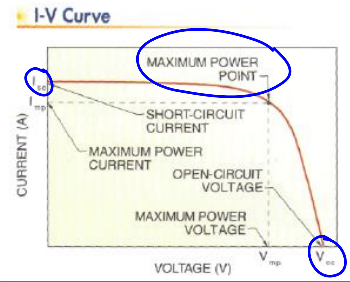
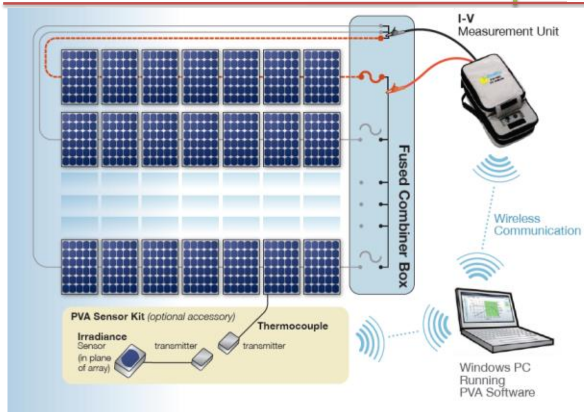
I-V Characteristic





ENEE5307
Renewable Energy
& PV Energy
Systems

Nasser Ismail
BZU-2015

The *current-voltage (I-V) characteristic*

- The *current-voltage (I-V) characteristic is the* basic electrical output profile of a PV device.
- *An I-V curve is the graphic representation* of all possible voltage and current operating points for a PV device at a specific operating condition.
- As voltage increases from zero, the current begins at its maximum and decreases gradually until the knee of the curve is reached.
- After the knee, small increases in voltage are associated with larger reductions in current, until the current reaches zero and the device is at maximum voltage.

بعد هذه النقطة تغير
بسيط في الفولتج يؤدي
الى تغير كبير في التيار

الفولتج الناتج من الخلية لا يعتمد على مساحة الخلية ،يعتمد على تكنولوجيا التصنيع ، سيليكون ..

بينما التيار رح يعتمد على ال surface area للخلية

FROM CELLS TO MODULES TO ARRAYS

- Individual cells produce about 0.5 V, بالعادة ال Voc للخلية الواحدة بحدود 0.5V
- The basic building block for PV applications is a *module* consisting of a number of pre-wired cells in series, all encased in tough, weather-resistant packages.
- A typical module has 36 cells in series and is often designated as a "12-V module" even though it is capable of delivering much higher voltages than that.
- 12-V modules may be desirable in certain very simple battery charging systems. قد تستخدم ال module في شحن بطارية 12 فولت ولكن يجب ان تكون بتعطي اعلى من 12 فولت بشوي حتى تشحن البطارية
- Large 72-cell modules are now quite common, some of which have all of the cells wired in series, in which case they are referred to as 24-V modules.

pre-wiring:
يعني بنشبكو مع بعض بطريقة معينة عالاغلب على التوالي وبعدها بتجمعو ب case ضد الظروف الجوية

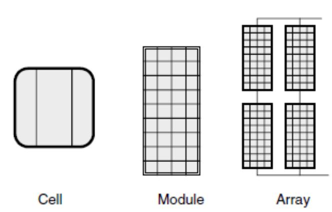
بالعادة بحطو 36 خلية مع بعض على التوالي ، وهذا ال module في هذه الحالة يسمى 12 Volt Module
مش بالضرورة تكون تعطي بالزبط 12 فولت

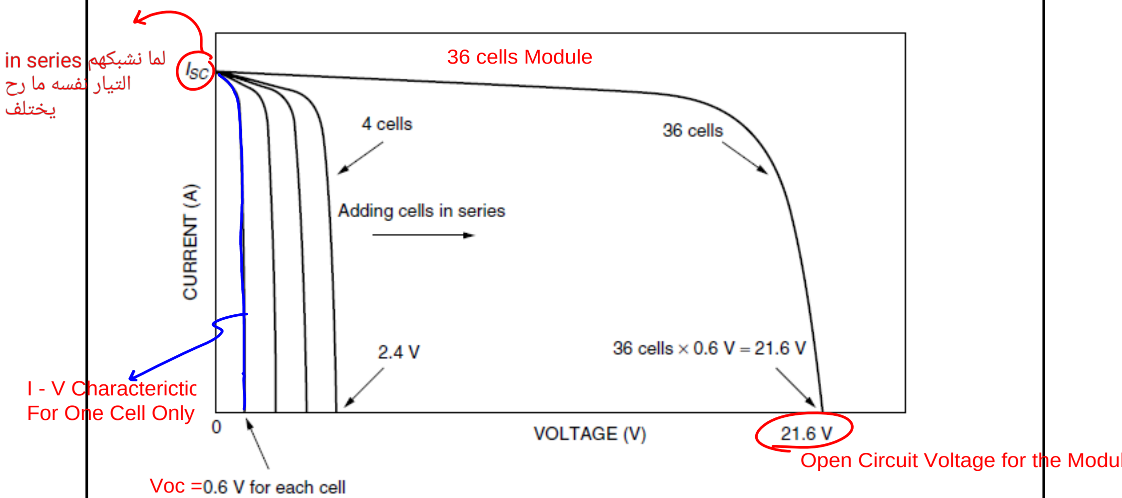
ال Total Output Power رح تعتمد على عدد ال modules وليس طريقة توصيلهم

FROM CELLS TO MODULES TO ARRAYS

combinations of modules

- Some 72-cell modules can be field-wired to act either as 24-V modules with all 72 cells in series or as 12-V modules with two parallel strings having 36 series cells in each.
- **Multiple modules, in turn, can be wired in series to increase voltage and in parallel to increase current, the product of which is power.**
- **An important element in PV system design is deciding how many modules should be connected in series and how many in parallel to deliver whatever energy is needed.**
- Such combinations of modules are referred to as an *array*.





For cells wired in series, their voltages at any given current add.
A typical module will have 36 cells.

number of cells

$$V_{\text{module}} = n(V_d - I R_S)$$

Voltage of One Cell

Example 8.4 Voltage and Current from a PV Module. A PV module is made up of 36 identical cells, all wired in series. With 1-sun insolation (1 kW/m^2), each cell has short-circuit current $I_{SC} = 3.4$ A and at 25°C its reverse saturation current is $I_0 = 6 \times 10^{-10}$ A. Parallel resistance $R_P = 6.6\ \Omega$ and series resistance $R_S = 0.005\ \Omega$.

a. Find the voltage, current, and power delivered when the junction voltage of each cell is 0.50 V.

b. Set up a spreadsheet for I and V and present a few lines of output to show how it works.

