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Design of Photovoltaic Systems

The University of Jordan

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Outline

- Legal Framework in Jordan
- Introduction to Solar Radiation & PV Fundamentals
- Design Steps of On-grid PV System
- Design Steps of Off-grid PV System
- Economical Evaluation of PV Projects

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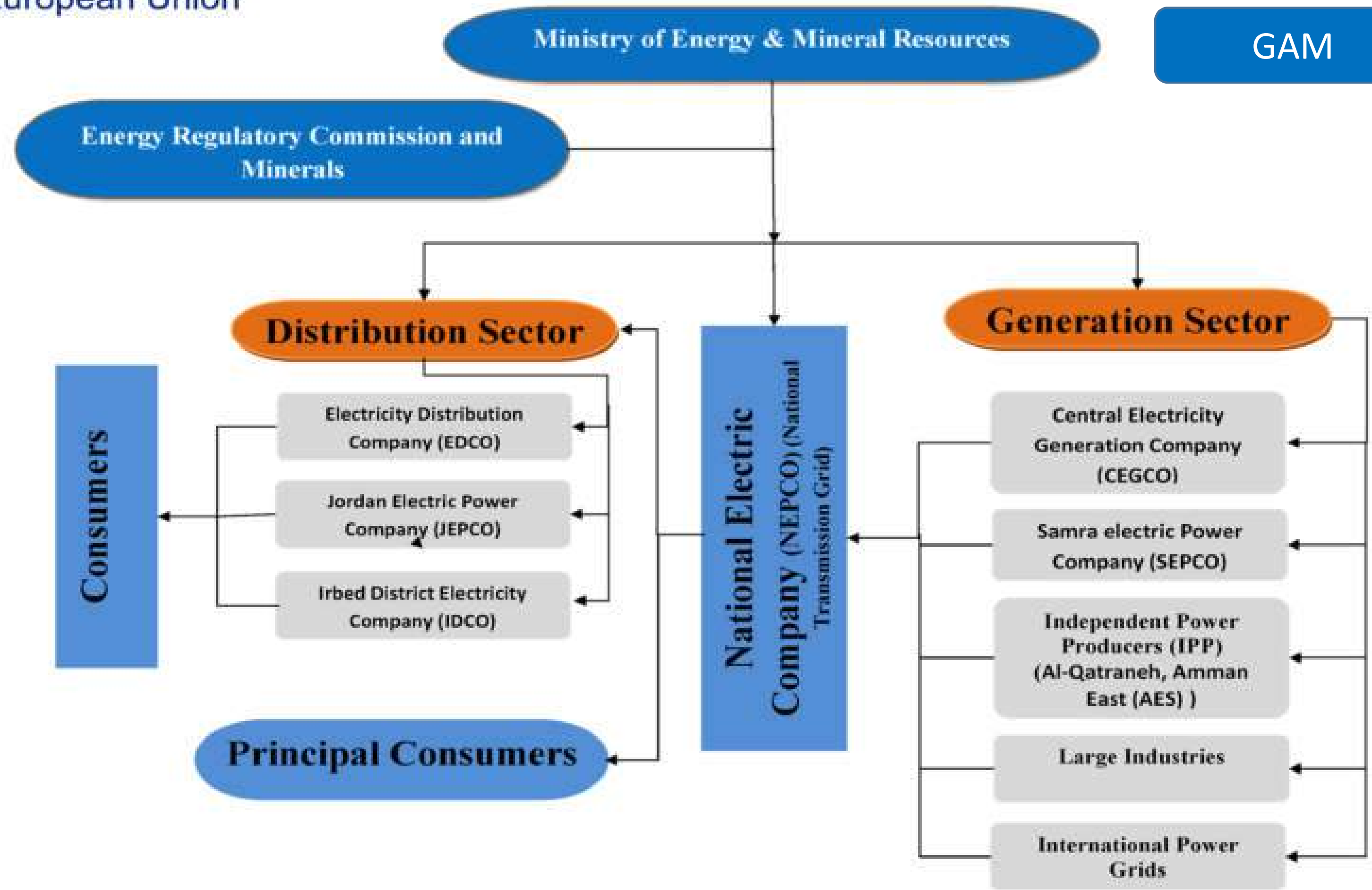
Legal Framework in Jordan

GAM



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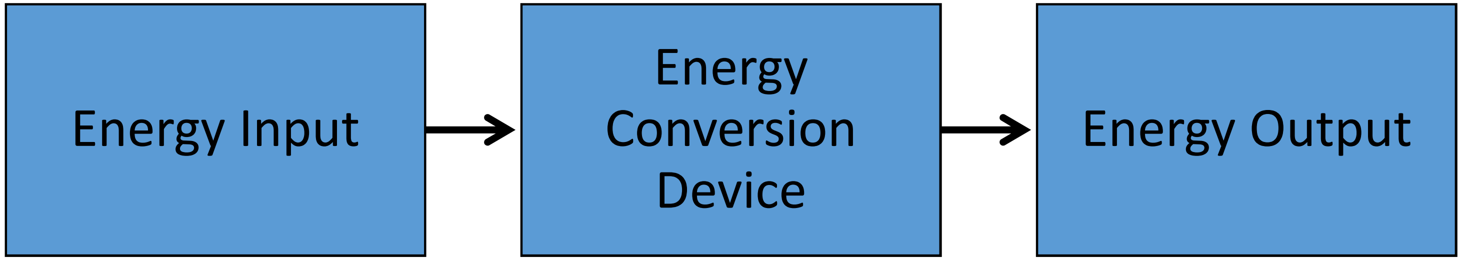
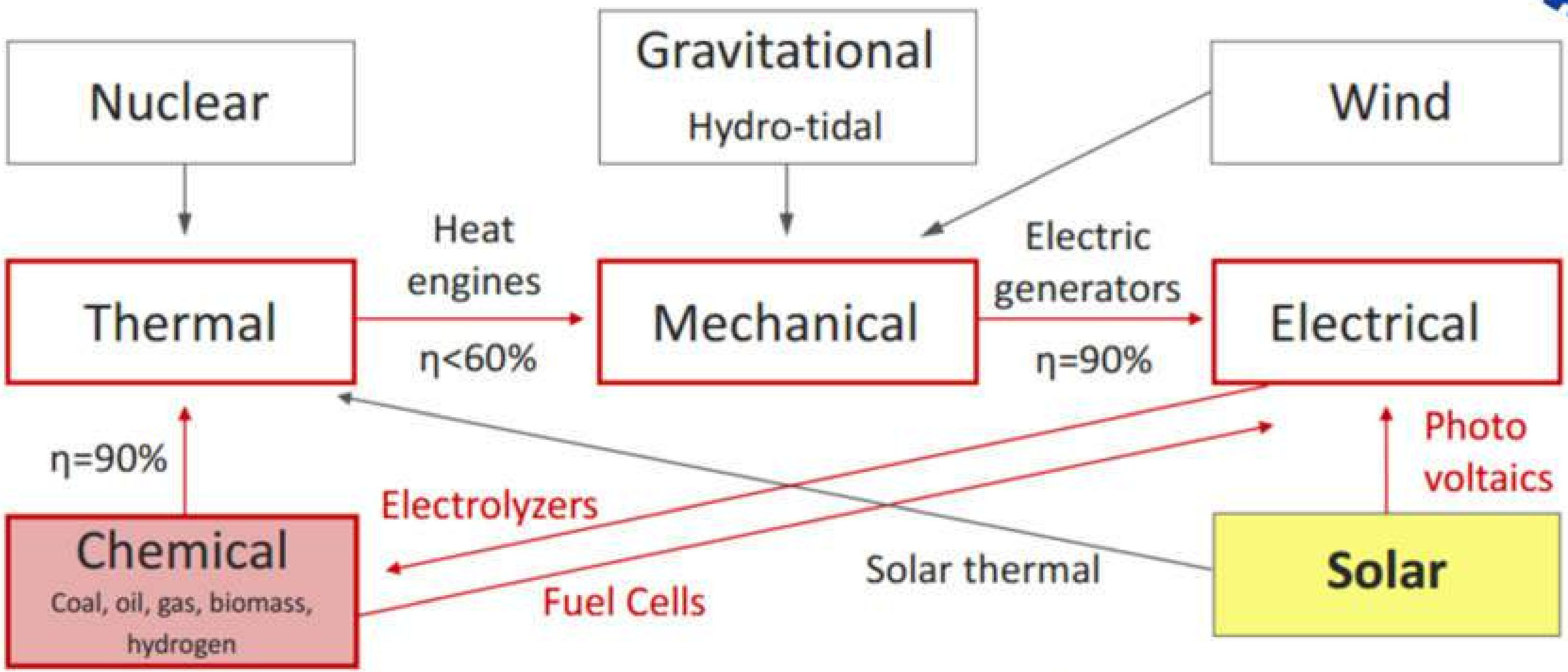
Energy Conversion



$$Efficiency = \frac{Useful\ Energy\ Output}{Energy\ Input}$$



(Source: L. Freris, D. Infield, Renewable Energy in power Systems, Wiley 2008)

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- The unit of energy is joule (J).
- Power is the energy per time and is expressed in watts (W).
- 1 watt is 1 joule per second.
- In this course we will use a more practical unit, which is generally used to express the electrical energy, kilowatthours (kWh)

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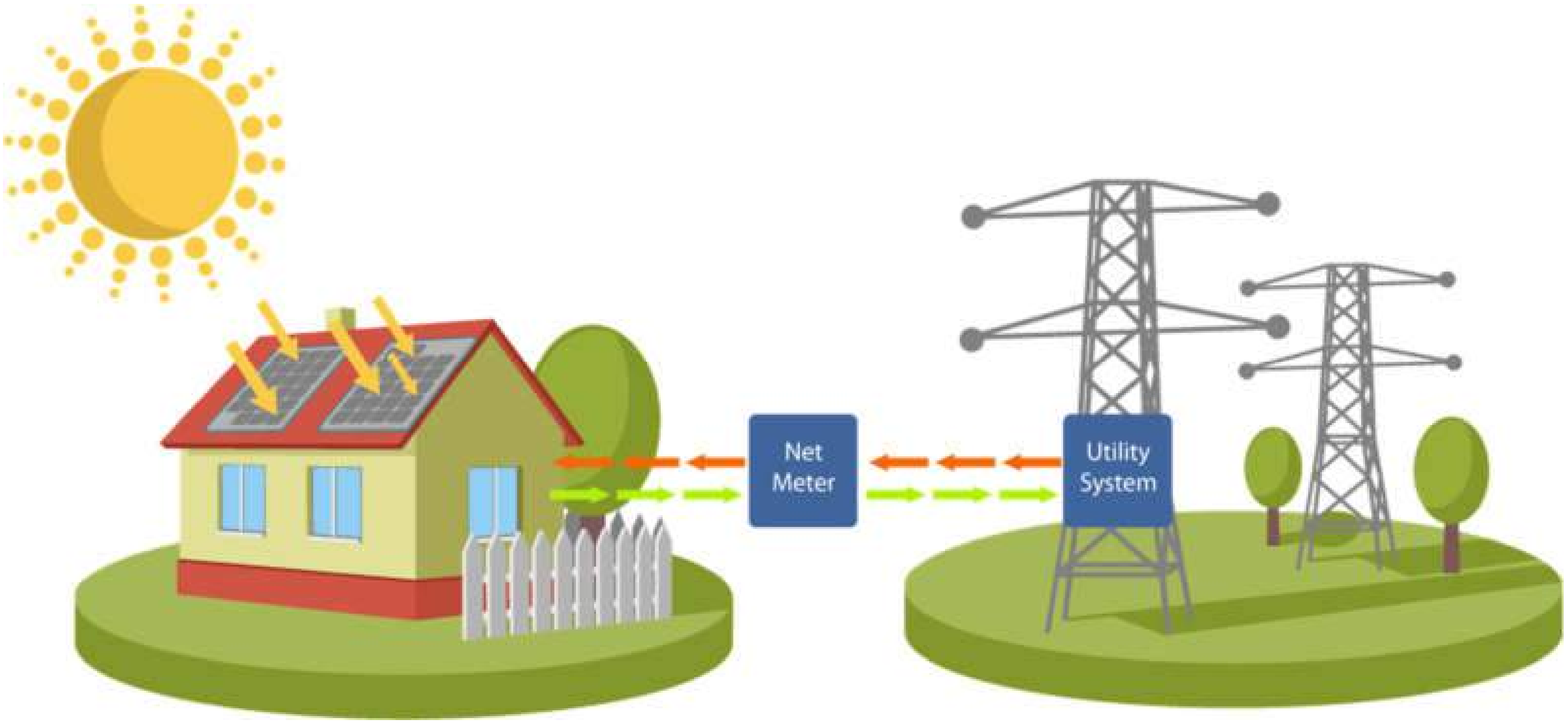
Net Metering vs Feed-in Tariff



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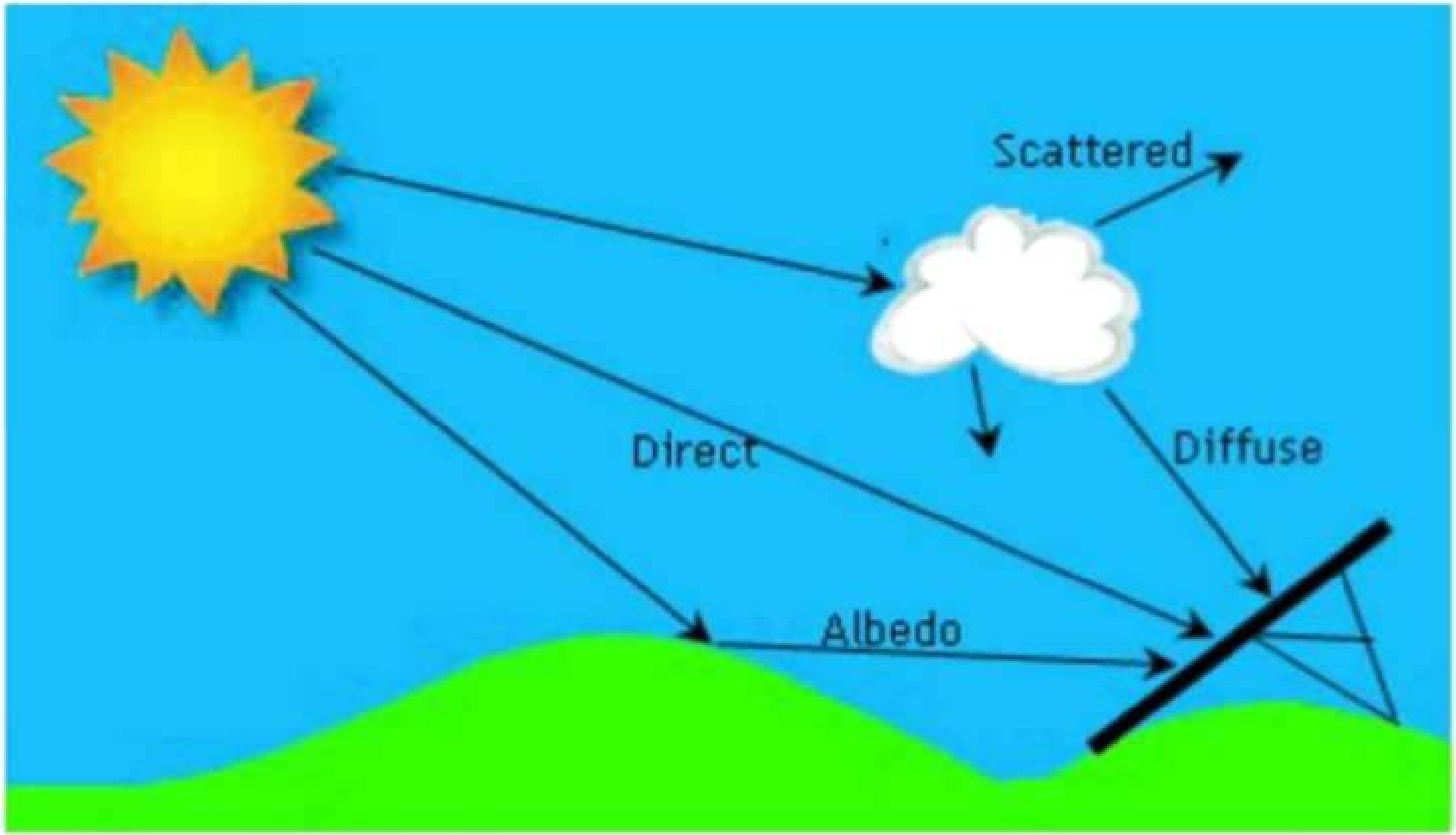
Solar Radiation & PV Fundamentals



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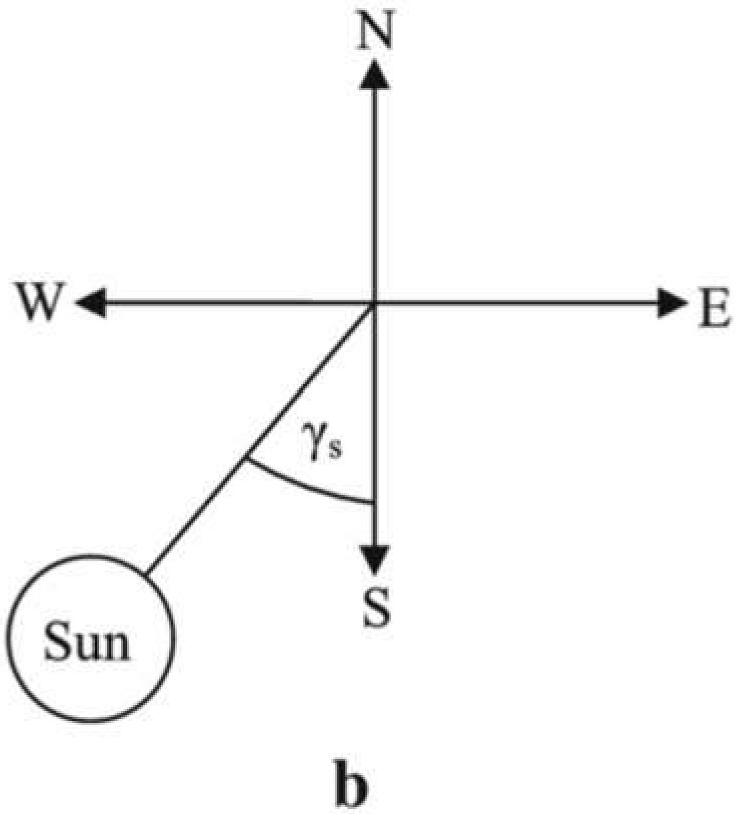
Azimuth Angle



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Azimuth Angle

Solmetric™

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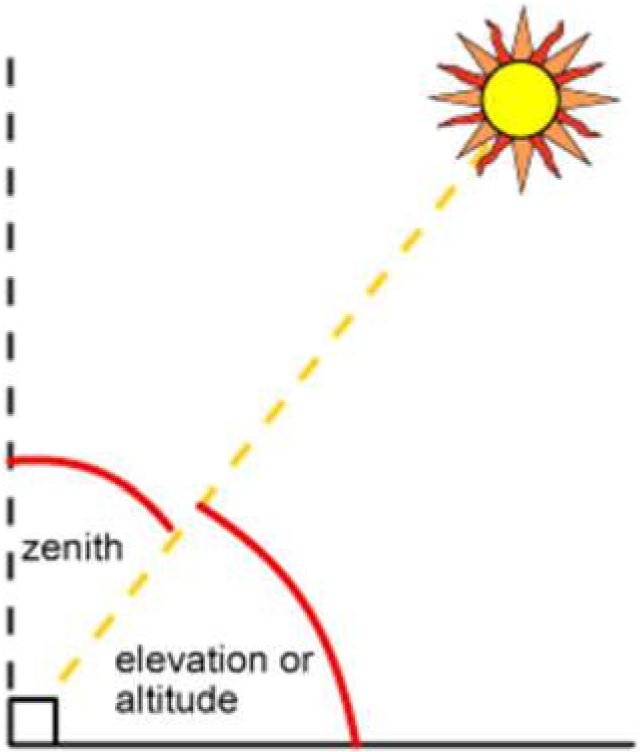
Elevation Angle



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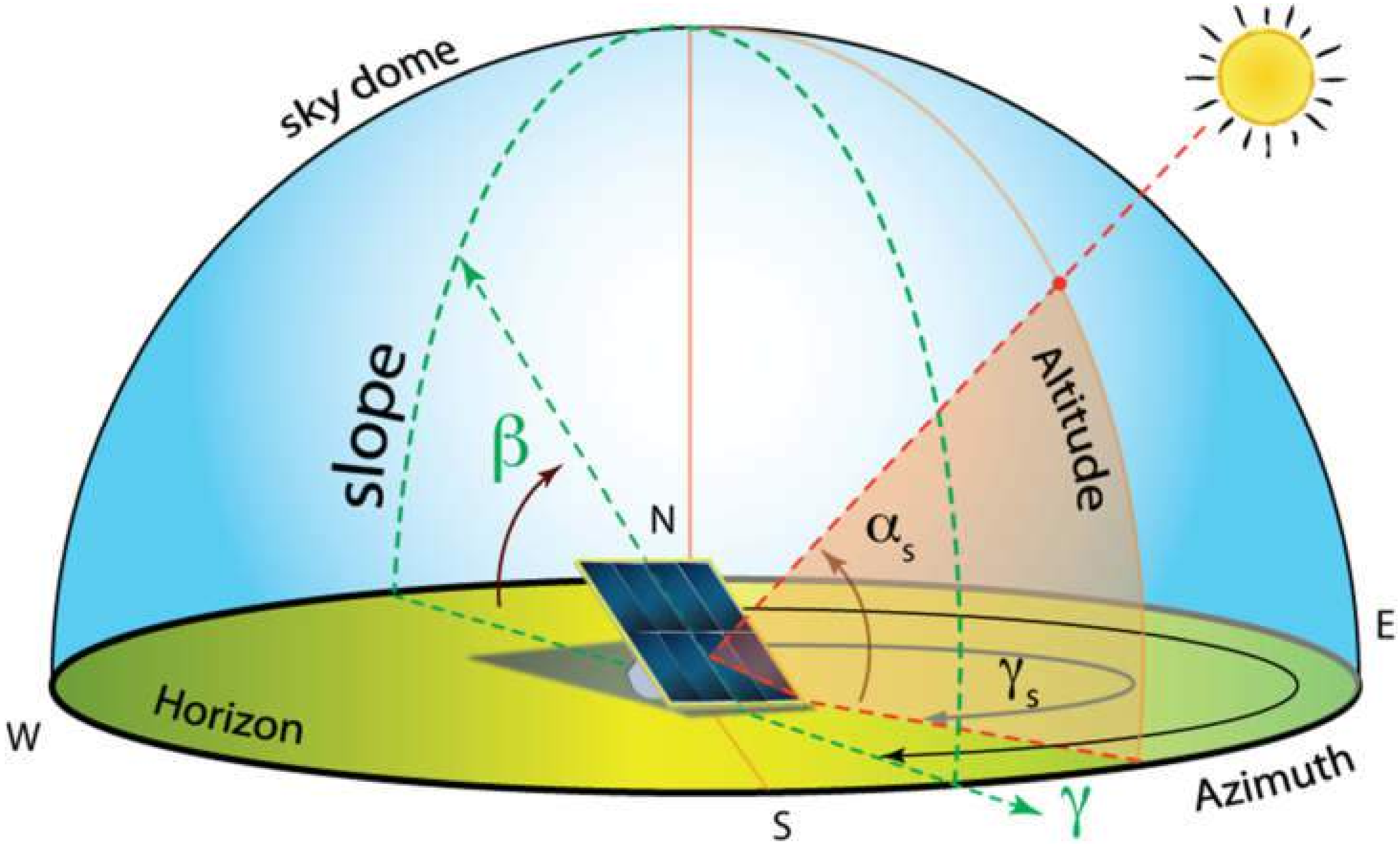
Tilt Angle



