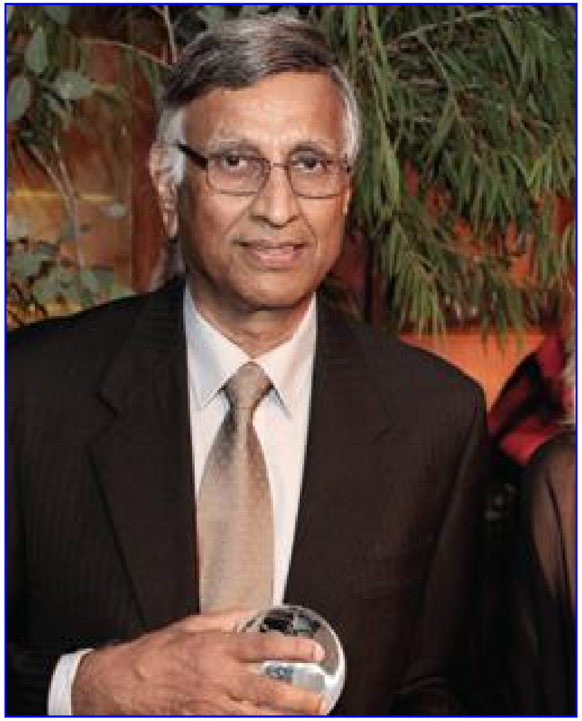
Solar power plants for residential, commercial, utility and off-grid applications Part 1

Professor Chem Nayar

INTERNATIONAL CONFERENCE 2014 POWER AND ENERGY SYSTEMS: TOWARDS SUSTAINABLE ENERGY, BANGALORE 13-15 MARCH, 2014

My Background

- BSc Elec Engg, MTech (IIT Kanpur), PhD (Wind Power), Univ. of Western Australia
- Professor of Electrical and Renewable Energy Engineering, Curtin University
- Visiting Professor –Hefei University, China University of Mining and Technology , United Arab Emirates University, Chiang Mai University (Thailand)
- 42 years teaching , research and industry experience
- Chairman, Regen Group Pty Ltd, Australia
- Director, Radiant Solar , Hyderabad, India
- Supervised /supervising 20 PhDs, 300 research papers, 8 million in research grants
- Winner of Sustainable Energy Industry Excellence Award 2011 : (1) The Ambassador Award and (2) Product and Technology Award
- Australian Committee for Power Engineering : Life Time Career Achievement Award , 2012



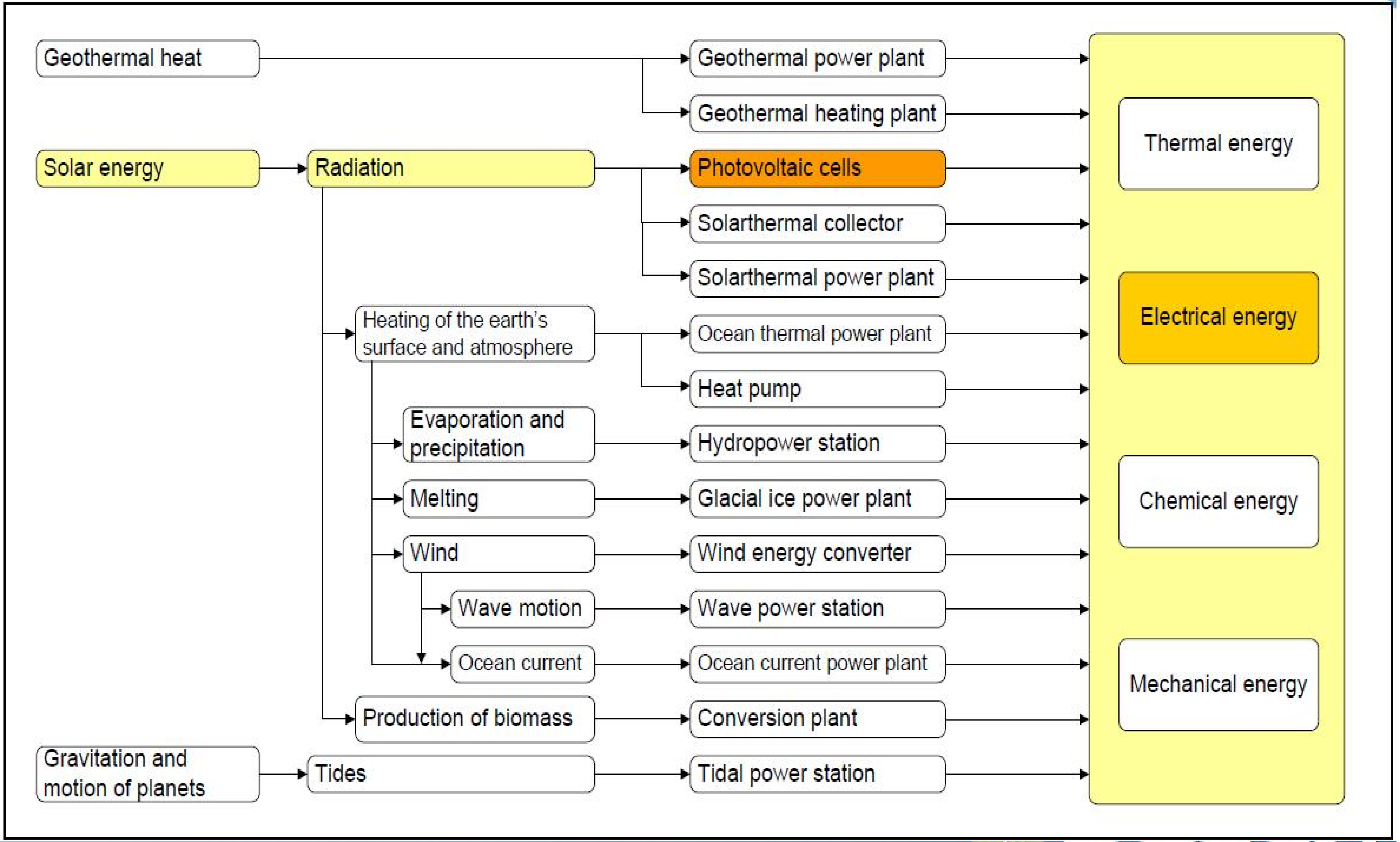
Professor Chem Nayar

Outline

- ❑ **Introduction**
- ❑ **Solar Energy – Facts**
- ❑ **Photovoltaic (PV)**
- ❑ **Power Electronics Converters**
- ❑ **Applications :**
  - ❑ **Residential**
  - ❑ **Commercial**
  - ❑ **Solar Farms**

Background photo: www.bso.vvs.be

Renewable Energy Definition



Source: Kaltschmitt et. al.

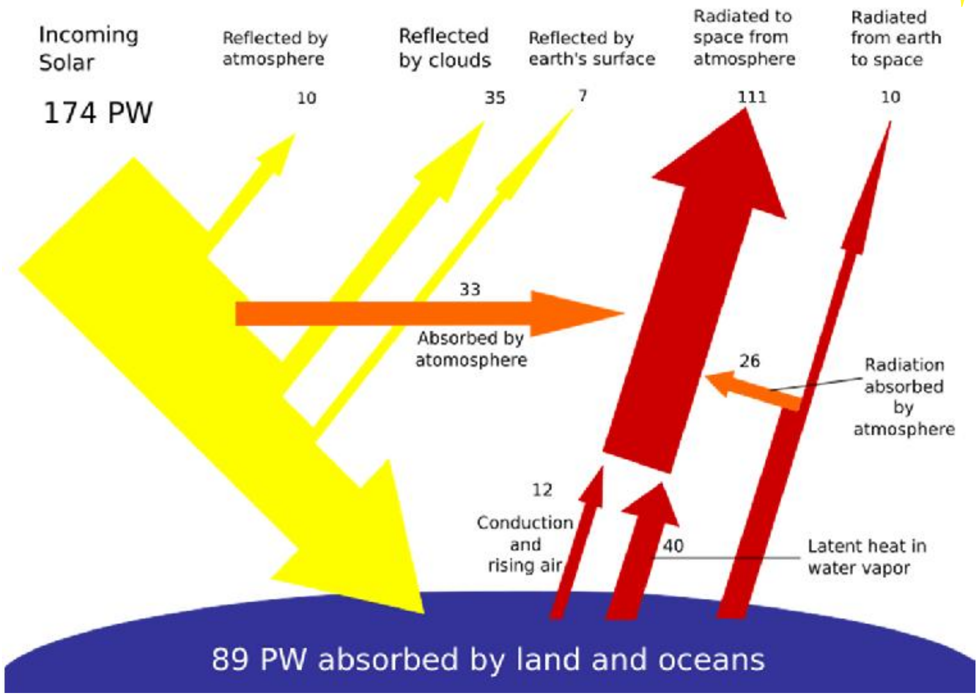
Solar Energy- Facts

Solar Power Density(Power Leaving the Sun) : $H_s = 63.54\ MW/m^2$
Radius of the sun : $R_s = 6.96 \times 10^8 m$
Power emitted by the sun : $P_s = H_s \times 4\,\Pi\, R_s^2 = 3.869 \times 10^{20}\ MW$
Distance of earth from the sun: $D = 1.5 \times 10^8\ km$
Power density at a distance d: $P_d = H_s\, R_s^2 / d^2$
Solar Constant: $S = H_s\, (R_s /D)^2 = 1368\ W/m^2$

- Earth receives 174 $\times 10^{15}$ W radiation ($\approx 1300 W/m^2$) at its upper atmosphere with around 30% reflected back.

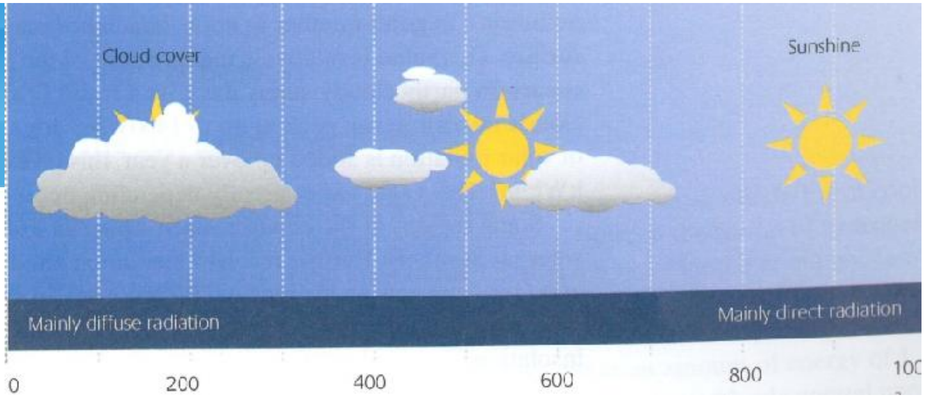
Solar Energy- Facts

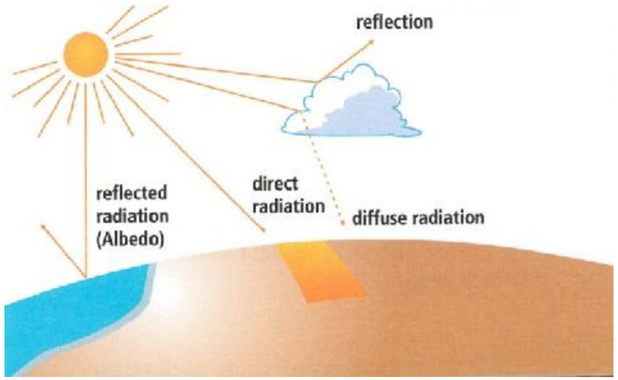
- The amount of solar energy reaching the surface of the planet in one year is double all of the Earth’s non-renewable resources (past and future) including uranium.

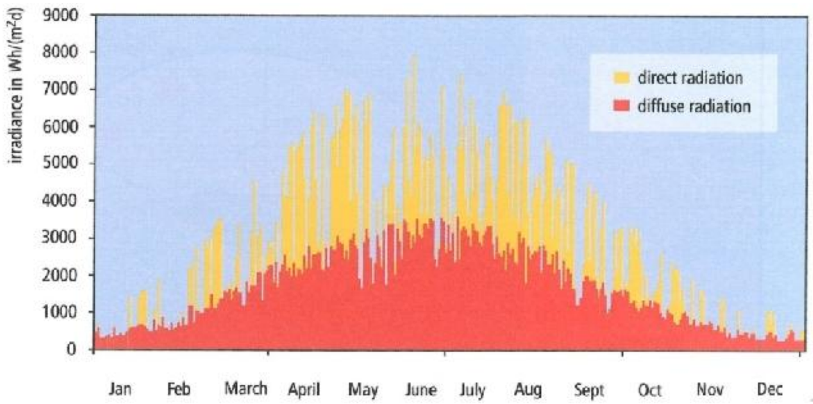


Direct and diffuse radiation

- Average irradiation (Solar Constant) falling on the upper atmosphere is E_0=1367W/m^2
- Reduces to 1000 W/m^2 on the surface due to
  - Reflection
  - Molecular absorption O_3, H_2O,O_2, CO_2
  - Molecular scattering (Rayleigh scattering)
  - Dust and pollution scattering (Mie scattering)
- Direct and diffuse (land and clouds) radiation sum together. On an partly cloudy day irradiation may reach 1400W/m^2.
- The annual sum of Irradiation is Insolation in kWh/m^2 which peaks at 2300kWh/m2 under ideal conditions and averages around 1000kWh/m2 in Europe







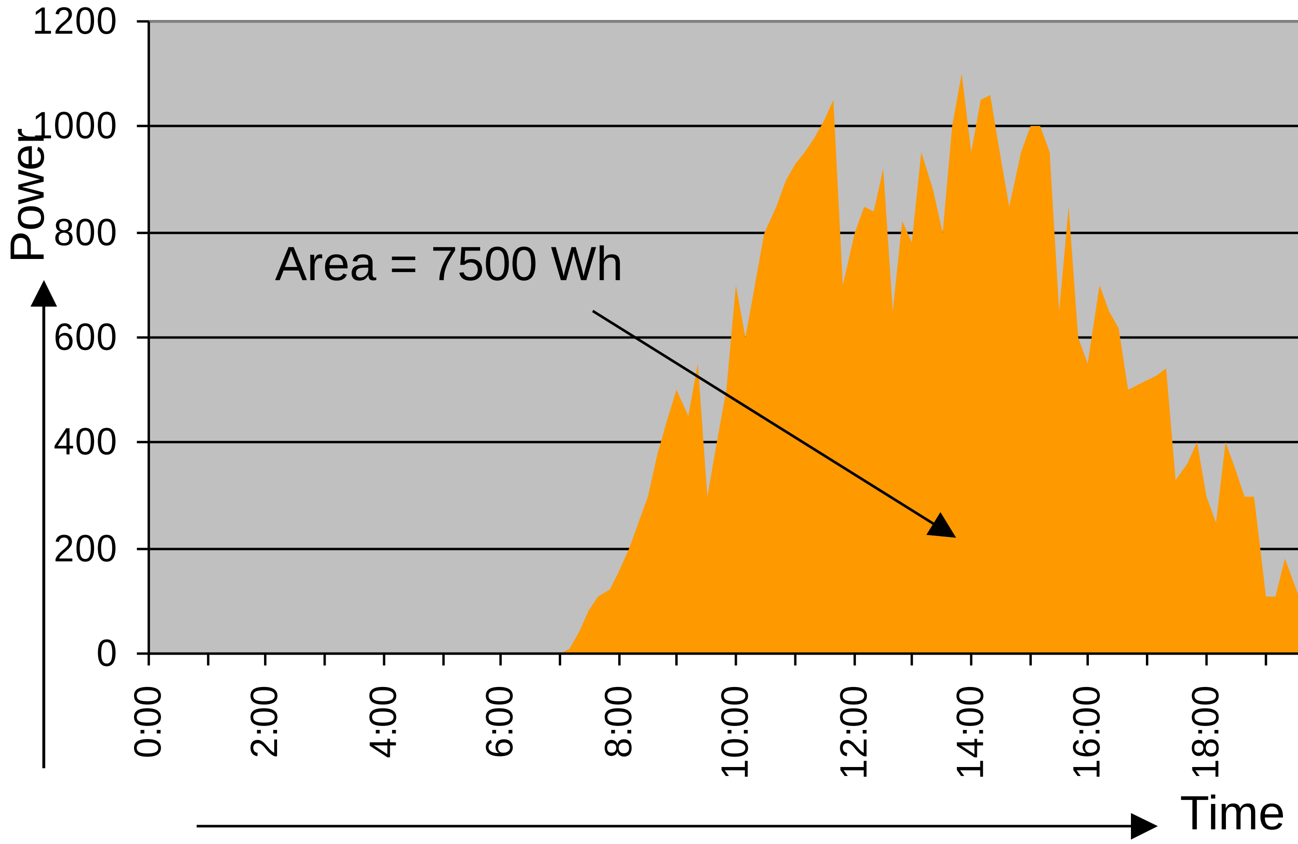
Solar Radiation data

Terminology

- Irradiance – instantaneous power received from the sun kW/m^2
- Irradiation – energy (kWh/m^2)
- **Solar Insolation**
  - integral of irradiation on a given surface area over a given time expressed as $kWh/m^2/yr$
- Peak Sun Hours
  - Measure of Irradiation
  - 1 PSH = $1kWh/m^2$

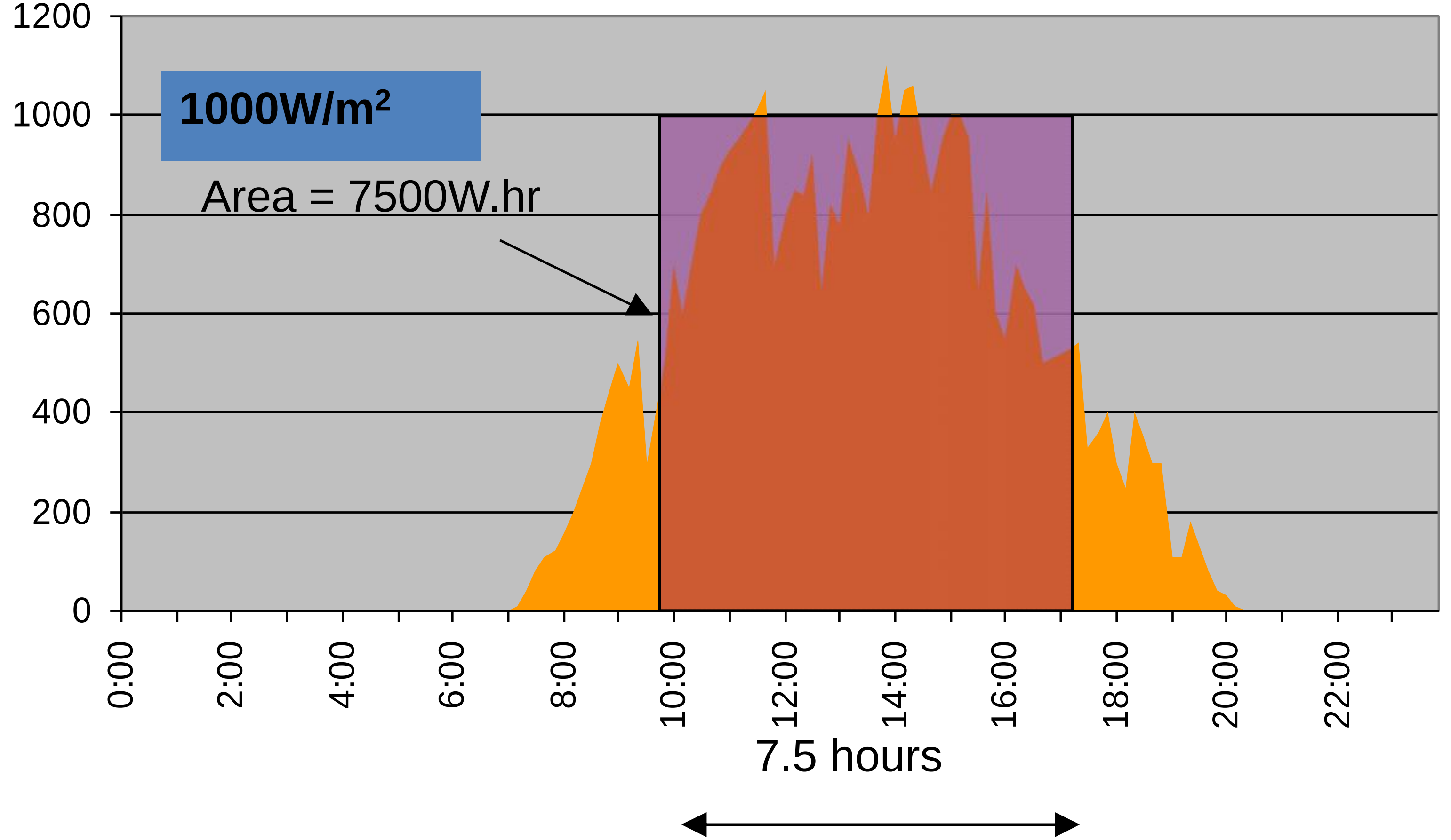
Energy from the Sun

Energy =Power x Time = Area under curve



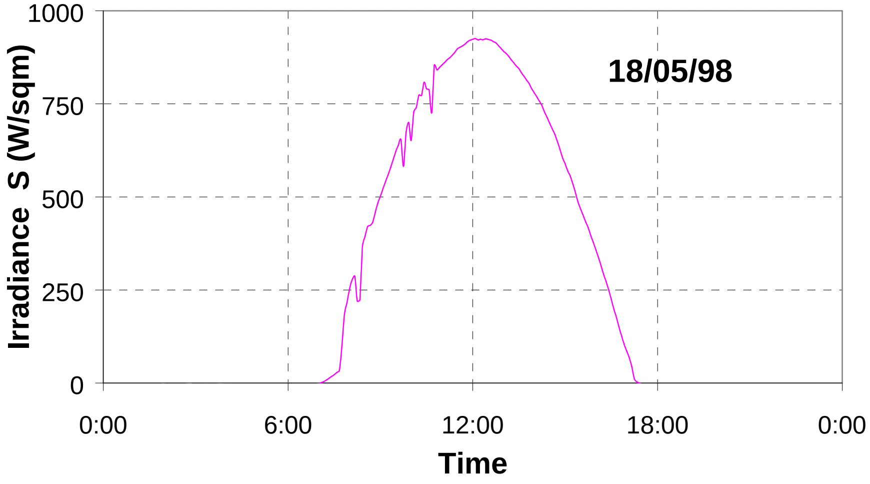
Peak Sun Hours

Equivalent Time at 1 peak sun (1000W/m^2)