- Solution: a. Using $V_d = 0.50$ V

$$I = I_{SC} - \underbrace{I_0(e^{38.9V_d} - 1)}_{I_d} - \frac{V_d}{R_P}$$

$$= 3.4 - 6 \times 10^{-10}(e^{38.9 \times 0.50} - 1) - \frac{0.50}{6.6} = 3.16 \text{ A}$$

هذه النقطة تقع على ال curve

صحيحة على درجة 25

$$V_{\text{module}} = n(V_d - I R_S) = 36(0.50 - 3.16 \times 0.005) = 17.43 \text{ V}$$

Power delivered is therefore (At the previouse operating point)

$$P(\text{watts}) = V_{\text{module}}\ I = 17.43 \times 3.16 = 55.0\ \text{W}$$

b. A spreadsheet might look something like the following:

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) = 6.00E-10
Short-circuit current at 1-sun (A) = 3.4

V_d	$I = I_{SC} - I_0\left(e^{38.9V_d} - 1\right) - \dfrac{V_d}{R_p}$	$V_{\text{module}} = n(V_d - I R_S)$	P (watts) $= V_{\text{module}} I$
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

بتغير قيمة Vd ضمن range معين وكل مرة بتغيرو احسب التيار

مع زيادة الفولتج التيار Vd بقل

الفولتج لل module بزيد

ال power متغيرة واقصى قيمة هي 55.02

mpp

Notice that we have found the maximum power point for this module, which is at $I = 3.16$ A, $V = 17.43$ V, and $P = 55$ W. This would be described as a 55-W module.

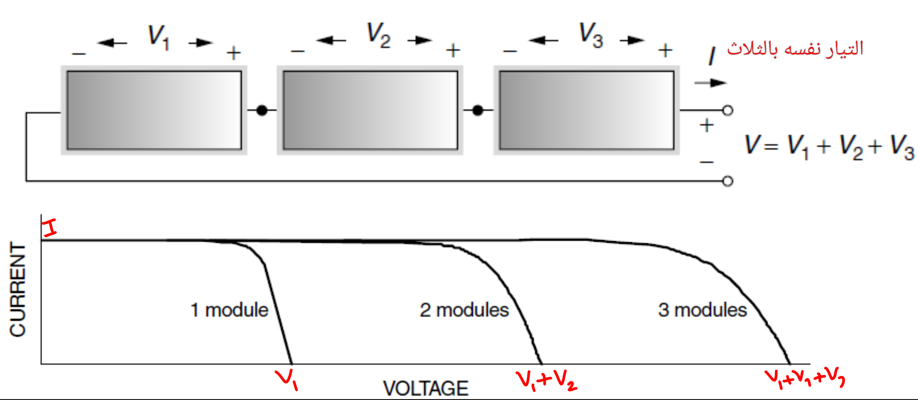
بتقدر توجد ال Voc اذا عوضت مكان التيار صفر بالمعادلة

ال Isc ما رح تتغير لانهم على التوالي ومعطاه بالمثال 3.4 A

From Modules to Arrays

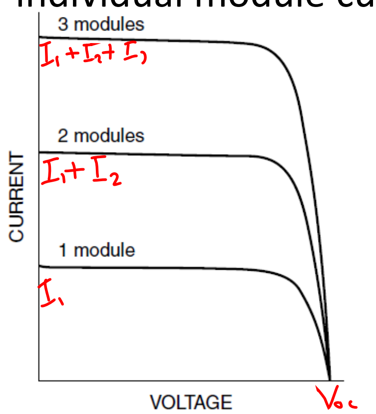
- Modules can be wired in series to increase voltage, and in parallel to increase current.
- Arrays are made up of some combination of series and parallel modules to increase power.
- For modules in series, the $I-V$ curves are simply added along the voltage axis.

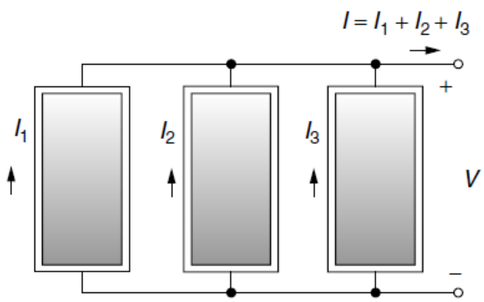
الشرط هنا لازم لازم يكون عندهم نفس ال current rating اما الفولتج ليس بالضرورة



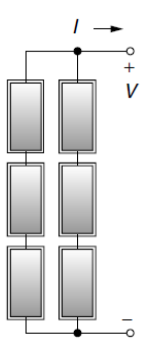
بنشبكهم parallel حتى نحصل على تيار اعلى
الشرط هنا يكون عندهم نفس الفولتج، التيار مش مهم

- For modules in parallel, the same voltage is across each module and the total current is the sum of the currents.
- That is, at any given voltage, the $I-V$ curve of the parallel combination is just the sum of the individual module currents at that voltage

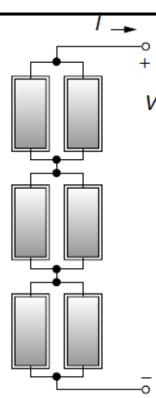




لو كانو ال Three panels لهم نفس المواصفات بالزبط المفروض
سواء شبكت توالي او توازي تطلع نفس قيمة ال mpp للحالتين



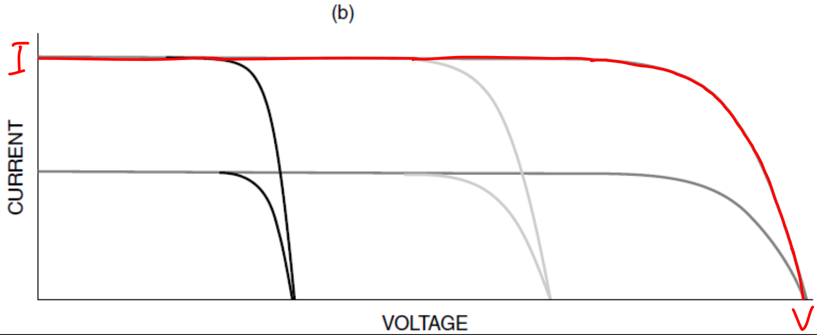
(a)



(b)

Two ways to wire an array with three modules in series and two modules in parallel.
Both I-V curves are the same