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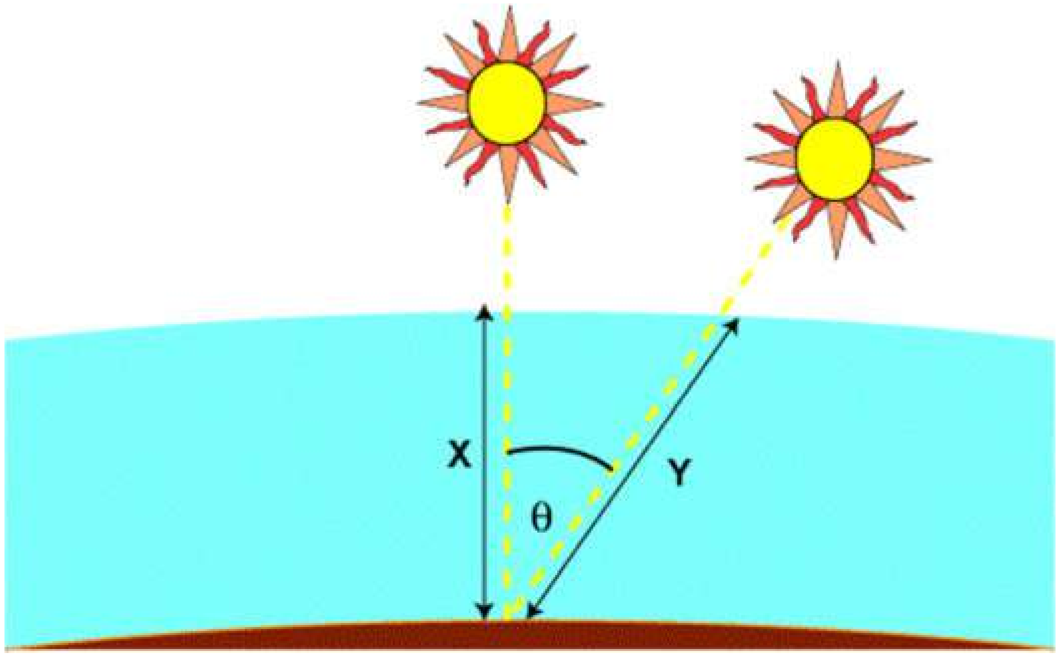
Air Mass



$$AM = \frac{1}{\cos \theta}$$

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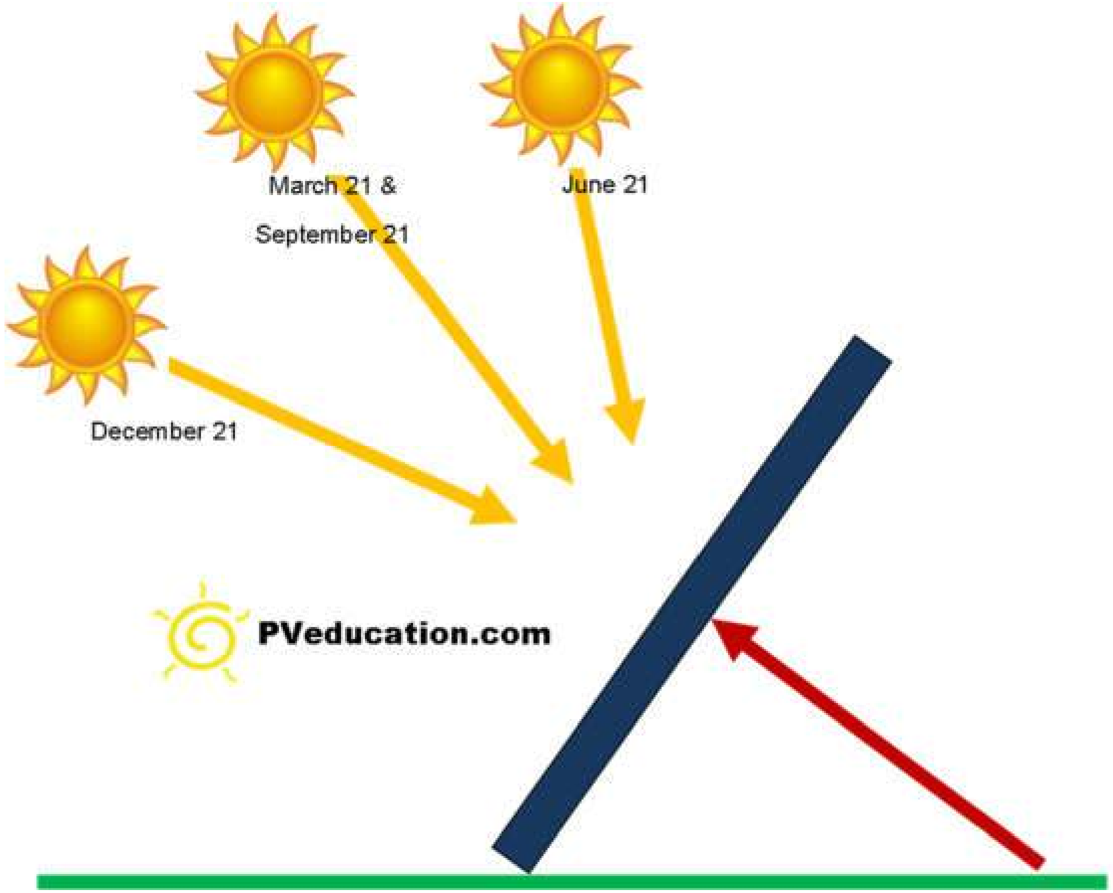
Sun Path (3D Sun Path)



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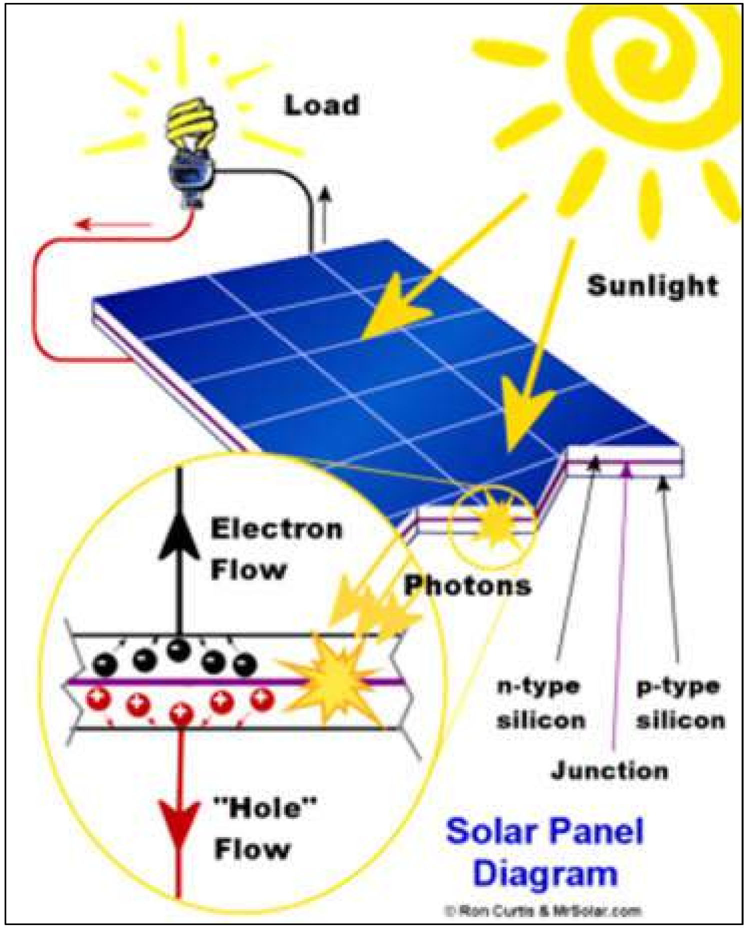
Solar Cell Working Principle



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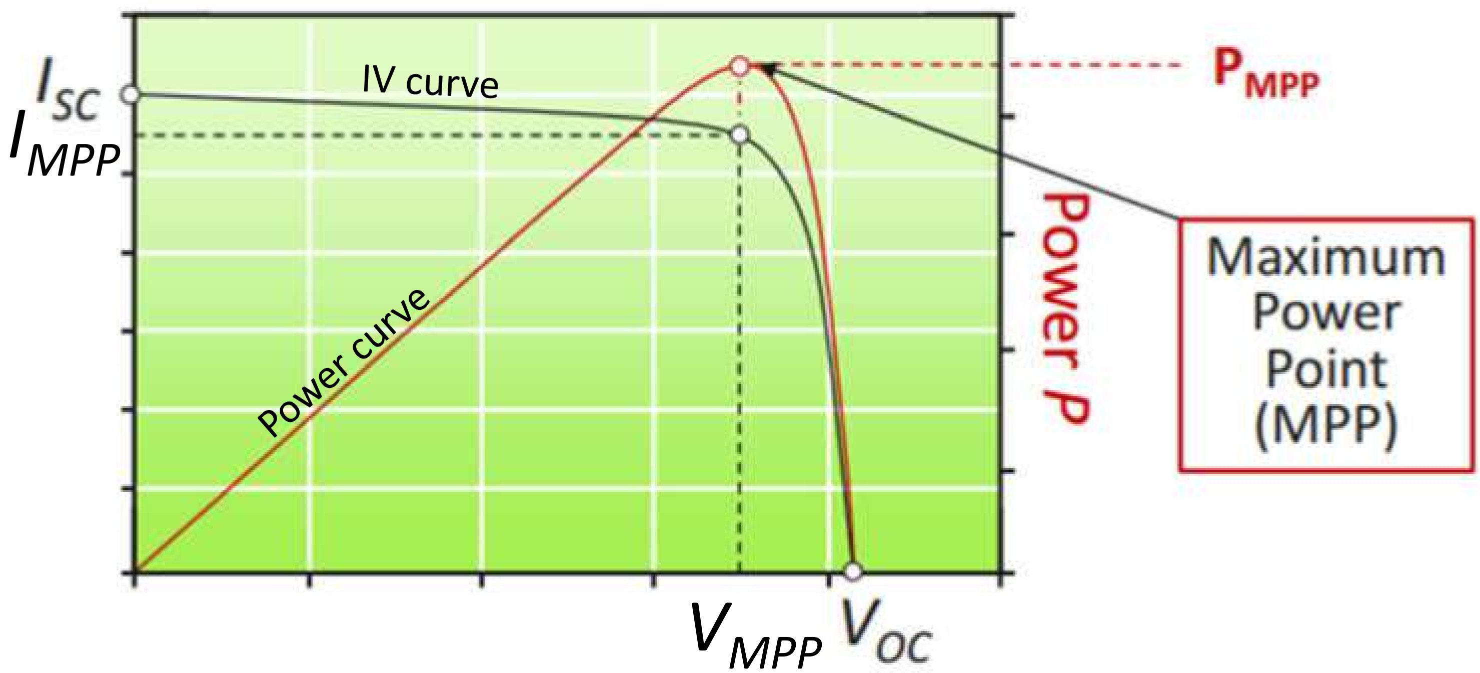
IV-Curve & MPPT



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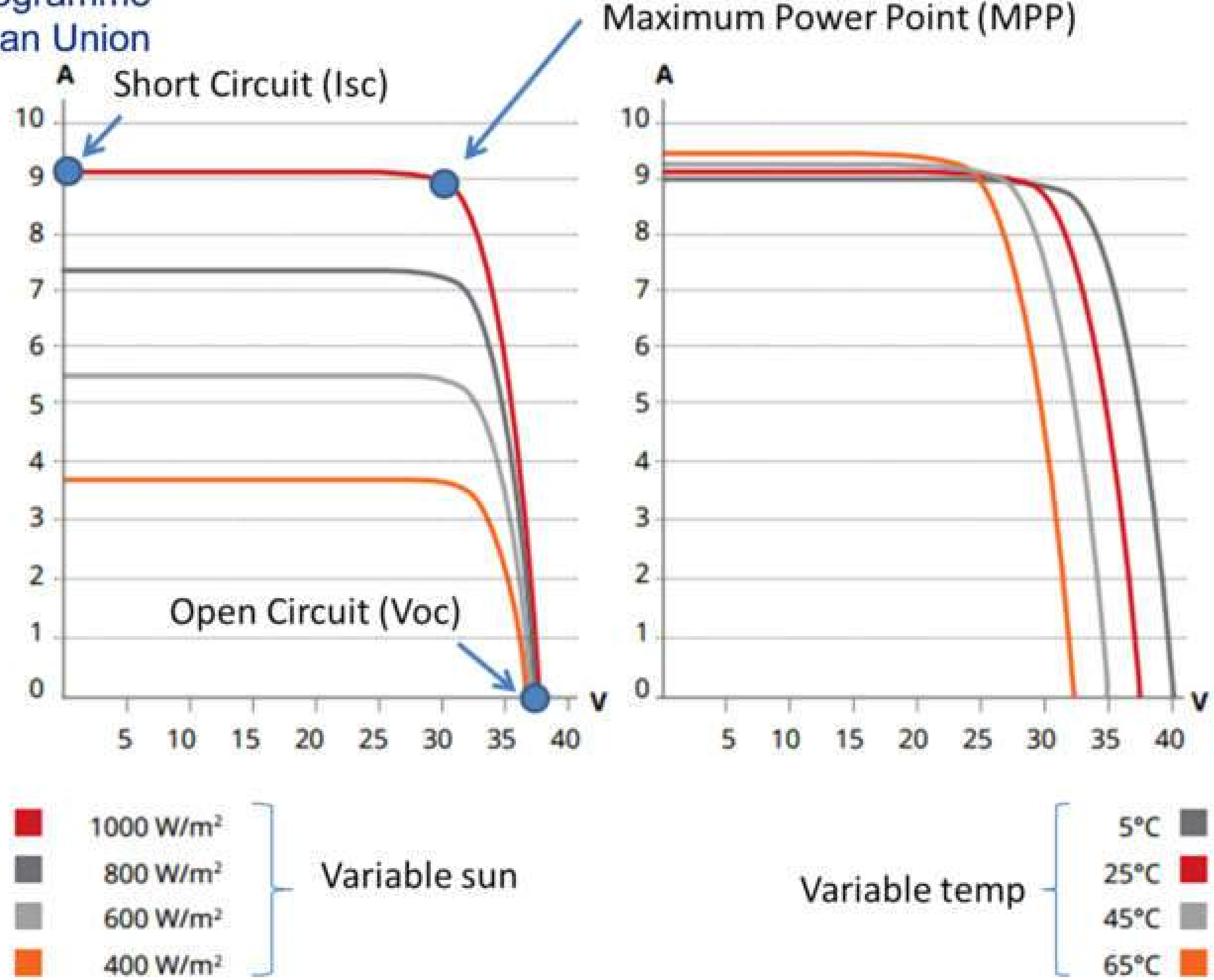

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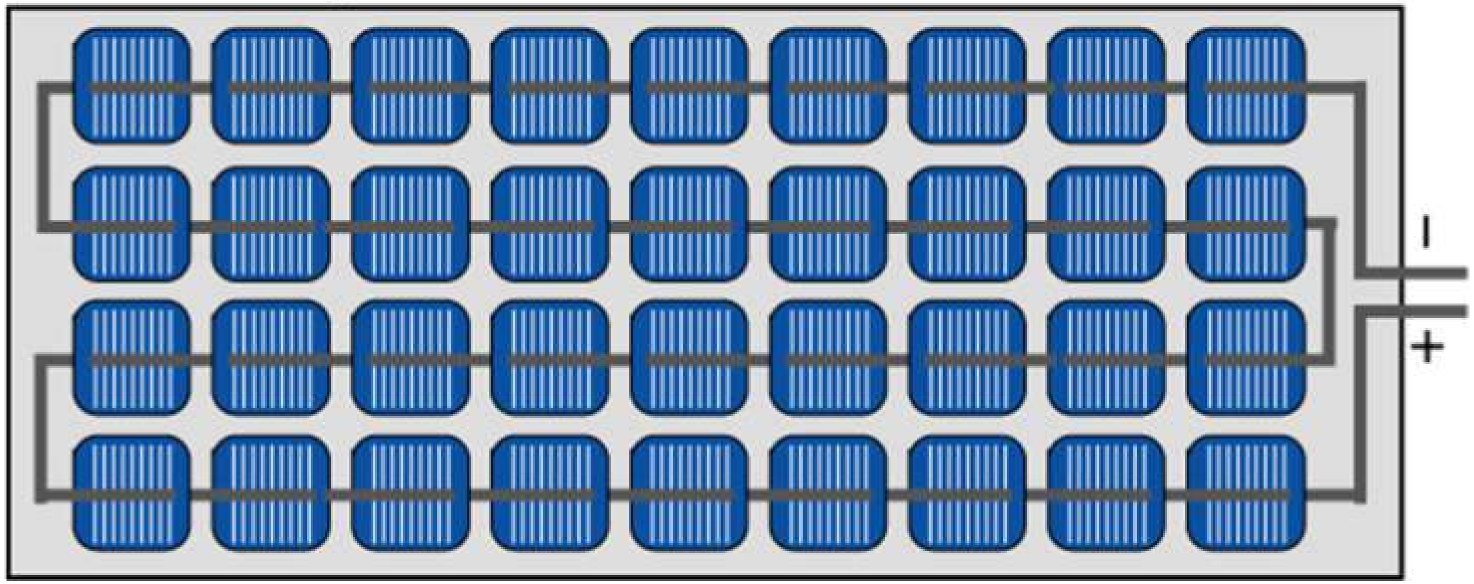
Module Circuit Design

A typical module has 36 cells connected in series



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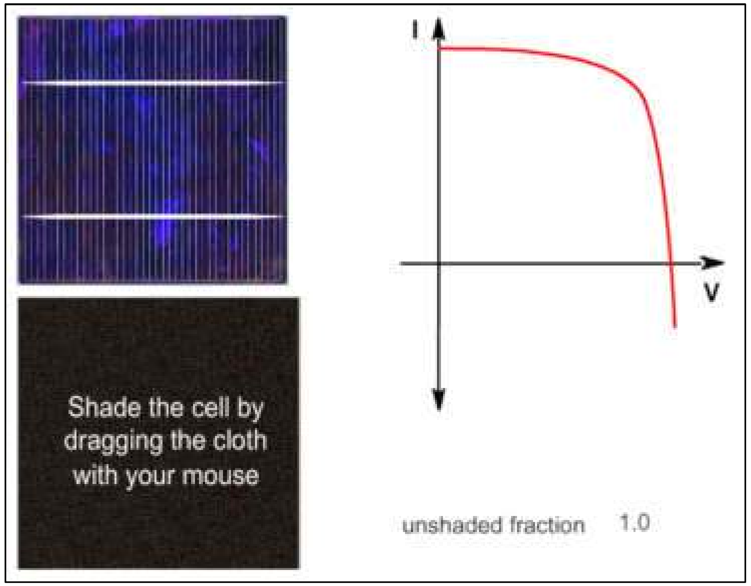
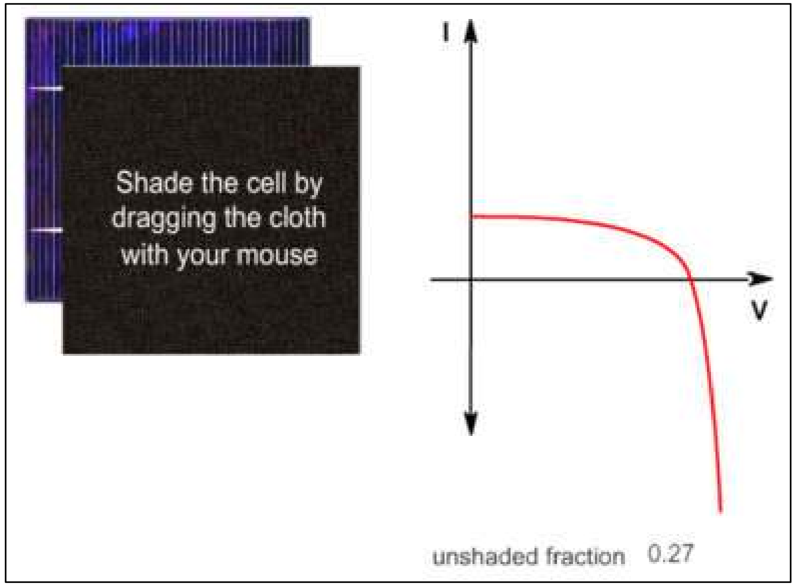
Shading Effect





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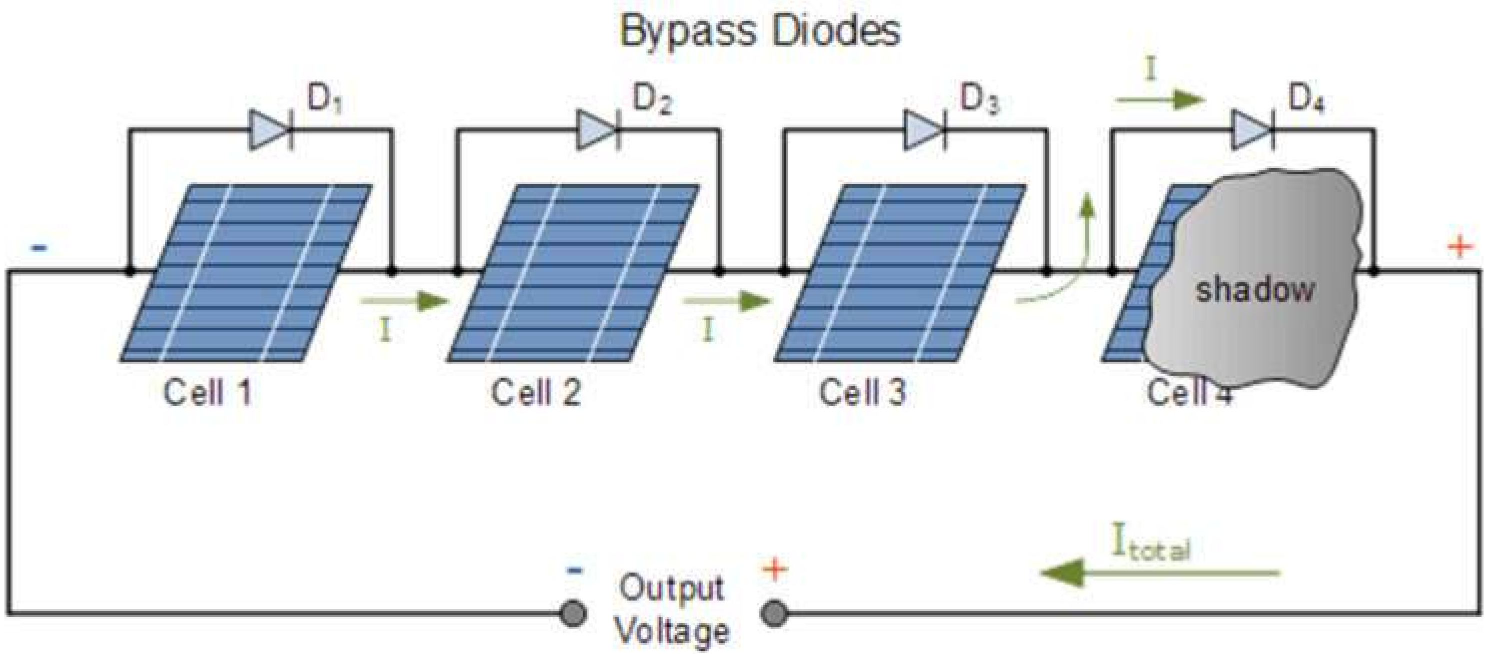
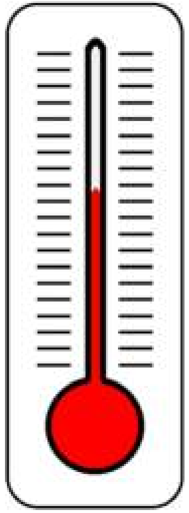
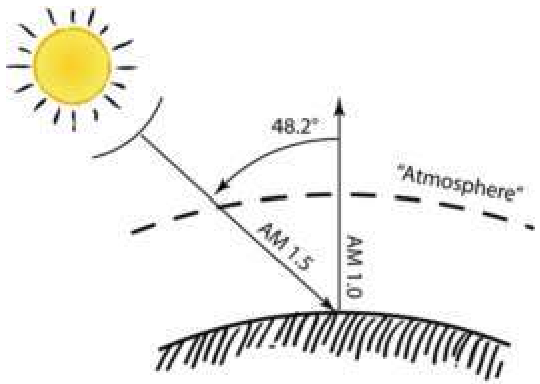
Bypass Diodes