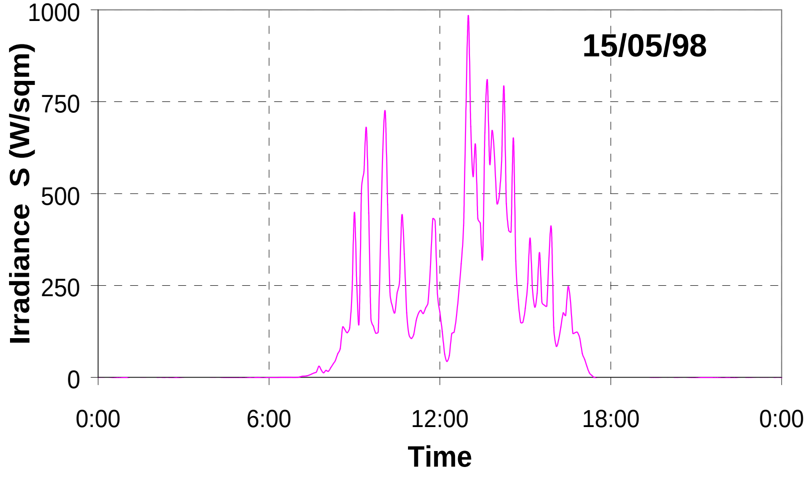


Solar Irradiance

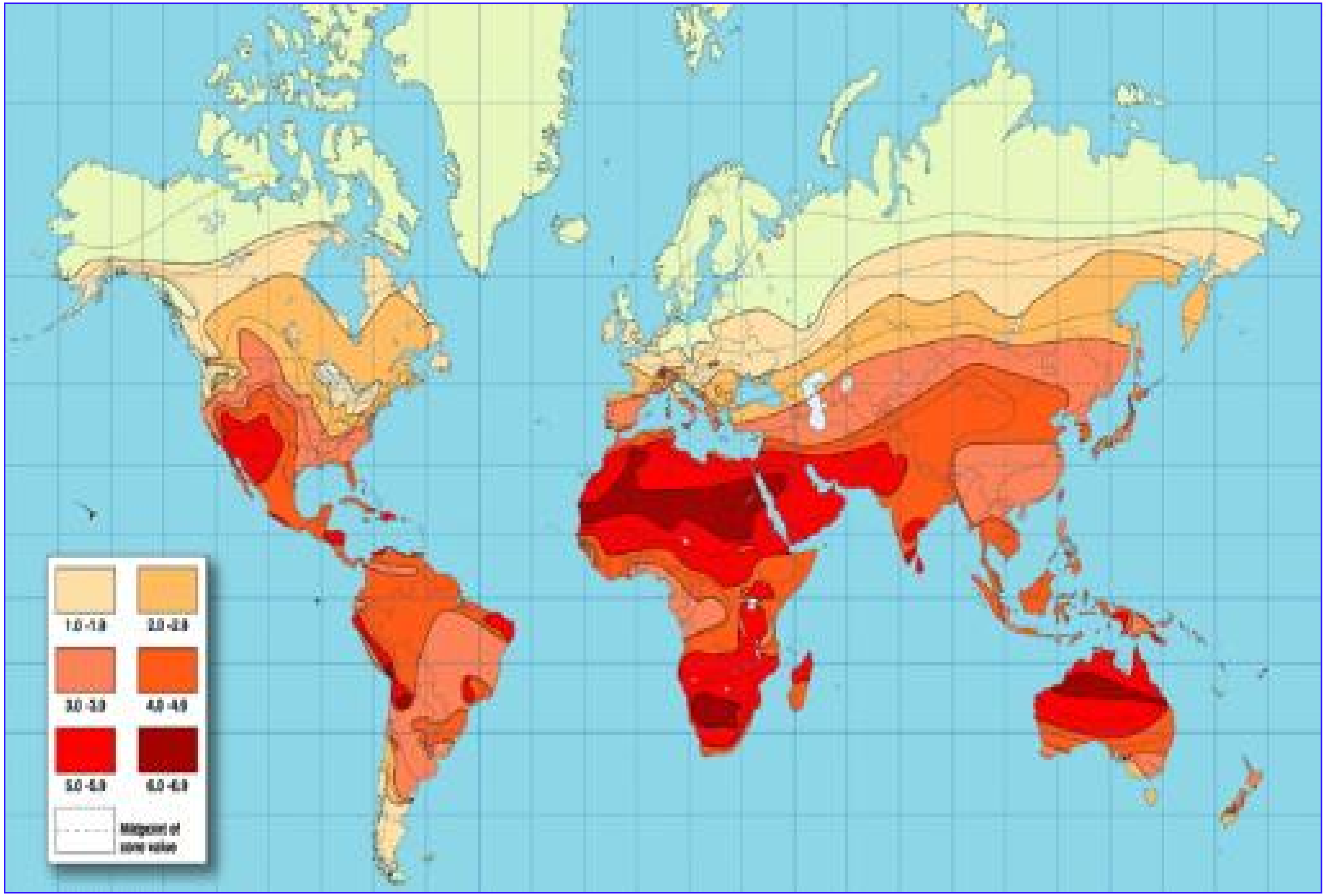
A typical sunny day in Perth



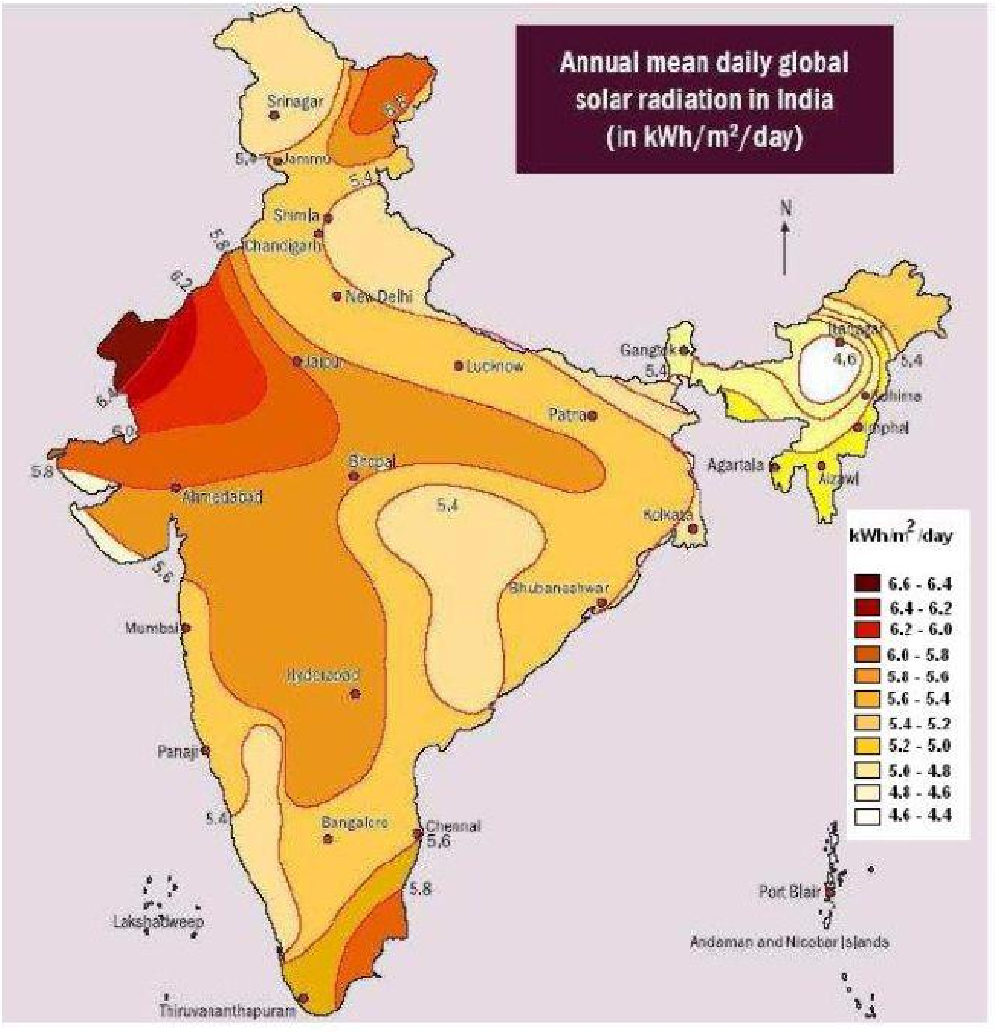
A Typical cloudy day in Perth



Solar Insolation Map)

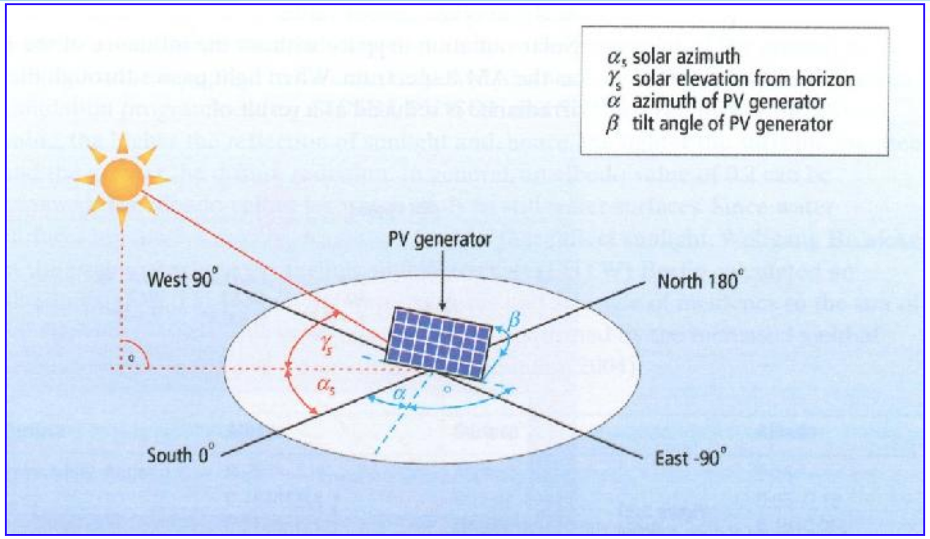


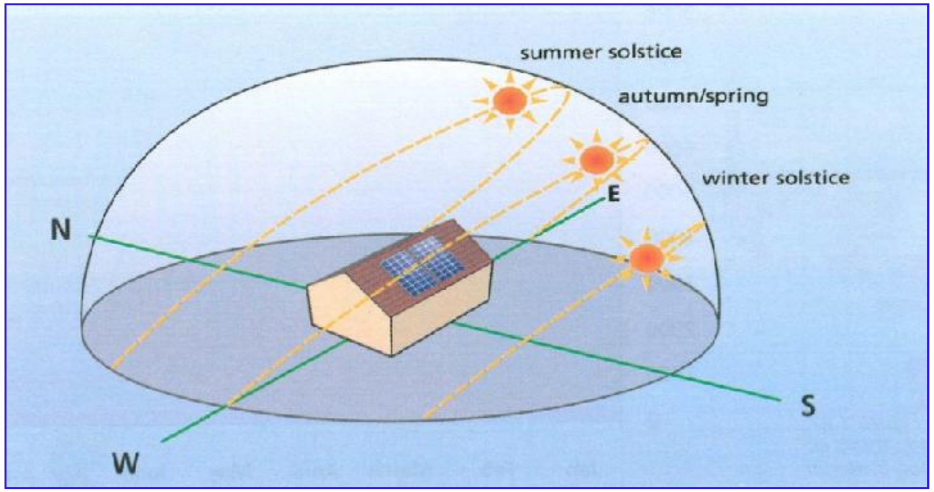
Solar Insolation Map-India



Angle Definition

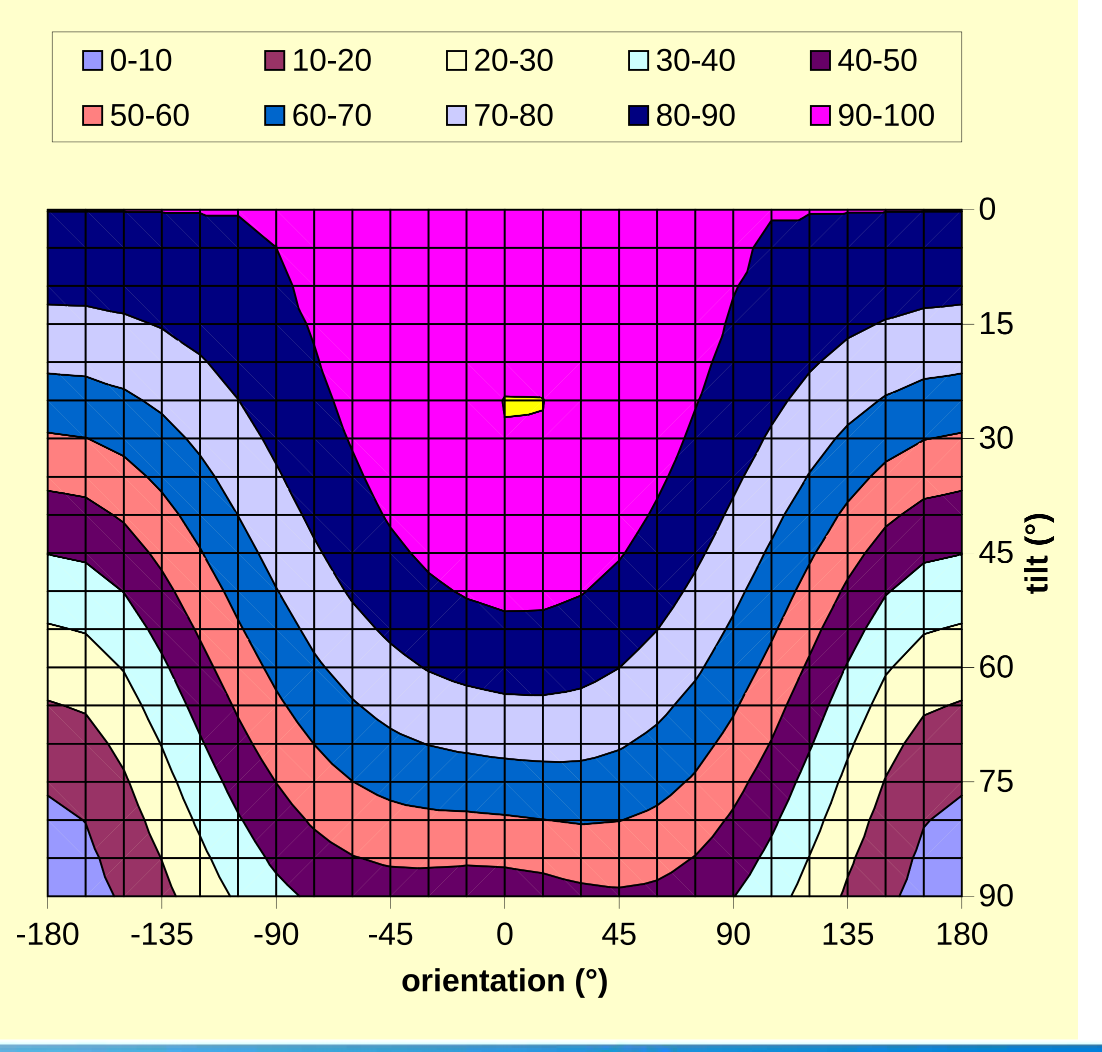
- Azimuth is east to west track of the sun
- Zenith or elevation is the height of the sun
- Tilt is the angle of the solar generator
- Air Mass factor AM $= \frac{1}{Sin\gamma_s}$





Optimum tilt & orientation

- Optimum orientation—face equator
  - i.e. due south in India
- Optimum tilt—typically equal to latitude
  - For example, Bangalore L =13° N
- To get subsidy from MNRE, follow this rule.



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- Introduction
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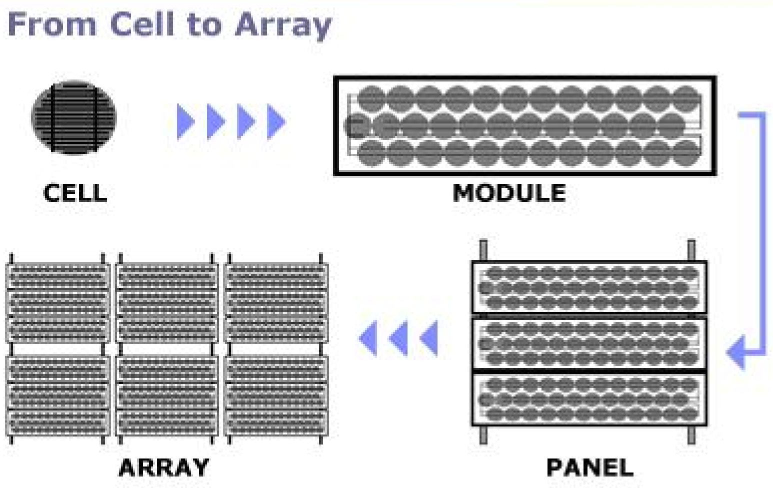
- Grid connected Inverters
- Applications :
  - Residential
  - Commercial
  - Solar Farms

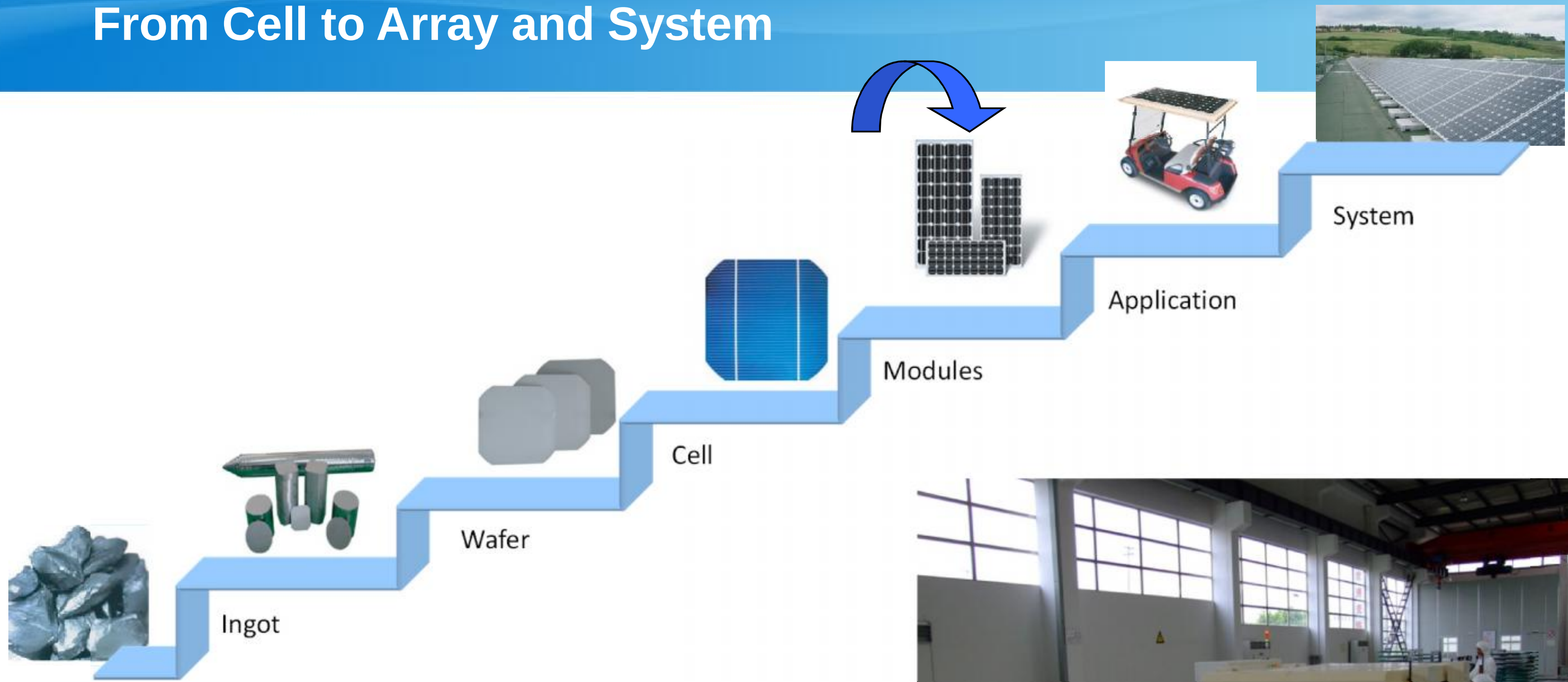
Background photo: www.bso.vvs.be

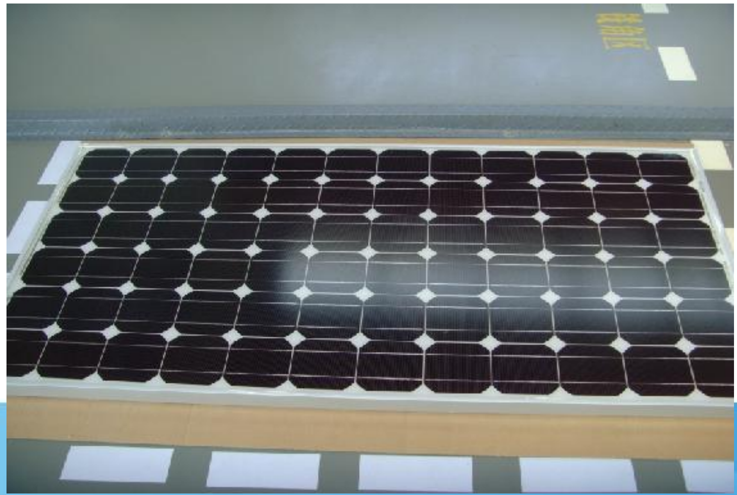
From Cell to Array and System

Cells	Semiconductor device that converts sunlight into direct current (DC) electricity
Modules	PV modules consist of PV cell circuits sealed in an environmentally protective laminate and are the fundamental building block of PV systems
String	Is a set of series connected Modules designed to produce a nominal working voltage whilst ensuring the it doesn’t exceed Vmax and Vmin at Tmin and Tmax respectively
Panels	PV panels include one or more PV modules assembled as a pre-wired, field-installable unit
Array	A PV array is the complete power-generating unit, consisting of any number of PV modules and panels
Balance of System	Frames, cables, connectors, trackers, instruments etc



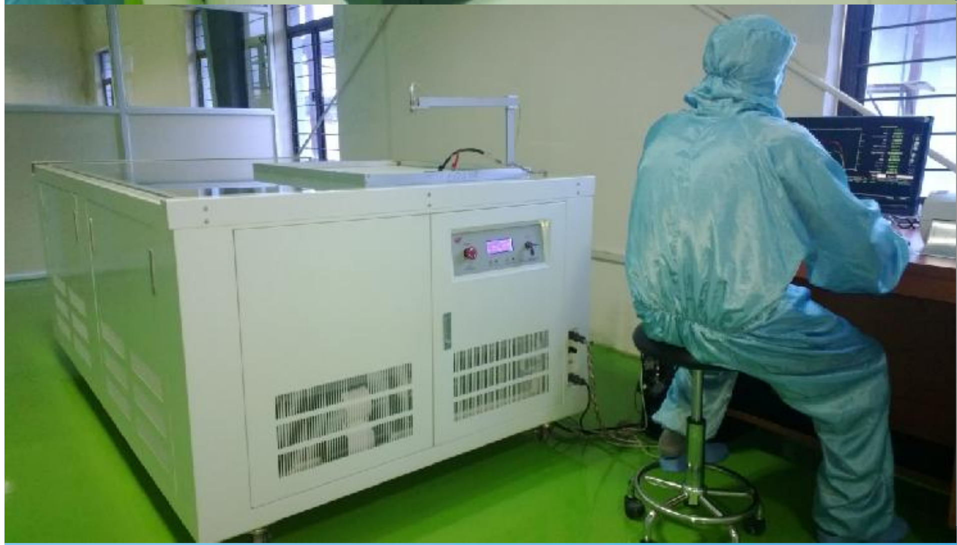
From Cell to Array and System





Module manufacturing



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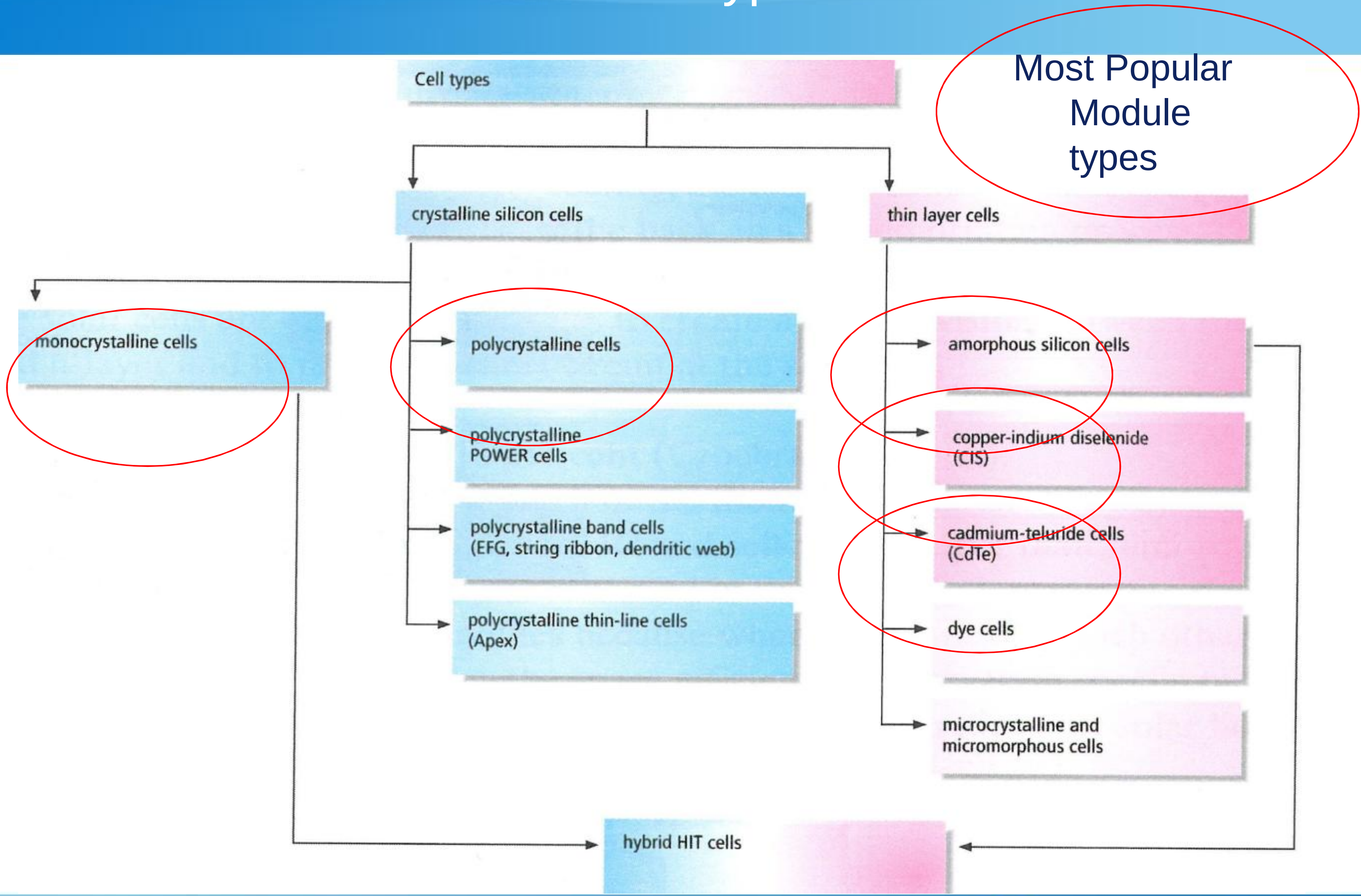
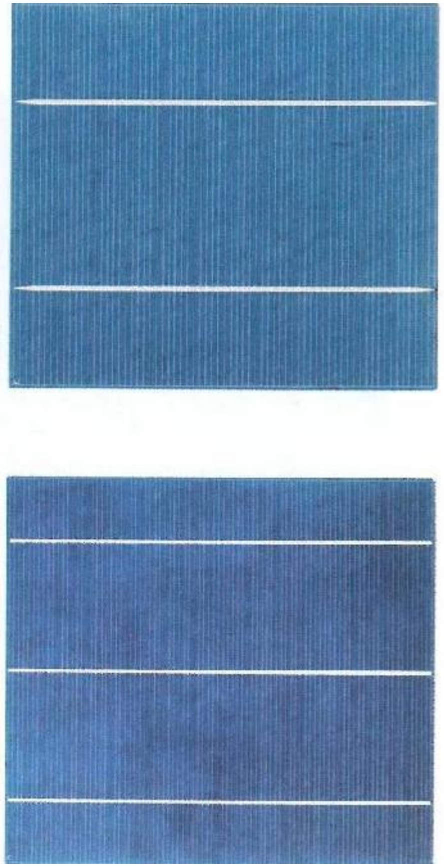
PV Module types