حل المثال عالدفتر
جزء موجه للجنوب وجزء للشمال

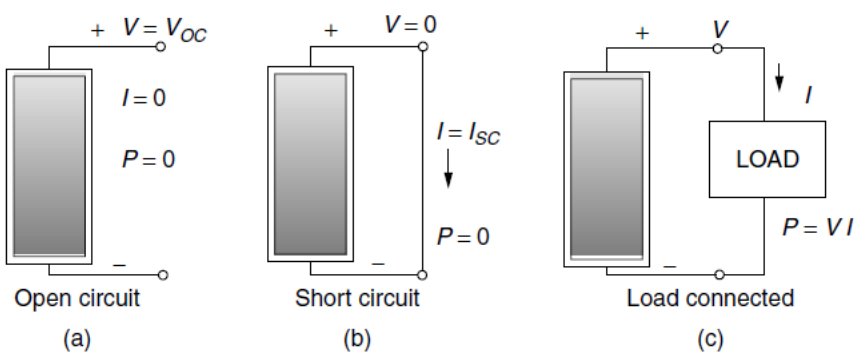


الي عندها بحسبو ال ratings لل panel

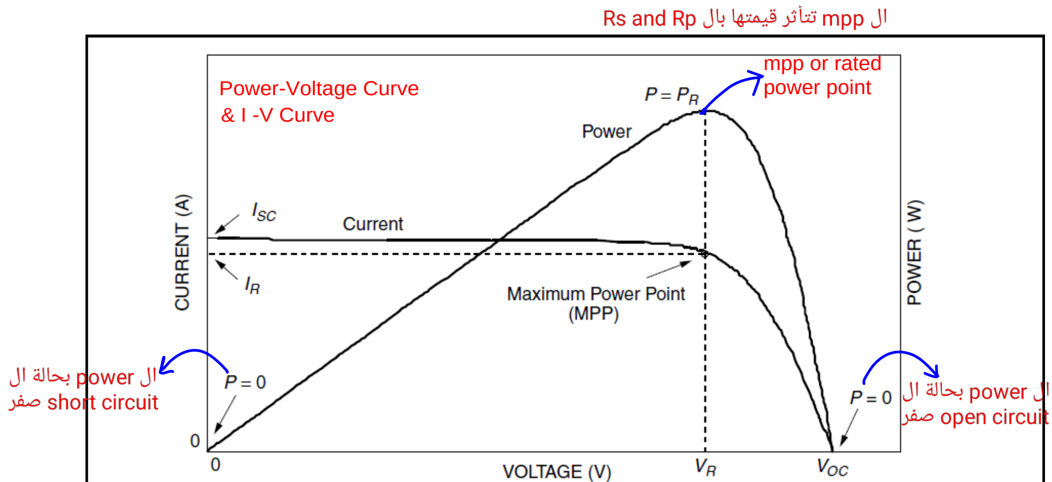
THE PV *I–V* CURVE UNDER STANDARD TEST CONDITIONS (STC)

بحالة بدك عند قيم
غير ال STC مثلا
درجة حرارة 40
لازم يكون معطيك ال
sensitivity او ال
power derating

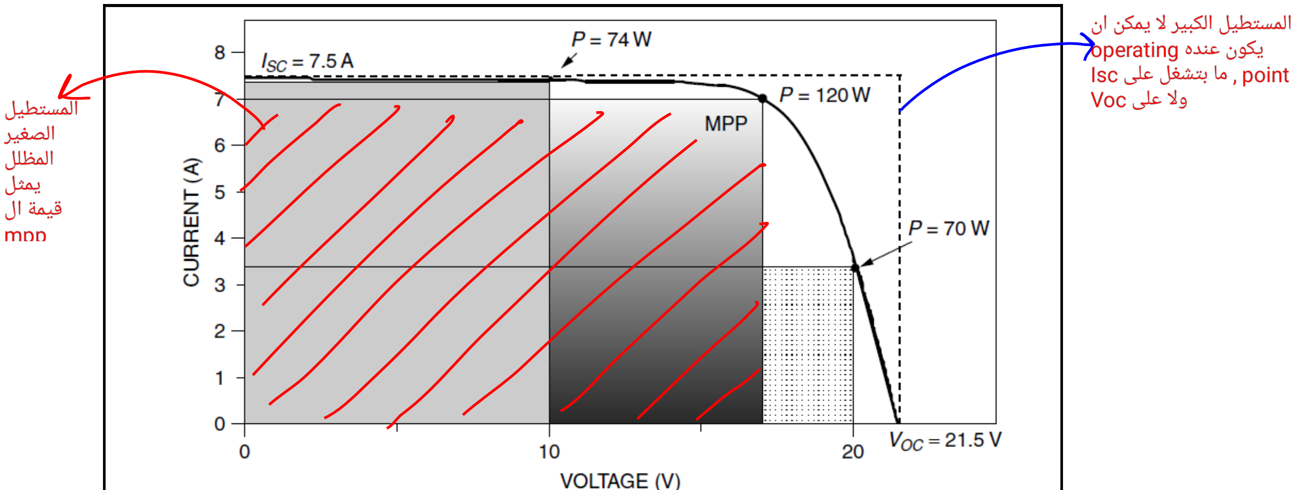
- Before the load is connected, the module sitting in the sun will produce an open-circuit voltage *Voc*, but no current will flow.
- If the terminals of the module are shorted together (which doesn't hurt the module at all, by the way), the short-circuit current *Isc* will flow, but the output voltage will be zero.
- In both cases, since power is the product of current and voltage, no power is delivered by the module and no power is received by the load.
- When the load is actually connected, some combination of current and voltage will result and power will be delivered.
- To figure out how much power, we have to consider the *I –V* characteristic curve of the module as well as the *I –V* characteristic curve of the load.



- No power is delivered when the circuit is open (a) or shorted (b).
- When the load is connected (c), the same current flows through the load and module and the same voltage appears across them.



The I –V curve and power output for a PV module.
At the maximum power point (MPP) the module delivers the most power that it can under the conditions of sunlight and temperature for which the I –V curve has been drawn.



- The maximum power point (MPP) corresponds to the biggest rectangle that can fit beneath the I –V curve.
- The fill factor (FF) is the ratio of the area (power) at MPP to the area formed by a rectangle with sides ***Voc*** and ***ISC***.

Fill Factor

قيمة ال FF بالعادة
بالسبعينات للسيليكون

- Fill factors around 70–75% for crystalline silicon solar modules are typical, while for multijunction amorphous-Si modules, it is closer to 50–60%.

$$\textit{Fill Factor}\ (FF) = \frac{\textit{Power at MPP (i.e. Rated Power)}}{V_{OC} I_{SC}} = \frac{V_R I_R}{V_{OC} I_{SC}}$$

نسبة المستطيل الصغير الى المستطيل الكبير

- Since PV *I* –*V* curves shift all around as the amount of insolation changes
- And as the temperature of the cells varies, standard test conditions (STC) have been established to enable fair comparisons of one module to another.

Standard Test Conditions :STC

- STC: include a solar irradiance of 1 kW/m^2 (1 sun), spectral distribution, corresponding to an air mass ratio of 1.5 (AM 1.5).
- The standard cell temperature for testing purposes is 25◦C (it is important to note that 25◦ is cell temperature, not ambient temperature).
- Manufacturers always provide performance data under these operating conditions,
- The key parameter for a module is its rated power; *PDC,STC.*
- Power adjustments to take into account temperature effects will be done later
- Also the actual ac power that the module and inverter combination will deliver will be estimated.