Standard Test Conditions (STC)





1000 W/m^2 25˚C Cell Temp. Air Mass 1.5

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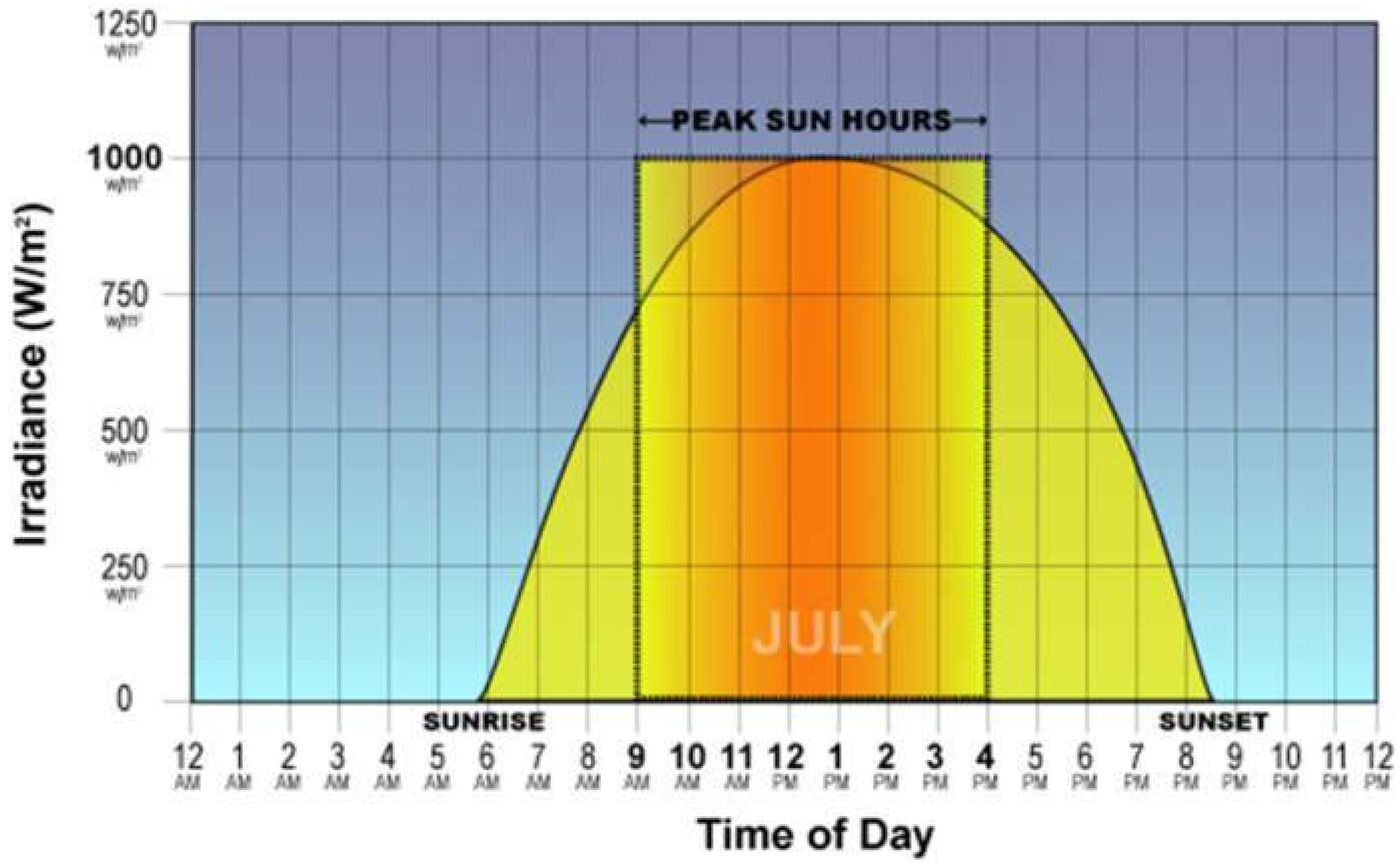
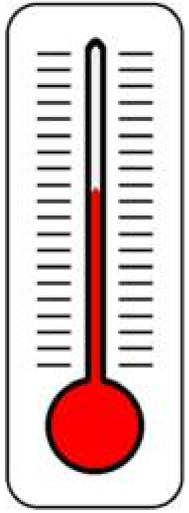
Peak Sun Hours



Nominal Operating Cell Temp. (NOCT)


800 W/m^2 20˚C Ambient Temp. 1 m/s

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Types of Solar Panels

Monocrystalline	Polycrystalline	Thin-film
Up to 23.5%	Up to 22%	Up to 18%
-0.39% / ˚C	-0.40% / ˚C	-0.32% / ˚C
Most expensive	Average	Cheapest

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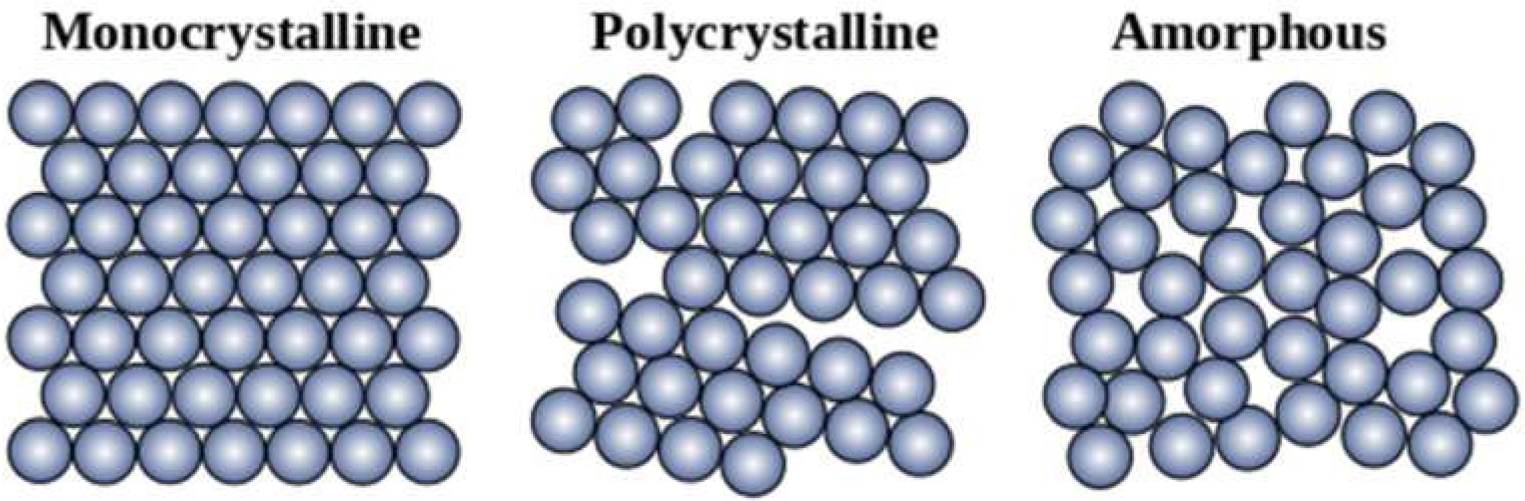
Types of Solar Panels



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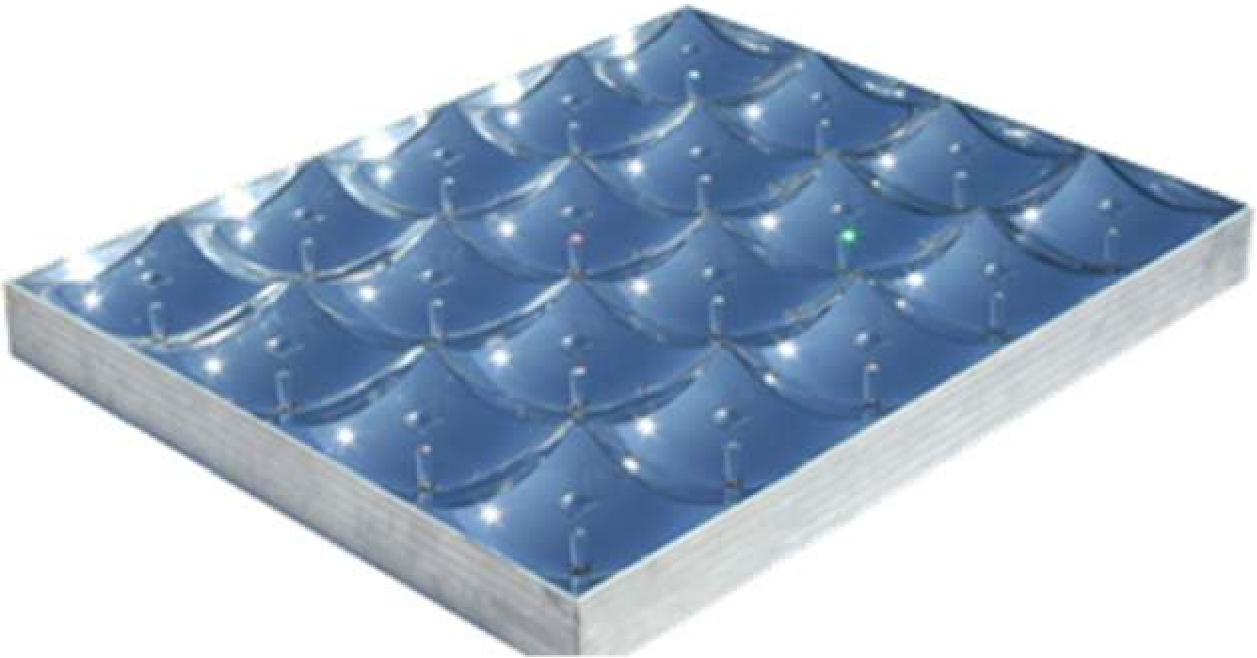
Concentrating Photovoltaics (CPV)



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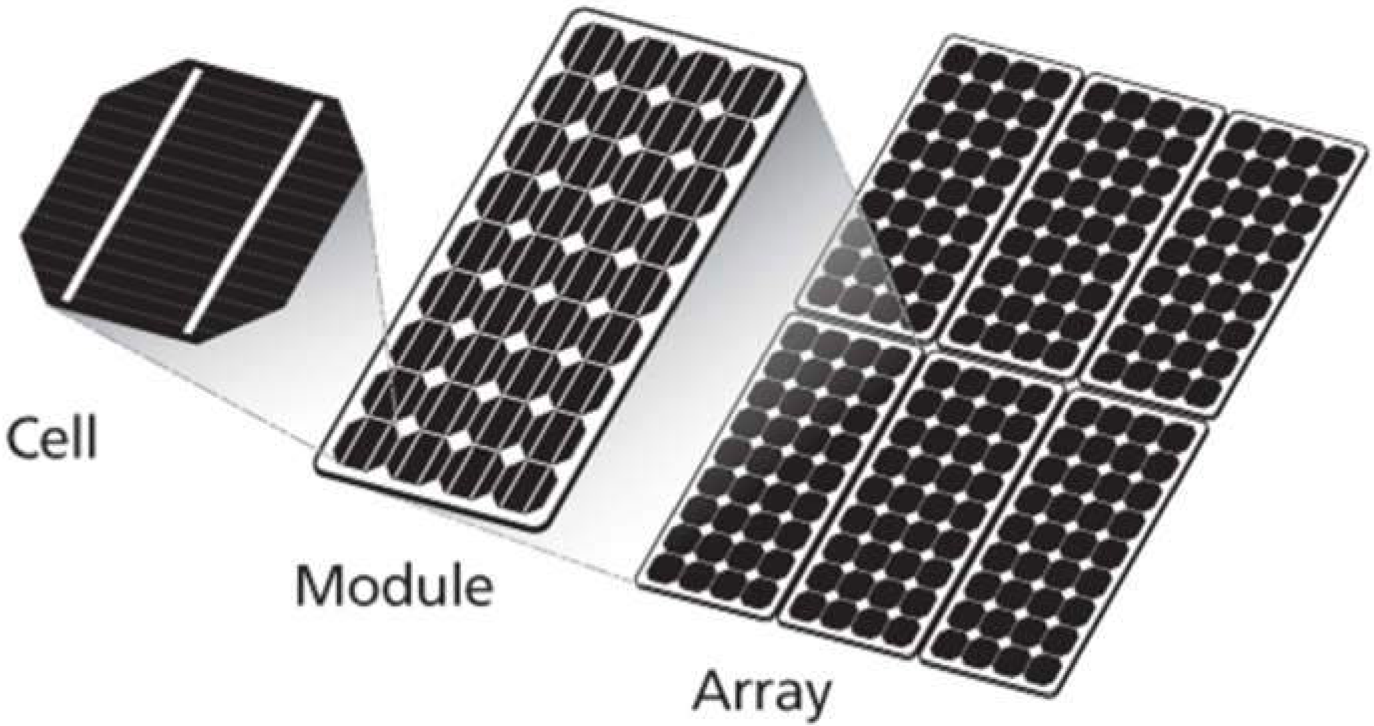
Cell, Module (Panel), Array



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Mounting Structure

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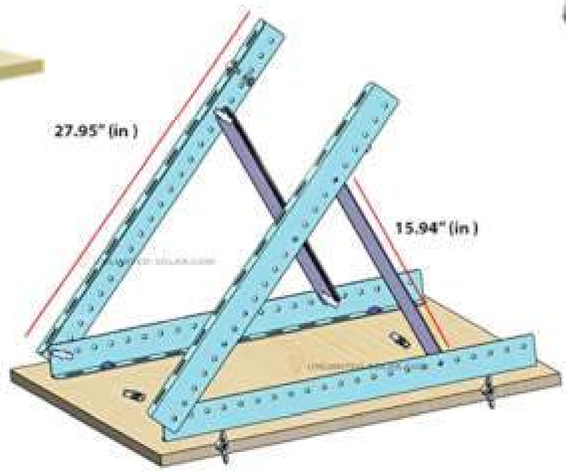
Types of Mounting Systems (According to orientation type)

Fixed



Adjustable

Tracking

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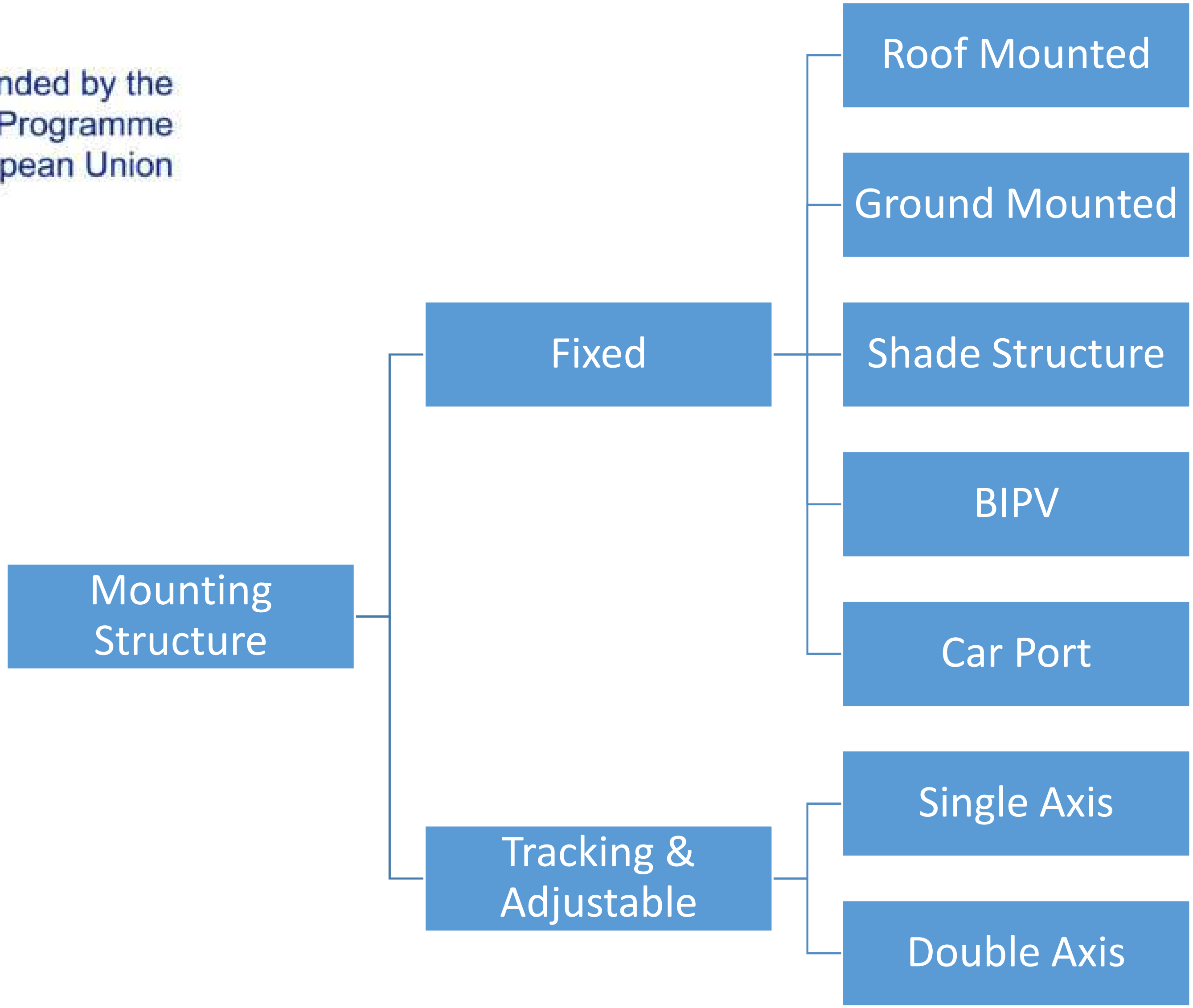

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Roof Mounted

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Ground Mounted

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Self-Ballasted Arrays

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Direct-Mounted Arrays

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Pole-Mounted Arrays

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Shade Structure

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Building Integrated Photovoltaics (BIPV)

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Car Ports

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Temperature Effect

Mounting Type	Increase in Cell Temperature [°C]
Ground Mounted and Car Ports	+20
Roof Mounted	+30
Facade	+35
BIPV	+45

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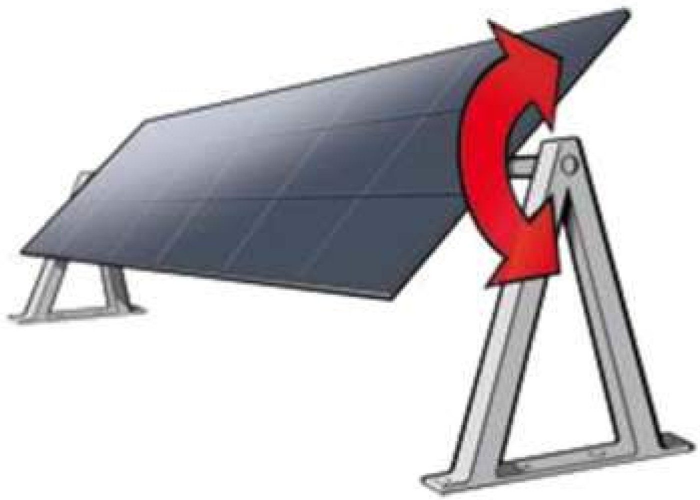
Single Axis Tracking



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Double Axis Tracking

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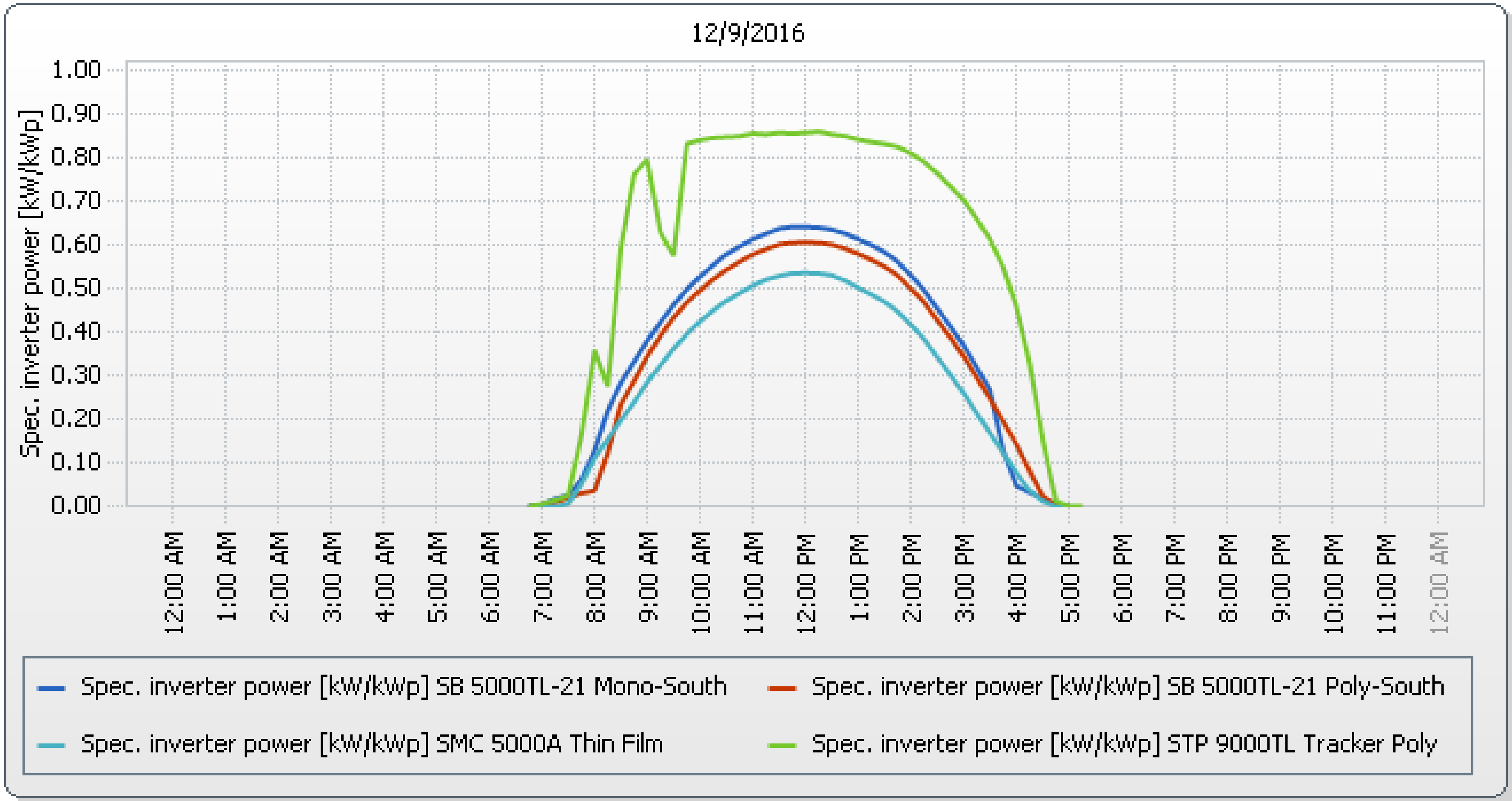

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Key factors in Mechanical Design and Module Layout

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Module physical characteristics.