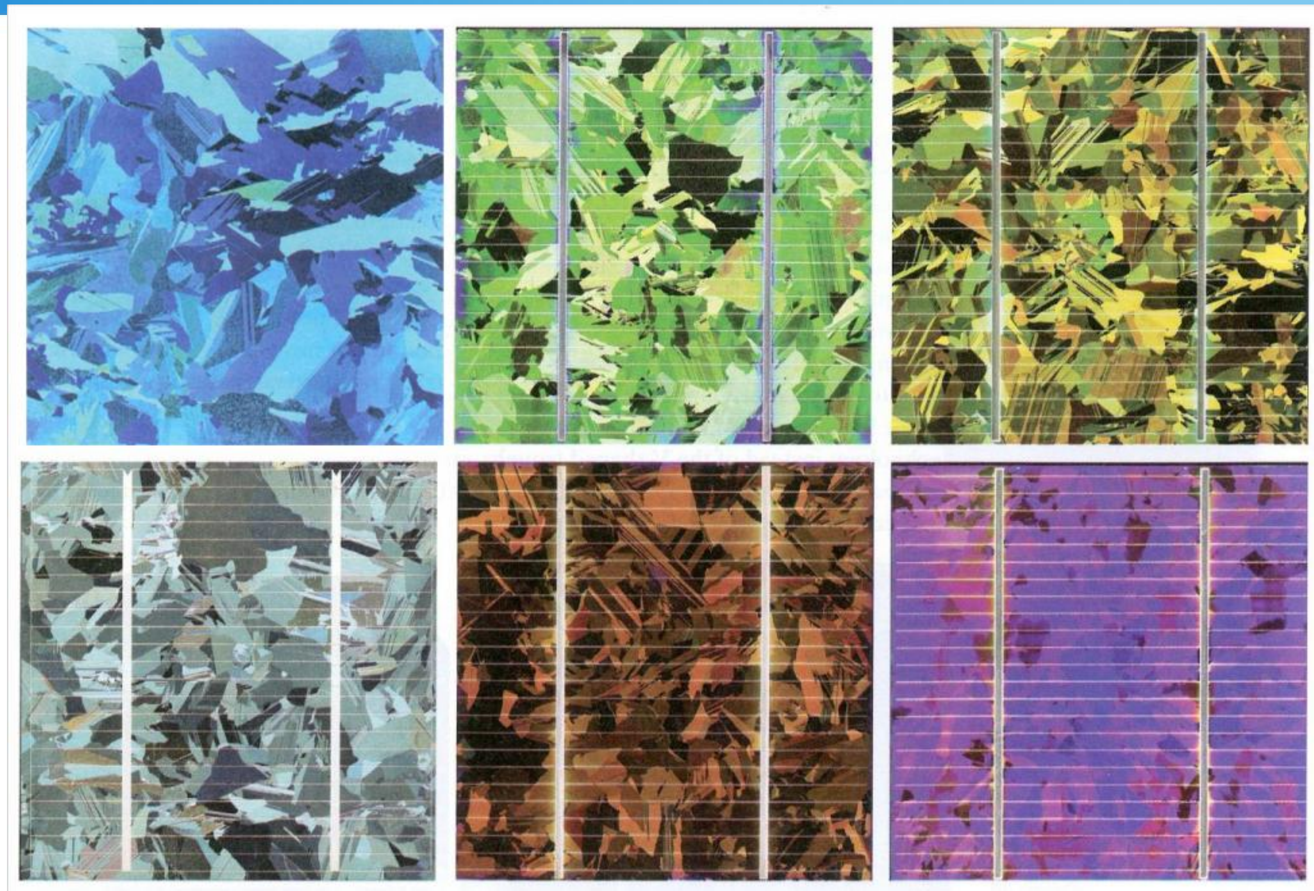


Key properties of the main types of PV cells

Attribute	**Monocrystalline**	**Polycrystalline**	**Amorphous (formless)**	**CdTe**	**CIS** **Copper indium diselenide**	**Indium gallium arsenide** **(Concentrating CPV)**
Efficiency %	15 - 18	Generally 9.5 – 14	5-7	7 – 8.5%	9-11	>30%
Form	Round, semi round or square	Square or semi round	Modular	Modular	Modular	
Size cm	Up to 15 x 15. Size controlled by multiple of crystal size	Up to 20.8 x 20.8 Size controlled by multiple of crystal size	80 x 244. Greater flexibility in physical size	120 x 60	120 x 60	
Thickness of active material mm	0.2 – 0.3	0.2 – 0.3	0.0003		.001 - .002	
Appearance	Uniform	Crystalline effect	Uniform	Uniform	Uniform	
Colour	Dark blue to black	Blue, grey, pink, brown, green, black	Reddish brown, blue or velvet	Dark green to black	Dark grey to black	
Operational benefits	Dominate the market wit poly. Highest efficiency in the ‘general purpose’ market	Lower efficiency wrt Mono is balanced by lower cost. Often used in building façades (BIPV) to visually enhance the appearance	Inexpensive. First to break $/W but land area & BOS costs are higher. Performance deteriorates significantly during year 1. Colour sensitive cells can be stacked to allow a wider portion of the spectrum to be captured. Work well in cloudy / part shaded conditions.	Cost effective. Some questions over disposal as the modules contain cadmium, a heavy metal	Best performing thin film technology. Not susceptible to light induced degradation	Uses expensive sophisticated semiconductors however focussing lenses reduce the amount of active material required by 98%. Temperature remains a problem
Larger Manufacturers	BP, Suntech, Sharp, Helios	Ersol, Q-Cells, Sunways	BP, Sharp, RWE	First Solar	Daystar, CIS Solartechnik	

PV Module Appearance showing front contacts



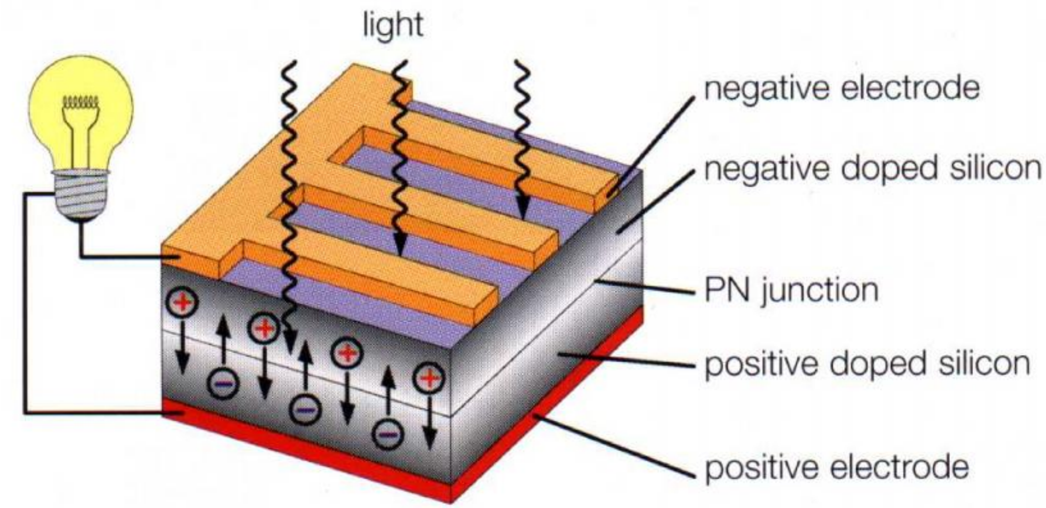


Monocrystalline

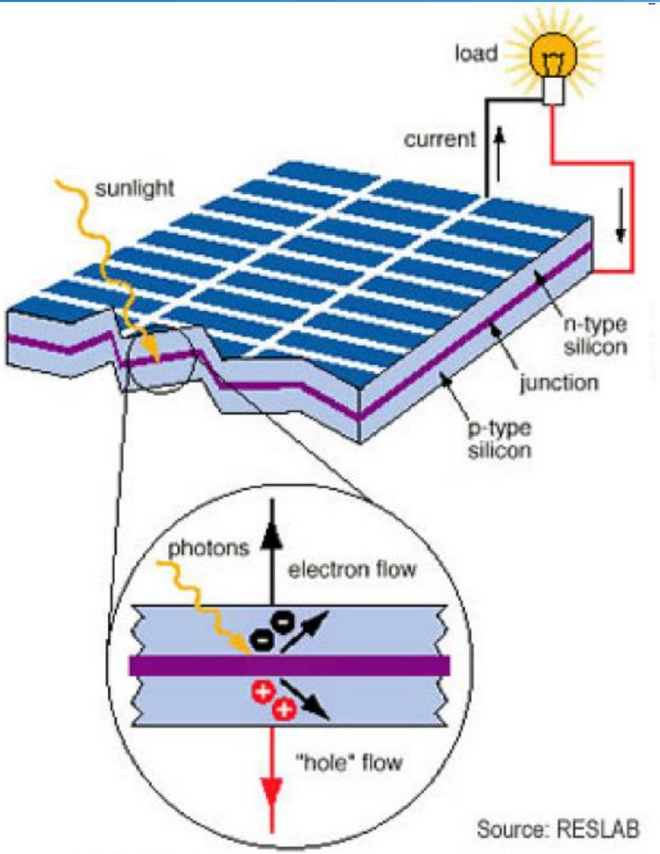
Polycrystalline

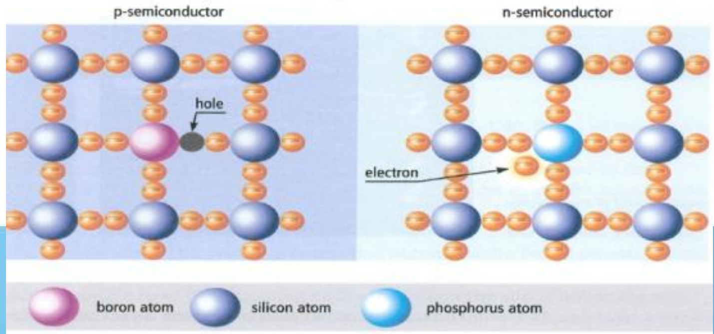
Solar Cells

- Solar cell operation is based on the ability of semiconductors to convert sunlight directly into electricity.
- PV = Photovoltaic or (*Photo = Light*) and (*Voltaic = electricity*).



The “Photovoltaic effect”





- A solar cell consists of two different doped semiconductors (for instance based on silicon)
- Doping agents are introduced into the silicon lattice.
  - Boron (for p-doped) has one electron less in its outer shell and therefore exhibits a hole
  - Phosphorous (for n-doped) has one additional electron in its outer shell
- If the p-n junction is exposed to light electrons absorb photons breaking the bonds allowing electrons to be pulled into the n-region. Holes formed as a result migrate in the opposite direction producing an open circuit voltage of circa 0.5V. This is called the **Photovoltaic effect**.
- Electrical contacts placed on the silicon allow a current to flow if a circuit is made.
- To get a significant voltage a number of solar cells is connected in series to form a solar module **.**

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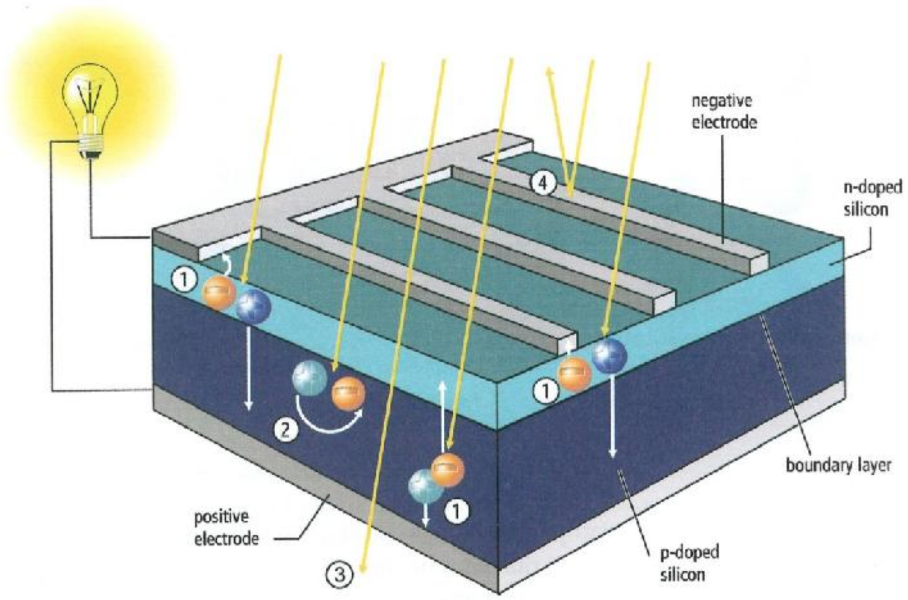
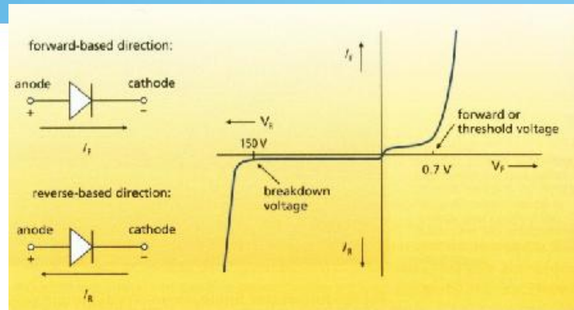
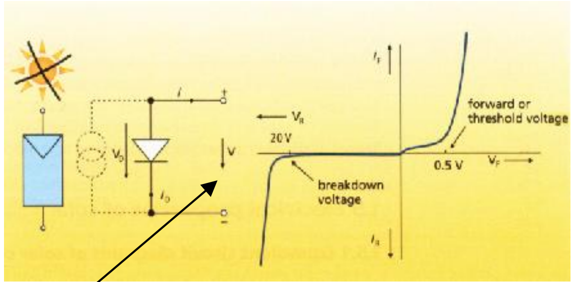
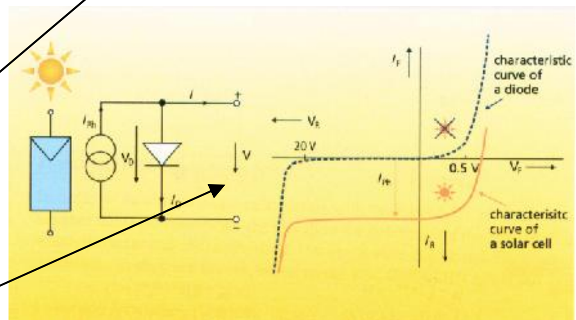
Solar Cell Equivalent Circuit

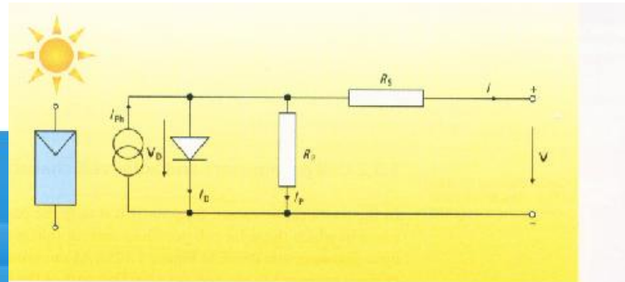
Typical Crystalline Module Construction





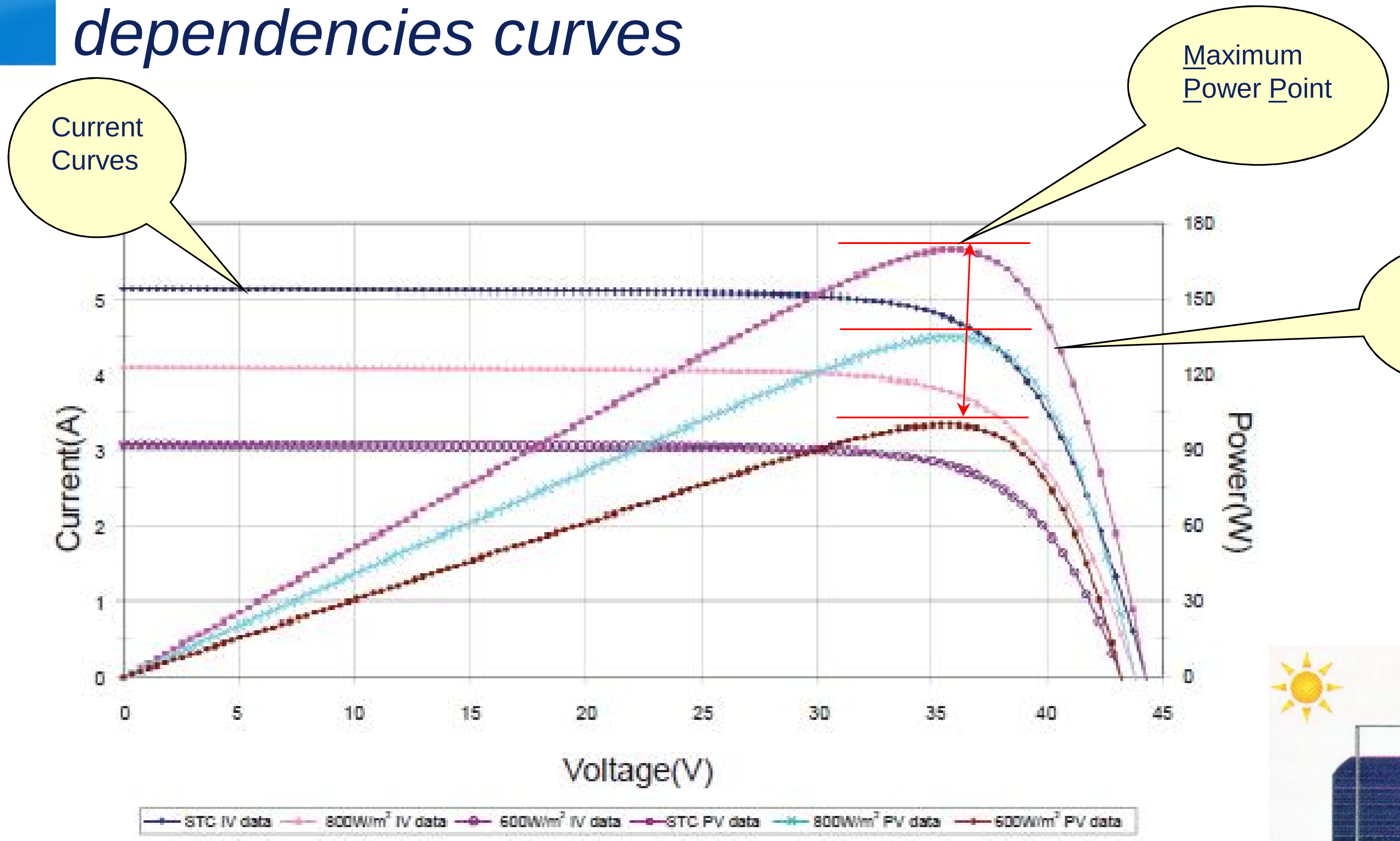


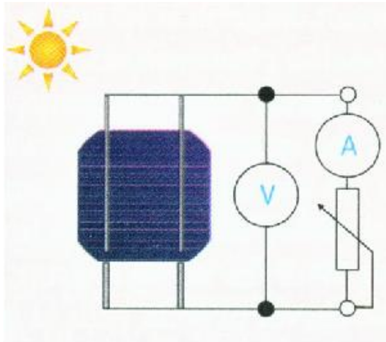




- **Without radiation the cell show a typical behavior of a diode**
- **The radiation adds a current source in parallel to the diode → equivalent circuit**

PV Electrical Characteristics – Voltage dependencies curves



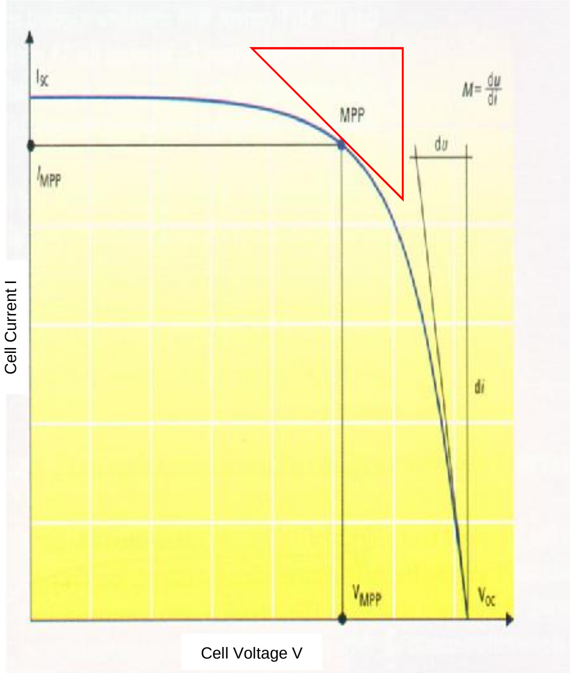


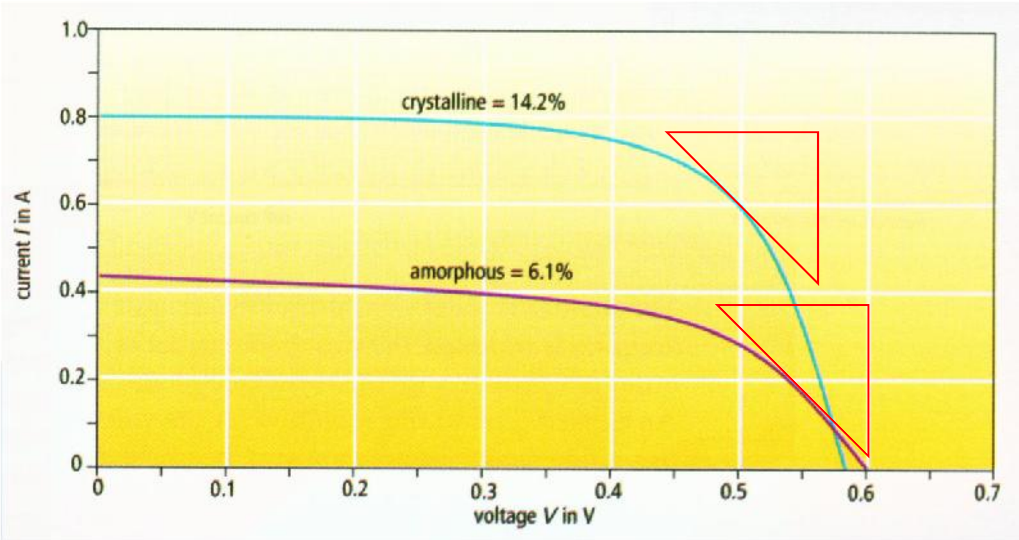
Power and Short Circuit current proportional to Irradiation.
Voltage is virtually independent of Irradiation above 100W/m^2

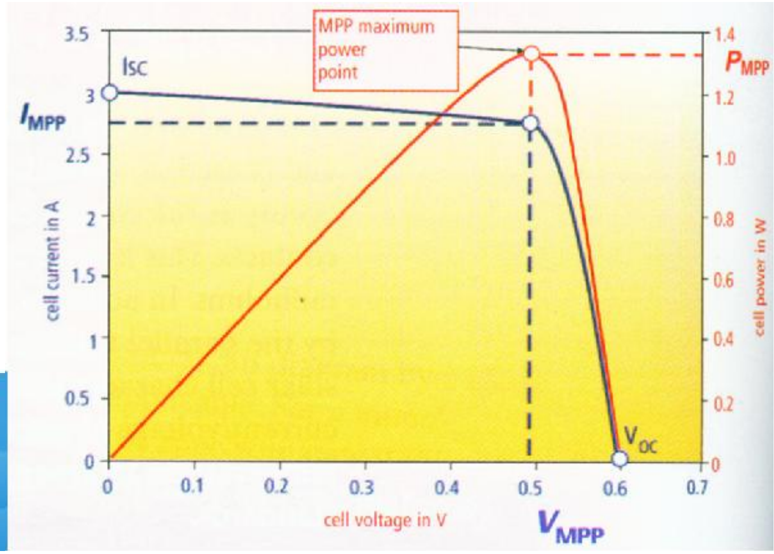
Module Maximum Power Point (MPP)