TABLE 8.3 Examples of PV Module Performance Data Under Standard Test Conditions (1 kW/m², AM 1.5, 25°C Cell Temperature)

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) mpp	120	165	150	64	40
Voltage at max power (V) Vr	16.9	34.6	34	16.5	16.6
Current at rated power (A) Ir	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%

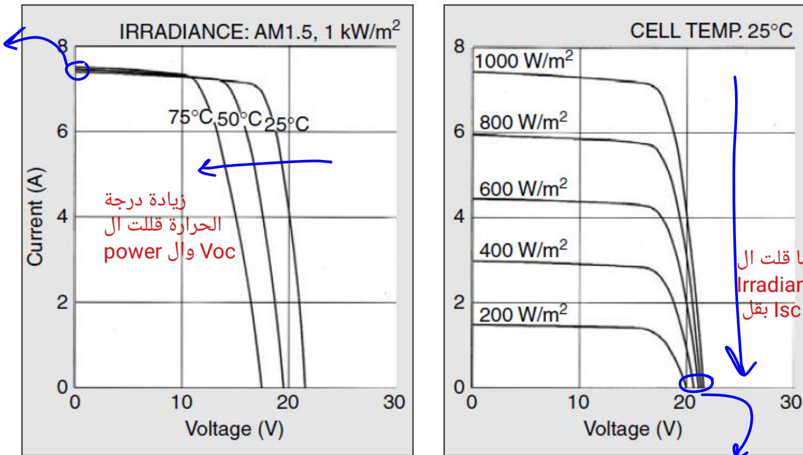
تأثير العوامل الخارجية على ال I-V Curve

IMPACTS OF TEMPERATURE AND INSOLATION ON *I–V* CURVES

- Manufacturers will often provide *I* –*V* curves that show how the curves shift as insolation and cell temperature changes.
- An example for the Kyocera 120-W multicrystal-silicon module described in Table 8.3. is given
- Notice as insolation drops, short-circuit current drops in direct proportion.
- **Cutting insolation in half, for example, drops *Isc* by half.**
- **Decreasing insolation also reduces *Voc*, but it does so following a logarithmic relationship that results in relatively modest changes in *Voc*.**

زيادة حرارة ال cell ممكن يكون من الجو او من خلال سيناريو مثل ال shading

تقريبا نفسه للثلاث حالات، بزيد ال Isc زيادة قليلة جدا مع زيادة الحرارة



وال Voc بقل شوي صغيرة ، العلاقة logerthmic not linear

Current-voltage characteristic curves under various cell temperatures and irradiance levels for the Kyocera KC120-1 PV module.

هذه ال curves متواجدة بال Datasheet للخلايا

Temp Effect

الحرارة بزيادتها بتخلي اداء ال pv اسوأ، تأثيرها سلبي

- As can be seen in previous, as cell temperature increases, the open-circuit voltage decreases substantially while the short-circuit current increases only slightly.
- **Photovoltaics, perhaps surprisingly, therefore perform better on cold, clear days than hot ones.**
- For crystalline silicon cells, *Voc* drops by about **0.37%** for each degree Celsius increase in temperature and *ISC* increases by approximately **0.05%.**

الحرارة بتزيدو بشكل بسيط جدا short circuit current

- The net result when cells heat up is the MPP slides slightly upward and toward the left with a decrease in maximum power (mpp) available of about **0.5%/◦C.**
- Given this significant shift in performance as cell temperature changes, it should be quite apparent that temperature needs to be included in any estimate of module performance.

ال Data sheet لازم يكون معطيك شو بصير بالفولتج لما تزيد الحرارة ، يعني لازم يعطيك sensitivity factor

احيانا بكون معطى معلومات بخصوص ال power

المقصود بالحرارة هي حرارة ال panel وليس الجو

احيانا بكون معطيك معلومات عن ال panel عند NOCT condition مش STC

Normal Operating Cell Temperature

NOCT

بكون معطيني معلومات عند NOCT معينة وهي 20 درجة اذا تغيرت ال cell temprature عن 20 بدي اشوف مقدار التغير واخده بالحسبان.

- Cells vary in temperature not only because ambient temperatures change, but also because insolation on the cells changes. Since only a small fraction of the insolation hitting a module is converted to electricity and carried away, most of that incident energy is absorbed and converted to heat.
- To help system designers account for changes in cell performance with temperature, manufacturers often provide an indicator called the NOCT, which stands for nominal operating cell temperature.
- The NOCT is cell temperature in a module when ambient is 20◦C, solar irradiation is 0.8 kW/m2, and windspeed is 1 m/s. To account for other ambient conditions, the following expression may be used:

اذا معروف عندي ال NOCT ودرجة حرارة الجو

$$T_{\text{cell}} = T_{\text{amb}} + \left(\frac{\text{NOCT} - 20^\circ}{0.8}\right) \cdot S$$

- where *T*cell is cell temperature (◦C), *T*amb is ambient temperature, and *S* is solar insolation (kW/m^2).

Impact of Cell Temperature on Power for a PV Module.

- Estimate cell temperature, open-circuit voltage, and maximum power output for the 150-W BP2150S module under conditions of 1-sun insolation and ambient temperature 30◦C. The module has a NOCT of 47◦C.
- Solution: cell temperature is estimated to be

بدنا نعمل estimation ل cell temprature

$$T_{\text{cell}} = T_{\text{amb}} + \left(\frac{\text{NOCT} - 20^\circ}{0.8}\right) \cdot S = 30 + \left(\frac{47 - 20}{0.8}\right) \cdot 1 = 64^\circ\text{C}$$

1 sun

- From Table 8.3, for this module at the standard temperature of 25◦C, *VOC* = 42.8 V. Since *VOC* drops by 0.37%/◦C, the new *VOC* will be about:

old Voc

$$Voc = 42.8[1 - 0.0037(64 - 25)] = 36.7\text{ V}$$

من الجدول السابق   change in T   الفولتج الجديد نزل ، لان الحرارة عالية

لو طالب بالنسبة للتيار Isc
بتطلع ال nominal Isc عند STC
وبتضرب ب (Coeff of current* change in T% + 1) التيار بزيد
Coeff of current = 0.0005
بالنسبة ل ال power بتقل بنسبة 5%- / C

- With maximum power expected to drop about 0.5%/◦C, this 150-W module at its maximum power point will deliver

  $P_{max} = 150\ W \cdot [1 - 0.005(64 - 25)] = 121\ W$

- which is a rather significant drop of 19% from its rated power.