Mechanical Characteristics	
Cell Type	Mono-crystalline PERC 156×156mm (6 inch)
No.of cells	72 (6×12)
Dimensions	1956×992×40mm (77.01×39.05×1.57 inch)
Weight	26.5 kg (58.4 lbs)
Front Glass	4.0mm, High Transmission, Low Iron, Tempered Glass
Frame	Anodized Aluminium Alloy
Junction Box	IP67 Rated
Output Cables	TÜV 1×4.0mm², Length:900mm or Customized Length

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Thermal characteristics of modules and effects of mounting system.

Temperature coefficients of Pmax	-0.39%/°C
Temperature coefficients of Voc	-0.29%/°C
Temperature coefficients of Isc	0.05%/°C

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Weather sealing of building penetrations and attachments.

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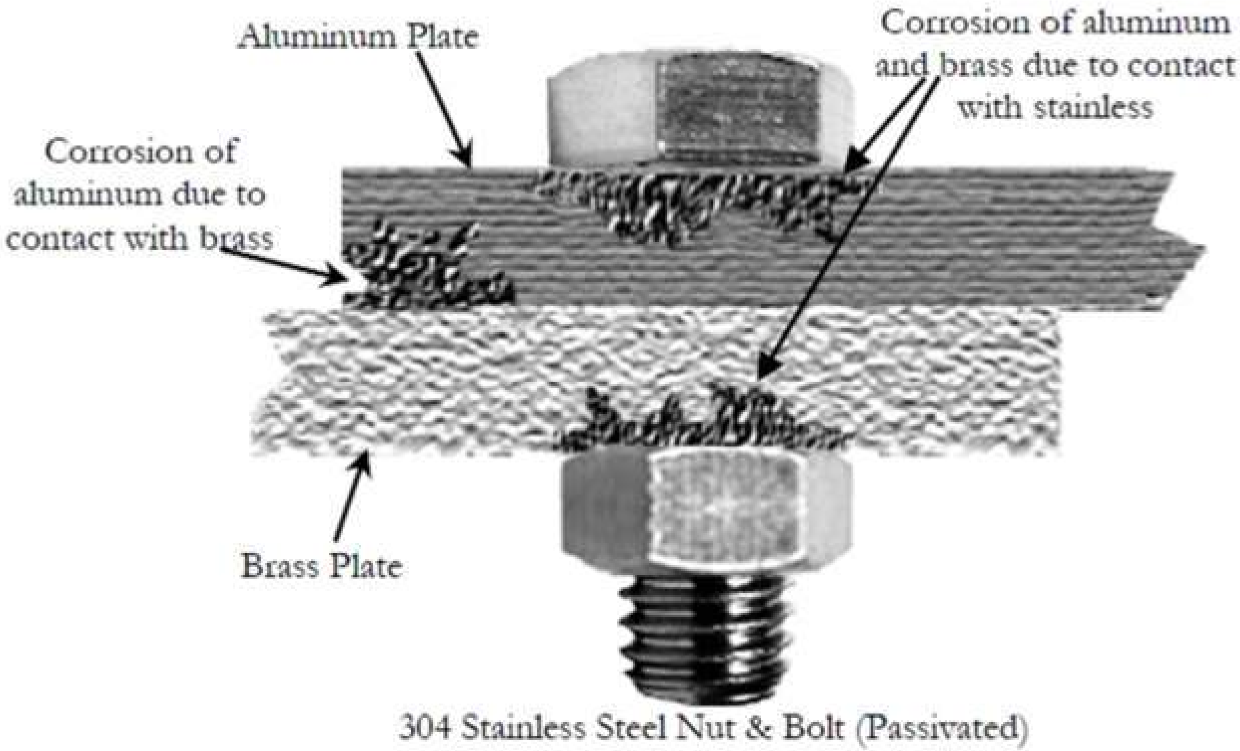
Materials and hardware compatibilities with the application environment.



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Materials and hardware compatibilities with the application environment.

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Aesthetics and appearance.

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Aesthetics and appearance.

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Aesthetics and appearance.

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Optimizing Array Performance

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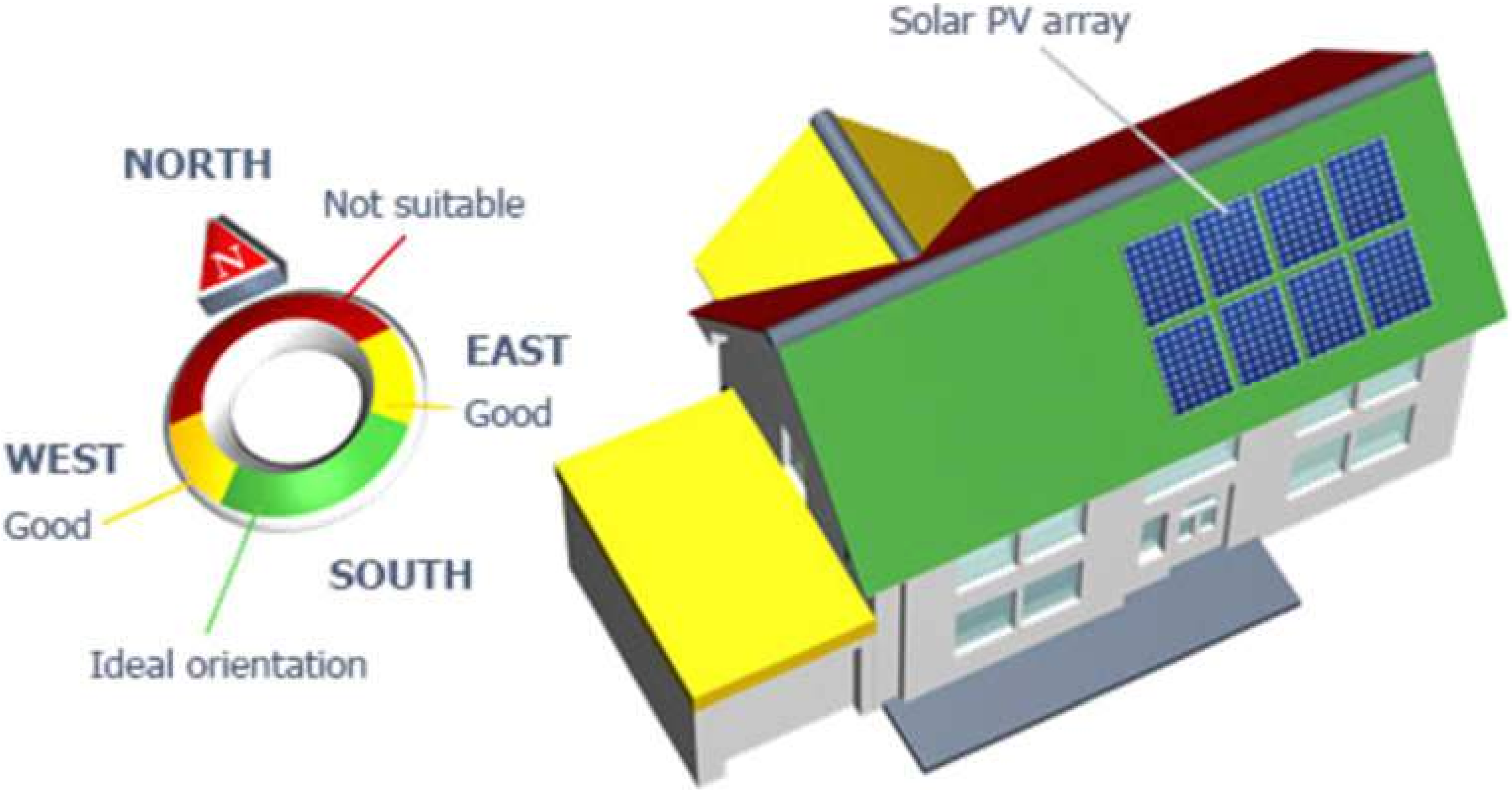
Optimum Tilt & Azimuth



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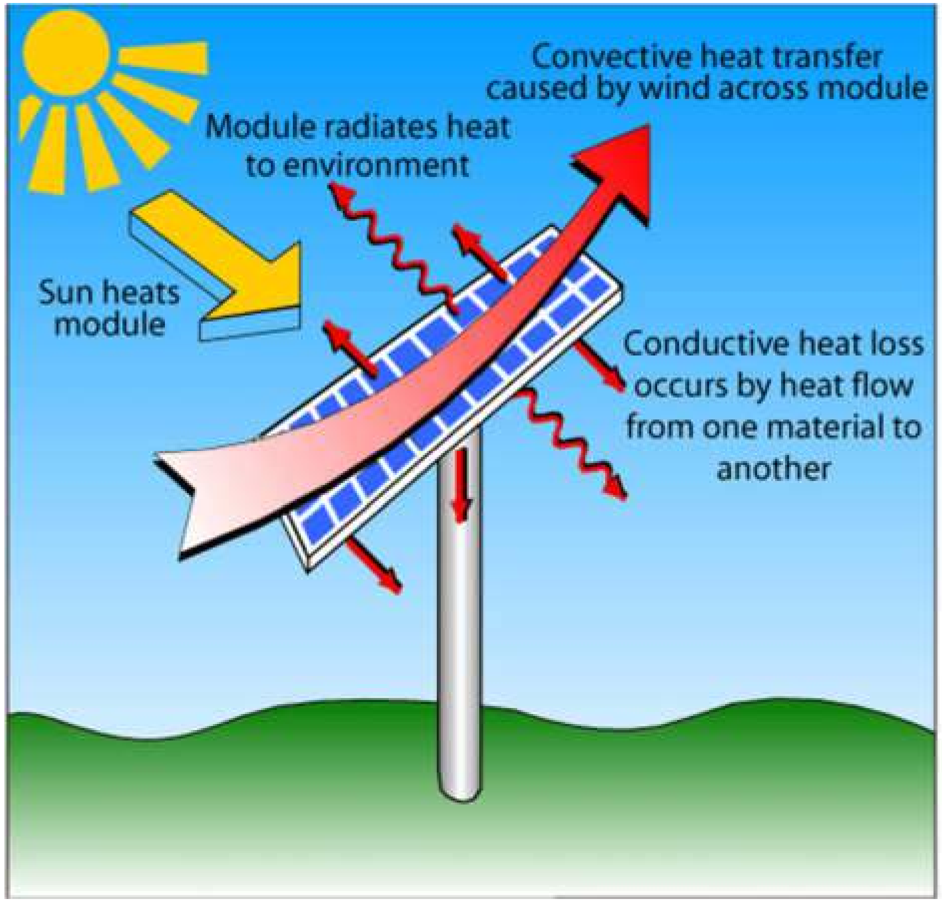

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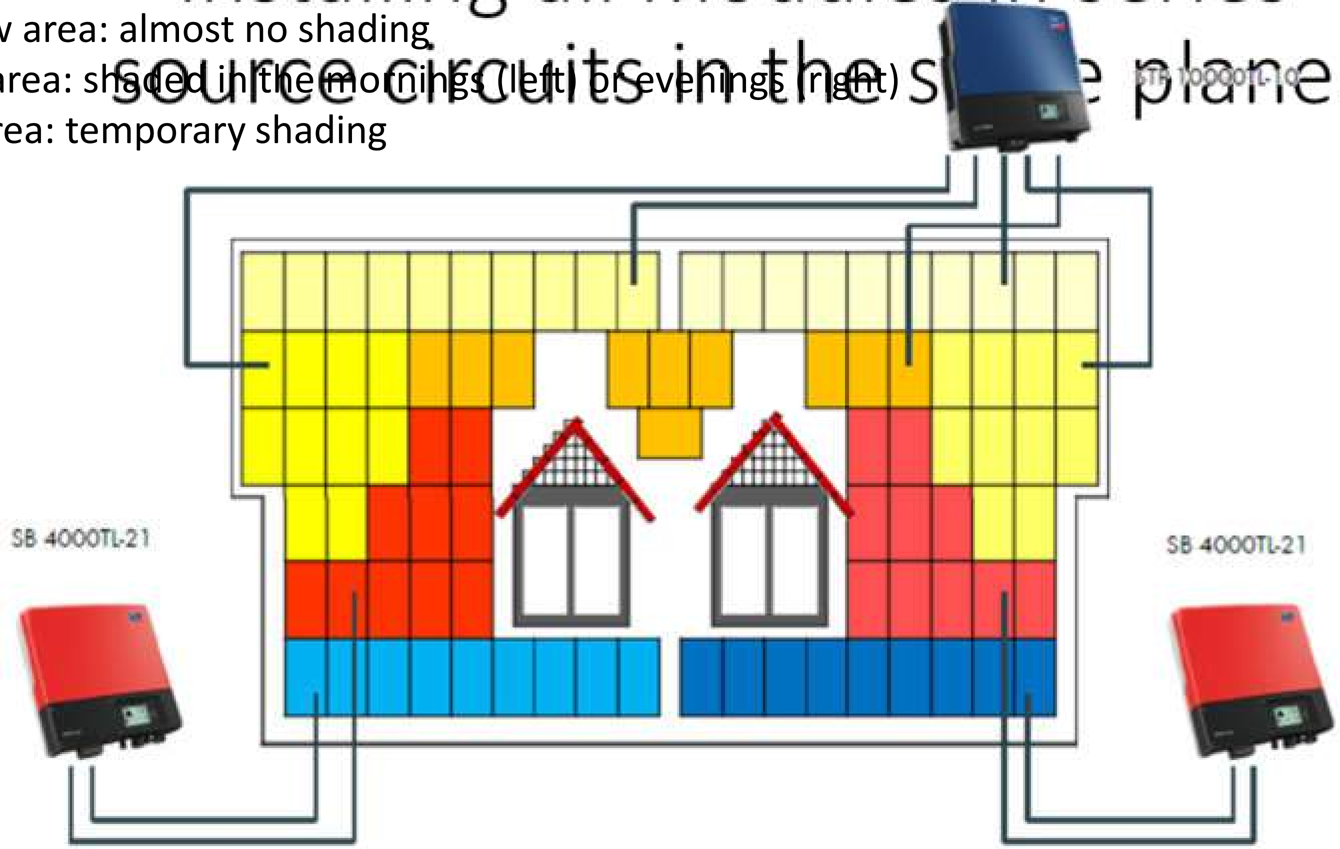
Installing all modules in series source circuits in the same plane.

yellow area: almost no shading
blue area: shaded in the mornings (left) or evenings (right)
red area: temporary shading



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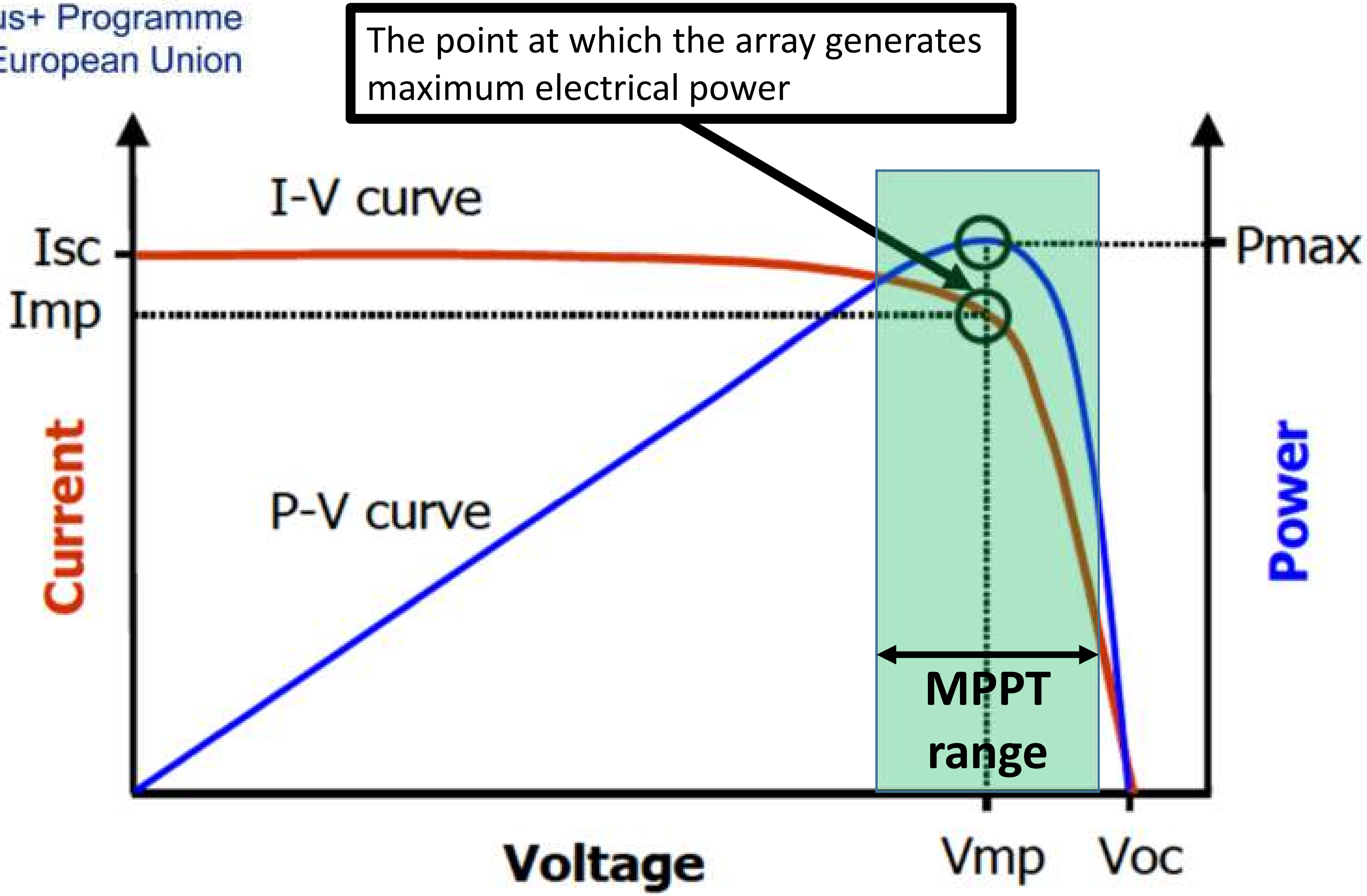

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Combiner box (if necessary)

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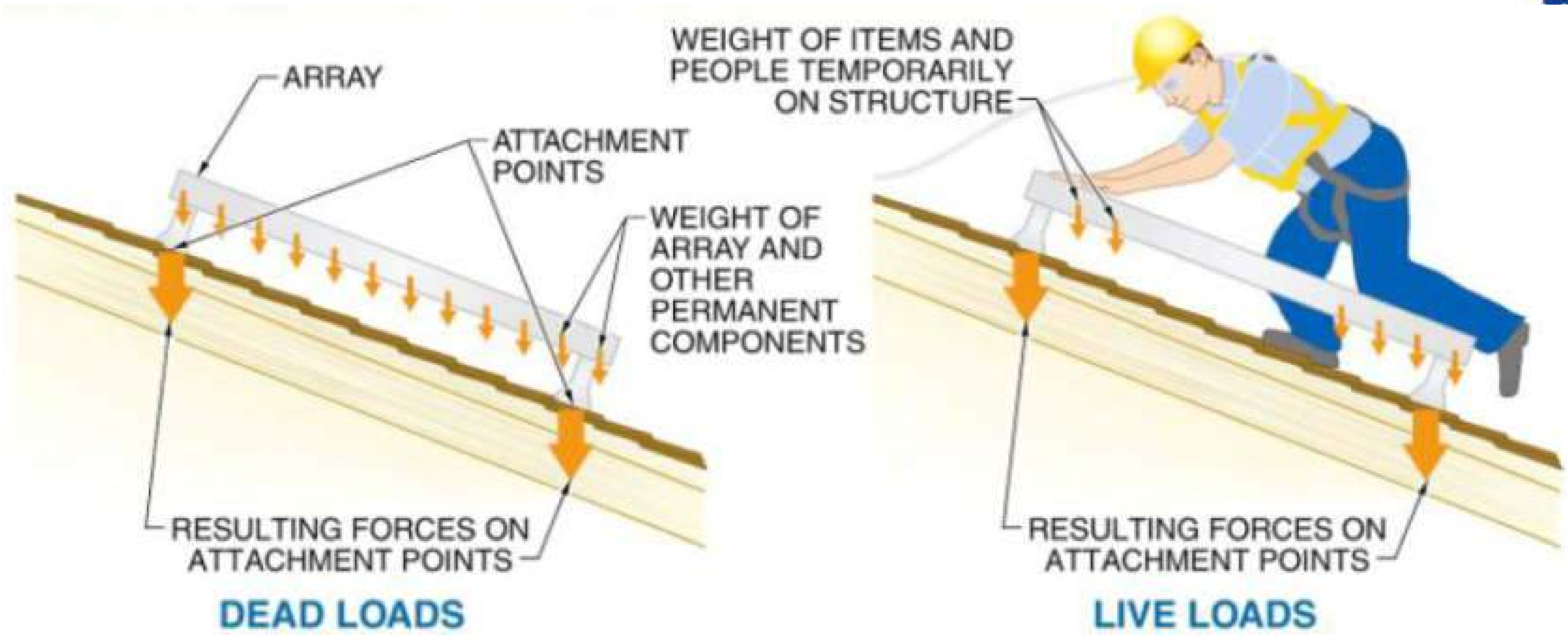

