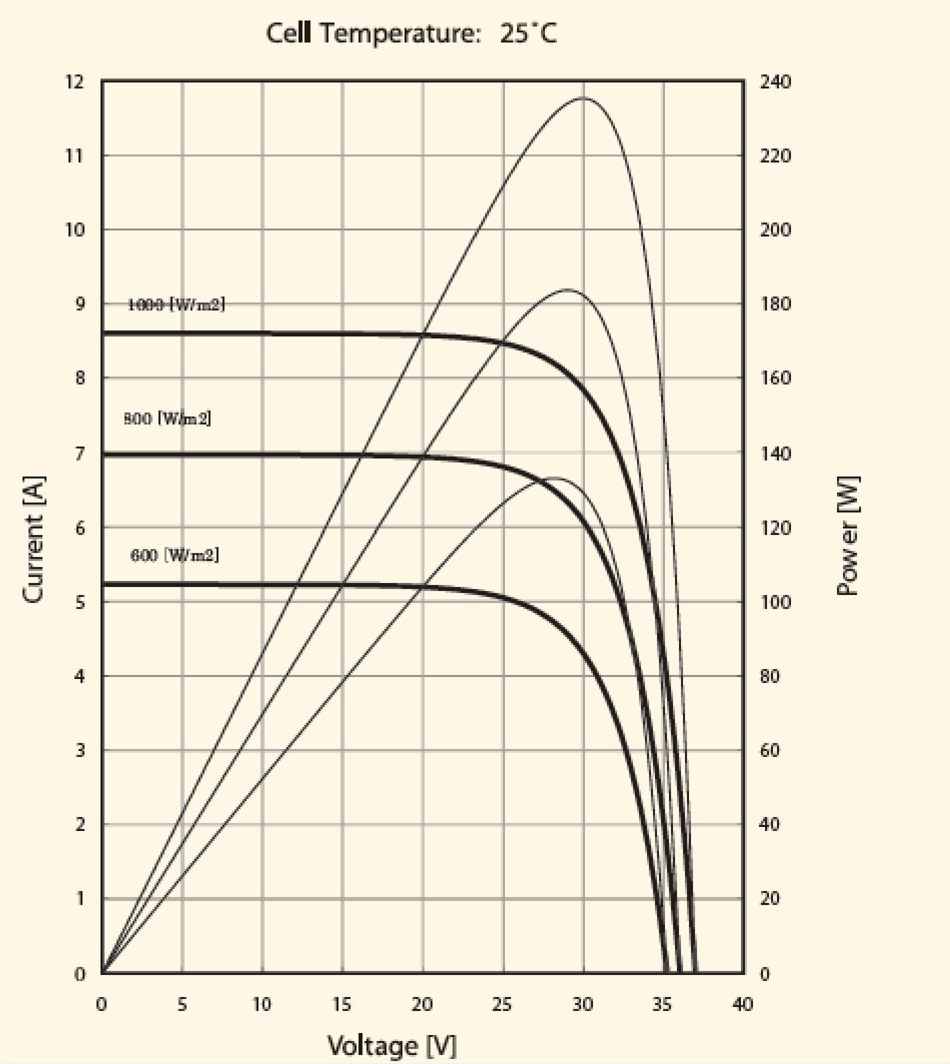
NU-U235F1

NEC 2008 Compliant
Module output cables 12 AWG with locking connectors

ELECTRICAL CHARACTERISTICS	
Maximum Power (Pmax)*	235 W
Tolerance of Pmax	+10%/-5%
Type of Cell	Monocrystalline silicon
Cell Configuration	60 in series
Open Circuit Voltage (Voc)	37.0 V
Maximum Power Voltage (Vpm)	30.0 V
Short Circuit Current (Isc)	8.60 A
Maximum Power Current (Ipm)	7.84 A
Module Efficiency (%)	14.4%
Maximum System (DC) Voltage	600 V
Series Fuse Rating	15 A
NOCT	47.5°C
Temperature Coefficient (Pmax)	-0.485%/°C
Temperature Coefficient (Voc)	-0.351%/°C
Temperature Coefficient (Isc)	0.053%/°C

*Measured at (STC) Standard Test Conditions: 25°C, 1 kW/m^2 insolation, AM 1.5

Data sheet of NU-U235F1(Sharp solar electricity)



Data sheet of NA-V135H1(Sharp solar electricity)