دراسة تأثير ال shading الحاصل على جزء من ال system

SHADING IMPACTS ON I –V CURVES

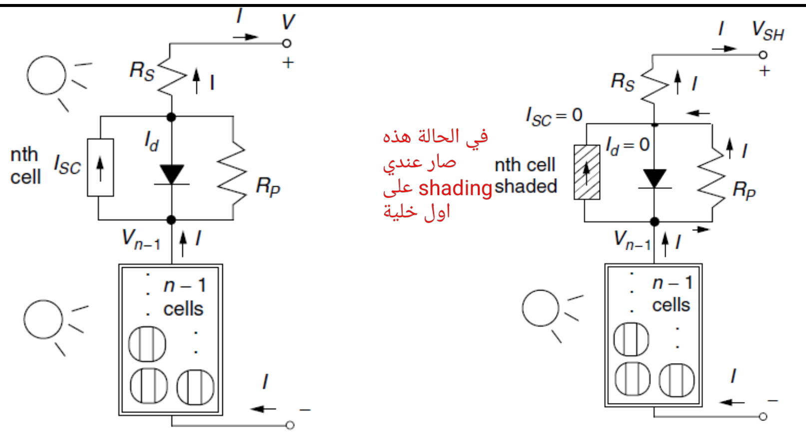
- The output of a PV module can be reduced dramatically when even a small portion of it is shaded.
- Unless special efforts are made to compensate for shade problems, even a single shaded cell in a long string of cells can easily cut output power by more than half.
- **External diodes,** purposely added by the PV manufacturer or by the system designer, can help preserve the performance of PV modules.
- The main purpose for such diodes is to mitigate the impacts of shading on PV *I –V* curves.
- Such diodes are usually added in parallel with modules or blocks of cells within a module.

اضافة diode parallel لا يتم على كل cell واحدة لانه ما عندي access عليها ، بضيفو ال diode على كل module بحيث اذا كانت shaded ما تعملي مشكلة

لازم نضيف عال system شغلة حتى تخفف ال shading، الحل هو اضافة External Diode

لو كان عندك 36 خلية وصار shading على خلية وحدة ، مقدار ال losses في التيار والفولتج وال power ليس بنسبة (1/36) ، رح يكون اسوأ من هذه النسبة بكثير ، ممكن خلية وحدة تخسرني نص ال power

بالوضع الطبيعي a
For n Cells
V = n Vcell



في الحالة هذه صار عندي shading على اول خلية

(a) All cells in the sun

(b) Top cell shaded

A module with *n* cells in which the top cell is in the sun (a) or in the shade (b)

$$V_{SH} = V_{n-1} - I(R_P + R_S)$$

With all *n* cells in the sun and carrying *I* , the output voltage was *V* so the voltage of the bottom *n* − 1 cells will be.

بحالة صار shading على خلية
V = n Vcell - Vcell
Vcell = V / n

$$V_{n-1} = \left(\frac{n-1}{n}\right) V$$

V is the voltage of the module

voltage drop on one shaded cell

$$V_{SH} = \left(\frac{n-1}{n}\right) V - I(R_P + R_S)$$

voltage drop

- The drop in voltage Δ V at any given current *I* , caused by the shaded cell, is given by:

الفولتج بالحالة الي ما صار فيها shading

$$\text{voltage drop} = \Delta V = V - V_{SH} = V - \left(1 - \frac{1}{n}\right) V + I(R_P + R_S)$$

الخسارة الي خسرتها ال بالفولتج بسبب ال shading

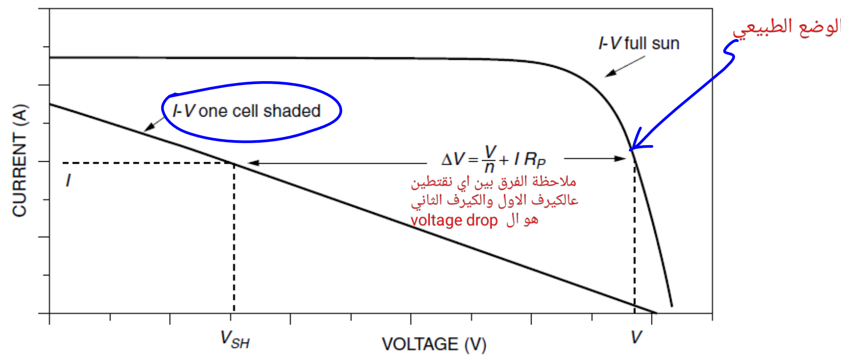
$$\Delta V = \frac{V}{n} + I(R_P + R_S)$$

- Since *Rp >> Rs , previous equation becomes*

$$\Delta V \cong \frac{V}{n} + I R_P$$

لاحظ كل ما زاد التيار بزيد ال voltage drop , شوف عالرسمة في السلايد التالي

- At any given current, the I –V curve for the module with one shaded cell drops by ΔV.
- The huge impact this can have is illustrated in



Example:
Impacts of Shading on a PV Module.

- The 36-cell PV module described in previous Example had a parallel resistance per cell of R_P = 6.6 . لل module كل بطلعو 36 * 6.6
- In full sun and at current I = 2.14 A the output voltage was found there to be V = 19.41 V. ال operating point
- If one cell is shaded and this current somehow stays the same, then:

a. What would be the new module output voltage and power?

b. What would be the voltage drop across the shaded cell?

c. How much power would be dissipated in the shaded cell?

Example solution

A) The drop in module voltage will be:

$$\Delta V = \frac{V}{n} + I R_P$$ مش معطي Rs لذلك استخدم المعادلة التقريبية

$$= \frac{19.41}{36} + 2.14 \times 6.6 = 14.66 \text{ V}$$

- The new output voltage will be 19.41 − 14.66 = 4.75 V.
- Power delivered by the module with one cell shaded would be :

  *P*module = *V I* = 4.75 V × 2.14 A = 10.1 W
- For comparison, in full sun the module was producing 41.5 W ضاع ال 3 ارباع ال power

Solution continued

b) All of that 2.14 A of current goes through the parallel plus series resistance (0.005) of the shaded cell, so the drop across the shaded cell will be :

Vc* = *I* (*RP* + *RS*) = 2.14(6.6 + 0.005) = 14.14 *V

- (normally a cell in the sun will add about 0.5 V to the module; this shaded cell subtracts over 14 V from the module).

C) The power dissipated in the shaded cell is voltage drop times current, which is

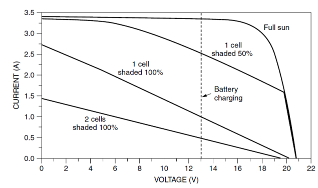
***P* = *Vc I* = 14.14 V × 2.14 A = 30.2 W**

- All of that power dissipated in the shaded cell is converted to heat, which can cause a local hot spot that may permanently damage the plastic laminates enclosing the cell.