- MPP is the point at which the product of voltage and current is maximum

- MPP is found on the IV curve where dV/dI = 1 i.e. 45° and on the PV curve where dV/dI = 0 i.e. 0°

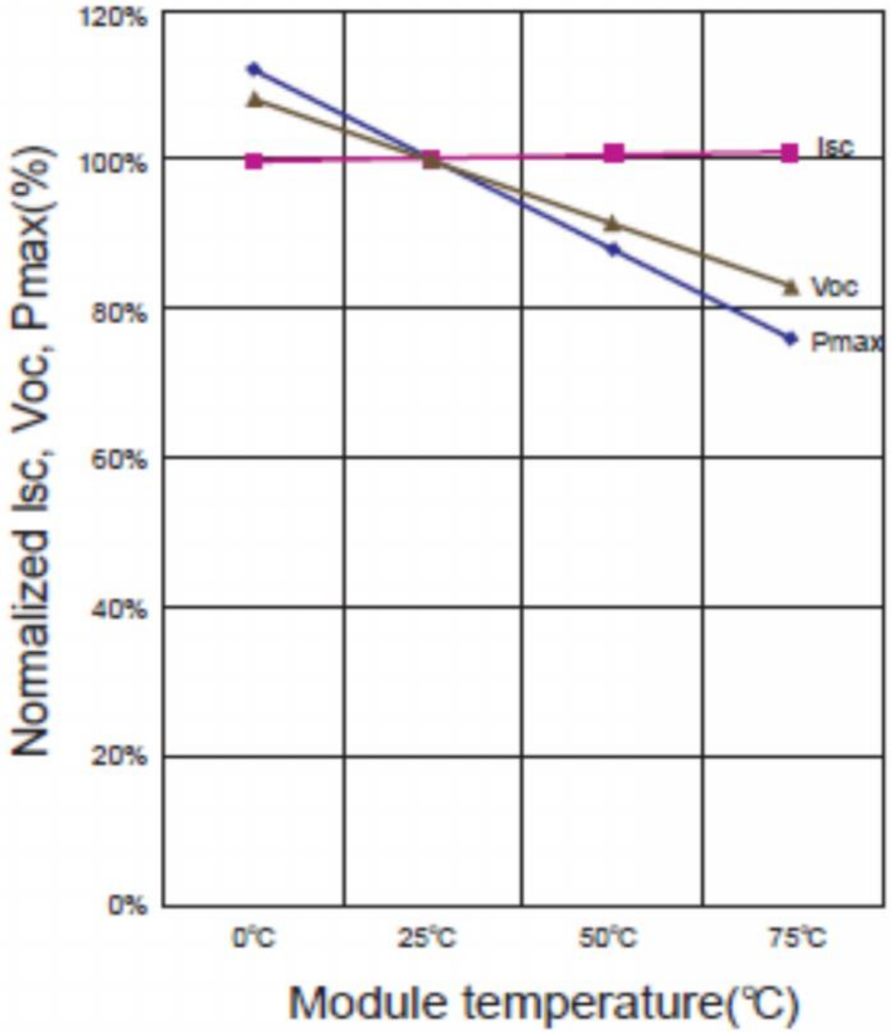






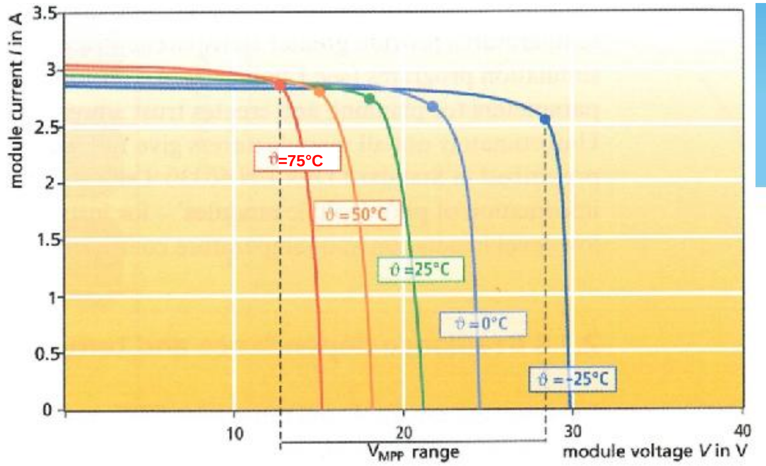
PV Electrical Characteristics – temperature dependencies

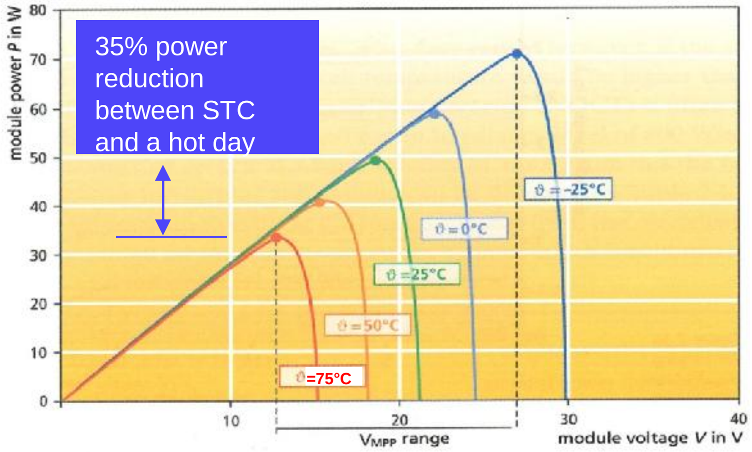
- Generally
  - Current rises with temperature
  - Power and voltage fall with temperature

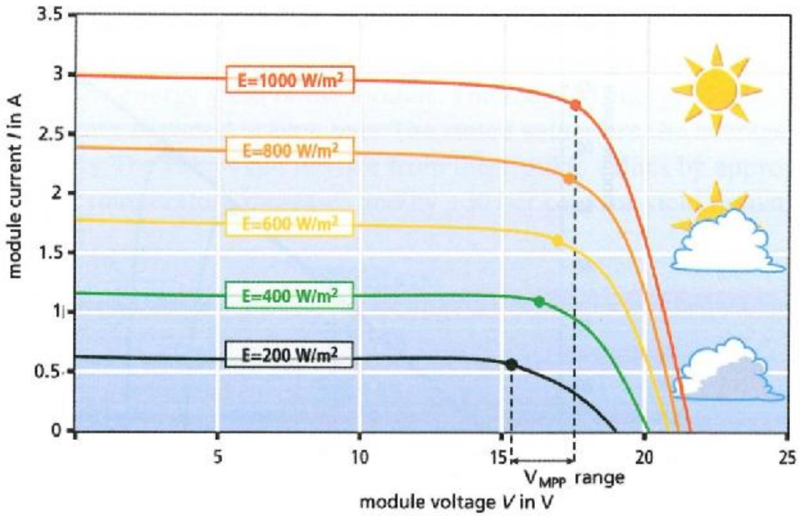


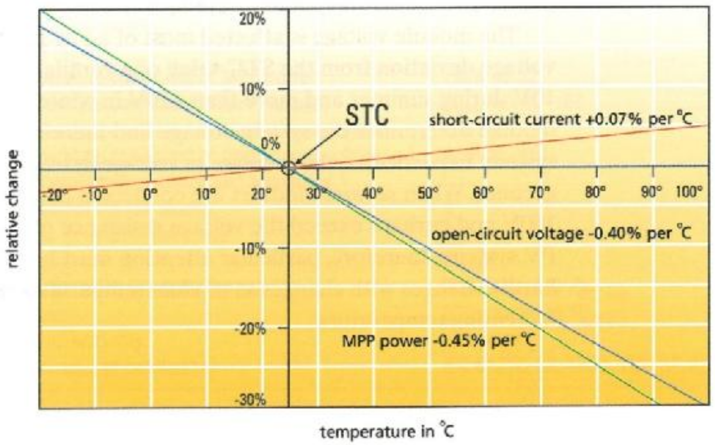
Electrical Characteristics – Crystalline Modules

- Generally
  - Current rises with temperature
  - Power and voltage fall with temperature
- Datasheets express thermal co-efficients in mA or mV/°C or % /°C
- Often Normal Operating Cell Temperature ‘NOCT’ is quoted which is the cell operating temperature under the following conditions
  - Irradiance 800 W/m2, air temperature 20ºC
  - Average wind speed of 1 m/s….
- NOCT is typically 25°C above ambient
- Thermal co-efficients are normally expressed for Voc and Isc however if Vmpp and Impp are given use them as well in the sizing calculations



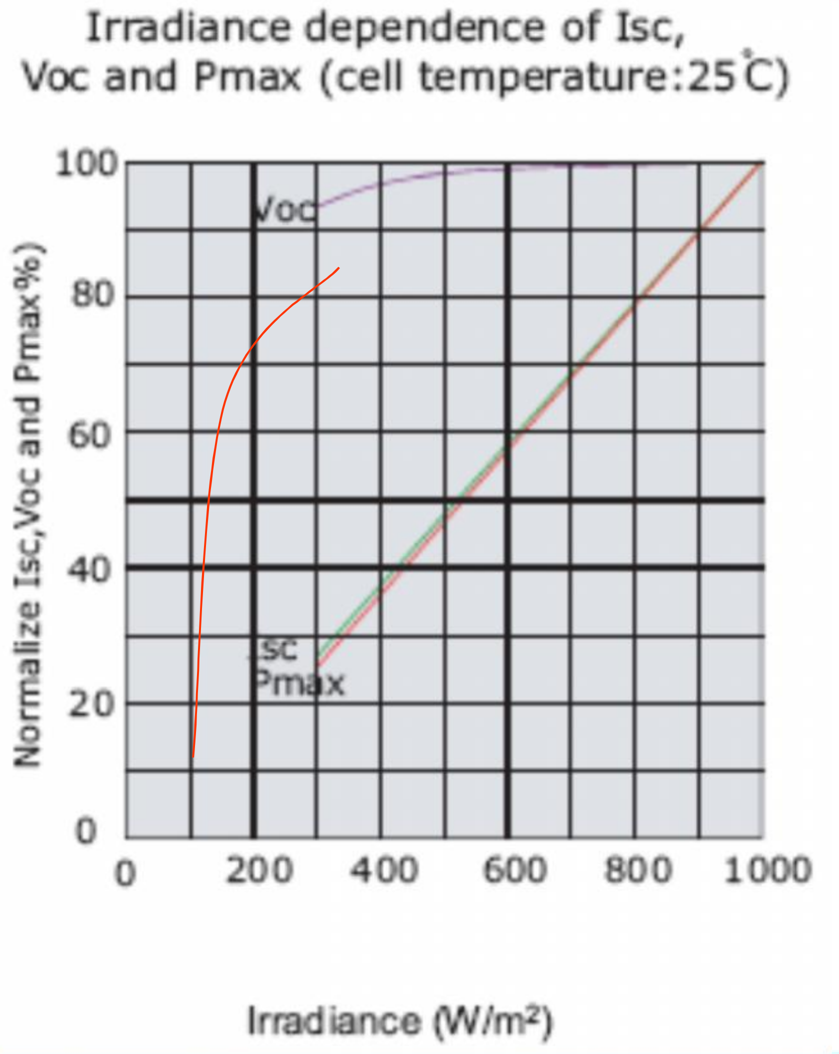






PV Electrical Characteristics – irradiance dependencies

- Short circuit current Isc and power are proportional to irradiation whilst voltage is virtually independent
- Voltage breaks down when irradiance is <100W/m^2



Photovoltaic Module- Standard Test Conditions

- **Standard test Conditions (STC)-**
  - the performance of a photovoltaic module under a defined set of conditions including
    - light intensity of 1000 W/m^2
    - temperature of 25°C
    - sunlight conforming to standard AM1.5 defining 'average' sunlight at sea level passing through the Earth's atmosphere at an angle of 41.8 degrees from the horizon.
- **NOCT**
  - Normal Operating Cell Temperature – module temperature at 80% load with an ambient of 20C. Typically NOCT is 45C making the ΔT 25C

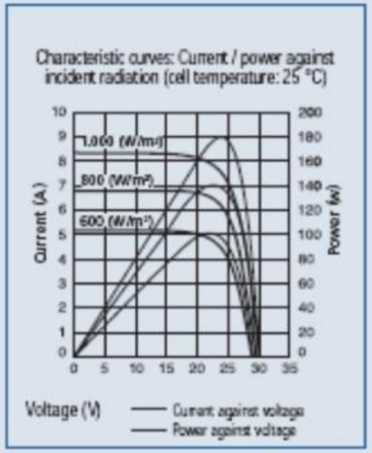
Data Sheet for a Sharp NU Crystalline Module

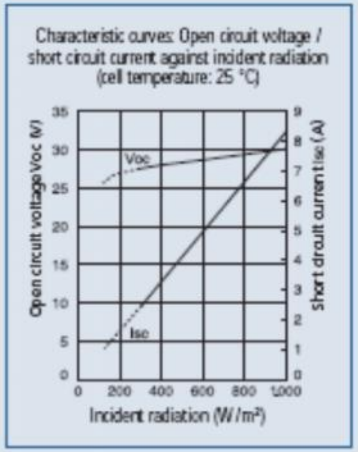
Electrical data

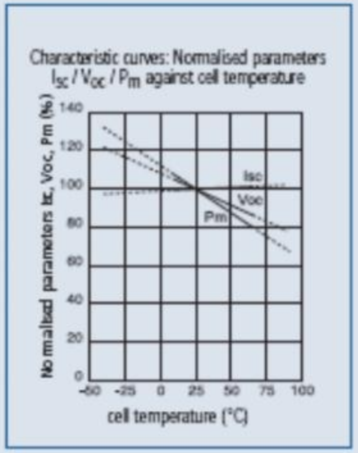
Module production in the EU		NU-185 (E1)	NU-180 (E1)				
Module production in Japan		**NU-S5 (E3E)**	**NU-S0 (E3E)**	**NU-S0 (E3Z)**	**NU-R5 (E3Z)**	**NU-R0 (E3E)**	
Rated power		185 W_p	180 W_p	180 W_p	175 W_p	170 W_p	
Open circuit voltage	V_{oc}	30.2	30.0	30.0	29.8	29.4	V
Short circuit current	I_{sc}	8.54	8.37	8.23	8.29	8.37	A
Voltage at maximum power	V_{pm}	24.0	23.7	23.7	23.2	22.4	V
Current at maximum power	I_{pm}	7.71	7.6	7.6	7.55	7.60	A
Module efficiency	η_m	14.1	13.7	13.7	13.4	13.0	%
Temperature coefficient - open circuit voltage	αV_{oc}	- 104	- 104	- 104	- 104	- 104	mV / °C
Temperature coefficient - short circuit current	αI_{sc}	+0.053	+0.053	+0.053	+0.053	+0.053	% / °C
Temperature coefficient – power	αP_m	- 0.485	- 0.485	- 0.485	- 0.485	- 0.485	% / °C

The electrical data apply under standard testing conditions (STC): Incident radiation 1.000 W/m² mit Lichtspektrum AM 1.5 with AM 1.5 light spectrum at a cell temperature of 25 °C. The power output is subject to a manufacturing tolerance of – 5 % and + 10 %. The modules manufactured in Europe and Japan are identical.

Characteristic curves







Applications

- Grid-coupled PV systems
- Grid-independent systems
- On-roof PV systems (roof parallel)
- On-roof PV systems (on stilts)
- Open air PV systems

Please read our extensive installation guide carefully prior to installing the photovoltaic modules.

Courtesy of Sharp

Data Sheet for a Sharp NA Thin Film Module

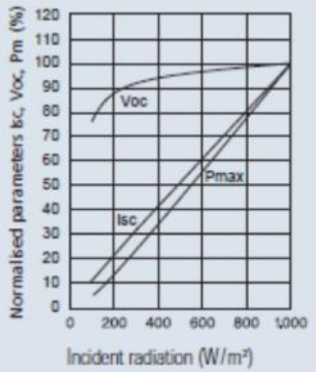
Staebler Wronski effect (6-12 months)

Electrical data

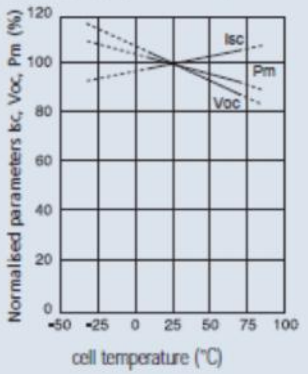
Module production in Japan		Initial value			Nominal value			
		NA-901WP	NA-851WP	NA-801WP	NA-901WP	NA-851WP	NA-801WP	
Rated power		105,9 W_p	100 W_p	94 W_p	90 W_p	85 W_p	80 W_p	
Open circuit voltage	V_{oc}	66.6	65.0	64.5	65.2	63.8	63.2	V
Short circuit current	I_{sc}	2.20	2.20	2.16	2.11	2.11	2.08	A
Voltage at maximum power	V_{pm}	53.5	52.0	50.5	49.3	49.0	47.6	V
Current at maximum power	I_{pm}	1.98	1.92	1.86	1.83	1.74	1.68	A
Module efficiency	η_m				8.5	8.1	7.6	%
Temperature coefficient - open circuit voltage	αV_{oc}	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	% / °C
Temperature coefficient - short circuit current	αI_{sc}	+0.070	+0.070	+0.070	+0.070	+0.070	+0.070	% / °C
Temperature coefficient – power	αP_m	-0.24	-0.24	-0.24	-0.24	-0.24	-0.24	% / °C

The electrical data apply under standard testing conditions (STC): Incident radiation 1,000 W/m² with AM 1.5 light spectrum at a cell temperature of 25 °C. The power output is subject to a manufacturing tolerance of ± 5 % and ± 10 %.

Characteristic curves: Current / power against incident radiation (cell temperature: 25 °C)



Characteristic curves: Normalised parameters I_{sc} / V_{oc} / P_m against cell temperature



- Grid-coupled PV systems
- Grid-independent systems
- On-roof PV systems (roof parallel)
- On-roof PV systems (on stilts)
- Open air PV systems

The instructions in the installation guide must always be observed (e.g. max 7 modules in a row, inverters without transformers are not permitted, 2 parallel lines must be protected with a blocking diode in each case).

A generator cabinet with the approved blocking diodes can be obtained from Sharp Hamburg.

Courtesy of Sharp

Data Sheet for a Sharp NA Thin Film Module

NA-V128H1 | NA-V121H1 | NA-V115H1

Amorphous Silicon/Microcrystalline Silicon
UL-Listed for 600-volt systems

ELECTRICAL DATA		NAMEPLATE VALUES NA-V128H1	NA-V121H1	NA-V115H1
Maximum power	Pmax	128	121	115
Open-circuit voltage	Voc	238	238	238
Short-circuit current	Isc	0.846	0.830	0.810
Voltage at maximum power	Vpmax	186 V	180 V	174 V
Current at maximum power	Ipmax	0.688 A	0.673 A	0.661 A
Module efficiency	η	9.0%	8.5%	8.1%
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).

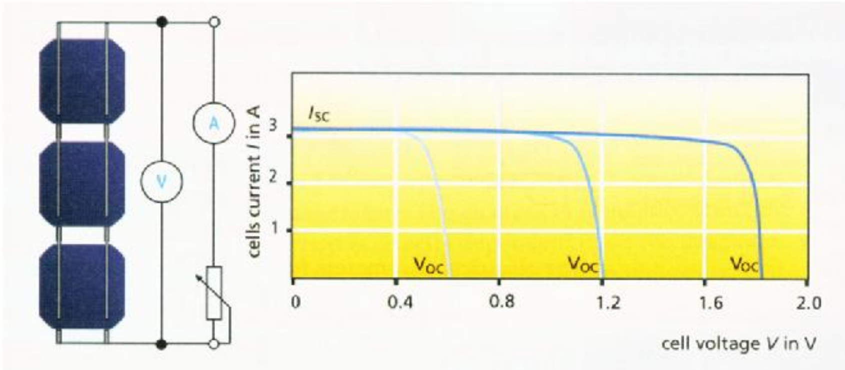
SPECIFICATIONS (I)	
Cell	Tandem architecture of amorphous and microcrystalline silicon
Cell Circuit	45 cells in series by 6 in parallel per quadrant: 4 quadrants in series (1080 total cells)
Dimensions	39.7” x 55.5” x 1.8” (1009 x 1409 x 46 mm)
Weight	42 lbs
Connection type	Cable with MC-4 connector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

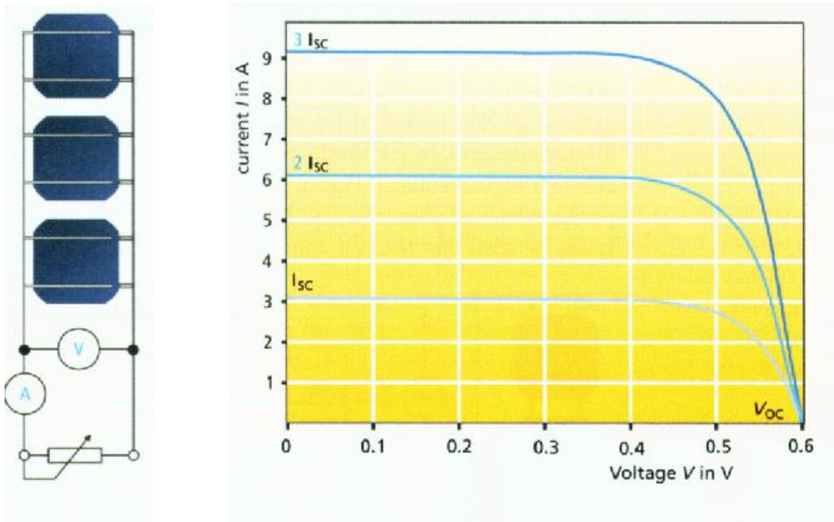
SPECIFICATIONS (II)		
Maximum system voltage	600	V_{DC}
Maximum mechanical load	1,600	Pa
Series Fuse Rating	2	A
Operating temperature (cell)	- 40 to +90	°C
Storage temperature	- 40 to +90	°C
Storage air humidity	Up to 90	%
Installation orientation	Portrait	

Courtesy of Sharp

Parallel and Series Connection of Modules

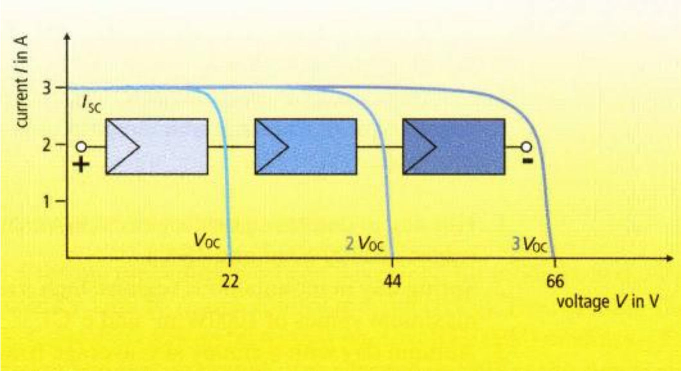
- A PV modules contains many (typ. 60-72) series connected cells with Voc typically 36-44 V
- To achieve the desired power modules may be connected in parallel or series

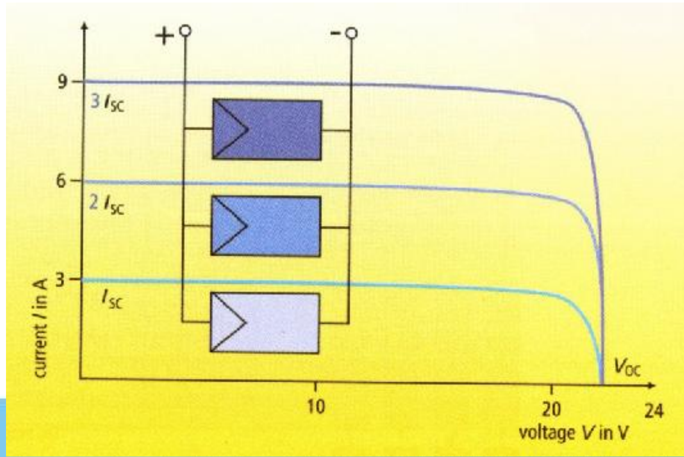




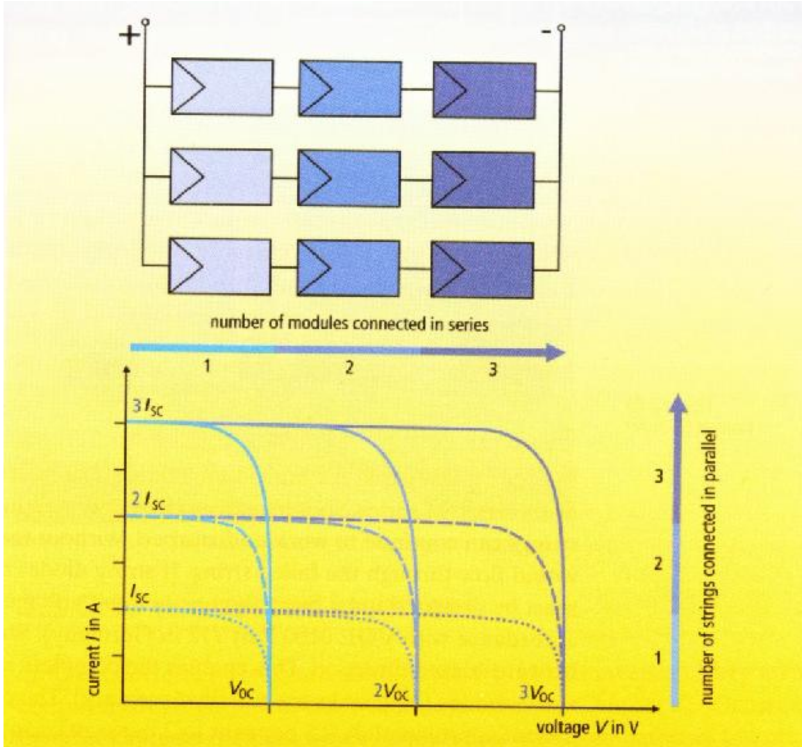
Interconnection of PV Modules

- PV Modules are interconnected into series and parallel groups to generate the desired power
  - Series connections dictates the system voltage
    - System designers must ensure the voltage range (due to temperature variation) is within the capability of the inverter, other BOS equipment and local standards
  - Parallel connections dictate the system current