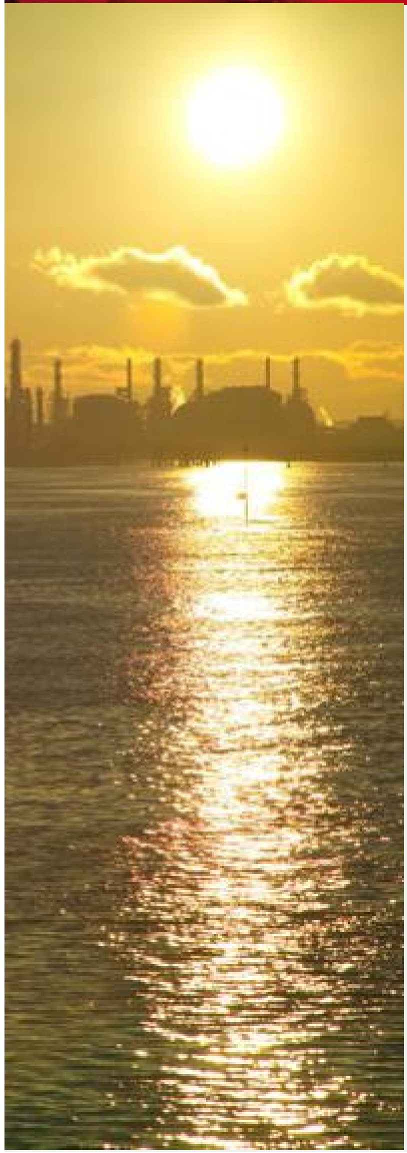
ELECTRICAL DATA		NAMEPLATE VALUES
		NA-V135H1
Maximum power	Pmax	135 W
Open-circuit voltage	Voc	249 V
Short-circuit current	Isc	0.870 A
Voltage at maximum power	Vpmax	188 V
Current at maximum power	Ipmax	0.720 A
Module efficiency	η	9.5%
Temperature coefficient – open circuit voltage	β	-0.3%/°C
Temperature coefficient – short circuit current	α	+0.07%/°C
Temperature coefficient – power	γ	-0.24%/°C

MADE IN JAPAN

The electrical data applies under standard test conditions (STC): Irradiance of 1,000 W/m² with an AM 1.5 spectrum at a cell temperature of 25° C. The power output is subject to a manufacturing tolerance of + 10% / - 5%

Output values are post initial Stabler-Wronski decay; actual measured initial values will be greater (approximately 15% for power).

Data sheet of NA-V135H1(Sharp solar electricity)



SPECIFICATIONS (I)	
Cell	Tandem architecture of amorphous and microcrystalline silicon
Cell Circuit	45 cells in series by 6 in parallel per quadrant: 4 quadrants in series (1080 total cells)
Dimensions	39.7" x 55.5" x 1.8" (1009 x 1409 x 46 mm)
Weight	42 lbs
Connection type	14 AWG Cable with MC-4 connector
Bypass diodes	4 (one per quadrant)
UL Listed	UL 1703
Fire Rating	Class C

SPECIFICATIONS (II)		
Maximum system voltage	600	V_{DC}
Maximum mechanical load	1,600	Pa
Series Fuse Rating	2	A
Operating temperature (cell)	- 40 to +90	°C
Storage temperature	- 40 to +90	°C
Storage air humidity	Up to 90	%
Installation orientation	Portrait	

I-V characteristics of PV

Maximum power of a PV module is not equal with n*maximum power of one cell.