ال power loss الي
خسرناها راحت على
شكل heat عال cell

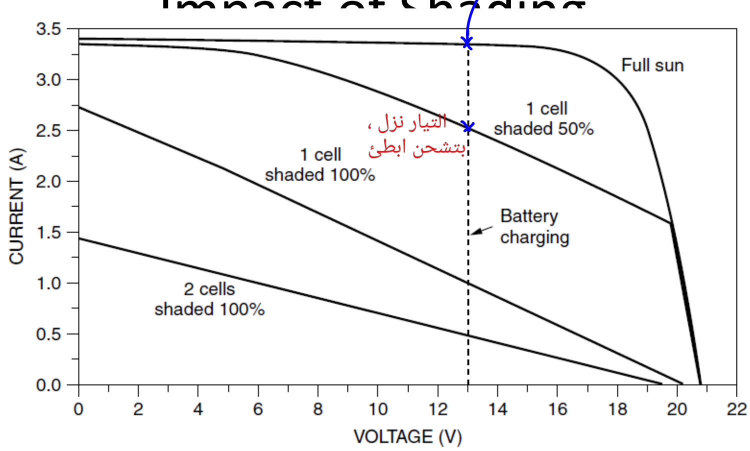
Impact of Shading

- The procedures demonstrated in previous Examples can be extended to develop *I –V* curves under various conditions of shading.
- Figure below shows such curves for the example module under full-sun conditions and with one cell 50% shaded, one cell completely shaded, and two cells completely shaded.
- Also shown on the graph is a dashed vertical line at 13 V, which is a typical operating voltage for a module charging a 12-V battery. The reduction in charging current for even modest amounts of shading is severe. With just one cell shaded out of 36 in the module, the power delivered to the battery is decreased by about two-thirds!



operating point for charging in normal conditions

Impact of Shading



بحالة شحن البطارية
الفولتج من الخلية لازم
يكون اعلى بشوي من قيمة
البطارية والتيار كل ما زاد
كل شحنت اسرع

Effects of shading on the *I –V* curves for a PV module. The dashed line shows a typical voltage that the module would operate at when charging a 12-V battery; the impact on charging current is obviously severe.

لتحسين الاداء

بالسيناريو الي صار لو
حطيت لل shaded cell
دايود Bypass diode
التيار بمر من خلال
الدايود، بالتالي الفولتج الي
رح يقل بكون قليل جدا
والخسارة في ال power
بتكون قليلة

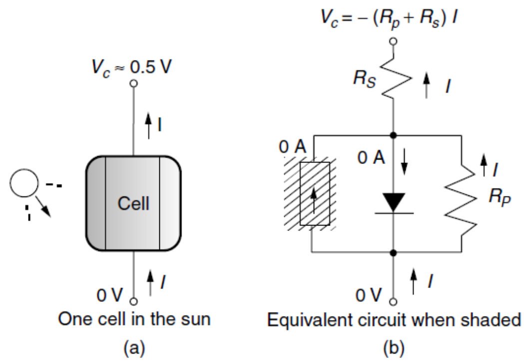
Bypass Diodes for Shade Mitigation

هذا الدايود يتم
اضافته ، يعني ليس
جزء من ال cell

- Previous Example shows not only how drastically shading can shift the *I* –*V* curve, but also how local, potentially damaging hot spots can be created in shaded cells.
- Figure 8.40 shows a typical situation. In Fig. 8.40a a solar cell in full sun operating in its normal range *contributes* about 0.5 V to the voltage output of the module, but in the equivalent circuit shown in 8.40b a shaded cell experiences a *drop* as current is diverted through the parallel and series resistances.
- This drop can be considerable (in previous Example it was over 14 V).
- The voltage drop problem in shaded cells could be to corrected by adding a *bypass diode* across each cell, as shown in Fig. 8.41.
- When a solar cell is in the sun, there is a voltage rise across the cell so the bypass diode is cut off and no current flows through it—it is as if the diode is not even there.

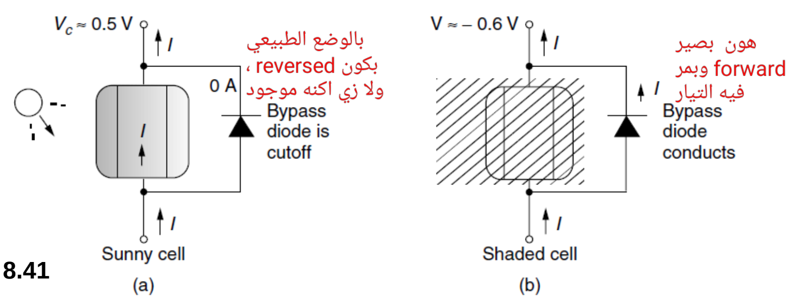
- The voltage drop problem in shaded cells could be to corrected by adding a *bypass diode* across each cell, as shown in Fig. 8.41. When a solar cell is in the sun, there is a voltage rise across the cell so the bypass diode is cut off and no current flows through it—it is as if the diode is not even there.
- When the solar cell is shaded, however, the drop that would occur if the cell conducted any current would turn on the bypass diode, diverting the current flow through that diode.
- The bypass diode, when it conducts, drops about 0.6 V. So, the bypass diode controls the voltage drop across the shaded cell, limiting it to a relatively modest 0.6 V instead of the rather large drop that may occur without it.

Figure 8.40



- In full sun a cell may contribute around 0.5 V to the module output;
- but when a cell is shaded, it can have a large voltage drop across it.

Figure 8.41



- Mitigating the shade problem with a bypass diode.
- In the sun (a), the bypass diode is cut off and all the normal current goes through the solar cell.
- In shade (b), the bypass diode conducts current around the shaded cell, allowing just the diode drop of about 0.6 V to occur.

مش عملي تحط دايود
لكل cell خلال
التصنيع ، بنحط على
module

Bypass Diodes Across Modules

- **In real modules, it would be impractical to add bypass diodes across every solar cell, but manufacturers often do provide at least one bypass diode around a module to help protect arrays, and sometimes several such diodes around groups of cells within a module.**
- **These diodes don't have much impact on shading problems of a single module, but they can be very important when a number of modules are connected in series.**
- **Just as cells are wired in series to increase module voltage, modules can be wired in series to increase array voltage.**
- **Also, just as a single cell can drag down the current within a module, a few shaded cells in a single module can drag down the current delivered by the entire string in an array.**
- **The benefit already demonstrated for a bypass diode on a single cell also applies to a diode applied across a complete module.**

- To see how bypass diodes wired in parallel with modules can help mitigate shading problems, consider Fig. 8.42, which shows *I* –*V* curves for a string of five modules).
- The graph shows the modules in full sun as well as the *I* –*V* curve that results when one module has two cells completely shaded. Imagine the PVs delivering charging current at about 65 V to a 60-V battery bank.
- As can be seen, in full sun about 3.3 A are delivered to the batteries. However, when just two cells in one module are shaded, the current drops by one-third to about 2.2 A.
- With a bypass diode across the shaded module, however, the *I* –*V* curve is improved considerably as shown in the figure.

Impact of bypass diodes. Drawn for five modules in series delivering 65 V to a battery bank. With one module having two shaded cells, charging current drops by almost one-third when there are no bypass diodes. With the module bypass diodes there is very little drop.