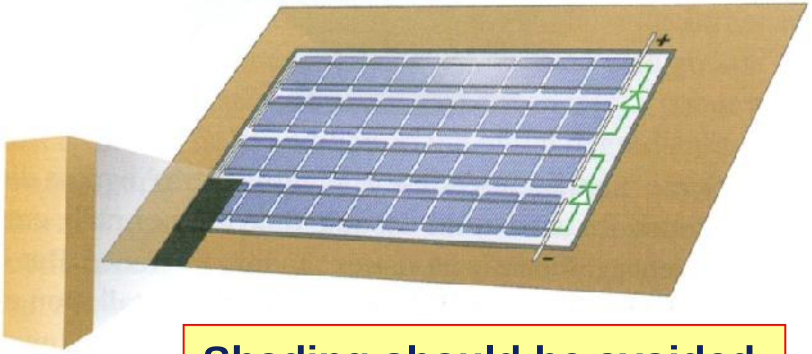


+ =

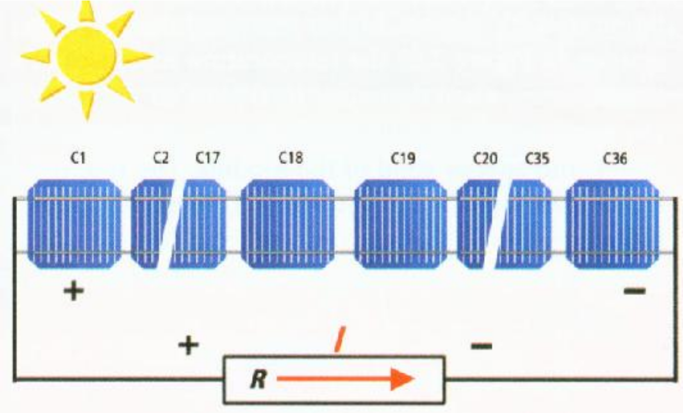


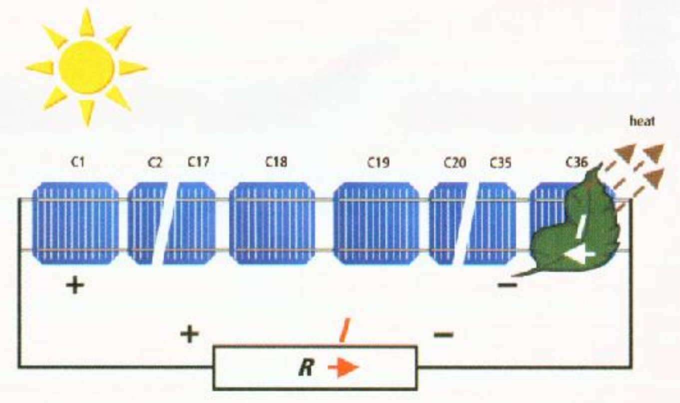
Shading of Crystalline Modules

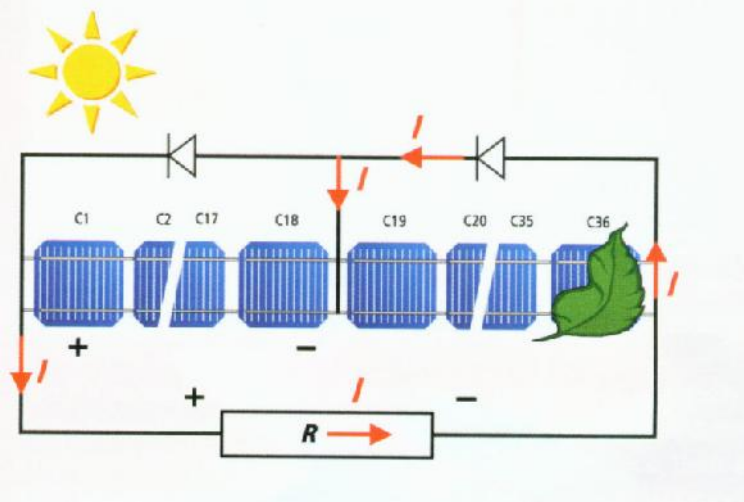
- A shaded PV cell becomes an electrical load as the reverse voltage withstand of the diode is exceeded.
- The shaded module becomes a load, current is limited to a maximum of Isc or load current. This can lead to hot spots and cell failure
- Adding a bypass diode in parallel with the cell allows current to be diverted around the shaded cell eliminating a failure mode



Shading should be avoided

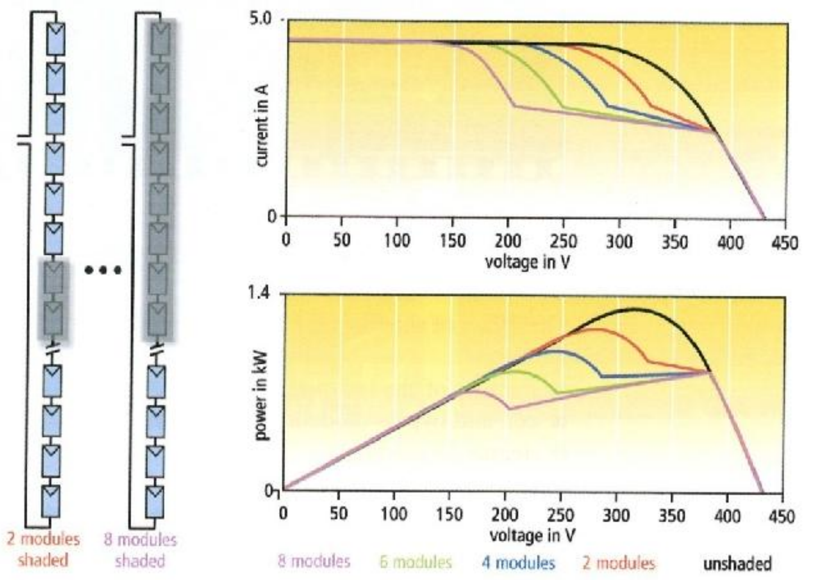


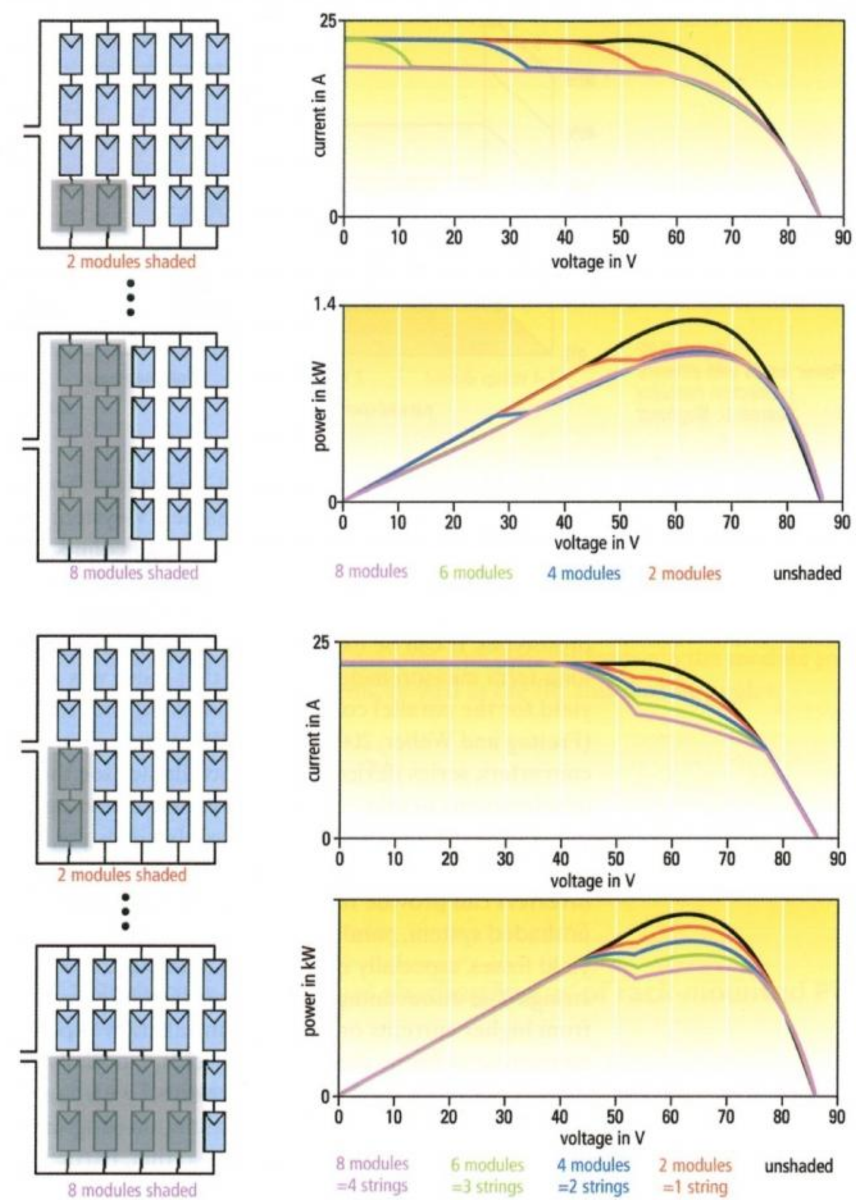




Practical effects of Shading

- Potentially 2 MPP points
- For parallel connected systems it's desirable to shade complete strings rather than a portion of all strings
  - The inverter can only track the right hand maxima as the left hand is not well defined
- In winter shading can be caused by modules mounted in front. Therefore it is desirable to make strings of the bottom row of modules in an array

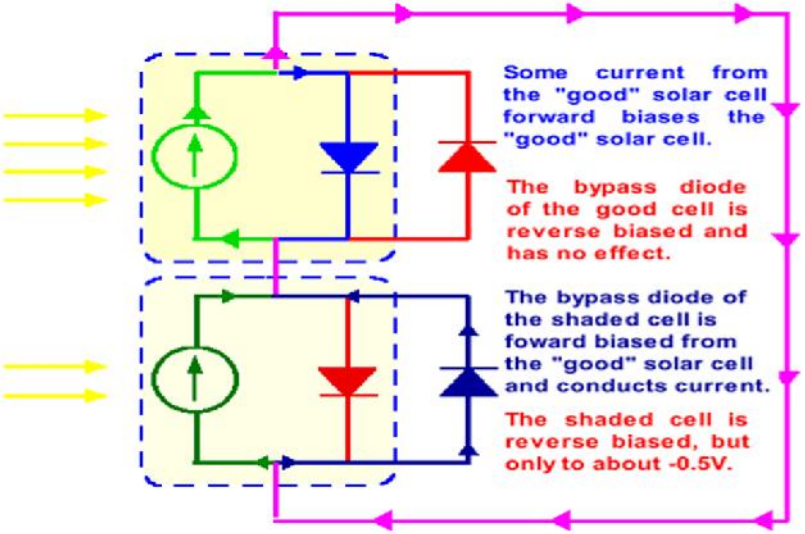




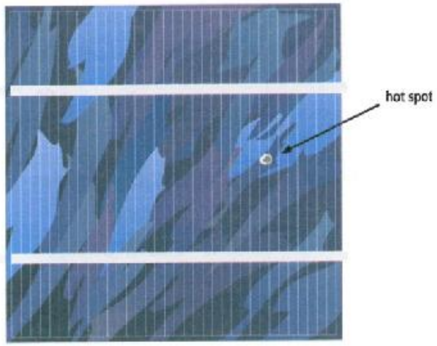
Bypass Diodes

- In a practical PV module containing 72 cells normally 3 or 4 bypass diodes are fitted in the terminal box
- In the diagram below, if diodes aren't fitted the string current is determined by the degree of shading (red line)
- On a PV module where 2 diodes are fitted with half of the module in shade, the IV curve follows the green line showing the MPP voltage drops by around 50%

IV Diagram of shaded modules with and without bypass diodes

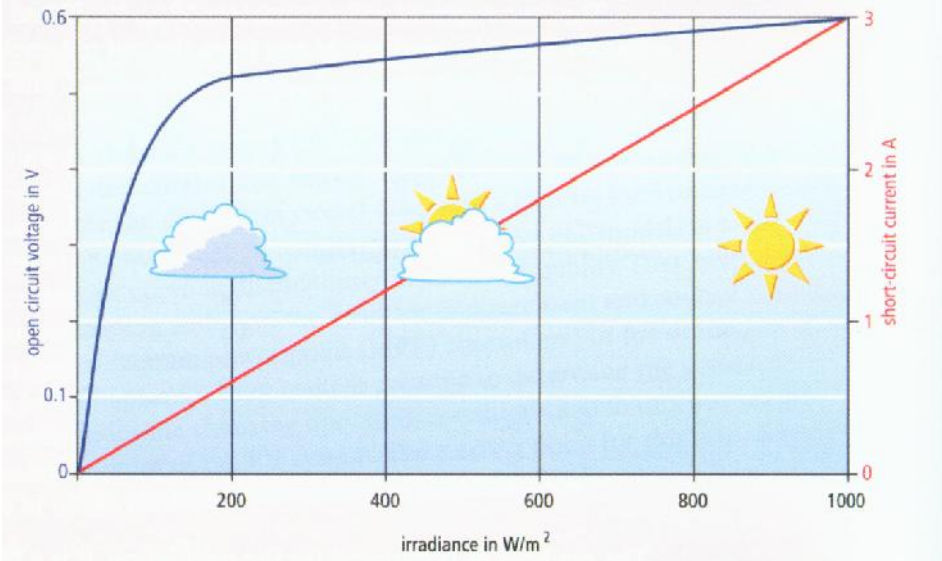


Mechanical Data	
Solar Cells	72 SunPower all-back contact monocrystalline
Front Glass	3.2 mm (1/8 in) tempered
Junction Box	IP-65 rated with 3 bypass diodes
Output Cables	900mm length cable / Multi-Contact connectors
Frame	Anodized aluminum alloy type 6063
Weight	15 kg, 33 lbs



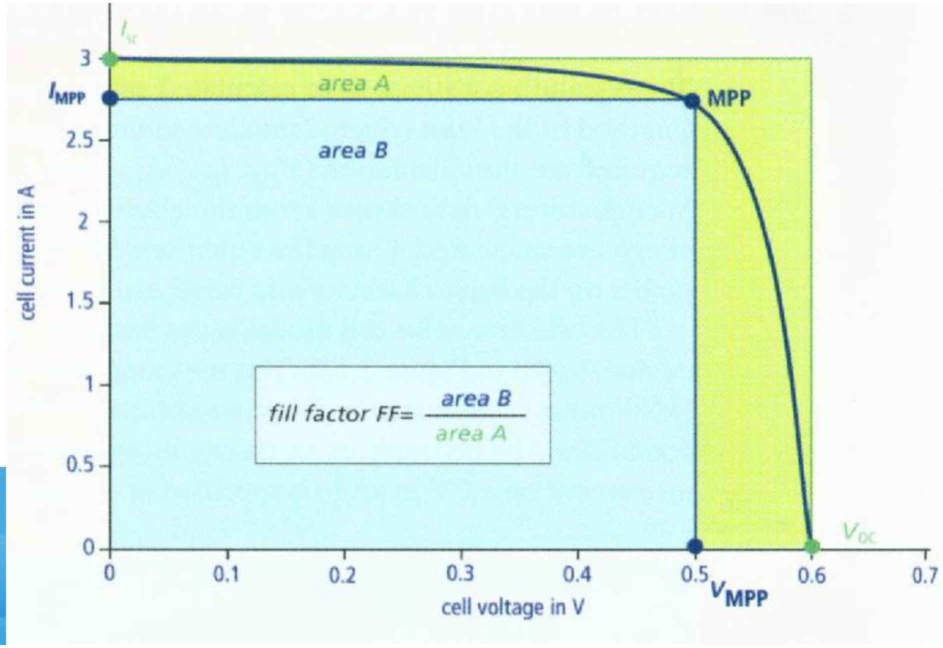
PV Cell / Module Quality

- The quality of a PV module is expressed as its Fill Factor
- Fill Factor is defined as the quotient of Maximum Power and Theoretical Maximum Power
- Fill Factor is typically 0.8 for crystalline modules and 0.6 for amorphous



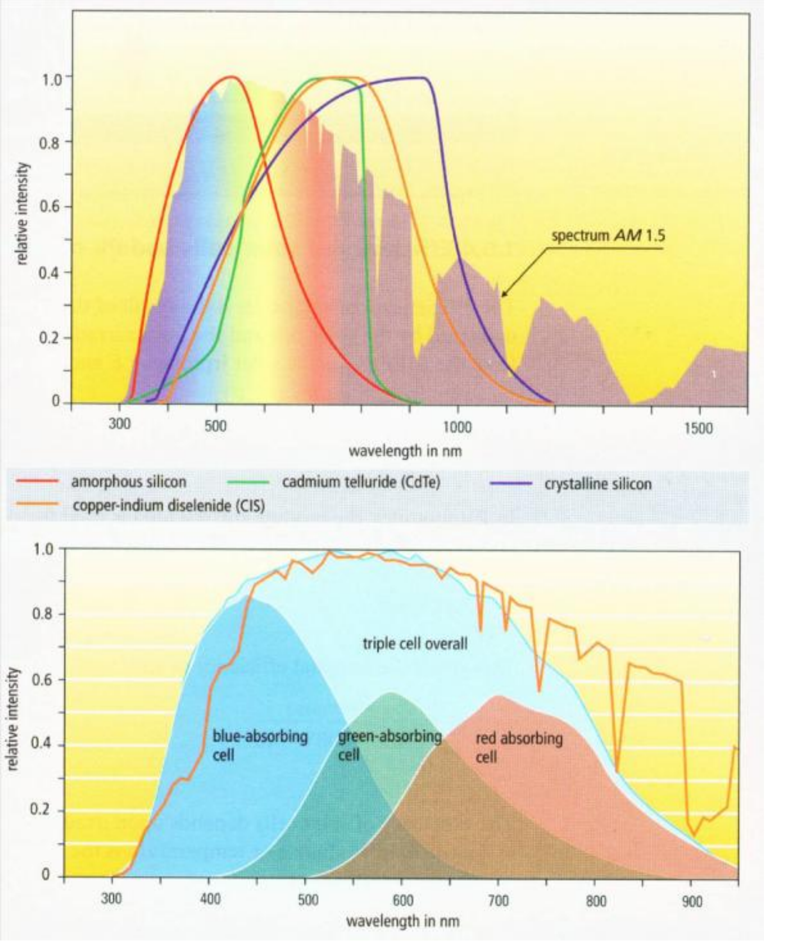
Module Type	Filling Factor
Crystalline	0.75 to 0.85
Amorphous	0.56 to 0.61
CIS	0.64 to 0.7
CDTE	0.47 to 0.64

$$FF = \frac{Vmpp \times \mathrm{Im}\,pp}{Voc \times Isc}$$



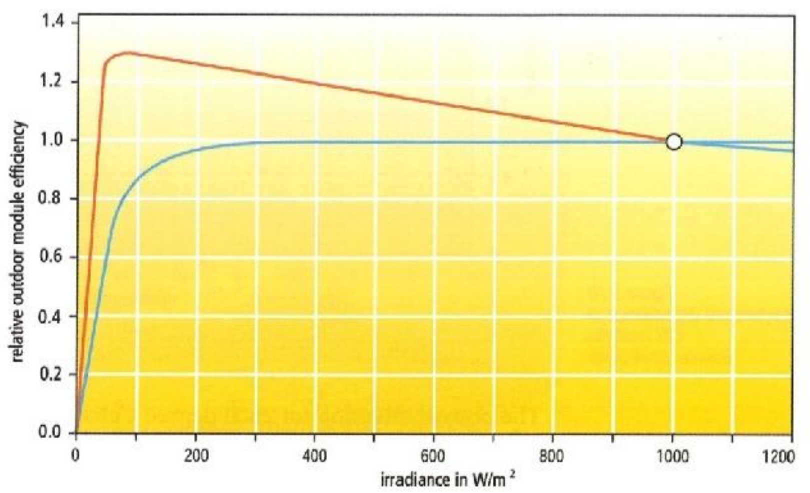
Module Spectral Response

- Crystalline cells are sensitive to longer wave length irradiation (towards infra red) whilst Amorphous cells to operate more efficiently towards the ultra violet part of the spectrum and generally work better under cloudy skies
- CdTe and CIS work best in the mid spectral region
- Amorphous modules often use stacked triple cells with each cell optimised for a different part of the spectrum

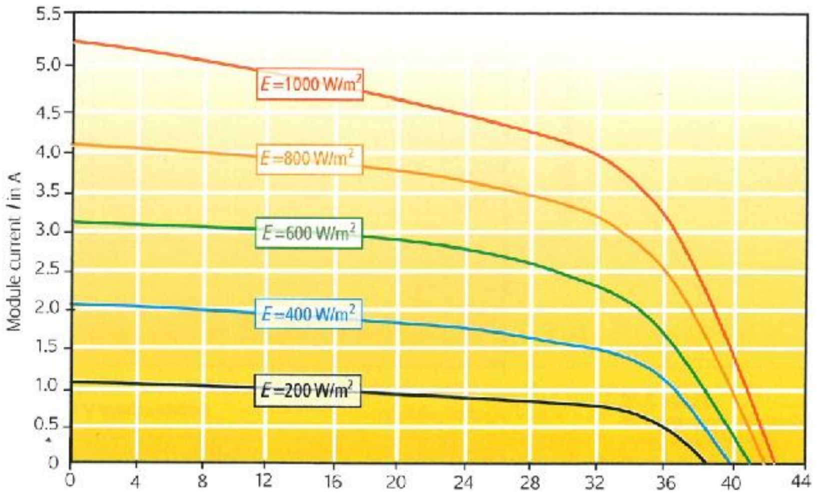


Electrical Characteristics – Thin Film Modules

- Staebler Wronski effect reduces output by around 15% over the first 6-12 months of operation. The output after 12 months is the nominal output
  - This effect has implications on inverter and string selection
- Module efficiency tend to increase in the summer and decrease in the winter
- Under low light conditions (500W/m^2), efficiency can increase by up to 30% over STC
  - Achieved by placing the blue sensitive cell at the top of the pile. Cloud tends to pass the blue portion of the spectrum more readily allowing thin film modules to work better under diffuse light conditions
- V_{mpp} increases slightly as irradiation decreases (unlike crystalline)
- Maximum power point is less well defined (particularly at higher irradiation) which places greater demands on the MPPT control system