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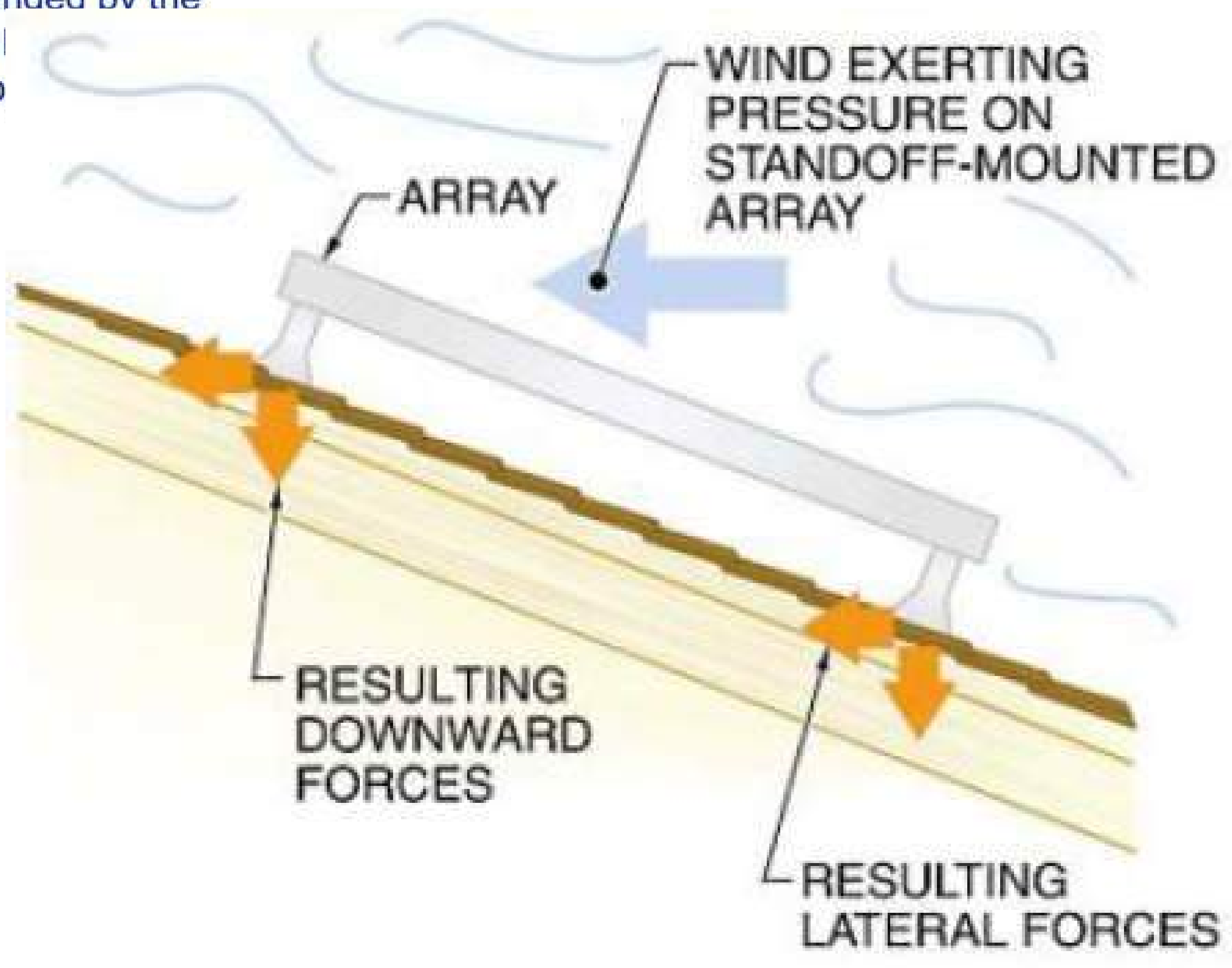

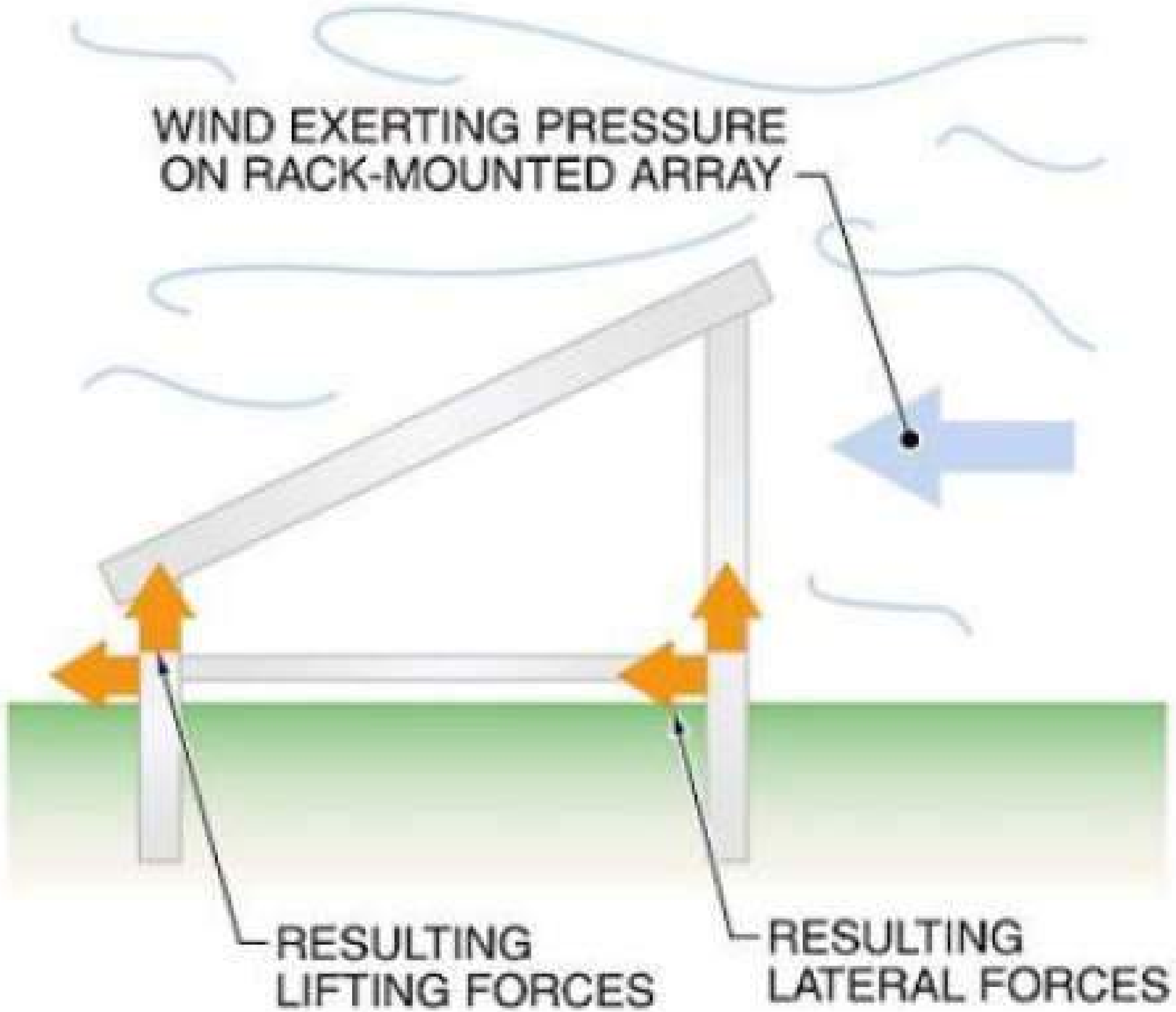
WIND EXERTING PRESSURE
ON RACK-MOUNTED ARRAY
RESULTING
LIFTING FORCES
RESULTING
LATERAL FORCES

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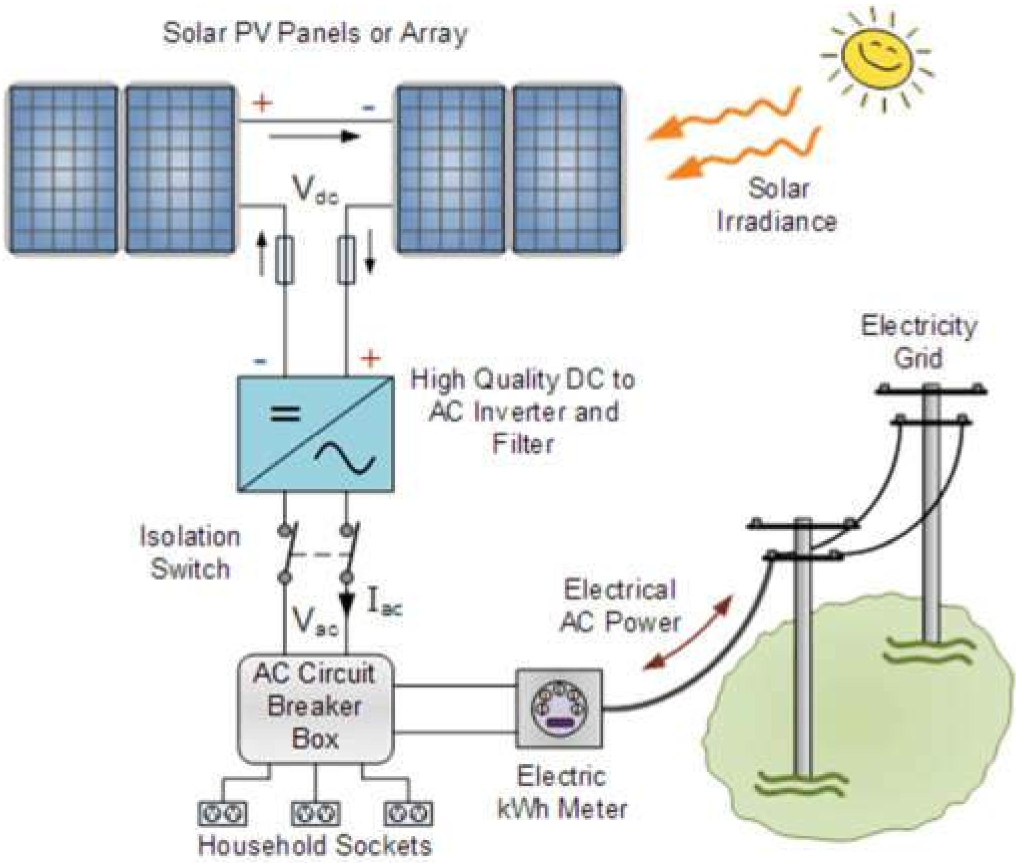
Design of On-grid System



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Design Steps of On-grid PV System

1. Energy Consumption
2. System Sizing (DC & AC)
3. Site Planning
4. Mounting Structure
5. Components selection
6. Shading Analysis
7. Module Layout
8. Solar panel selection
9. String Configuration
10. Wires and electrical components sizing
11. Losses Estimation
12. Energy Yield
13. BOQ
14. Economical Evaluation

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Energy Consumption

- Calculate the yearly energy consumption in kWh, or the average monthly consumption

- If the facility is not built yet, estimate the energy consumption for all loads
- Consumption = Wattage × Operational time

- Example:
- The yearly energy consumption for a house in Amman is 16000 kWh

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شركة الكهرباء الأردنية المساهمة العامة المحدودة عمان

فاتورة شهر /نيسان/ 2012

قسيمة المشترك

تاريخ القراءة	2012/04/10	وقت القراءة	11:32
اسم المشترك	[redacted]		(34 18 9252)
رقم ونوع الاشتراك	01/210825/009300		سكني
فترة الاستهلاك	من: 3/2012		إلى: 4/2012
رقم الفاتورة	20120400	رقم الإضبارة	675363
رقم الملف	01/30806/675363	معامل الضرب	1.0000
رقم العداد	000002006113477	الخصم (٪)	0

القراءة السابقة	القراءة الحالية	كمية الاستهلاك
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البيان	فلس	دينار
قيمة الإستهلاك	852	17317
فرق اسعار الوقود	000	0
اجرة العداد	200	0
الرسوم: فلس الريف	983	99
الرسوم: رسم التلفزيون	000	1
الرسوم: رسم النفايات	581	500
قيمة الفاتورة	616	17919
حساب التسوية	000	0
القيمة المطلوبه	616	17919

تفاصيل الذمم السابقة

رقم الفاتورة	فلس	دينار
********	***	**
********	***	**
********	***	**
********	***	**
********	***	**
********	***	**
رصيد سابق	***	**
مجموع قيمة الذمم	***	**

• يفصل التيار ما لم تسدد الفاتورة خلال شهر من تاريخ الاصدار

• لا تعتبر هذه القسيمة وصلاً بقيمة المطالبة الا بعد ختمها بالة وختم صندوق الشركة والبنوك المعتمدة ومكاتب شركة البريد الاردني

ملاحظات:

13/3/2012 ... وتم عمل التسوية المالية

System Sizing

- Divide the yearly consumption by 1560 kWh/kWp/y or the average monthly consumption by 130 kWh/kWp/y

- The result is the maximum AC system size in units of kW that is allowed to be installed as specified in the regulations of EMRC.

- Example:

- Max. AC System size = $\dfrac{16000\,\frac{kWh}{y}}{1560\,\frac{kWh}{kWp.y}}$ = **10.25 kWp**

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System Sizing

- Selected inverter is: **SMA STP 10000-TL kW**

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System Sizing

- Max. DC System size = **10.2 kWp**
- This is according to manufacturers specifications

14 Technical Data

14.1 Sunny Tripower 10000TL

DC Input

Maximum DC power at cos φ = 1	10,200 W
Maximum input voltage	1,000 V
MPP voltage range	320 V to 800 V
Rated input voltage	600 V
Minimum input voltage	150 V
Initial input voltage	188 V
Maximum feedback current	2 A
Maximum input current, input A	22.0 A
Maximum input current, input B	11.0 A

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DC / AC Ratio

- PV designer may choose to oversize the inverter in order to maximize the power production, due to the following:

1. Actual PV module power vs. module nominal power
2. Financial considerations

- DC / AC ratio depends greatly on the location!

- Recommended DC / AC ratio in Jordan is 1.05 – 1.15

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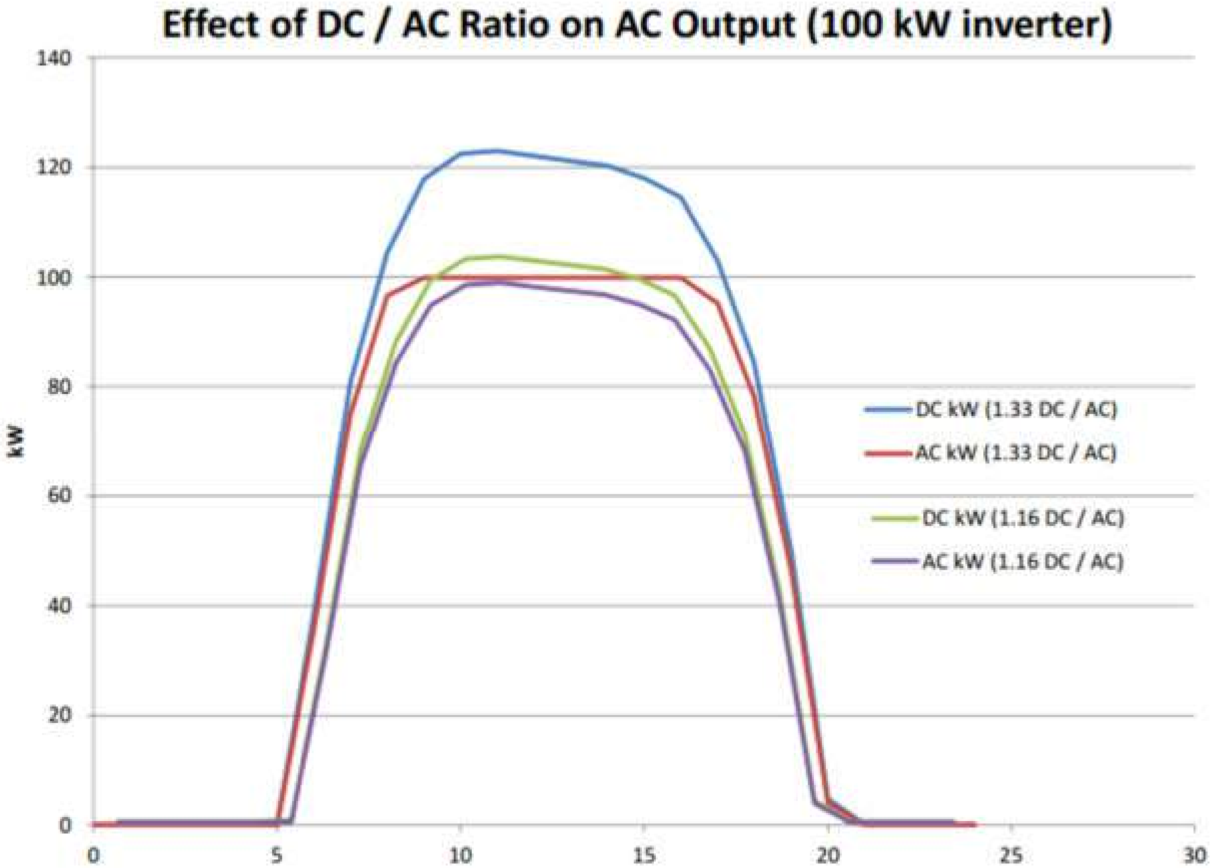
DC / AC Ratio



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Site Planning

- Suitable roof for mounting?
- Solar access for the site?
- Shading objects (location and dimensions)
- Orientation and tilt of the roof
- Suggested location of the inverter
- Location of AC switchboards
- Coordinates of the project
- Pictures for the location
- Available area
- Horizon shading
- Connection voltage
- CB data
- Elec. Room pictures

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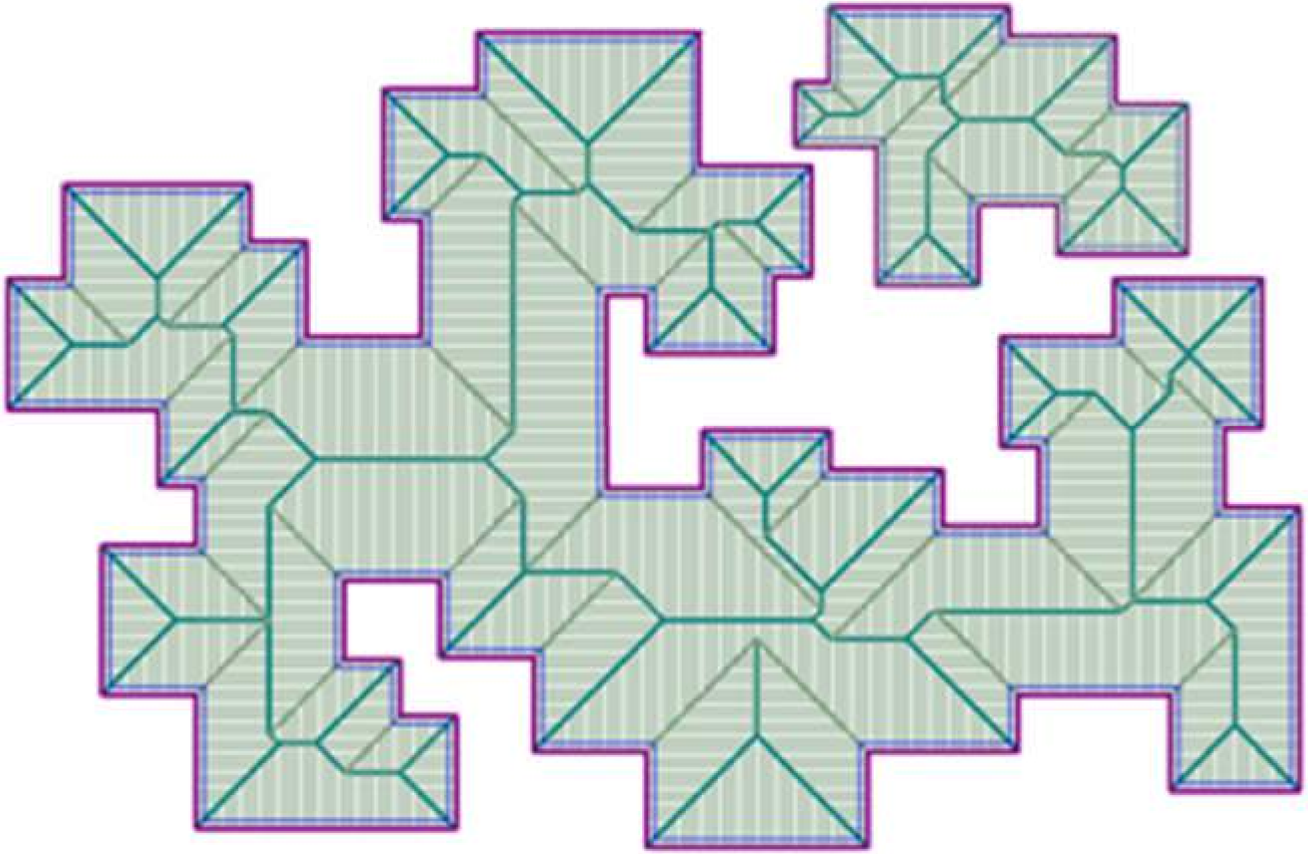
Suitable roof for mounting?



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Solar access for the site?

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Orientation and tilt of the roof

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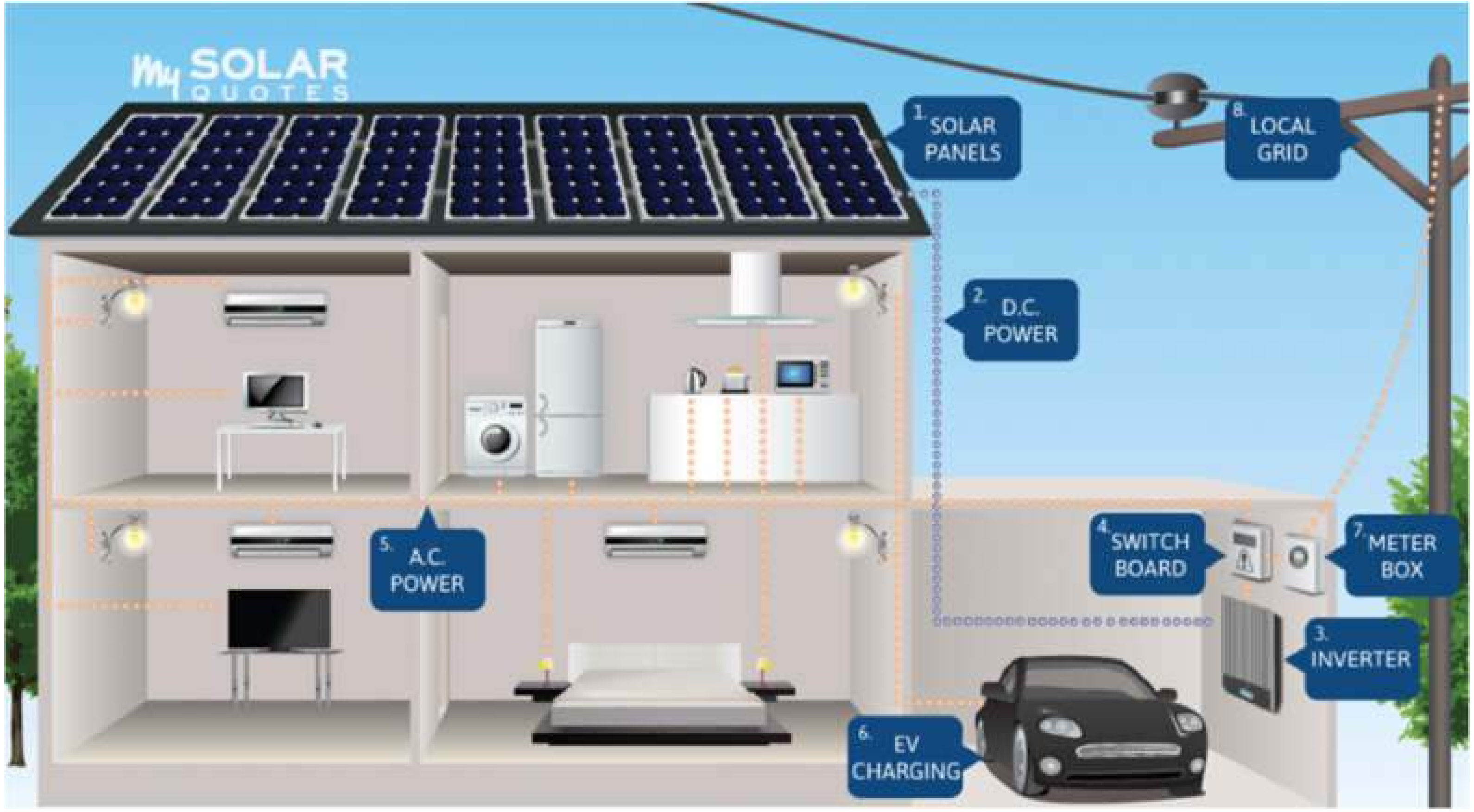
Location of AC switchboards