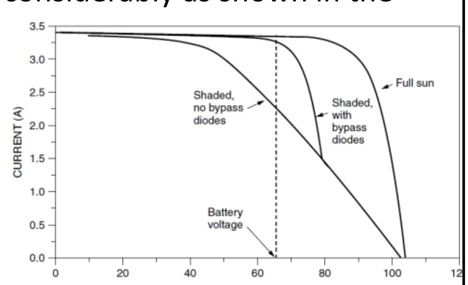


Fig. 8.42

في مثال عالدفتر

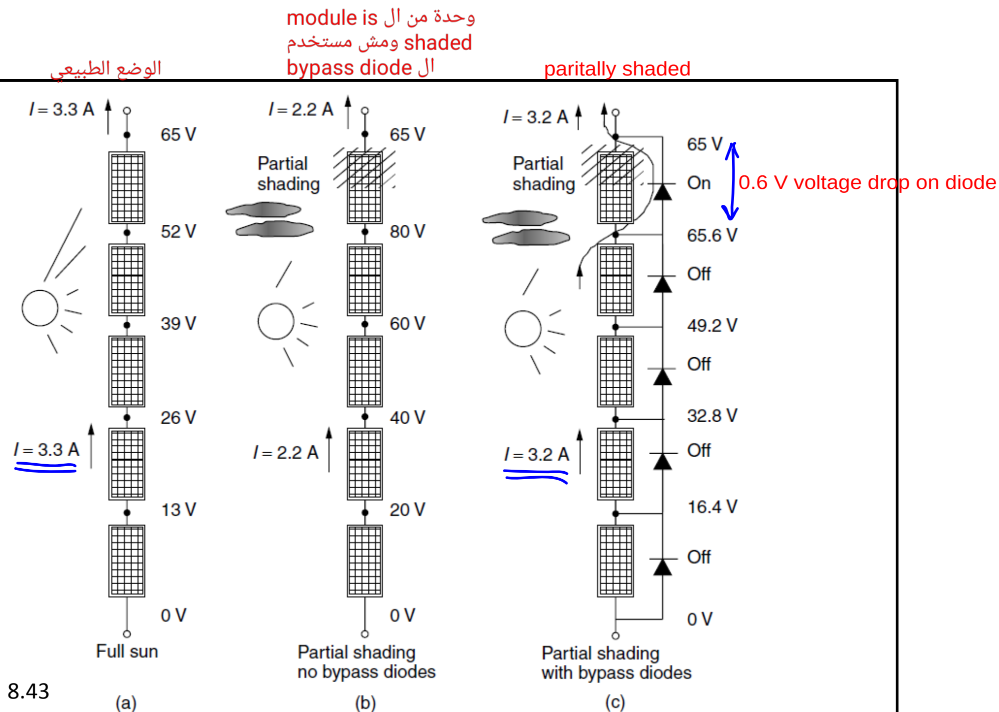


Fig. 8.43

Without bypass diodes, a partially shaded module constricts the current delivered to the load (b). With bypass diodes, current is diverted around the shaded module.

- Figure 8.43 (previous slide) helps explain how the bypass diodes do their job. Imagine five modules, wired in series, connected to a battery that forces the modules to operate at 65 V.
- In full sun the modules deliver 3.3 A at 65 V. When any of the cells are shaded, they cease to produce voltage and instead begin to act like resistors (6.6 per cell in this example) that cause voltage to drop as the other modules continue to try to push current through the string.
- Without a bypass diode to divert the current, the shaded module loses voltage and the other modules try to compensate by increasing voltage, but the net effect is that current in the whole string drops.
- If, however, bypass diodes are provided, as shown in Fig. 8.43c, then current will go around the shaded module and the charging current bounces back to nearly the same level that it was before shading occurred.

في مشكلة اخرى، لو كان عندك ثلاث modules موصلين عالتوازي، اذا كلهم خاضعين لنفس الظروف من حيث الاشعاع فش مشكلة، فرضا لو صار على وحدة منهم shading سواء كلي او جزئي، الخلية رح يقل يصير عليها فولتج قليل جدا وهي مشبوكة مع خلايا عالتوازي لهم فولتج عالي، يعني بتصير تسحب الخلية تسحب تيار منهم، ال bypass diode ما بحل هذه المشكلة

الحل هو بتوصيل دايود على التوالي مع كل خلية يسمى Blocking Diode

Blocking Diodes

بالوضع الطبيعي لما فش shading هذا الدايود ايضا بكون forward وعليه voltage drop يعني في loss power بس بتكون قليلة جدا واقل من الي بحالة ال shading وبدون هذا

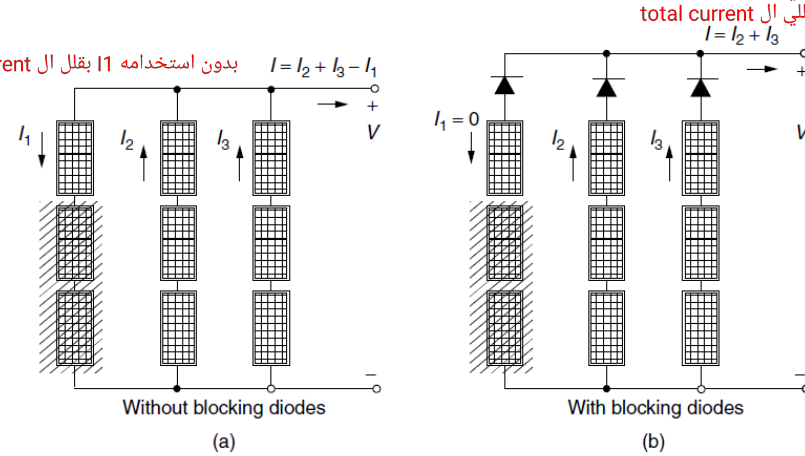
- When strings of modules are wired in parallel, a problem may arise when one of the strings is not performing well.
- Instead of supplying current to the array, a malfunctioning or shaded string can withdraw current from the rest of the array.
- By placing *blocking diodes* (also called *isolation diodes*) at the top of each string as shown in Fig. next slide, the reverse current drawn by a shaded string can be prevented

وظيفة هذا ال diode

Blocking Diodes

هون فش I1 ، يعني الفكرة اذا ما رح يساهم في ال total current ما يقلل ال total current

بدون استخدامه I1 بقلل ال total current



Blocking diodes prevent reverse current from flowing down malfunctioning or shaded strings.

Few more Notes

- The current of a PV device is directly proportional to surface area and solar irradiance.
- In other words, for a given device, doubling the surface area exposed to solar radiation will double the current output.
- Likewise, doubling solar irradiance on the device surface will double current.