Efficiency of Amorphous Vs Crystalline cells under carying Irradiation

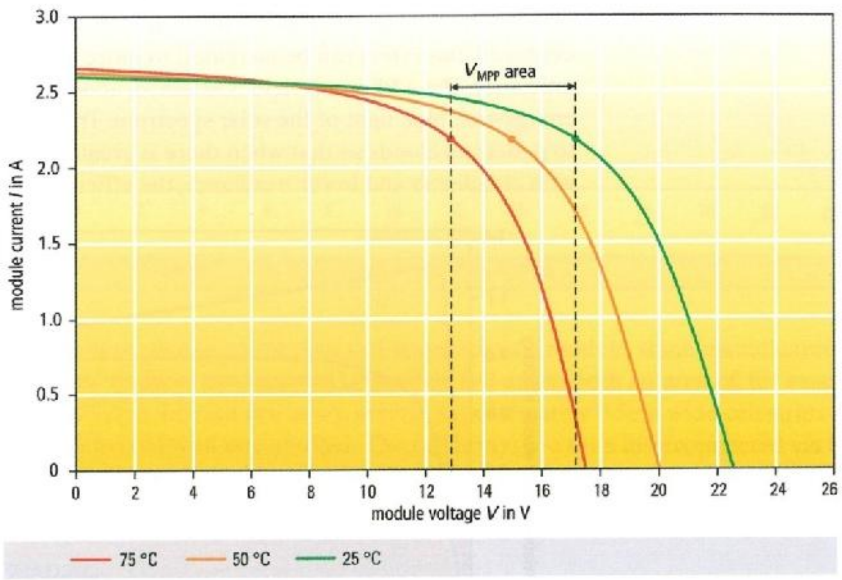


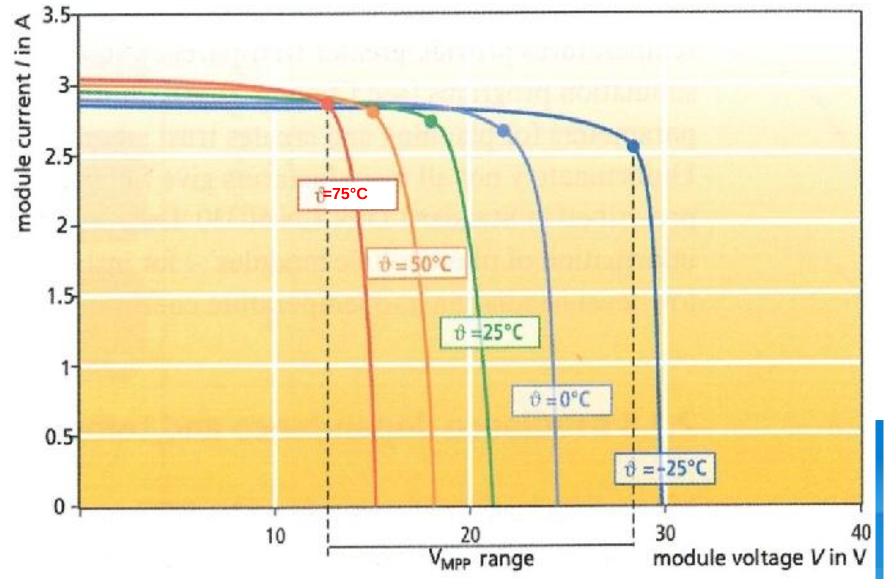
Current – Voltage curves for thin film triple cell modules under varying irradiation

Temperature Behaviour of Thin Film Modules

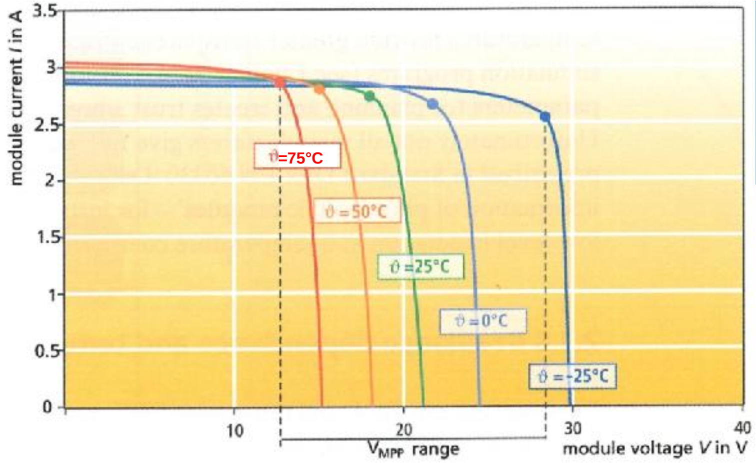
- The effects of temperature on amorphous modules is less pronounced than for their crystalline Counterparts (top right Vs bottom right) by around 30%

Temperature coefficient	Amorphous modules	CIS modules	CdTe modules
Open-circuit voltage	−0.19 to −0.5%/°C	−0.26 to −0.5%/°C	−0.22 to −0.43%/°C
Short-circuit current	+0.01 to +0.1%/°C	+0.01 to +0.1%/°C	+0.02 to +0.08%/°C
MPP power (STC)	−0.1 to −0.3%/°C	−0.33 to −0.6%/°C	−0.18 to −0.36%/°C

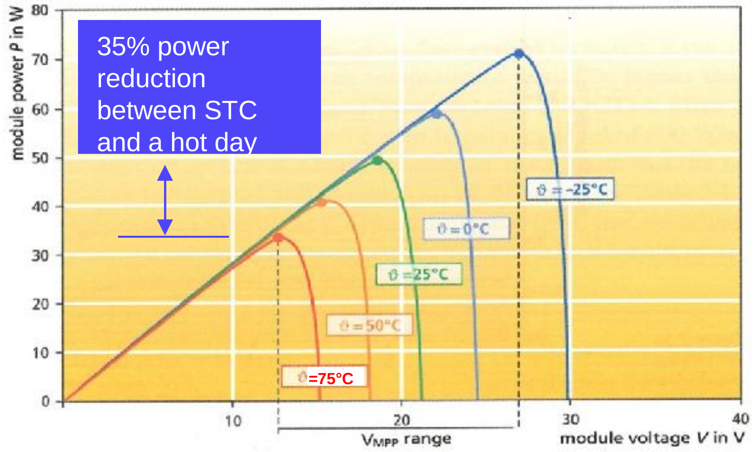


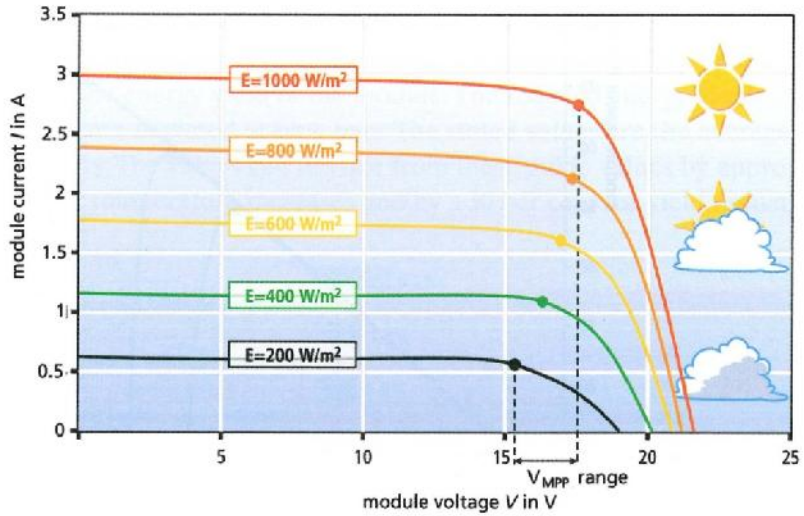


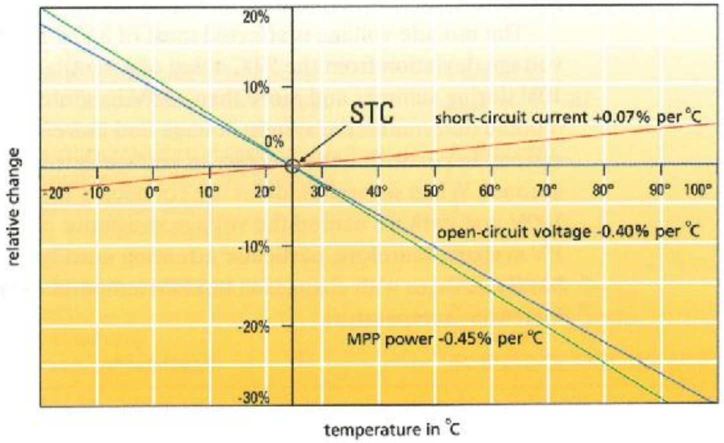
Electrical Characteristics – Crystalline Modules



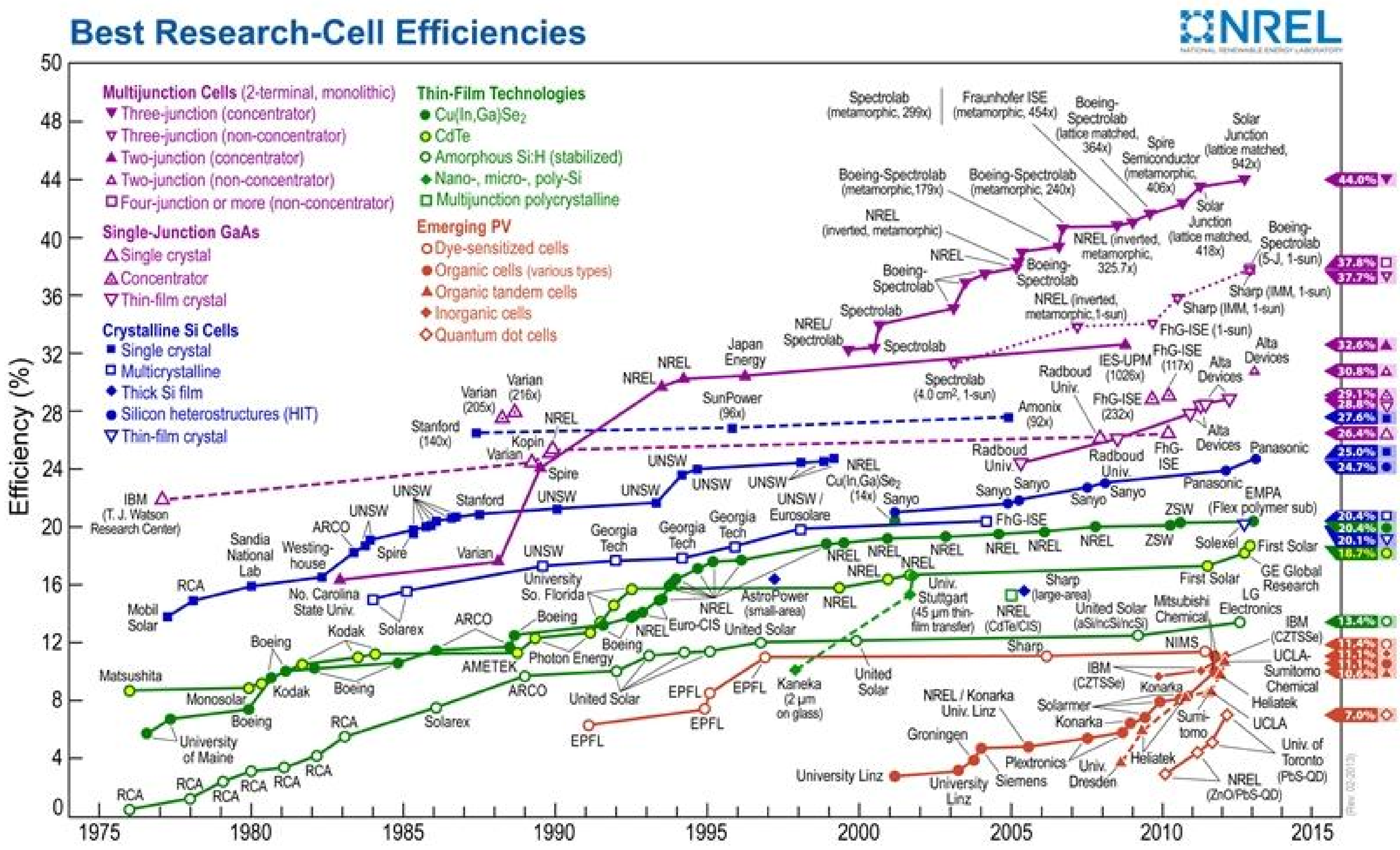
- Generally
  - Current rises with temperature
  - Power and voltage fall with temperature
- Datasheets express thermal co-efficients in mA or mV/°C or % /°C
- Often Normal Operating Cell Temperature 'NOCT' is quoted which is the cell operating temperature under the following conditions
  - Irradiance 0.8 kW/m2, air temperature 20ºC
  - Average wind speed of 1 m/s….
- NOCT is typically 25°C above ambient
- Thermal co-efficients are normally expressed for Voc and Isc however if Vmpp and Impp are given use them as well in the sizing calculations





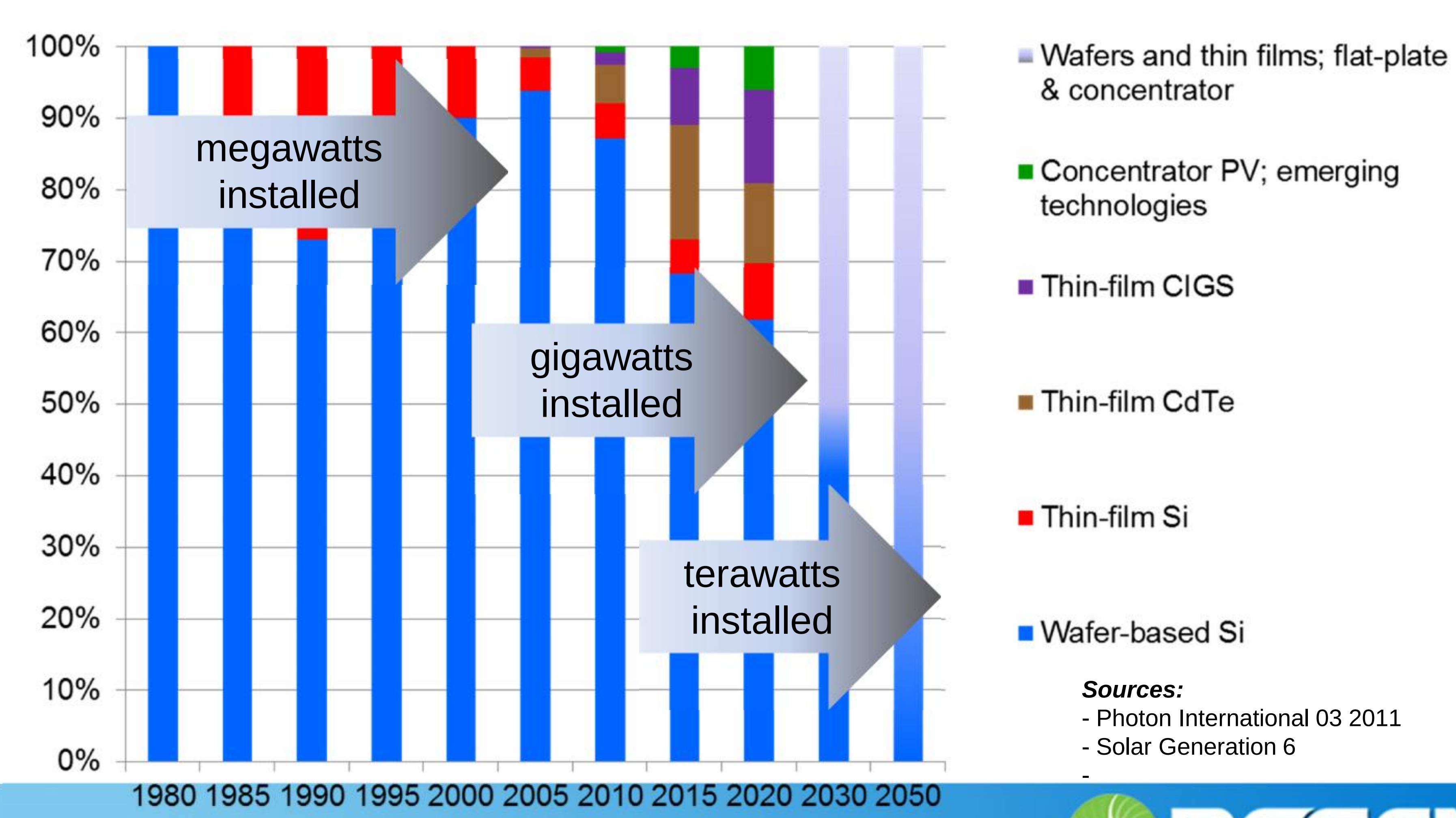


Best efficiencies laboratory cells



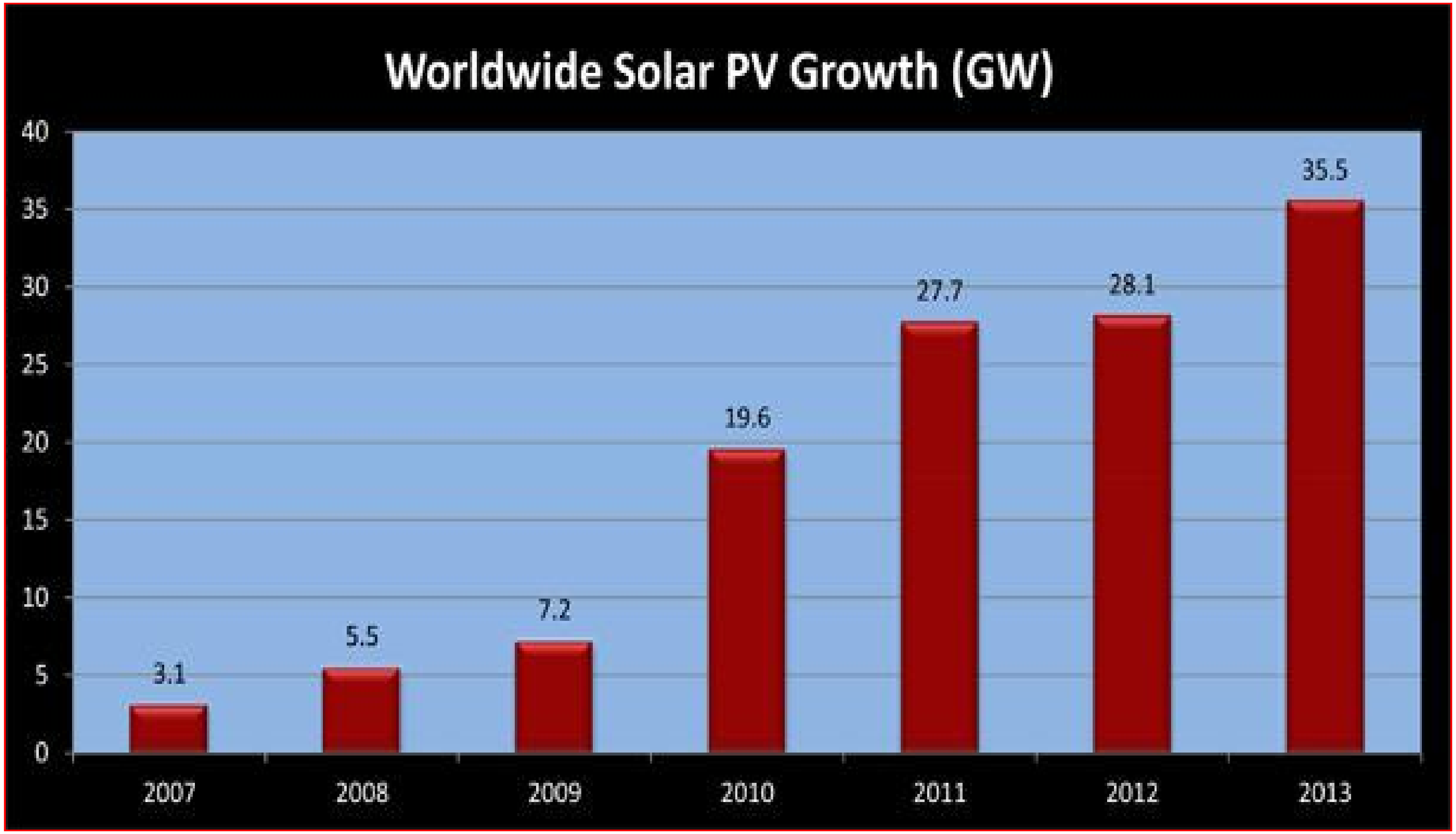
http://www.solarplaza.com/article/1975-2013-all-solar-efficiency-records-in-one-char

PV Technology shares

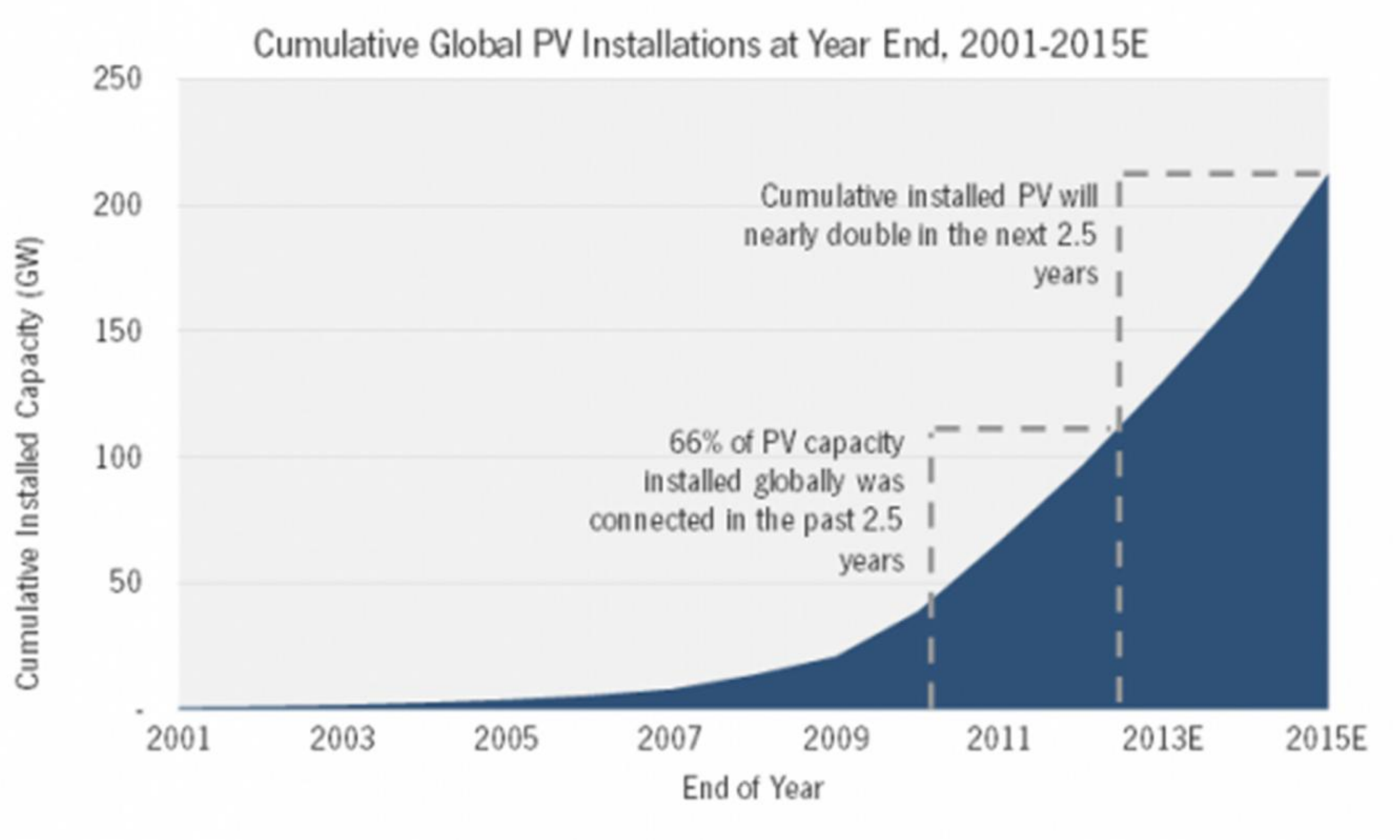


Sources:
- Photon International 03 2011
- Solar Generation 6
-

Solar PV Growth



Cumulative installed capacity (IEA PVPS, 2013)



World PV Installed Capacity

Latest capacity table

Capacity growth continues rapidly and has now broken through 21 GW. In the last quarter of 2013, the USA became the first country to break the 5 GW level (see here).

The leading countries for the deployment of utility scale solar power stations of 4 MW+ as at the end of 2013 were as follows:

Rank	Country See basis of figures here. © Wiki-Solar.org	Cumulative to date Plants	 Capacity	New in 2013 Plants	 Capacity
1	United States	263	5,026	101	2,783
2	China	205	4,345	60	1,647
3	Germany	269	3,412	27	194
4	Spain	170	1,688	2	29
5	India	158	1,587	51	666
6	Italy	82	876	3	22
7	France	46	647	16	143
8	United Kingdom	112	630	69	443
9	Canada	44	605	22	217
10	Ukraine	13	477	6	201
11	Thailand	38	333	2	22
12	Czech Republic	24	233	0	0
13	Romania	13	221	12	214
14	Bulgaria	10	209	1	14
15	Japan	8	126	2	79
16	Greece	12	118	1	60
17	Portugal	11	110	3	21
18	South Africa	3	89	3	89
19	South Korea	7	81	1	13
20	Peru	4	71	1	18

http://wiki-solar.org/region/countries/index.html

Ranking of the Top 10 Companies

Top 10 PV Module Suppliers in 2013

2013 Rank	Module Supplier	Change from 2012
1	Yingli Green Energy	-
2	Trina Solar	+1
3	Sharp Solar	+3
4	Canadian Solar	-
5	Jinko Solar	+3
6	ReneSola	+7
7	First Solar	-2
8	Hanwha SolarOne	+2
9	Kyocera	+5
10	JA Solar	-3

Photovoltaic market by segment

Segment	Application	Typ. Power Range	Nett Power Exporters
Off Grid	Remote applications without grid connection…	To 30kW	N/A
	Chargers for battery powered equipment – telecoms masts and traffic signage etc	<100W	N/A
	Mobile applications such as small boats	<1kW	N/A
Domestic	Rooftop	1-15kW	Possibly
Commercial	Office Windows and rooftop	10-150kW	Yes
	Public building rooftop (Stadia, Arena, airport, station….)	15kW-30MW	Yes
	Agricultural rooftop (barns…)	15kW-5MW	Yes
	Industrial rooftop	20kW-5MW	Possibly
Utility	Industrial Roof	200-2000kW	Yes
	Field	500-500MW	Yes

How much land for 1MW?