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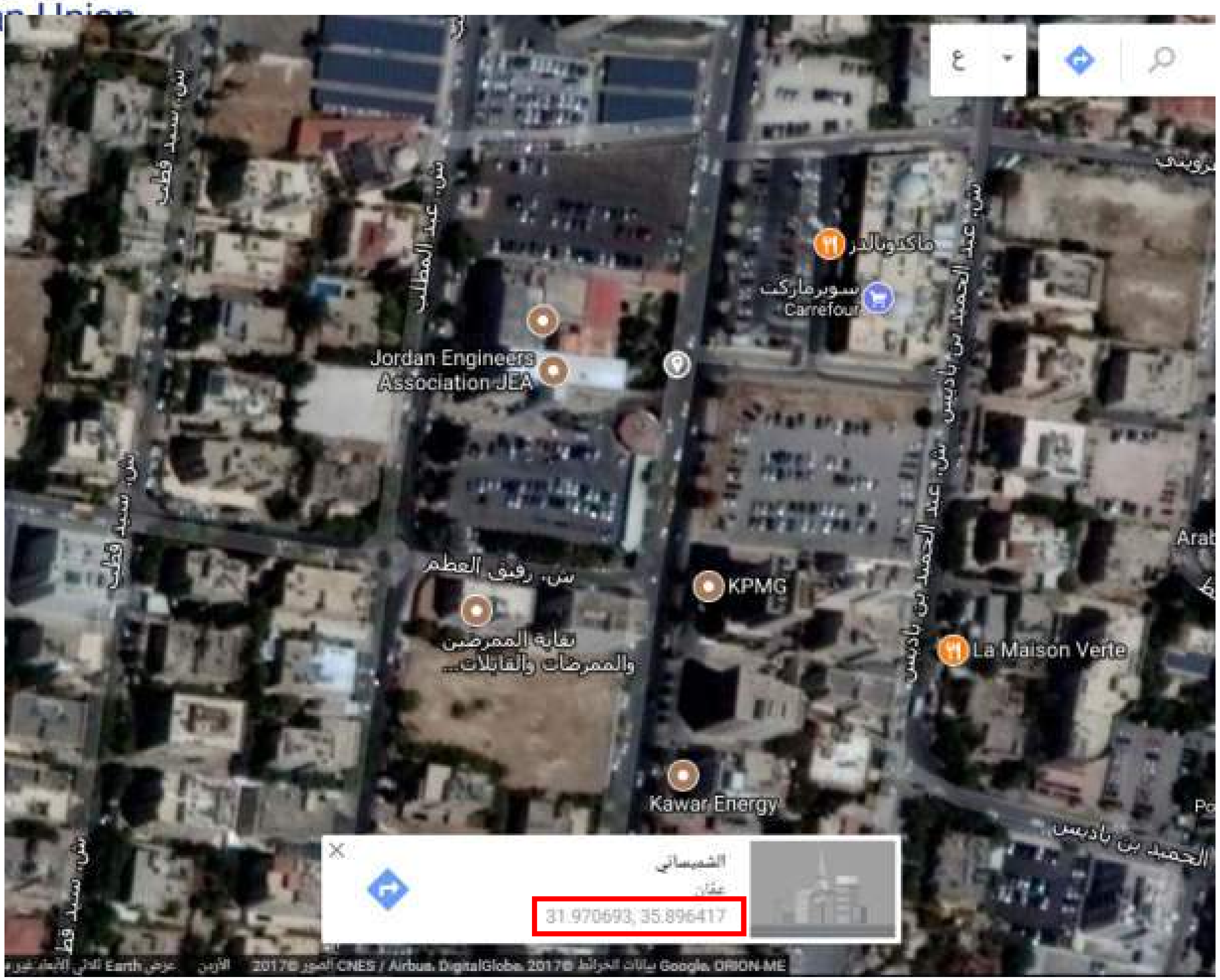
Coordinates of the project



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Connection voltage
Single Phase or 3-Phase?

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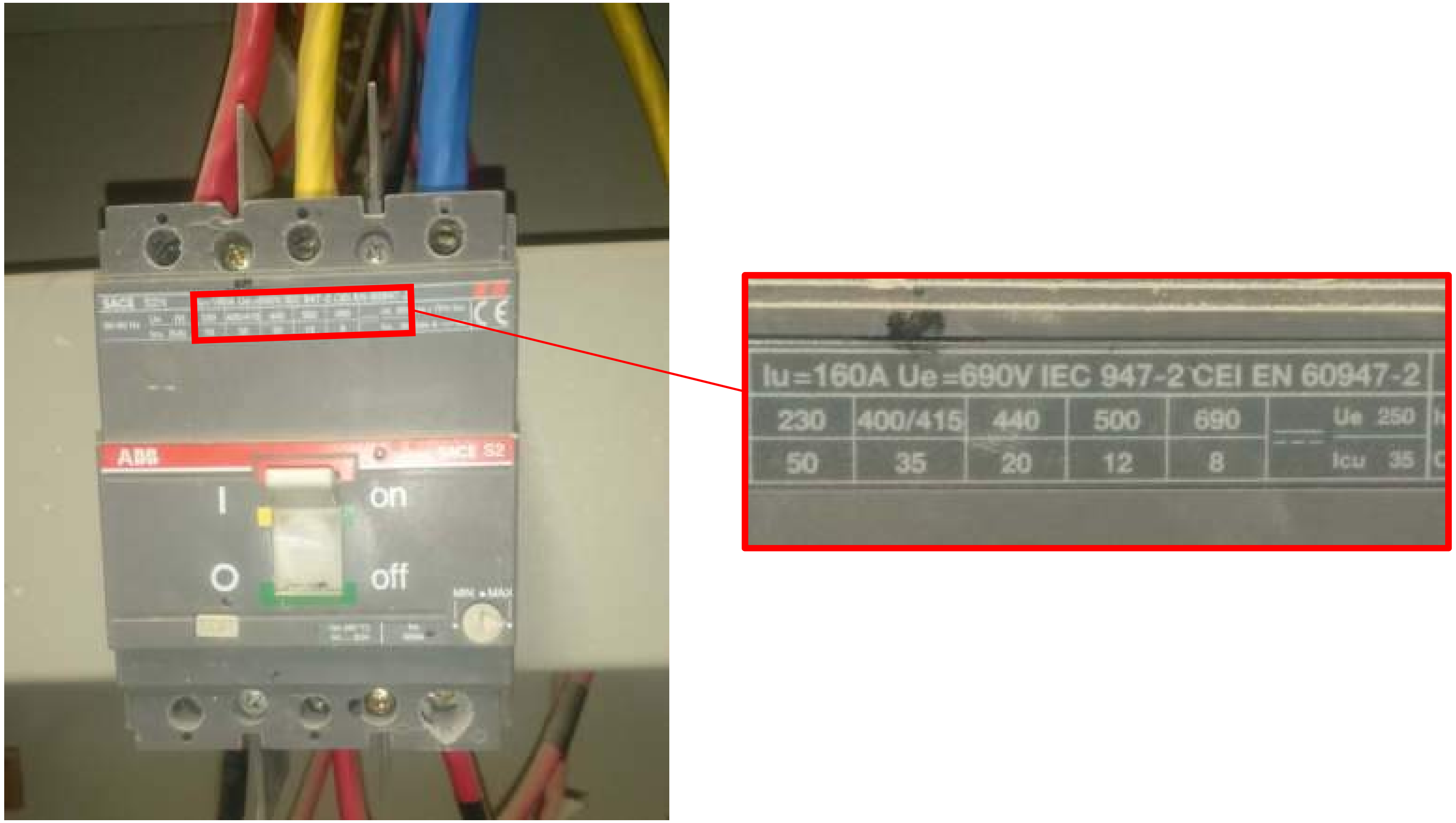
CB data



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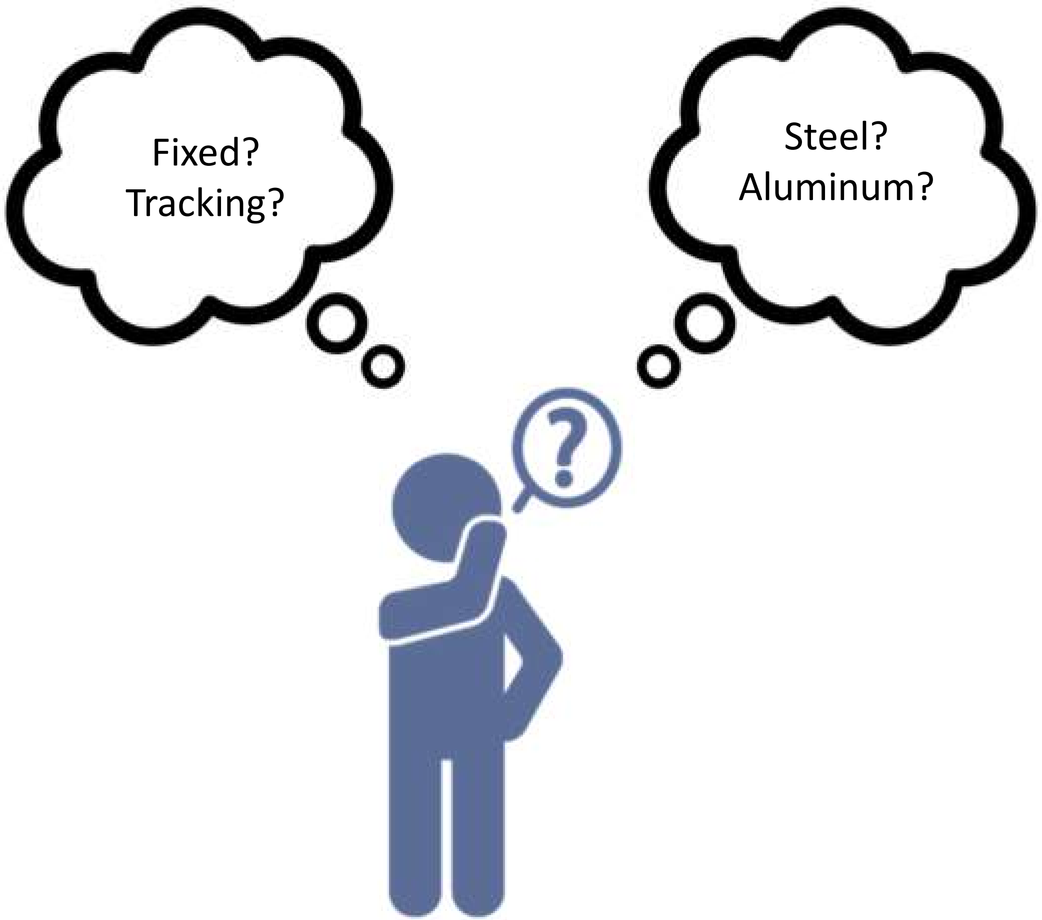
Mounting Structure



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Components selection

- Select the manufacturers for:

- Solar panels
- Mounting structure
- DC & AC cables
- Protection devices

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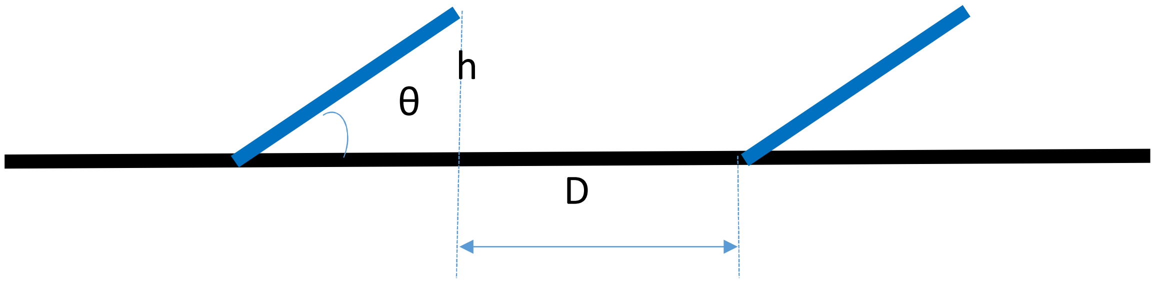
Shading Analysis



$$D = 2h$$

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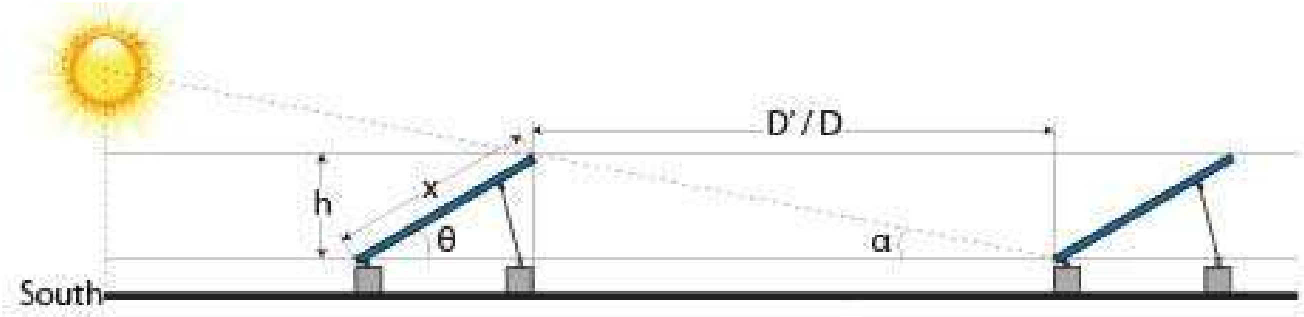
Shading Analysis



$$D' = h / \tan(\alpha)$$

D' = Maximum shadow length
h = height of obstruction
α = solar altitude angle (at 9:00 AM or 3:00 PM in 21th December)
α = 23.5˚ in Amman at 9:00 in 21th December

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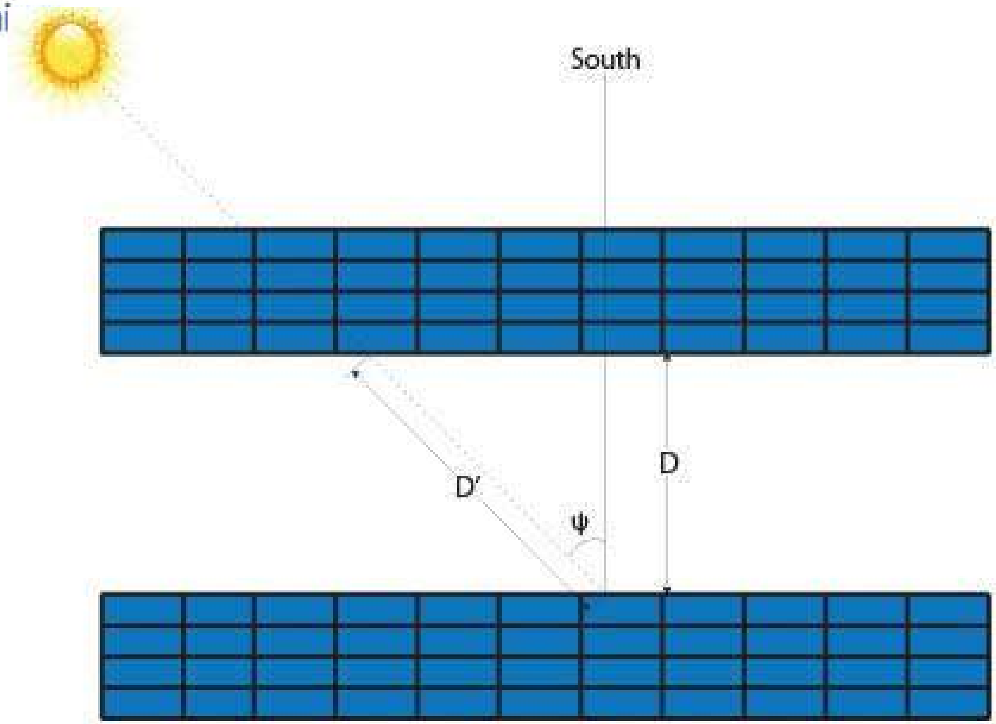
Shading Analysis



$$D = D' \times \cos(180 - \psi)$$

- D = Minimum array row spacing
- ψ = solar azimuth angle (at 9:00 AM or 3:00 PM)
- Ψ = 141˚ in Amman at 9:00 AM

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Shading Analysis

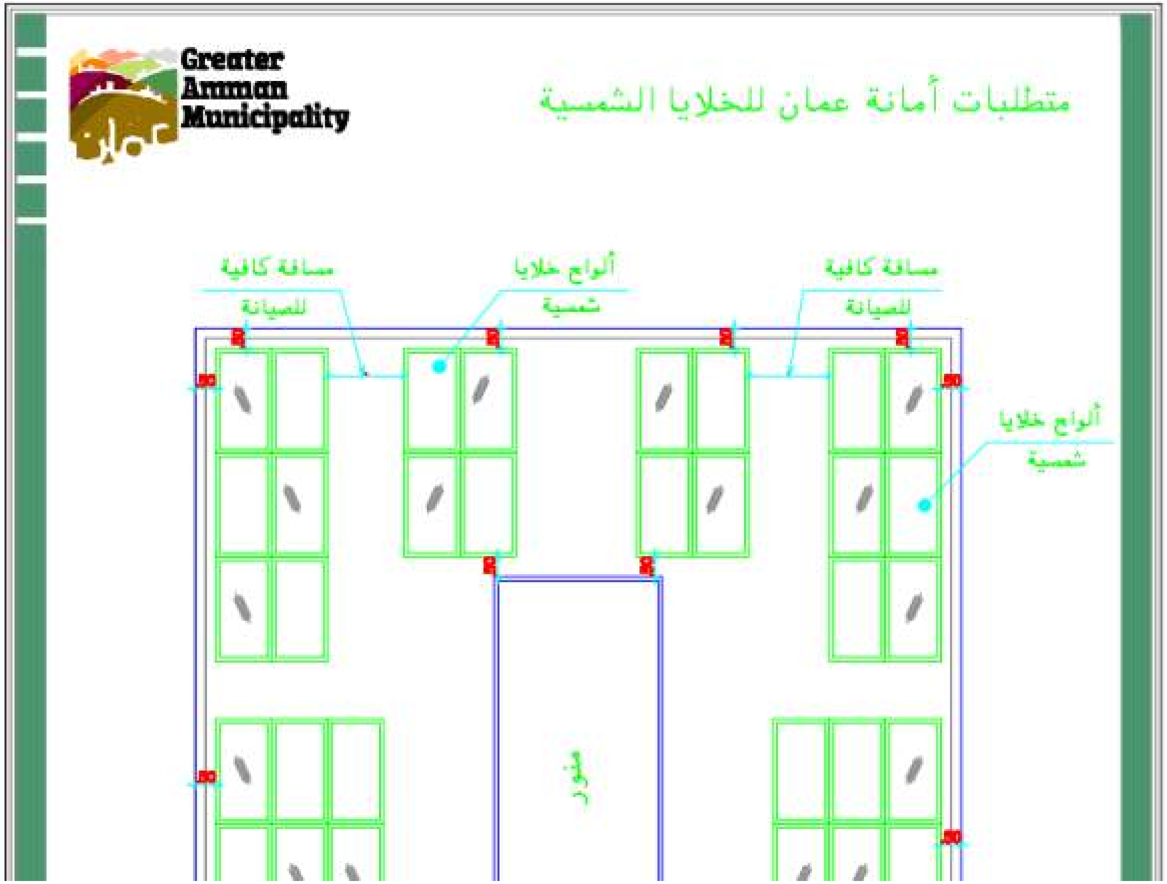
- Example:
- If the solar panels mounted in landscape (x=1m) layout and 30˚ tilt angle
- h = 1 x sin(30) = 0.5m
- D’ = 0.5/ tan (23.5) = 1.15 m
- D = 1.15 x Cos(180 - 141) = 0.9m

- These equation can be applied for any shading object

Module Layout

- بعض تعليمات تركيب الواح الخلايا الشمسية على أسطح المباني حسب القرار رقم 19 الصادر عن مجلس الأمانة بتاريخ 25-2-2015

- 1-5 إن يتم تركيب وحدات الخلايا الشمسية بطريقة محكمة وان يتم مراعاة تأثير الرياح والثلوج عليها.
- 2-5 مراعاة تأثير وزن نظام الخلايا الشمسية على الأسطح.
- 3-5 مراعاة عدم تغطية المناور أو إغلاق للممرات.
- 7-5 عدم استغلال المساحات تحت القواعد و الألواح الشمسية لأغراض أخرى


Greater
Amman
Municipality
متطلبات أمانة عمان للخلايا الشمسية
مسافة كافية للصيانة
ألواح خلايا شمسية
مسافة كافية للصيانة
ألواح خلايا شمسية
منور

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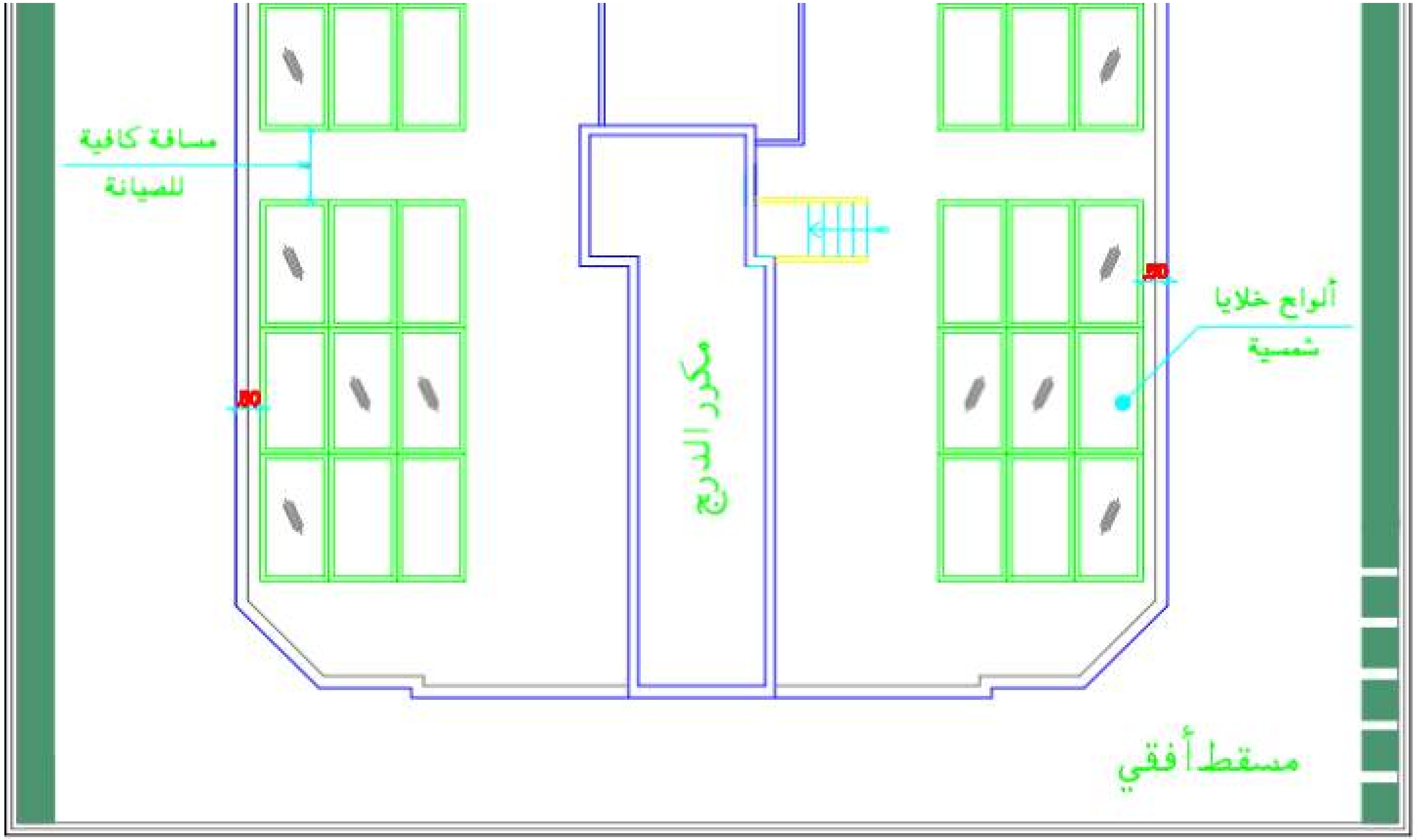