- The maximum power point is located on the knee of the I-V curve and is the highest efficiency operating point for a PV device for the given conditions of solar irradiance and cell temperature.
- Due to the shape of the curve, maximum power voltage is typically about 70% to 80% of the value of the open-circuit voltage, while maximum power current is typically about 90% of the value of the short circuit current.
- Maximum power voltage and current can be measured only while the PV device is connected to a load that operates the device at maximum power.

شكل ال curve
يحدد ال mpp

لو كان معك fill factor 72%
وجربت تحسبه وطلع اطلع
هناك احتمالين :
اما انك مش حاسب عند ال 1 sun
او في مشكلة بالخلية او صاير shading او من مقاومة الاسلاك

- Most commercial crystalline silicon PV cells have fill factors exceeding 70%, while the fill factor for many thin-film materials is somewhat less.
- For a higher fill factor cell, the current decreases much less with increasing voltage up to the maximum power point, and decreases much more with increasing voltage beyond maximum power.
- A decrease in fill factor over time indicates problems with PV devices, including degradation of the cells or, more commonly, increased resistance of the wiring or connections in the system.

Efficiency

ال input power هي ال irradiance الي نازلة على ال panel

- *Efficiency is the ratio of power* output to power input.
- The efficiency of PV devices compares the solar power input to the electrical power output.
- Solar irradiance is multiplied by the area of the PV device to determine watts of solar power, which can then be directly compared to watts of electrical power.
- PV cell efficiencies vary considerably among different PV technologies, and for the same material and technology, efficiencies vary widely between laboratory samples and commercial devices.

- Efficiency is expressed as a percentage and is calculated with the following formula:

بالعادة تحسب عند اشعاع 1000

$$\eta = \frac{P_{mp}}{E \times A}$$

input power

- *Pm - maximum power (in W)*
- *E = solar irradiance (in W/m2)*
- *A = area (in m^2)*

Example

- For example, what is the efficiency of a PV module with a surface area of 1.2 m^2 and a maximum power output of 160 W when exposed to 1000 W/m^2 solar irradiance?

$$\eta = \frac{P_{mp}}{E \times A}$$

$$\eta = \frac{160}{1000 \times 1.2}$$

$$\eta = \frac{160}{1200}$$

$$\eta = \mathbf{0.133} \text{ or } \mathbf{13.3\%}$$

- Cells with higher efficiencies require less surface area to produce each watt of power, which saves some costs for raw materials, mounting structures, and other equipment.
- However, higher efficiency modules are generally no less expensive than less efficient ones, because the price for modules is generally based on the maximum power rating and not on the size.
- For modules, efficiencies are often based on the entire module laminate area including the frame, and spacing between individual cells in the module.
- For individual cells, there is none of this extra area to affect the efficiency.
- This is one reason why module efficiencies are lower than their associated best cell efficiencies.

الكفاءة تعتمد على المساحة ، كل ما قلت بتزيدالكفاءة

ال Op ممكن تكون اي نقطة عال I V curve ما عدا الاطراف

Operating point

- The operating point on an I-V curve is determined by the electrical load of the system.
- For example, if a battery is connected to a PV module, the battery voltage sets the operating voltage of the module. It also establishes the operating current that flows between the device and battery.
- If an incandescent lamp or DC motor is connected to a PV device, the effective resistance of the lamp filament or motor determines the operating point.
- Short-circuit current is associated with zero load resistance and open-circuit voltage is associated with infinite load resistance.
- Every point in between the two states has a specific load resistance that increases from left to right along the I-V curve.

وال load هو الي بفرض ال op

Operating point اكبر كفاءة تحصل عليها عند التشغيل على ال mpp

- PV cells operate most efficiently at their maximum power points. However, the maximum power point is constantly changing due to changes in solar irradiance and cell temperature.
- Consequently, some systems use maximum power point tracking (MPPT) to dynamically match the electrical loads to PV output in order to maximize the performance.
- This function is included in most interactive inverters and some battery charge controllers.
- The electrical load resistance required to operate a PV device at any point can be calculated using Ohm's law.

- For the maximum power point, the formula is:

$$R_{mp} = \frac{V_{mp}}{I_{mp}}$$ impedance at mpp

where

R_{mp} = resistance at maximum power point (in Ω)

V_{mp} = maximum power voltage (in V)

I_{mp} = maximum power current (in A)

- For example, a module has maximum power voltage of 15 V and maximum power current of 3 A.
- What resistance is required to operate the module at the maximum power point, and what is its maximum power?

$$R_{mp} = \frac{V_{mp}}{I_{mp}}$$

$$R_{mp} = \frac{15}{3}$$

$$R_{mp} = 5\,\Omega$$

$$P_{mp} = V_{mp} \times I_{mp}$$

$$P_{mp} = 15 \times 3$$

$$P_{mp} = 45\ \mathrm{W}$$

I-V Curve Measurement

① • A variable resistive load, such as a rheostat or adjustable resistor, can be used to load a PV device over nearly its entire I-V curve.

مقاومة متغير من
صفر الى infinity

- When combined with meters measuring voltage and current, this method can be used to generate the I-V curves of small PV devices or individual modules which can be then used to identify the key I-V curve parameters

Automated I-V Curve Measurement

- Automatic Measurement of I-V curve can be done using an electronic load
- (2) This electronic load can be implemented using commercially available electronic loads
- Many other techniques can be used to implement the electronic load using (3) capacitive charging, (4) MOSFET , (5) DC-Dc converter

Junction Box

موجود عال panel وفي
داخله bypass diode

- A junction box on the back of a module provides a protected location for electrical connections and bypass diodes.

ايضا تشبيكات
اسلاك ال panel

هون عنا two bypass
diode
يعني ال cells مقسمة الى
مجموعتين لكل مجموعة
دايود
بامكانك تعملهم على

لازم تكون عالية حتى
يكفلوها لفترة اطول

Reliability

mechanical tests

- Reliability of modules is assured through series Design qualification tests which include thermal cycling, humidity and freezing, impact and shock, immersion, cyclic pressure, twisting, vibration and other mechanical tests, and excessive and reverse current electrical tests.
- Design qualification has important implications for product warranties offered by manufacturers.
- As a result, most major module manufacturers offer warranties of 20 years or more, guaranteeing module peak power output of at least 80% of initial nameplate ratings.
- This equates to a degradation rate of no more than 1% per year.
- These exceptionally long warranty periods are not typical among other electrical equipment and appliance warranties, but are offered to assure buyers of the long term performance of PV systems.

بخضعوا ال design لظروف
مختلفة مثل درجات حرارة عالية
او منخفضة
تسمى thermal cycling

بعد 20 سنة بتصير تعطي
80% من ال mpp وال
rating values

ENEE5307 Renewable Energy and Photovoltaic Energy Systems (Instructor Nasser Ismail) BIRZEIT UNIVERSITY

Module Label

•Module labels must include performance ratings for the module and may include other information used to design a PV system.