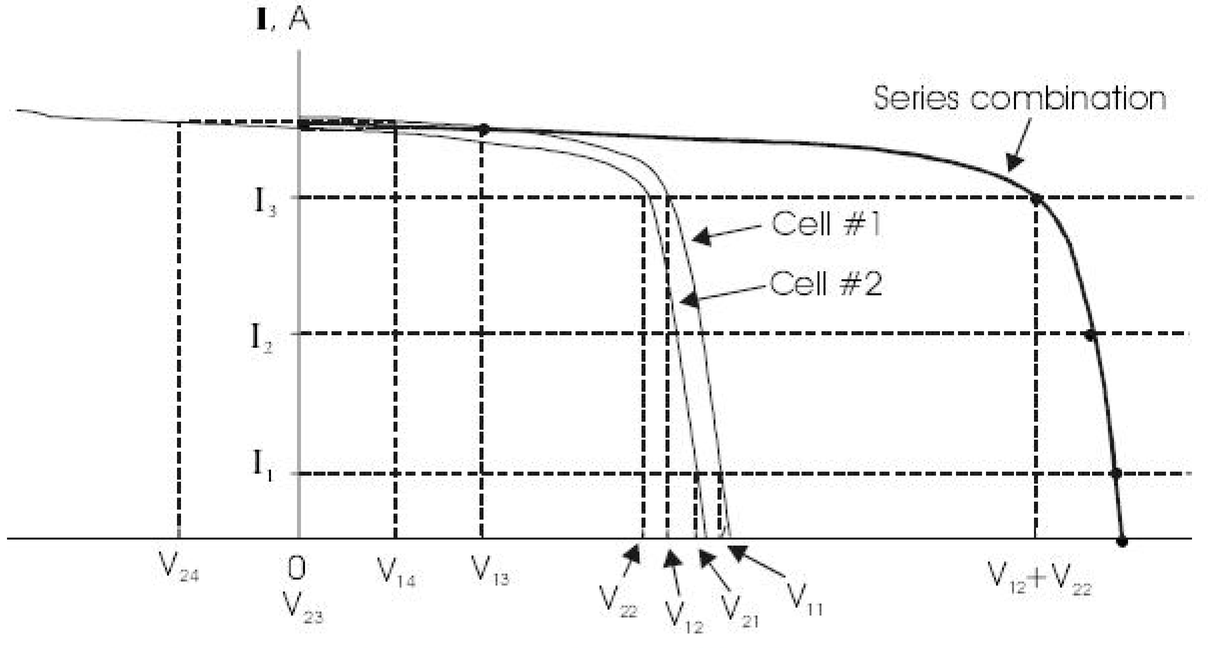
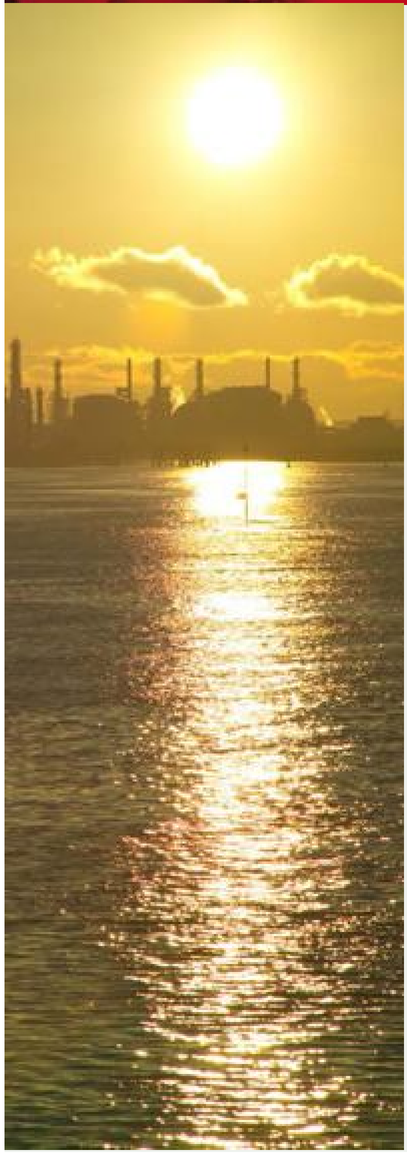


Figure 3.8 Determination of composite operating characteristic for a PV module.

At SC condition one cell produce power and one cell dissipate this power.

Exercise #1



Voltage and current of a module with 36 cells are given in the next slide. (At 1 KW/m^2, 25 °C)

a) Plot V-I curve.

b) Determine I_{sc} and V_{oc}.

c) Plot the P-V curve for the cell.

d) Find P_{max} of the module.

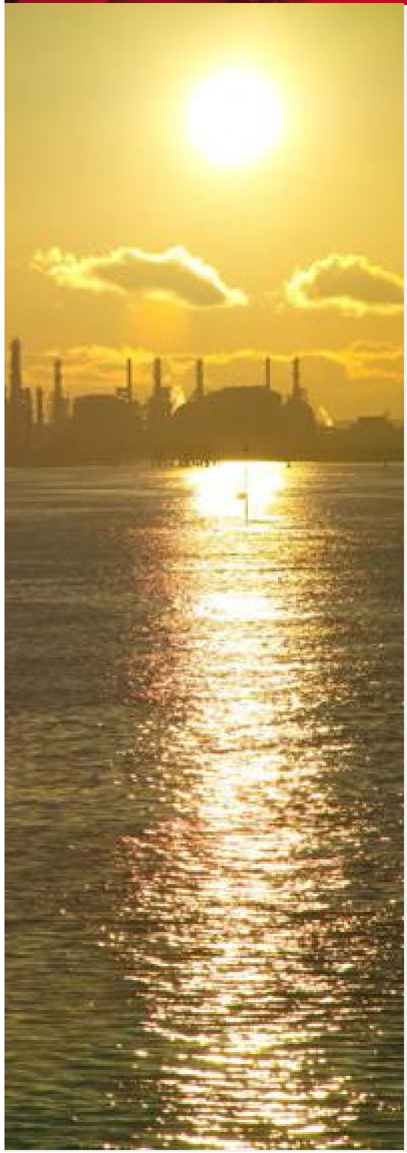
e) Find parameters of equivalent circuit.

f) Find reverse saturation current.

g) Determine R_L(Load resistance) to work in maximum power.

h) Plot V-I curve of the derived model and compare it with part *a*

i) Repeat a, c, d, g at 0.4 KW/m^2.



Vcell	Icell
0.0000	5.6999
0.3000	5.6993
0.4000	5.6974
0.5000	5.6143
0.5100	5.5750
0.5200	5.5180
0.5300	5.4361
0.5400	5.3197
0.5500	5.1566
0.5600	4.9329
0.5700	4.6325
0.5800	4.2407
0.5900	3.7448
0.6000	3.1367
0.6100	2.4131
0.6200	1.5777
0.6300	0.6353
0.6350	0.1308
0.6360	0.0280
0.6362	0.0059