- Typical PV module efficiency is <10% for thin film types and up to 20% for crystalline
- Obviously the land coverage must be <100%. Take 40% as typical to allow for access and services
- Modules can be orientated for the highest peak kW (kWp) or the greatest kWh
- Peak irradiation levels are important. Generally 1000W/m^2 but up to 1300W/m^2 is possible.
- General rule of thumb is 5 acres (20,000 m^2 or 4 cricket grounds)

PV Market

- Incentive driven with the goal of reaching grid parity
- Total market expected to reach 15-17GW in 2010
- Segment where CT is active will reach around 6-8GW
- Germany dominate the market with 40% of central inverter installations however the market is slowing as the government aggressively reduces incentives
- PV market remains attractive as module prices decline sharply
- Large projects will source PV modules at €1.60/ W for crystalline and €1/W for thin film
- PV modules account for about 70% of project capital cost. Inverter 5-7%.
- Key emerging markets include USA, Italy, India, China, Canada & S. Africa

Outline

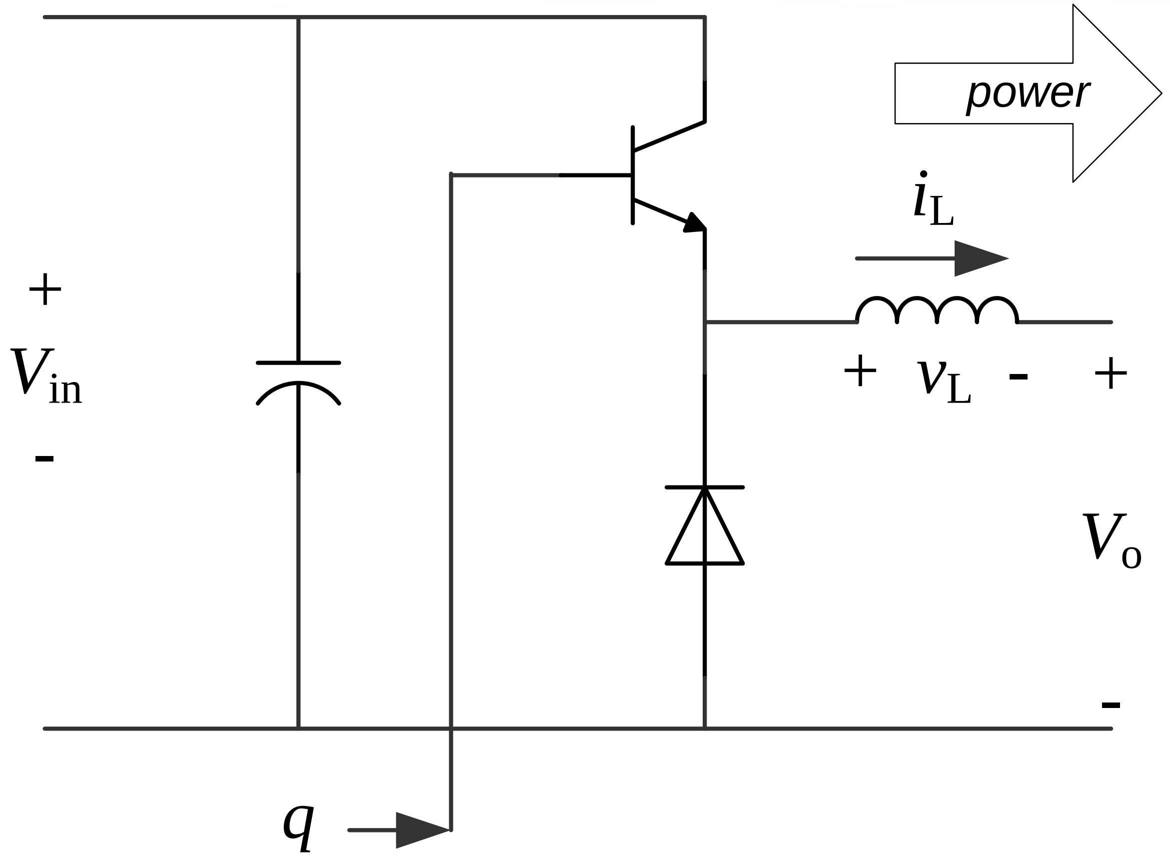
- ❑ Introduction
- ❑ Solar Energy – Facts
- ❑ Photovoltaic (PV)
- ❑ **Power Electronics Converters**
- ❑ Applications :
  - ❑ Residential
  - ❑ Commercial
  - ❑ Solar Farms

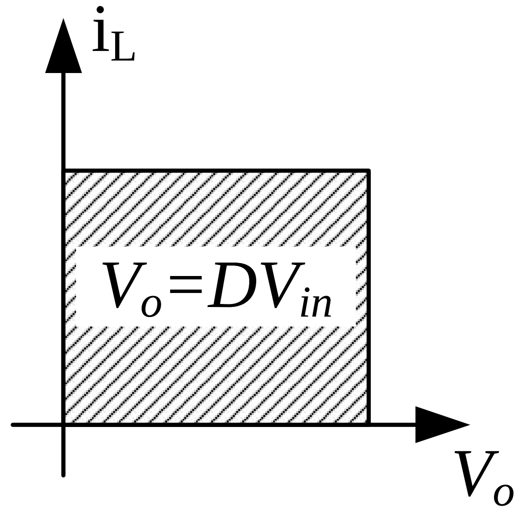
Background photo: www.bso.vvs.be

Functions of Power Electronic Converters

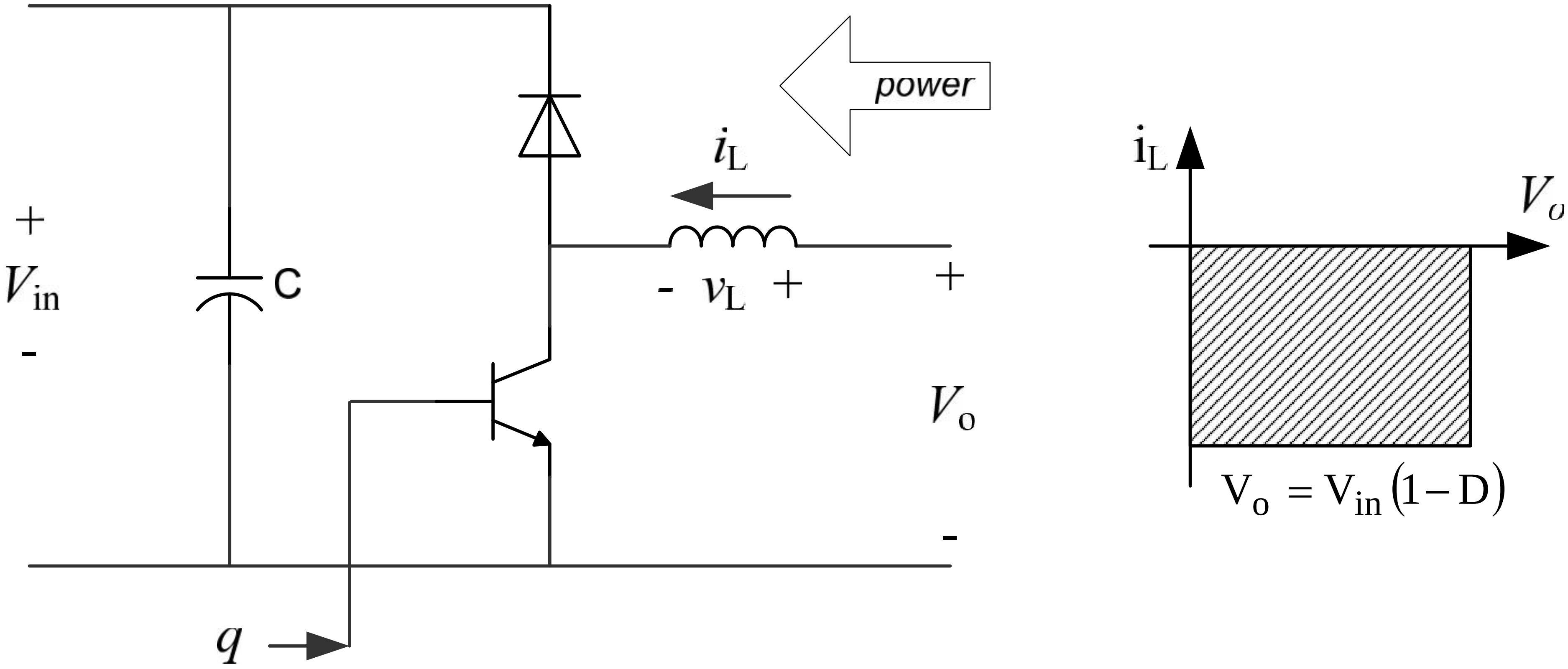
- **Power Conversion**
  - ac-dc, dc-ac, ac-ac, dc-dc; voltage and frequency control
- **Interconnection with Grid & System Protection**
  - meeting requirements of interconnection standards
- **Resource Control (optimize sources and loads)**
  - maximum power point tracking
- **Power System Support**
  - power and reactive power control, dispatch etc.

Switching Power Pole and the power flow: Buck Converter



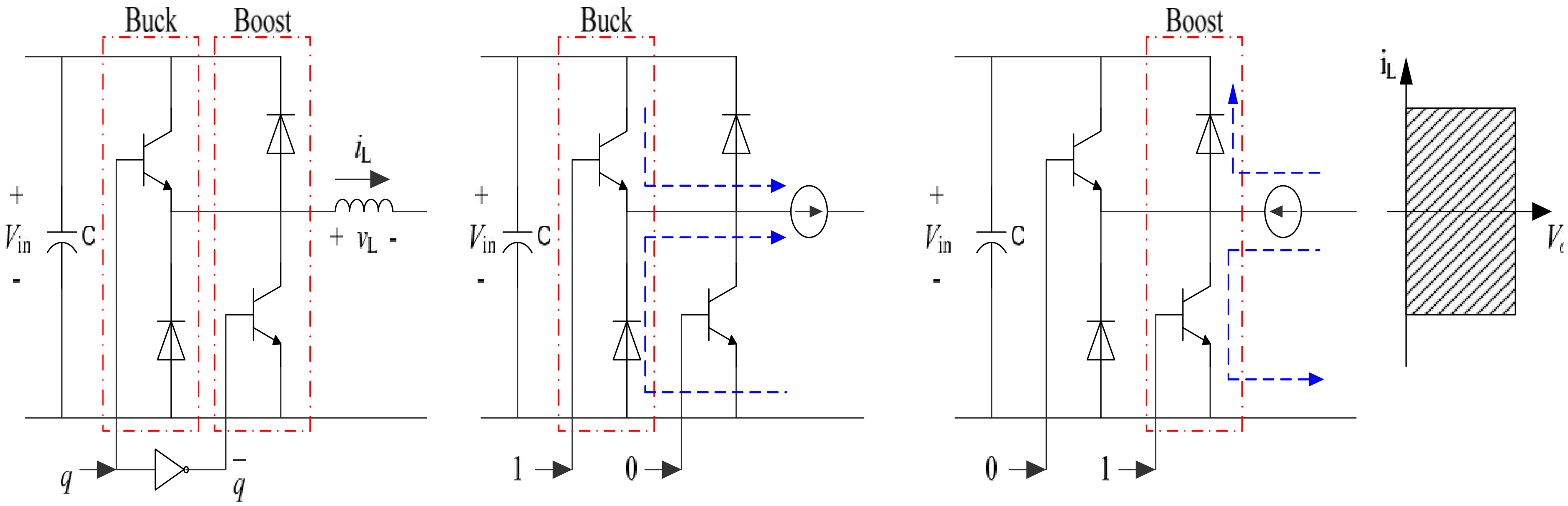


Boost Converter – Reversal of Current Flow



(a) (b)

Bidirectional Switching Power Pole



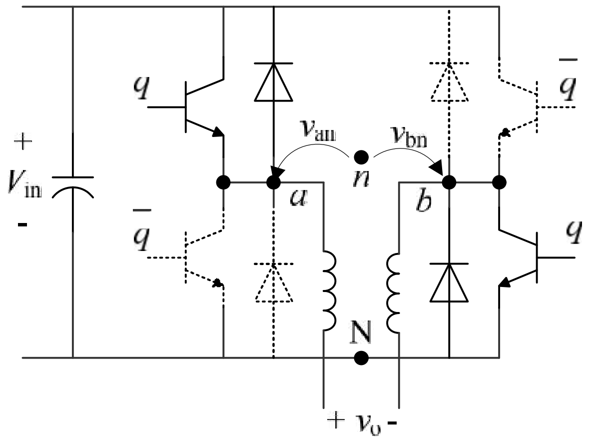
(a)

(b) i_L=positive

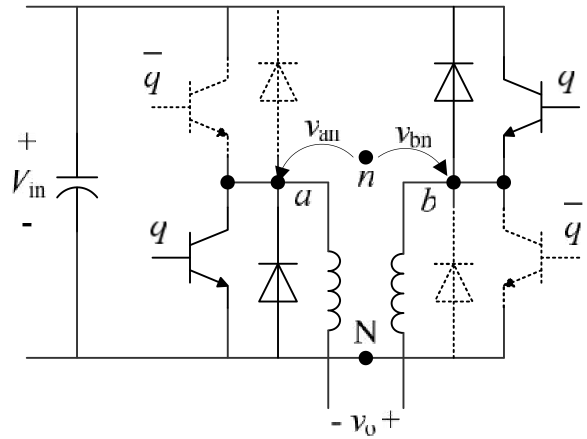
(c) i_L=negative

(d)

Single-Phase Inverter

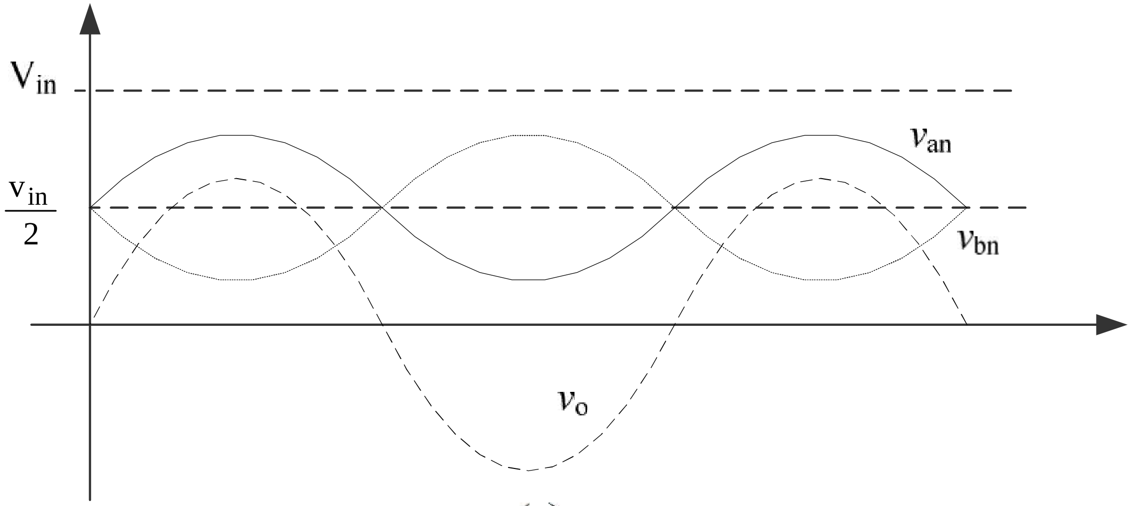


(a)

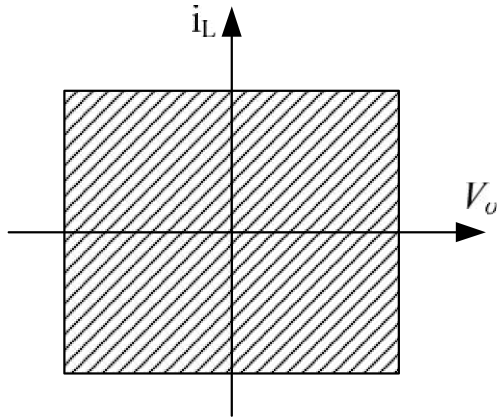


(b)

$$\frac{V_o}{V_{in}} = 2D - 1$$

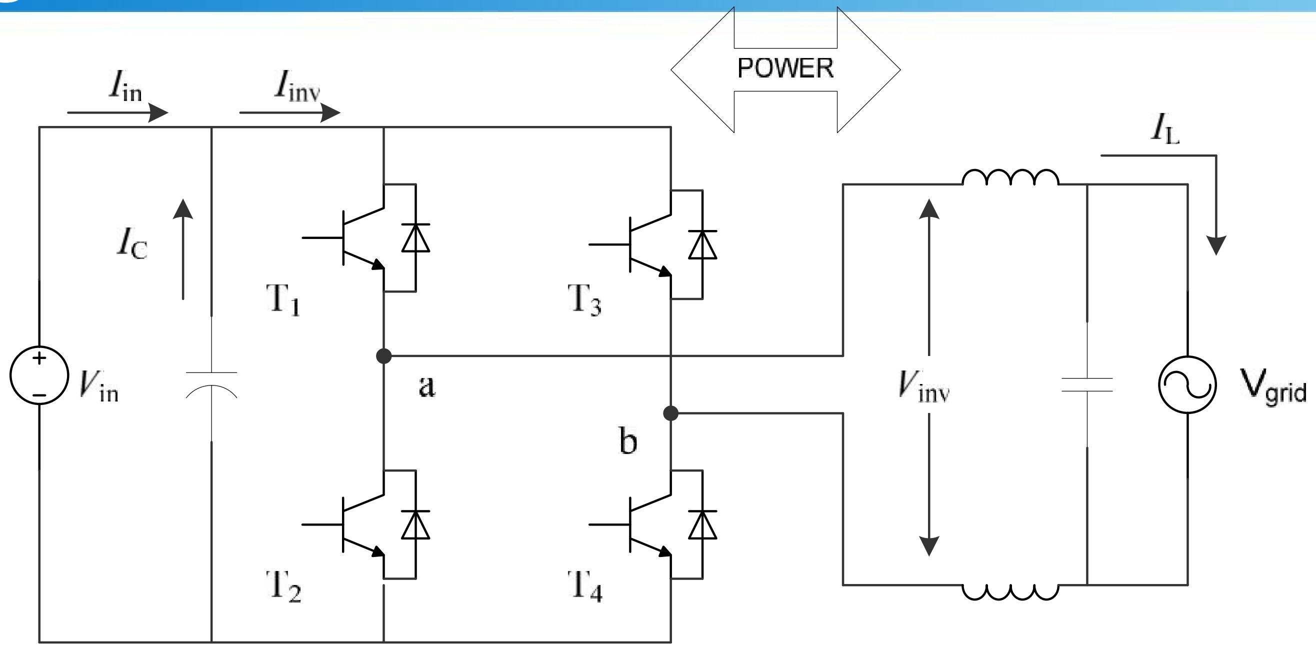


(c)



(d)

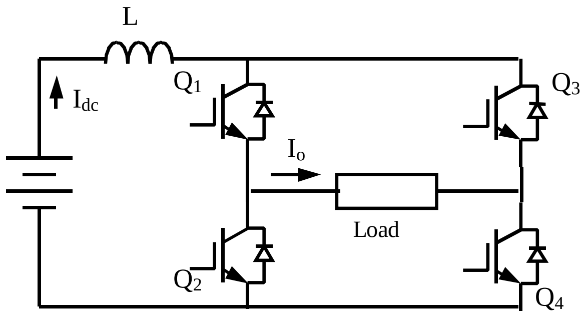
Single Phase Grid Connected Inverter



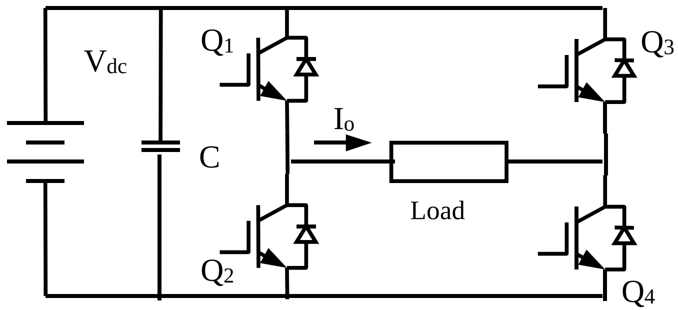
Mode	T_1	T_2	T_3	T_4	D_3	D_4	V_{op}	I_{load}
1	ON	OFF	OFF	ON	OFF	OFF	V_{dc}	pos
2	ON	OFF	OFF	OFF	ON	OFF	0	pos
3	OFF	ON	ON	OFF	OFF	OFF	$-V_{dc}$	neg
4	OFF	ON	OFF	OFF	OFF	ON	0	neg

Current Source/Voltage Inverter

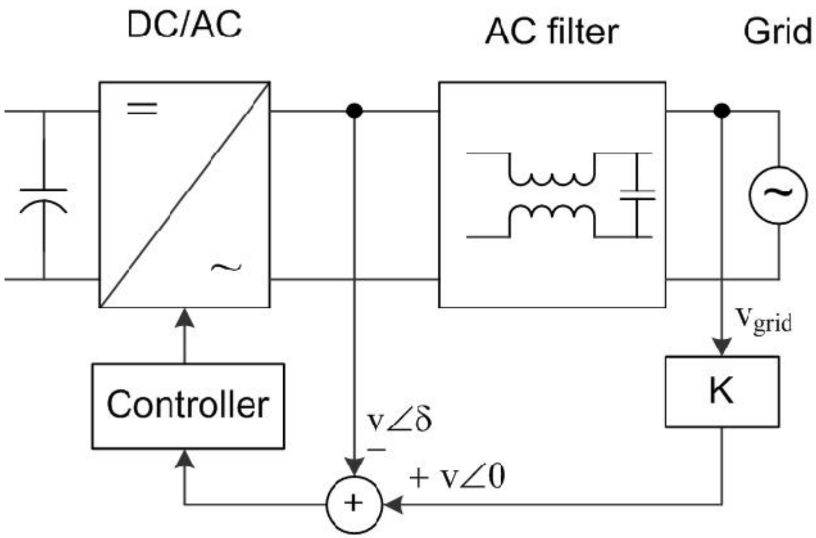
- A current source inverter (CSI) has an inductor in series with the DC input



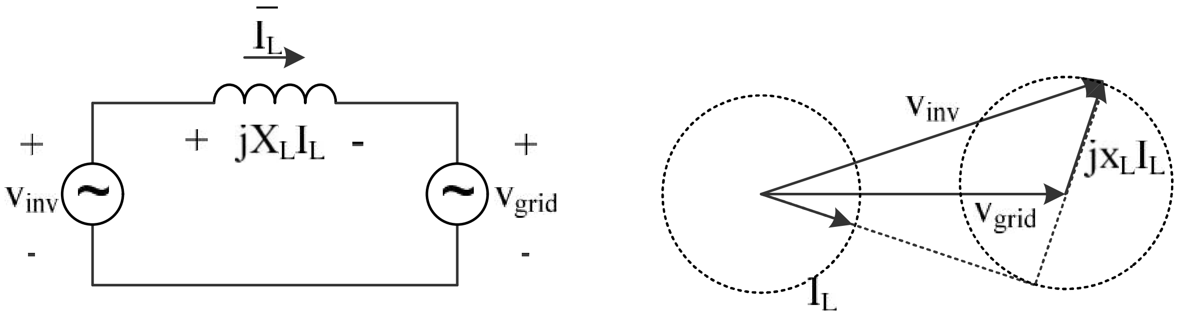
- A voltage source inverter (VSI) has a capacitor across the DC input
  - Voltage controlled VSI (VCVSI)
  - Current controlled VSI (CCVSI)