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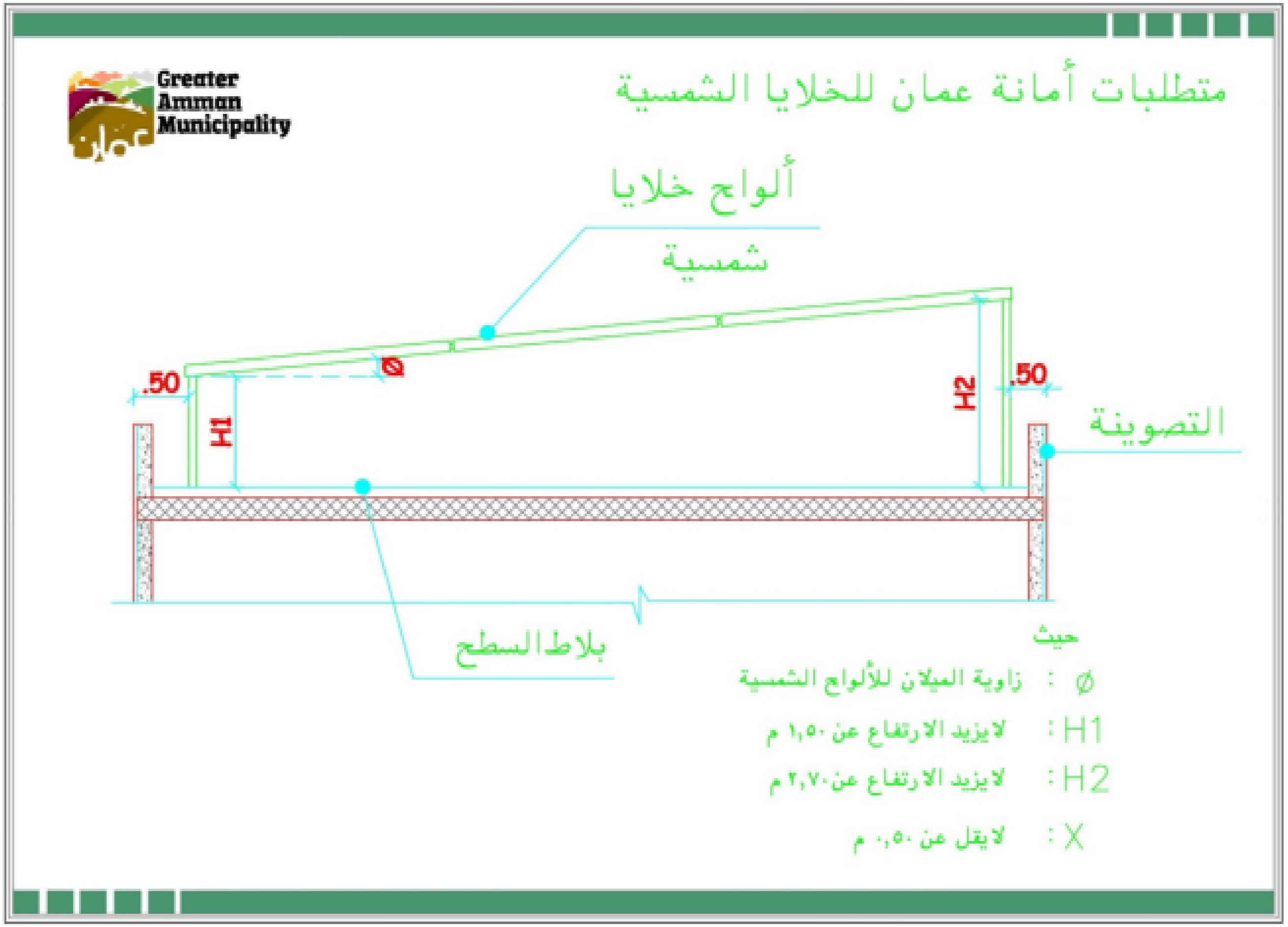

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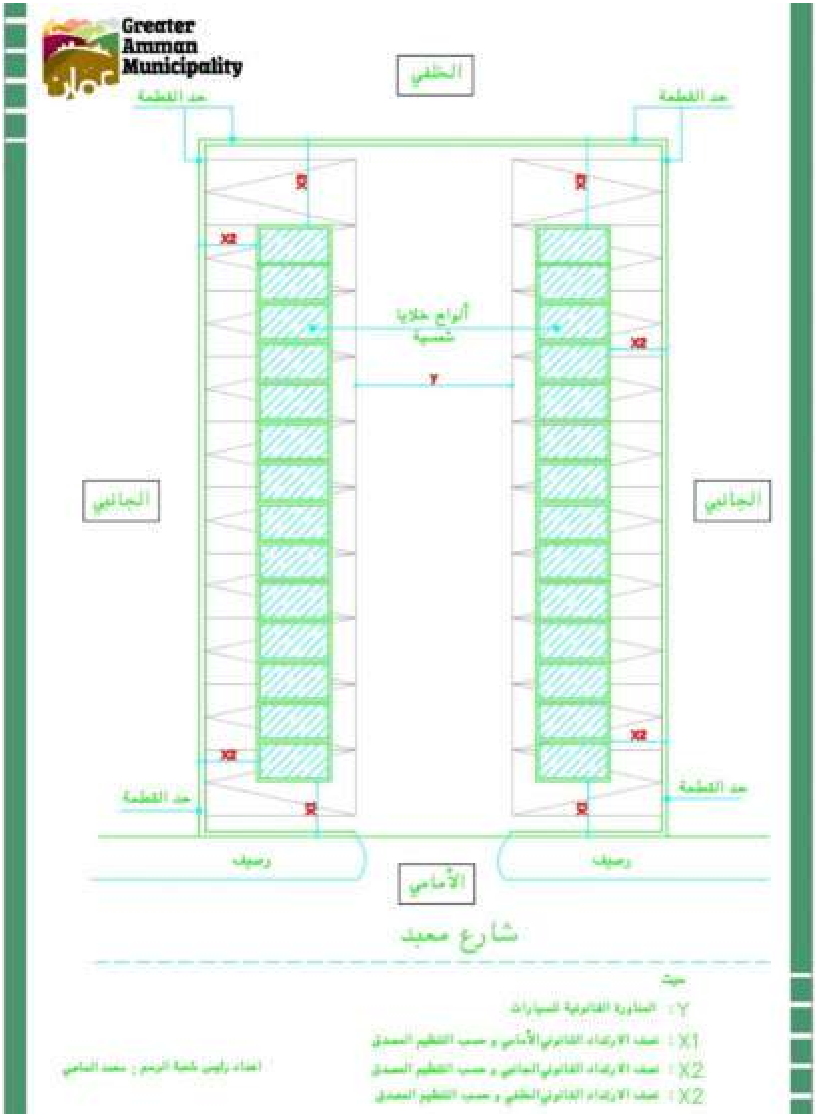

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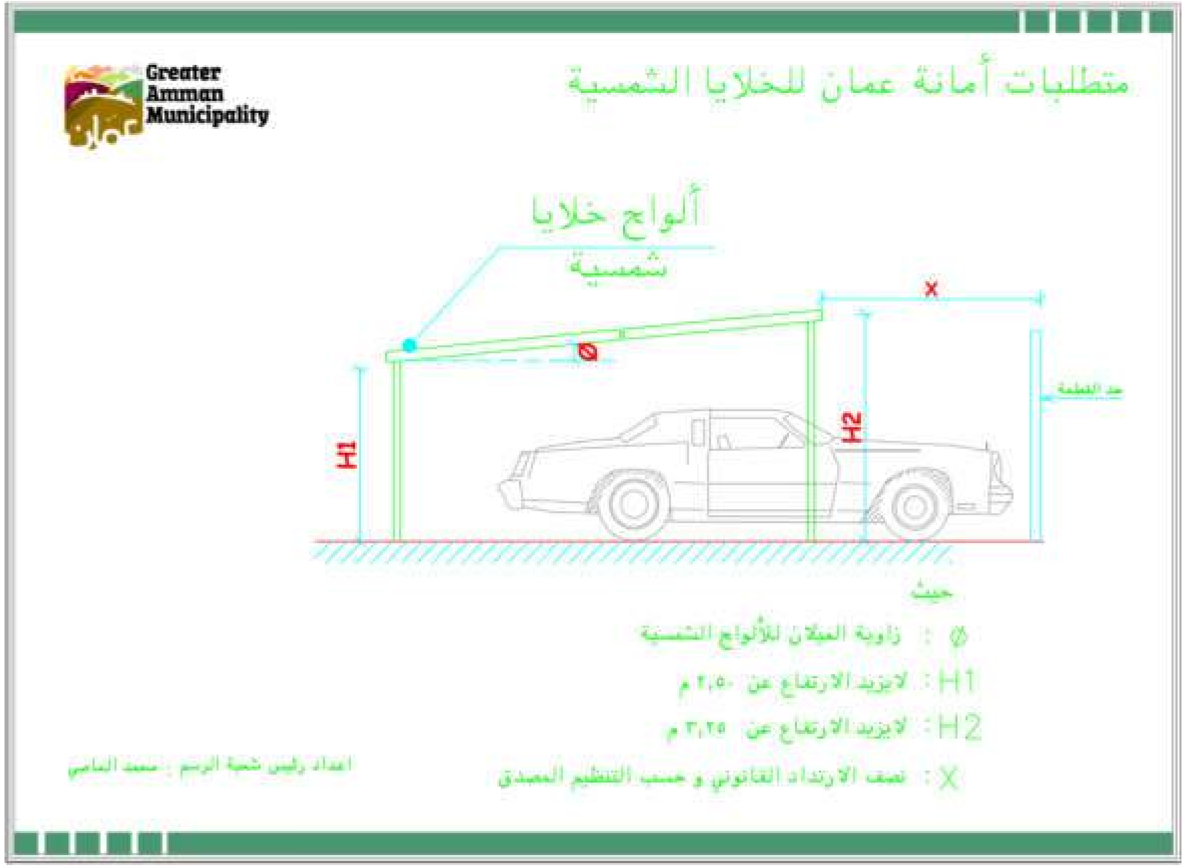

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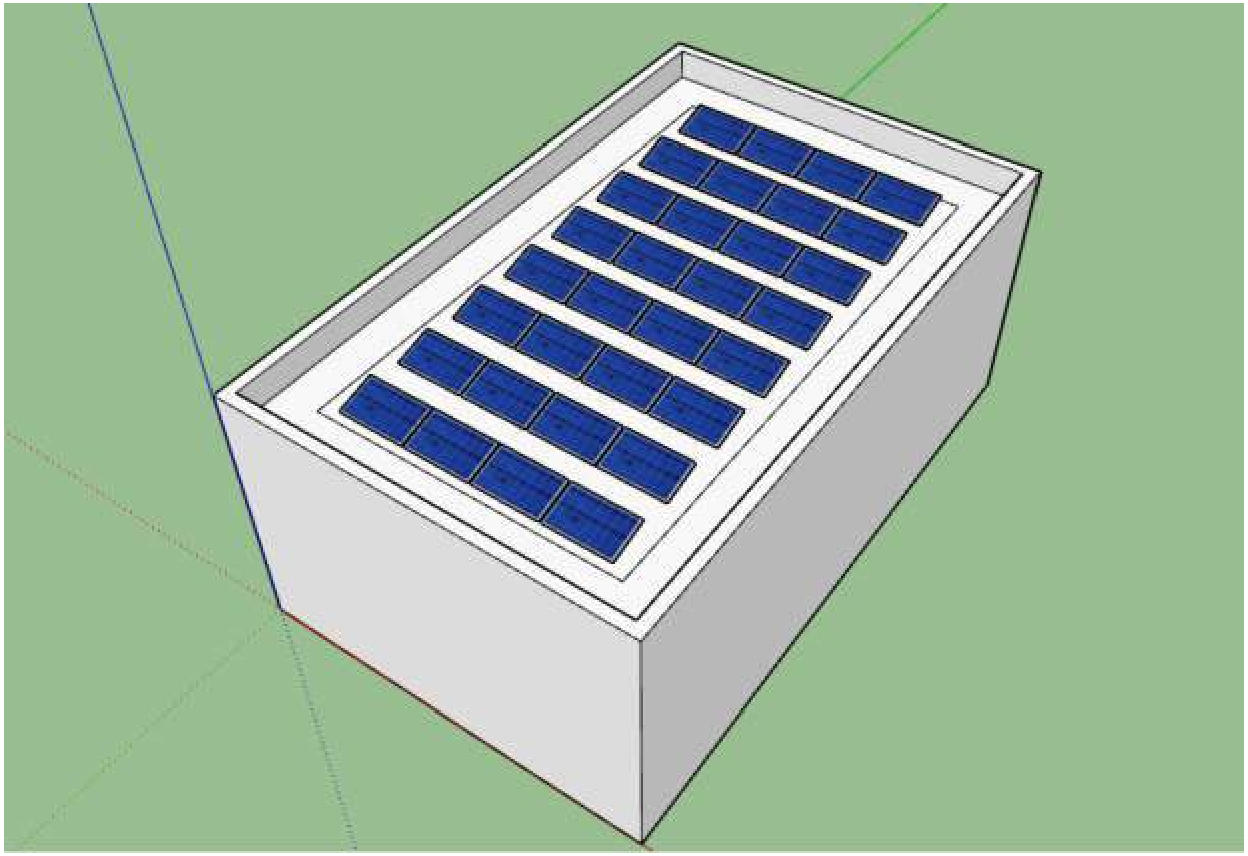

Solar panel selection

- 32 solar panels can installed on the roof
- Rated power of each panel = 10.2 / 32 ≈ 0.315 kWp
- Selected module: Trina Solar – TALLMAX315 Multi

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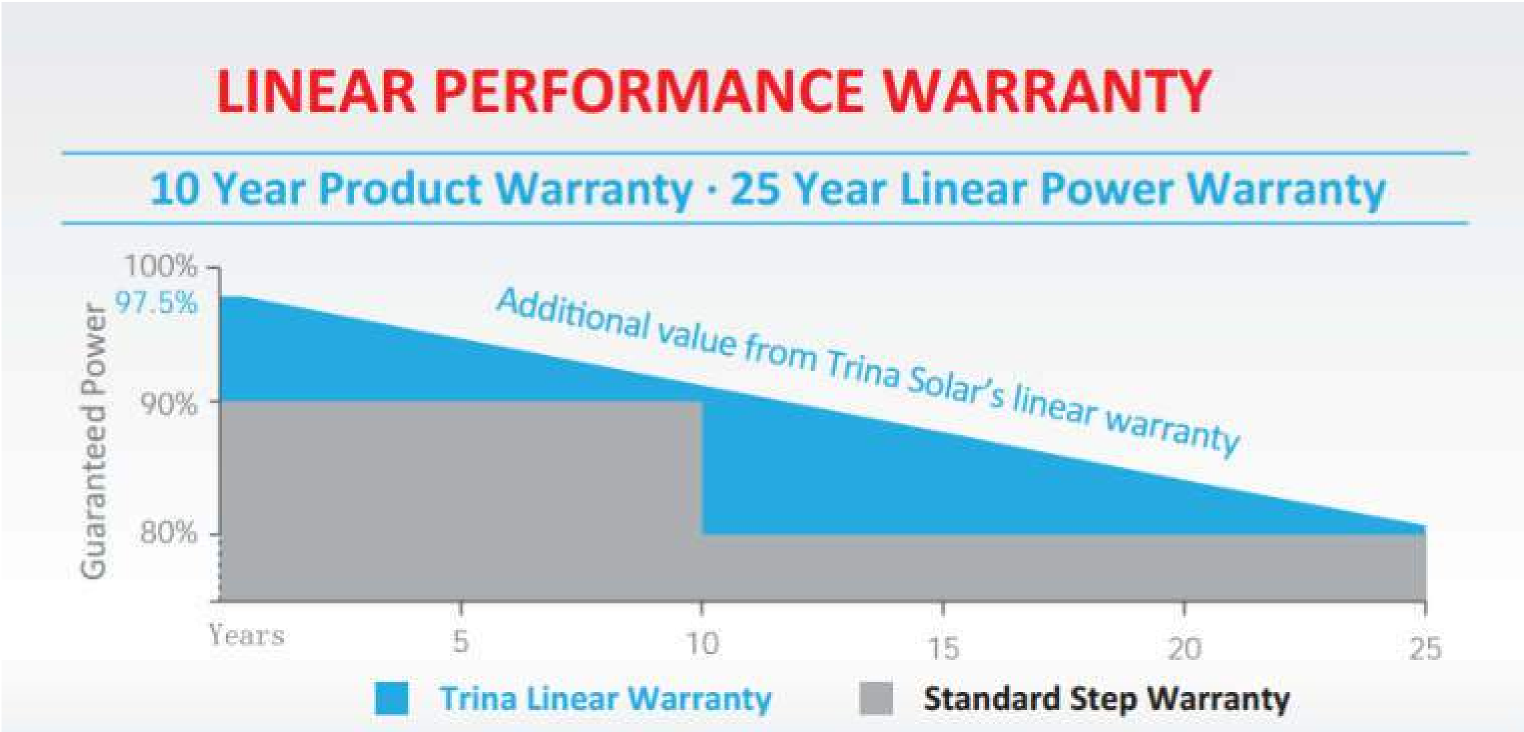

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ELECTRICAL DATA (STC)

Peak Power Watts-P_{MAX} (Wp)*	310	315	320	325
Power Output Tolerance-P_{MAX} (W)	0 ~ +5			
Maximum Power Voltage-V_{MPP} (V)	37.0	37.1	37.1	37.2
Maximum Power Current-I_{MPP} (A)	8.38	8.51	8.63	8.76
Open Circuit Voltage-V_{OC} (V)	45.5	45.6	45.8	45.9
Short Circuit Current-I_{SC} (A)	8.85	9.00	9.10	9.25
Module Efficiency η_m (%)	16.0	16.2	16.5	16.8

STC: Irradiance 1000 W/m², Cell Temperature 25°C, Air Mass AM1.5.
*Test tolerance: ±3%.

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ELECTRICAL DATA (NOCT)

Maximum Power-P_{MAX} (Wp)	230	234	238	242
Maximum Power Voltage-V_{MPP} (V)	34.3	34.3	34.4	34.5
Maximum Power Current-I_{MPP} (A)	6.72	6.83	6.91	7.02
Open Circuit Voltage-V_{OC} (V)	42.2	42.3	42.5	42.6
Short Circuit Current-I_{SC} (A)	7.15	7.27	7.35	7.47

NOCT: Irradiance at 800 W/m², Ambient Temperature 20°C, Wind Speed 1 m/s.

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MECHANICAL DATA

Solar Cells	Multicrystalline 156 × 156 mm (6 inches)
Cell Orientation	72 cells (6 × 12)
Module Dimensions	1956 × 992 × 40 mm (77.0 × 39.1 × 1.57 inches)
Weight	22.5 kg (49.6 lb)
Glass	3.2 mm (0.13 inches), High Transmission, AR Coated Tempered Glass
Backsheet	White
Frame	Silver Anodized Aluminium Alloy
J-Box	IP 67 or IP 68 rated
Cables	Photovoltaic Technology Cable 4.0mm² (0.006 inches²), 1200 mm (47.2 inches)
Connector	MC4 Compatible or Amphenol H4/UTX
Fire Type	Type 1 or Type 2

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TEMPERATURE RATINGS

Nominal Operating Cell Temperature (NOCT)	44°C (±2°C)
Temperature Coefficient of P_{MAX}	- 0.41%/°C
Temperature Coefficient of V_{OC}	- 0.32%/°C
Temperature Coefficient of I_{SC}	0.05%/°C

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String Configuration

14 Technical Data

14.1 Sunny Tripower 10000TL

DC Input

Maximum DC power at cos φ = 1	10,200 W
Maximum input voltage	1,000 V
MPP voltage range	320 V to 800 V
Rated input voltage	600 V
Minimum input voltage	150 V
Initial input voltage	188 V
Maximum feedback current	2 A
Maximum input current, input A	22.0 A
Maximum input current, input B	11.0 A
Maximum input current per string input A*	33.0 A
Maximum input current per string input B*	12.5 A
Number of independent MPP inputs	2
Strings per MPP input, input A	4
Strings per MPP input, input B	1

* To be observed in the event of short-circuit of the electronic string fuse

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String Configuration

ELECTRICAL DATA (STC)

Peak Power Watts-P_{MAX} (Wp)*	310	315	320	325
Power Output Tolerance-P_{MAX} (W)	0 ~ +5			
Maximum Power Voltage-V_{MPP} (V)	37.0	37.1	37.1	37.2
Maximum Power Current-I_{MPP} (A)	8.38	8.51	8.63	8.76
Open Circuit Voltage-V_{OC} (V)	45.5	45.6	45.8	45.9
Short Circuit Current-I_{SC} (A)	8.85	9.00	9.10	9.25
Module Efficiency η_m (%)	16.0	16.2	16.5	16.8

STC: Irradiance 1000 W/m², Cell Temperature 25°C, Air Mass AM1.5.
*Test tolerance: ±3%.

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String Configuration

TEMPERATURE RATINGS

Nominal Operating Cell Temperature (NOCT)	44°C (±2°C)
Temperature Coefficient of P_{MAX}	- 0.41%/°C
Temperature Coefficient of V_{OC}	- 0.32%/°C
Temperature Coefficient of I_{SC}	0.05%/°C

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String Configuration

Mounting Type	Increase in Cell Temperature [°C]
Ground Mounted and Car Ports	+20
Roof Mounted	**+30**
Facade	+35
BIPV	+45

Max. temp in Amman = 40˚C

Min temp. in Amman = -4 ˚C

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String Configuration

- Max. number of modules per each string =
- Max. MPP Voltage / Max. Module Voltage ($V_{oc\,(STC)}$ @ -4˚C)
- $V_{oc\,(STC)}$ @ -4˚C = (45.6 + |-4 – 25| x 0.0032 x 45.6) = 49.8 V
- 800 / 50 = 16.1
- Max. number of modules per each string = **16 module**

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String Configuration

- Min. number of modules per each string =
- Min. MPP Voltage / Min. Module Voltage ($V_{mp\,(STC)}$ @ 70˚C)
- $V_{mp\,(STC)}$ @ 70˚C = (37.1 - ((70 – 25) x 0.0032 x 37.1) = 31.8 V
- 320 / 31.8 = 10.1
- Min. number of modules per each string = **11 module**

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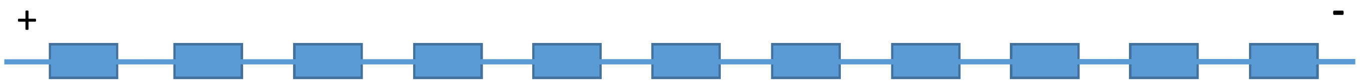
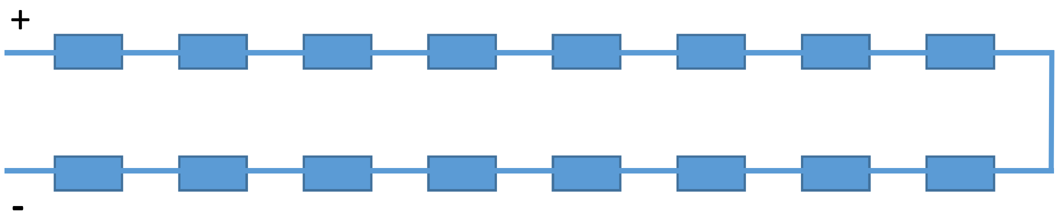
String Configuration

11 Module



1 6 Module



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String Configuration

- String configuration:
- Input A: 1 x 16 Module
- Input B: 1 x 16 Module

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Wires and electrical components sizing

- DC cables (Module's Isc x 1.56) = 9 x 1.56 = 14 A
- AC cables (Inverter's max. output current x 1.25) = 33 x 1.25 = 41.25 A
- **NOTE:** Voltage drop across DC & AC cables is recommended to be less than 2-3% (Voltage drop = I x R x L)
- Circuit breaker size (Ampacity) > Max. AC Current

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Losses Estimation

- Shading losses ≈ 3%
- Soiling losses ≈ 3% (with continuous cleaning)
- Voltage drop ≈ 2%

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Energy Yield

Optimum PV System Energy Yield in Amman, kWh/kWp/year

- Energy yield = Optimum energy yield – Total Losses

	20˚ SE	15˚ SE	10˚ SE	5˚ SE	0˚	5˚ SW	10˚ SW	15˚ SW	20˚ SW
10˚	-4.9%	-4.7%	-4.6%	-4.5%	-4.5%	-4.5%	-4.6%	-4.7%	-4.8%
15˚	-3.0%	-2.8%	-2.6%	-2.5%	-2.4%	-2.5%	-2.6%	-2.7%	-3.0%
20˚	-1.7%	-1.4	-1.2%	-1.1%	-1.0%	-1.0%	-1.2%	-1.3%	-1.6%
25˚	-0.9%	-0.6%	-0.4%	-0.3%	-0.2%	-0.2%	-0.3%	-0.5%	-0.8%
30˚	-0.8%	-0.4%	-0.2%	-0.1%	1820	-0.0%	-0.1%	-0.3%	-0.7%
35˚	-1.3%	-0.9%	-0.6%	-0.5%	-0.4%	-0.5%	-0.6%	-0.8%	-1.2%
40˚	-2.3%	-2.0%	-1.7%	-1.5%	-1.5%	-1.5%	-1.6%	-1.9%	-2.2%
45˚	-4.0%	-3.6%	-3.4%	-3.2%	-3.1%	-3.2%	-3.3%	-3.5%	-3.8%
50˚	-6.2	-5.9%	-5.6%	-5.5%	-5.4%	-5.5%	-5.5%	-5.7%	-6.0%

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Economical Evaluation

- Simple Payback Period
- Levelized Cost of Energy (LCOE)

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Simple Payback Period

$$\text{Simple Payback Period} = \frac{CAPEX}{Yearly\ Savings}$$

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CAPEX

- PV Modules
- Inverter
- Mounting Structure
- DC & AC Cables
- Installation
- Permissions

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Levelized Cost of Energy (LCOE)

$$LCOE = \frac{CAPEX + OPEX}{Total\ Energy\ Yield}$$

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Off-grid System Design

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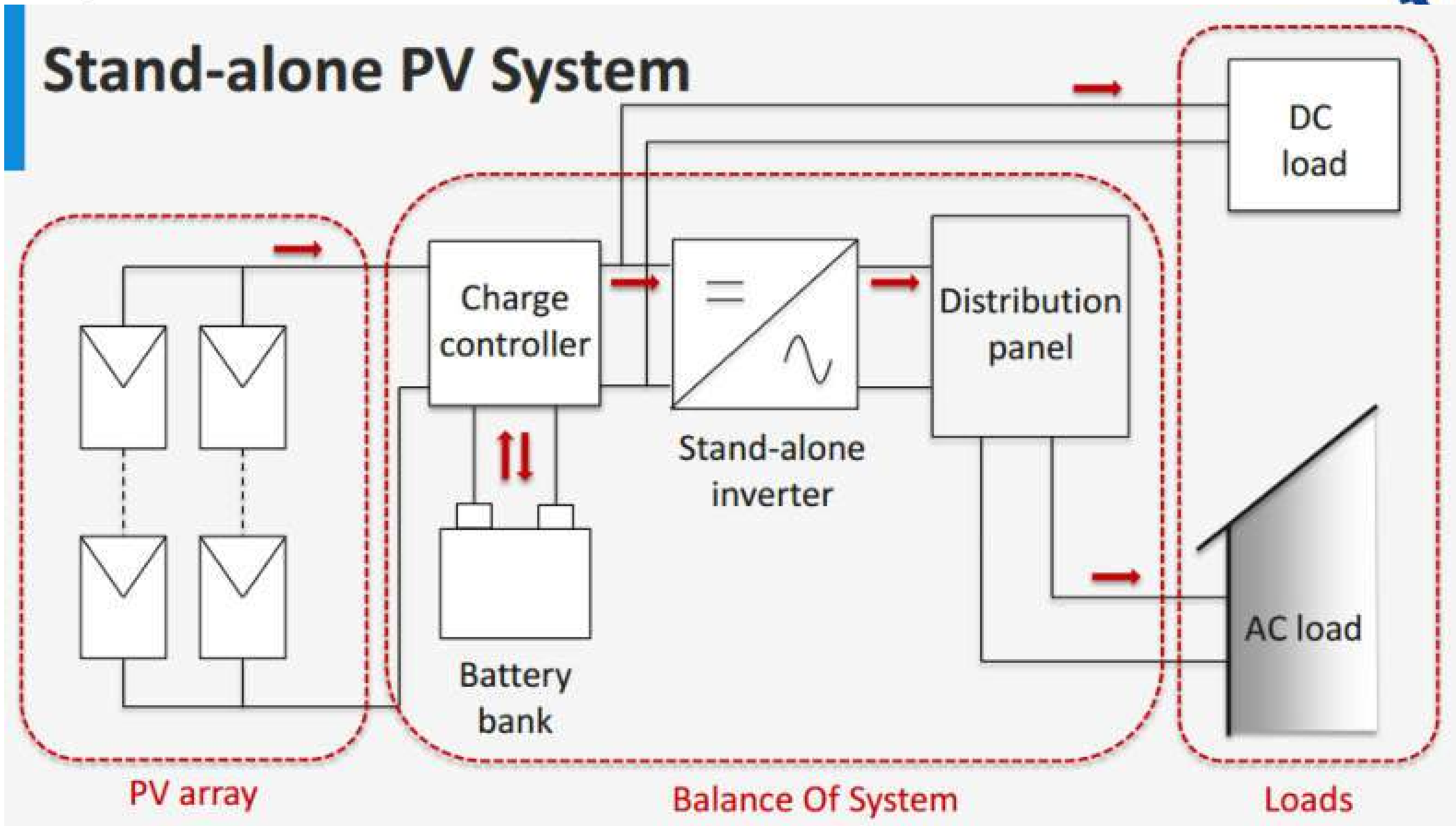
System Configuration



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- **A. LOADS**

- **(A1): Inverter efficiency (decimal).**
- This quantity is used as a power adjustment factor when current is changed from **dc to ac**. The efficiency of the inverter selected for this application is assumed to be **0.85**.

- **(A2): Battery bus voltage.**
- This is nominal dc operating voltage of the system. The battery bus voltage for this application is **24 volts**. Which corresponds to the required **dc input voltage for the inverter.**

- **(A3): Inverter ac voltage.**
- The output voltage of the inverter selected for this application is **220 volts**.

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- The components (appliances) that the system will power are:

1. 5 lights (30w each, combined rated wattage 150, used 2 hours/day.
2. Refrigerator, rated wattage 500, used 5 hours/day.
3. 3 ceiling fans (45w each, combined rated wattage 135, used 8 hours/day.
4. Washer, rated wattage, 1500, used 6 hours/week or 0.86 hours/day.
5. Television, rated wattage 200, used 4 hours/day.
6. Toaster, rated wattage 1500, used 0.25 hours/day.

- The appliances are listed under the column heading **Appliance.**

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- **(A4): The rated wattage** is listed for each appliance in column (A4).

Appliance	(A4) Rated Wattage
5 lights (30W each)	150
Refrigerator	500
3 ceiling fans (45w each)	135
Washer	1500
Television	200
Toaster	1500

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- **(A5): Adjustment factor.**
- The adjustment factor is related to the efficiency of the inverter and reflects the actual power consumed from the battery bank to operate ac loads from the inverter. For ac loads, the value (A1) is inserted in column (A5). For this application the adjustment factor is **0.85**. **For dc loads** operating from the battery bank an adjustment factor of **1.0** is used.

- **(A6): Adjusted wattage.**
- Dividing the rated wattage (A4) by the adjustment factor (A5) adjusts the wattage to compensate for the inverter inefficiency and gives the actual wattage consumed from the battery bank (A4 / A5).

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Appliance	(A4 / A5)	Adjusted Wattage (A6)
5 lights (30W each)	150 / 0.85	176
Refrigerator	500 / 0.85	588
3 ceiling fans (45w each)	135 / 0.85	159
Washer	1500 / 0.85	1765
Television	200 / 0.85	235
Toaster	1500 / 0.85	1765

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- **(A7): Hours per day used.**
- The number of hours each appliance is used per day is listed in column (A7). **The duty cycle, or actual time of load operation, must be considered here. For example, a refrigerator may be functional 24 hours a day, but the compressor may only operate 5 hours per day.**

- **(A8): Energy per day.**
- The amount of energy each appliance requires per day is determined by multiplying each appliance's adjusted wattage (A6) by the number of hours used per day (A7). (A6) x (A7)

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Appliance	(A6 × A7)	Energy per Day (A8)
5 lights (30W each)	176 × 2	352
Refrigerator	588 × 5	2940
3 ceiling fans (45w each)	159 × 8	1272
Washer	1765 × 0.86	1518
Television	235 × 4	940
Toaster	1765 × 0.25	441

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- (A9): Total energy demand per day.
- **The Sum of the Quantities in column (A8)** determines the total energy demand required by the appliances per day. For this application the total energy per day for the load is **7463** watt-hours.

- (A10): Total amp-hour demand per day.
- **In order to size the battery bank the total electrical load is converted from watt-hours to amp-hours**. Amp-hours are determined by dividing the total energy demand per day (A9) by the battery bus voltage (A2). (A9) / (A2).
- **7463 watt-hours / 24 volts = 311 amp-hours.**

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- **(A11): maximum ac power requirement.**
- The sum of the rated wattages (A4) for all appliances is equal to **3985 watts.** Note that this is the maximum continuous power required and does not include surge requirements.
- **(A12): maximum dc power requirement.**
- The sum of the adjusted wattages (A6), or dc power, for all appliances is equal to **4688 watts.**

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- **B. BATTERY SIZING**

- DESIGN TEMPERATURE: The location where batteries are stored should be designed to minimize fluctuations in battery temperature. For this application the design temperature is assumed to be **25 degrees C.**

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- **(B1): Days of storage desired/required (autonomy).**

- In this application, the battery storage system is designed to provide the necessary electrical energy for a period equivalent to **7 days without any sunshine**.

- This time period is considered a moderate level of storage for non-critical applications. **Less critical applications may use 3 to 4 days of storage**, although this would increase the depth of the battery cycling and reduce battery life.

- **For critical applications such as those that would impact public safety, more days of storage may be desirable.**

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- **(B2): Allowable depth-of-discharge limit (decimal).**
- The maximum fraction of capacity that can be withdrawn from the battery as **specified by the designer**. Note that the battery selected must be capable of this limit or greater depth of discharge. For this application the allowable depth- of discharge is **0.8.**

- **(B3): Required battery capacity.**
- The required battery capacity is determined by first multiplying the total amp-hours per day (A10) by the days of storage required (B1), 311 x 7 = 2177, and then dividing this number by the allowable depth of discharge limit (B2). [(A10) x ((B1) / (B2))]
- 311 x (7 / .8) = **2721 amp-hours**

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- **(B4): Amp-hour capacity of selected battery.**
- Once the required number of amp-hours has been determined (B3), batteries or battery cells can be selected using manufacturers' information. **Exide 6E95-11** industrial grade batteries were selected for this application because of their long cycle life and rugged construction.

- ***Figure B.4*** shows that Exide 6E95-11's capacity for a 5 day rate is **478 amp-hours.** Since battery capacity may vary with the rate of discharge, the amp-hour capacity that corresponds to the required days of storage should be used.

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TYPE	VOLTS PER UNIT	NORMAL A.H. CAP	20 DAY (480 HR) A.H	20 DAY (480 HR) AMPS	10 DAY (240 HR) A.H	10 DAY (240 HR) AMPS	5 DAY (120 HR) A.H	5 DAY (120 HR) AMPS	3 DAY (72 HR) A.H	3 DAY (72 HR) AMPS	32° F (0° C) 500 HR A.H.
6E95-5	12	180	192	0.40	192	0.80	192	1.60	192	2.67	184
6E95-7	12	270	288	0.60	288	1.20	288	2.40	288	4.00	276
6E95-9	12	360	383	0.80	383	1.60	383	3.19	383	5.32	368
6E95-11	12	450	478	1.00	478	1.99	478	3.98	478	6.64	459
6E120-9	12	500	538	1.12	538	2.24	538	4.48	538	7.47	516
6E120-11	12	625	673	1.40	673	2.80	673	5.61	673	9.35	646
6E120-13	12	750	808	1.68	808	3.37	808	6.73	808	11.22	776
6E120-15	12	875	942	1.96	942	3.93	942	7.85	942	13.08	904
3E120-17	6	1000	1077	2.24	1077	4.49	1077	8.98	1077	14.96	1034
3E120-19	6	1125	1212	2.53	1212	5.05	1212	10.10	1212	16.83	1163
3E120-21	6	1250	1346	2.80	1346	5.61	1346	11.22	1346	18.69	1292
3E120-23	6	1375	1481	3.09	1481	6.17	1481	12.34	1481	20.57	1422
3E120-25	6	1500	1616	3.37	1616	6.73	1616	13.47	1616	22.44	1551
3E120-27	6	1625	1750	3.65	1750	7.20	1750	14.58	1750	24.31	1680
3E120-29	6	1750	1885	3.93	1885	7.85	1885	15.71	1885	26.18	1809

Amps

- ***Figure B.4*** – Exide Battery Specification Sheet

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- **(B5): Number of batteries in parallel.**
- The number of batteries or battery cells needed to provide the required battery capacity (B3) by the amp-hour capacity of the selected battery (B4). (B3) / (B4).
- **2721 amp-hours / 478 amp-hours = 6 (round up from 5.6).**

- **(B6): Number of batteries in series.**
- The number of batteries needed to provide the necessary dc system voltage is determined by dividing the battery bus voltage (A2) by the selected battery or battery cell voltage (taken from manufacturer's information). (A2) / battery voltage.
- **24 volts / 12 volts = 2.**

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- **(B7): Total Number of batteries.**
- Multiplying the number of batteries in parallel (B5) by the number of batteries or battery cells in series (B60 determines the total number of batteries needed. (B5) x (B6).
- 6 x 2 = **12.**

- **(B8): Total battery amp-hour capacity.**
- The total rated capacity of selected batteries is determined by multiplying the number of batteries in parallel (B5) by the amp-hour capacity of the selected battery (B4). (B5) x (B4).
- 6 x 478 amp-hours = **2868 amp-hours.**

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- **(B9): Total battery kilowatt-hour capacity.**
- [2868 amp-hours x 24 volts] / 1000 = **68.8 kilowatt-hour.**

- **(B10): Average daily depth of discharge.**

- **The 0.75 factor is used by assuming that the PV array meets the load during peak sun hours or 0.25 of the day and the batteries supply the load for the other 0.75 of the day**. For the lighting load profile that operates only at night this factor would be 1.0, due to the load being entirely supplied by the batteries. [0.75 x (A10)] / (B8).
- **(0.75 x 311) / 2868 = 0.08**

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- **C. PHOTOVOLTAIC ARRAY SIZING**

- The size of the photovoltaic array is determined by considering the available solar insulation, the tilt and orientation of the array and the characteristics of the photovoltaic modules being considered.

- The array is sized to meet the average daily load requirements for the month or season of the year with the **lowest ratio daily insulation to the daily load.**

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- **If the load is constant, the designer must consider the time of the year with the minimum amount of sunlight (in the Northern hemisphere, typically December or January).**

- Knowing the insulation available (at tilt) and the power output required, the array can be sized using module specifications supplied by manufacturers.

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- The array is sized to meet the average daily demand for electricity during the worst insulation month of the year, which is December in Jordan.

- The array will face south and because the sun is low in the sky during December will be tilted at an angle of **50 degrees** from the horizontal in order to maximize the insulation received during December.

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- DESIGN MONTH: December
- DESIGN TILT: 50 degrees for maximum insulation during the design month.

- **(C1): Total energy demand per day (A9).**
- **7463 watt-hours.**

- **(C2): Battery round trip efficiency.**
- A factor between 0.70 and 0.90 is used to estimate battery round trip efficiency. For this application **0.85** is used because the battery selected is relatively efficient and because a significant percentage of the energy is used during daylight hours.

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- **(C3): Required array output per day.**
- The watt-hours required by the load are adjusted (upwards) because batteries are less than 100% efficient. Dividing the total energy demand per day (C1) by the battery round trip efficiency (C2) determines the required array output per day.
- (C1) / (C2).
- **7463 watt-hours / 0.85 = 8780 watt-hours.**

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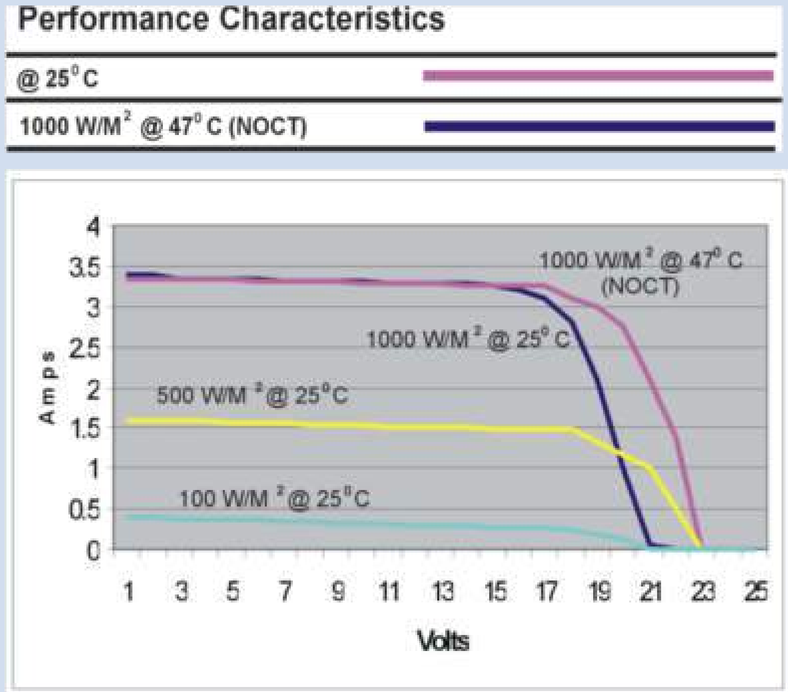
- **(C4): Selected PV module max power voltage at STC x 0.85.**
- Maximum power voltage is obtained from the manufacturer's specifications for the selected photovoltaic module, and **this quantity is multiplied by 0.85 to establish a design operating voltage** for each module (not the array) to the left of the maximum power voltage and to ensure acceptable module output current.
- Siemens Solar M55 modules are used in this application. According to Figure C.4
- ***C.4*** the maximum power voltage at STC for the Siemens Solar M55 is 17.4 volts.
- 17.4 volts x 0.85 = **14.8 volts.**

Power Specifications*	
Model	M55
Power	53.0 Watts
Current (typical at load)	3.05 Amps
Voltage (typical at load)	17.4 Volts
Short Circuit Current (typical)	3.27 Amps
Open Circuit Voltage (typical)	2.18 Volts
Physical Characteristics	
Length	50.9 in/1293 mm
Width	13 in/330 mm
Depth	1.4 in/36 mm
Weight	12.6 lb/5.7 kg

*Power specifications are at standard test conditions of: 1000 W/M , 25˚C cell temperature and spectrum of 1.5 air mass.



The IV curve (current vs. Voltage) above demonstrates typical power response to various light levels at 25˚C cell temperature, and at the NOCT (Normal Cell Operating Temperature), 47˚C.

Figure C.4 – Siemens Solar M55 module specifications

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- **(C5): Selected PV module guaranteed power output at STC.**
- This number is also obtained from the manufacturer’s specifications for the selected module. Figure C.4 shows the nominal power output at 1000 watts/m^2 and 25 degrees C is 53 watts.
- The guaranteed power output is 90% of this value, or **47.7 watts.**

- **(C6): Peak sun hours at optimum tilt.**
- This figure is obtained from solar radiation data for the design location and array tilt for an average day during the worst month of the year. Peak sun hours for this application in December equal **3.8 hours.**

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- **(C7): Energy output per module per day.**
- The amount of energy produced by the array per day during the worst month is determined by multiplying the selected photovoltaic power output at STC (C5) by the peak sun hours at design tilt (C6). (C5) x (C6).
- **47.7 x 3.8 = 181 watt-hours/day**

- **(C8): Module energy output at operating temperature.**
- **A de-rating factor of 0.90 (for moderate climates and non-critical applications)** is used in this application to determine the module energy output at operating temperature. Multiplying the de-rating factor (DF) by the energy output module (C7) establishes an average energy output from one module. DF x (C7).
- **0.90 x 181 watt-hours/day = 163 watt-hours/day**

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- **(C9): Number of modules required to meet energy requirements.**
- Dividing the required output per day (C3) by the module energy output at operating temperature (C8) determines the number of modules required to meet energy requirements. (C3 / (C8).
- 8780 watt-hours / 163 watt-hours = **54 modules**

- **(C10): Number of modules required per string.**
- Dividing the battery bus voltage (A2) by the module design operating voltage (C4), and then rounding this figure to the next higher integer determines the number of modules required per string. (A2) / (C4).
- 24 volts / 14.8 volts = 1.62 (rounded to **2 modules**).

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- **(C11): Number of string in parallel.**
- Dividing the number of modules required to meet energy requirements (C9) by the number of modules required per string (C10) and then rounding this figure to the next higher integer determines the number of string in parallel. (C9) / (C10).
- 54 modules / 2 modules = **27 strings** (if not a whole number round to next integer)

- **(C12): Number of modules to be purchased.**
- Multiplying the number of modules required per string (C10) by the number of strings in parallel (C11) determines the number of modules to be purchased. (C10) x (C11).
- 2 x 27 = **54 modules**

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- **C. Charge Controller Sizing**

- Solar charge controllers are specified by both amperage and voltage.

- You will need a *solar controller* that can support the voltage of your solar panel array, and then output to the battery bank's voltage **(24 VDC in this application).**

- The basic formula for sizing a solar charge controller is to take the short circuit current (**Isc**) of the array and multiply it by 1.56.
- **3.27 x 1.56 x 27 = 138 Amps**

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References

- http://www.nepco.com.jo/
- http://www.emrc.gov.jo/index.php/ar/
- https://www.pveducation.org/index.php
- https://www.ammancity.gov.jo/ar/main/index.aspx
- Energy Conversion, by Kenneth C. Weston
- Planning and Design, SMA Solar Academy

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Thank You!