Voltage Controlled VSI

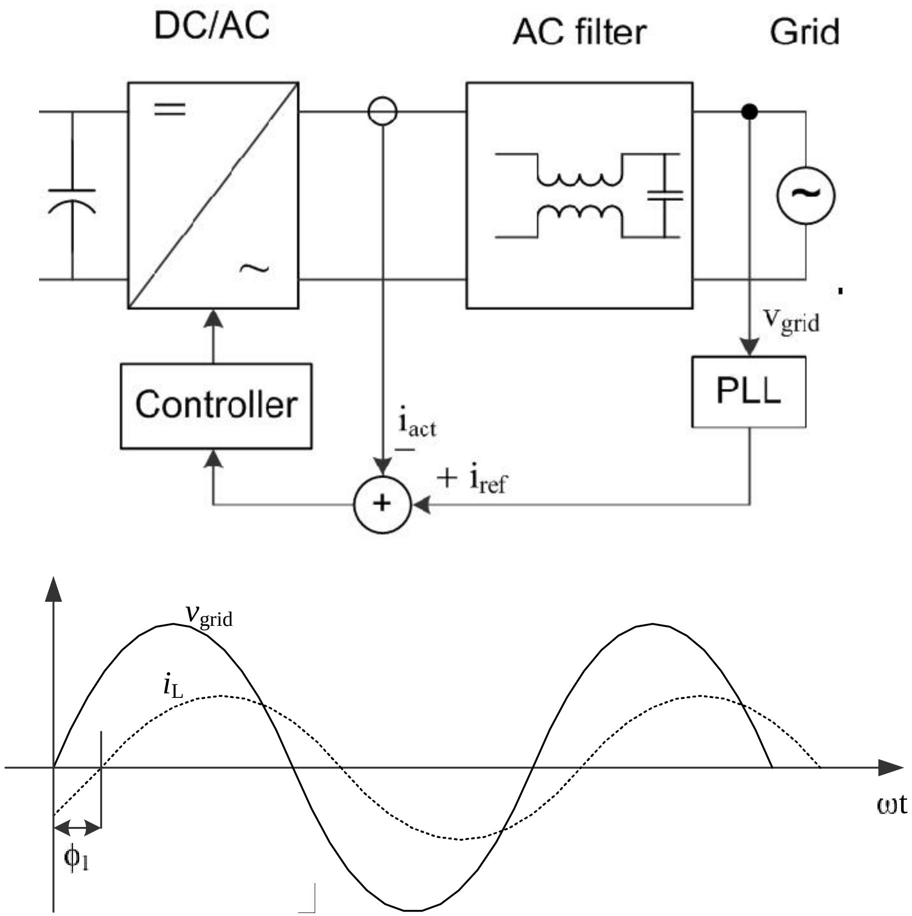


$$P_g = \frac{V_g V_c}{X_L} \sin\delta ; Q_g = \frac{V_g V_c}{X_L} \cos \text{¢} - \frac{V_g{}^2}{X_L}$$



(c)

Current Controlled VSI

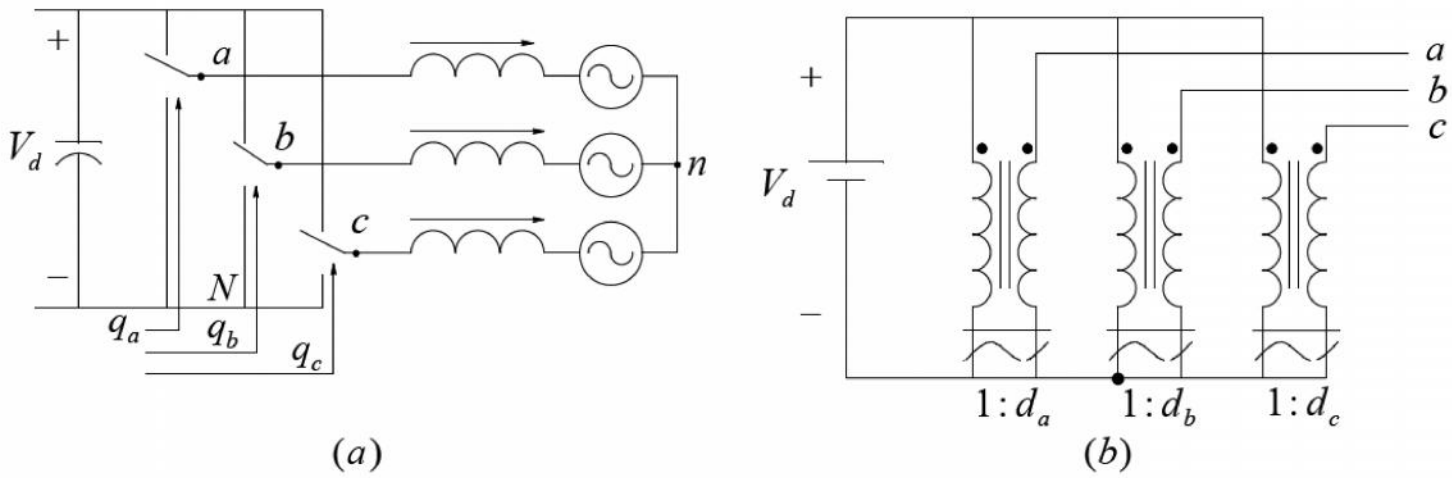


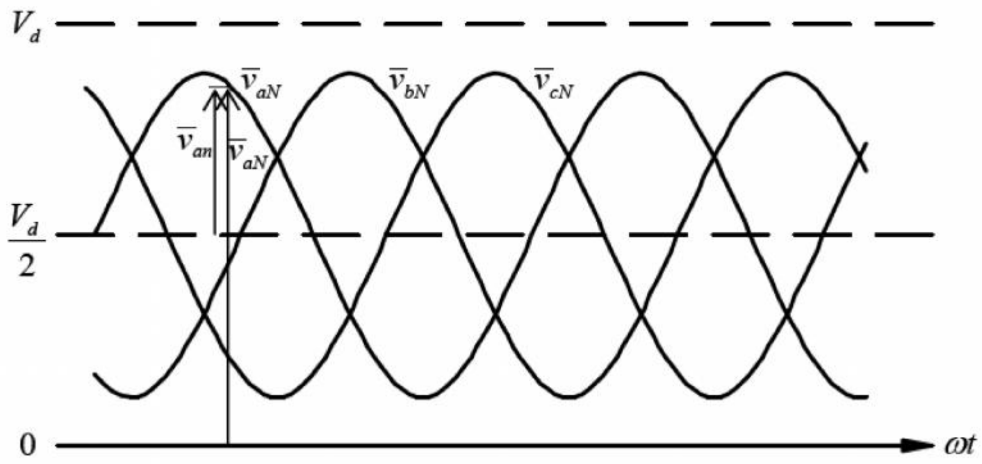
Real power and Reactive power can be controlled by regulating the magnitude, and the phase angle of the current.

$$P_{grid} = V_{grid} I_L \cos \phi_1$$

$$Q_{grid} = V_{grid} I_L \sin \phi_1$$

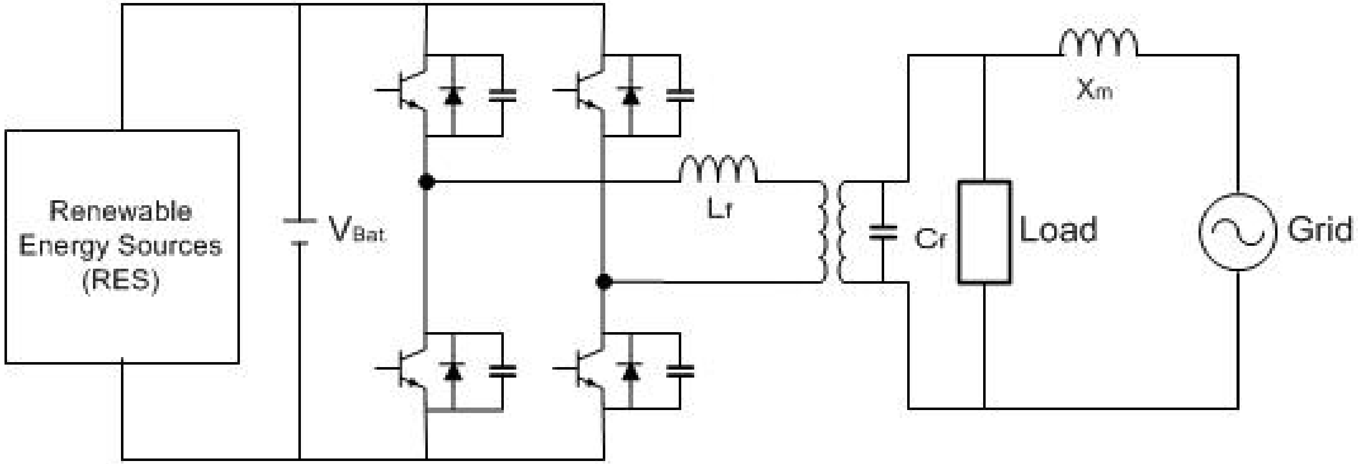
Three-Phase Inverter-Sine PWM

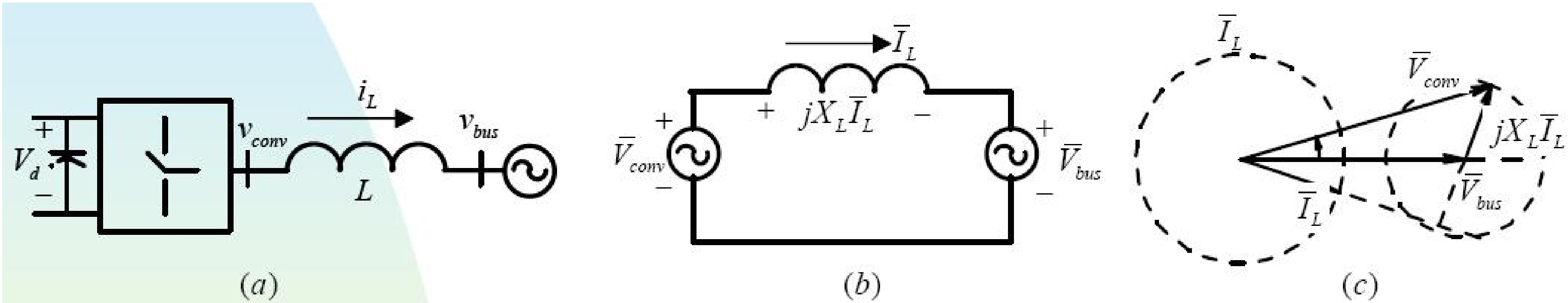




$$(V_{ll})_{\max} = \frac{\sqrt{3}}{2} V_d \sim 0.867 V_d$$

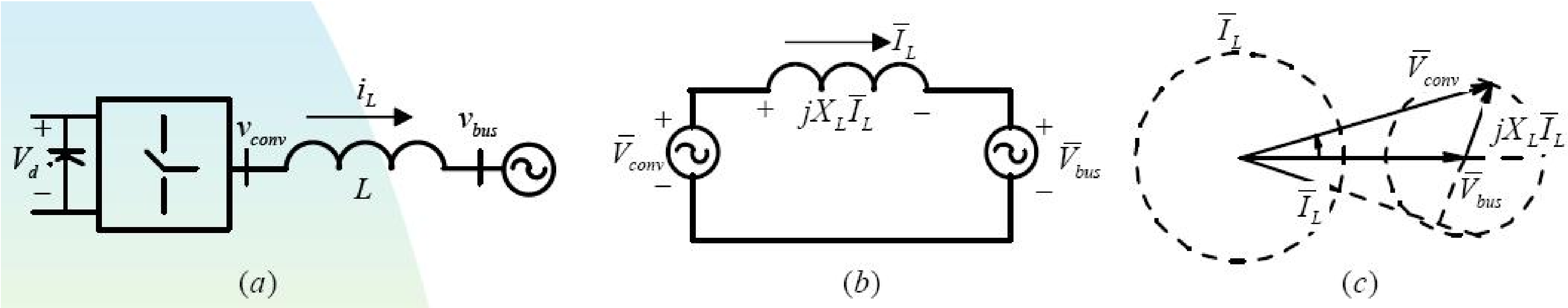
Voltage Controlled VSI





$$P_g = \frac{V_g V_c}{X_L} \sin\delta; Q_g = \frac{V_g V_c}{X_L} \cos\text{¢} - \frac{V_g^{\,2}}{X_L}$$

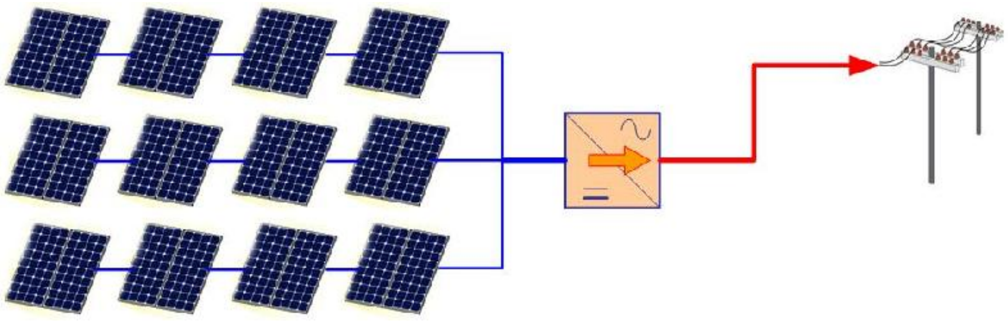
Current Controlled VSI



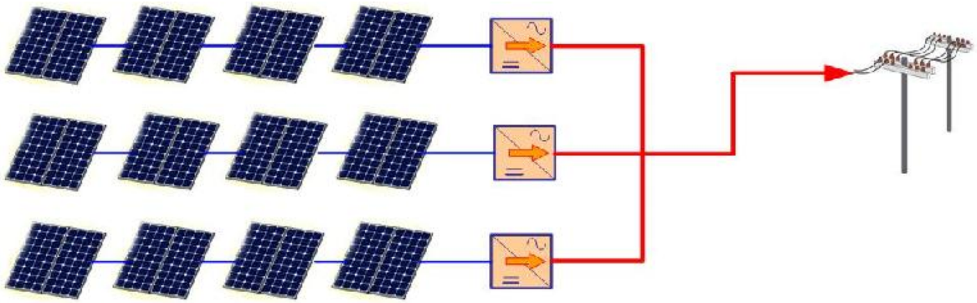
Real power and Reactive power can be controlled by regulating the magnitude, and the angle

Pg= VIg cos   Qg= VIg sin $I_L = I_g$

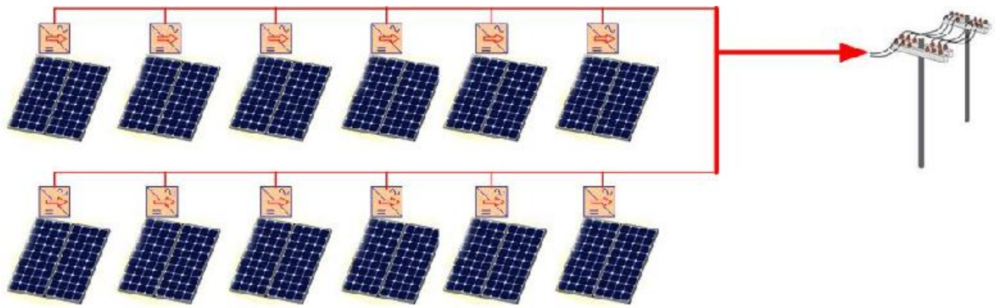
PV Grid Connected Systems



Grid connected
Central inverter
topology

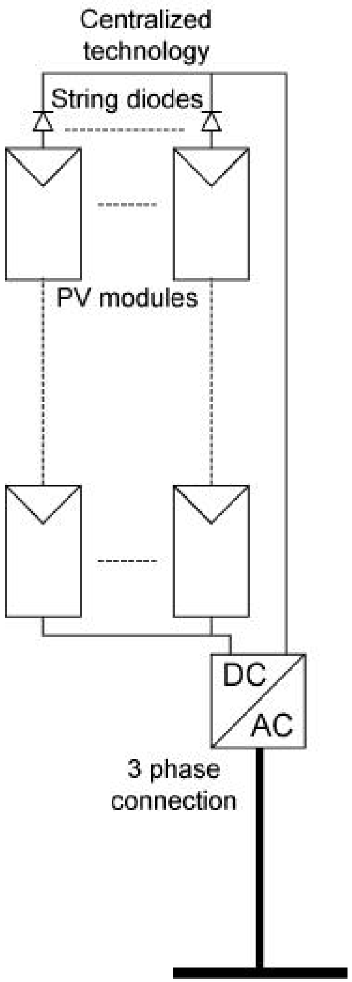


Grid connected
String inverter
topology



Grid connected
Micro- inverter
topology

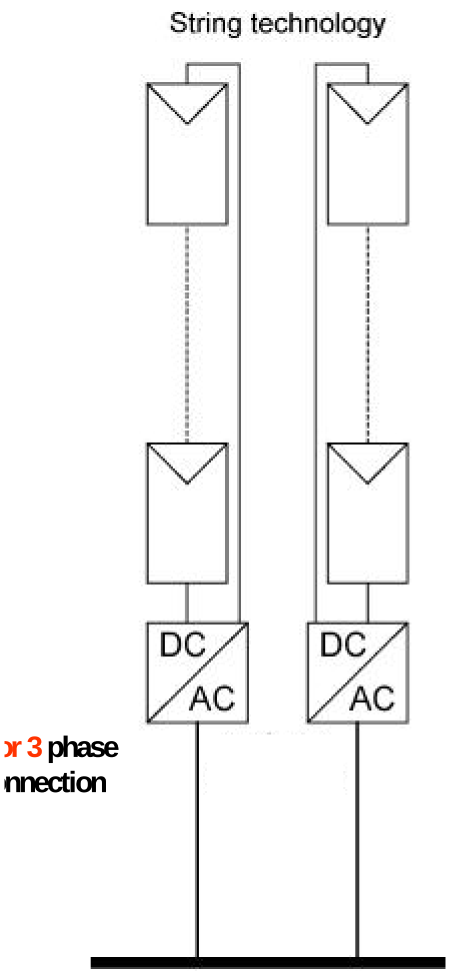
Central Inverter Topology



Typical power range >100kW < 1MW

- Advantages
  - High conversion efficiency at near maximum power
  - Lowest cost per Watt
- Disadvantages
  - Large DC/AC converter efficiency is reduced at low loads
  - Single point of failure
  - String mismatch, both module variation and shading, reduces power harvest
  - Some PV modules require string diodes

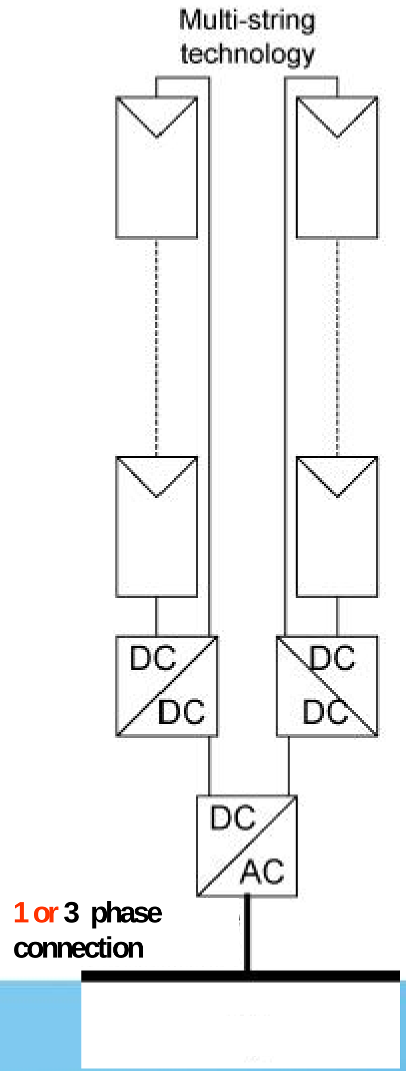
String Technology



- Typical power range < 3kW per inverter

- Advantages
  - MPPT is well matched to single string
  - Weatherproof inverter is generally located adjacent to the string reducing installation costs
- Disadvantages
  - Costly
  - Lower MTBF due to product volume
  - 20 year life expectancy on outdoor equipment??

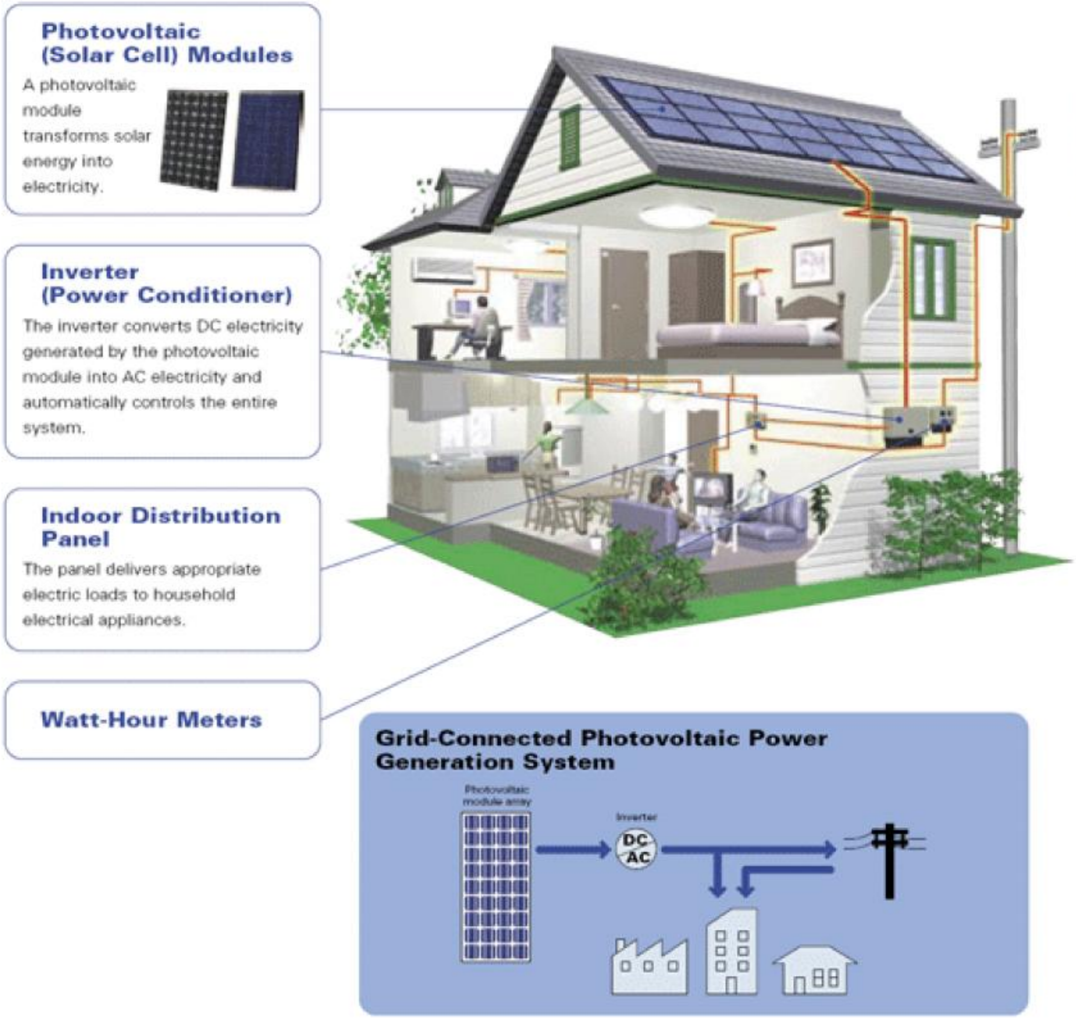
Multi-string Technology



- Typical power range
  >3kW < 50kW per inverter

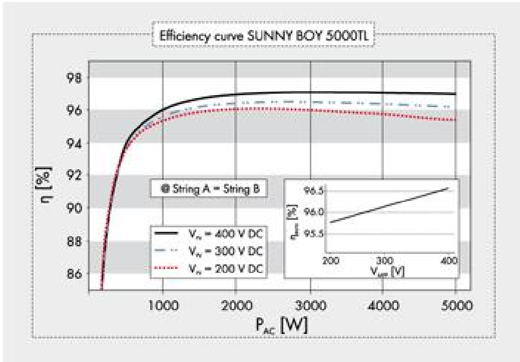
- Advantages
  - MPPT is well matched to with upto 6 independent trackers
  - DC/DC voltage controller optimises DC/AC conversion stage
  - Transformerless
- Disadvantages
  - Efficiency is reduced with second stage of conversion
  - Large DC/AC converter efficiency is reduced at low loads
  - Expensive compared to central inverters

Grid connected Inverters-String Type



Grid connected Inverter

SMA brand
Sunny Boy
3000TL



Transformerless
Max. efficiency 97%
Multi-string technology
Shade management
Integrated DC disconnector

Technical data	Sunny Boy 3000TL
Input (DC)	
Max. DC power (@ cos φ = 1)	3200 W
Max. DC voltage	550 V
MPP voltage range	188 V – 440 V
DC nominal voltage	400 V
Min. DC voltage / start voltage	125 V / 150 V
Max. input current / per string	17 A / 17 A
Number of MPP trackers / strings per MPP tracker	1 / 2
Output (AC)	
AC nominal power (@ 230 V, 50 Hz)	3000 W
Max. AC apparent power	3000 VA
Nominal AC voltage; range	220, 230, 240 V; 180 – 280 V
AC grid frequency; range	50, 60 Hz; ± 5 Hz
Max. output current	16 A
Power factor (cos φ)	1
Phase conductors / connection phases	1 / 1
Efficiency	
Max. efficiency / Euro-eta	97.0 % / 96.3 %
Protection devices	
DC reverse-polarity protection	●
ESS switch-disconnector	●
AC short circuit protection	●
Ground fault monitoring	●
Grid monitoring (SMA Grid Guard)	●
Galvanically isolated / all-pole sensitive fault current monitoring unit	– / ●
Protection class / overvoltage category	I / III
General data	
Dimensions (W / H / D) in mm	470 / 445 / 180
Weight	22 kg
Operating temperature range	-25 °C ... +60 °C
Noise emission (typical)	≤ 25 dB(A)
Internal consumption (night)	< 0.5 W
Topology	transformerless
Cooling concept	Convection
Electronics protection rating / connection area (as per IEC 60529)	IP65 / IP54
Climatic category (per IEC 60721-3-4)	4K4H

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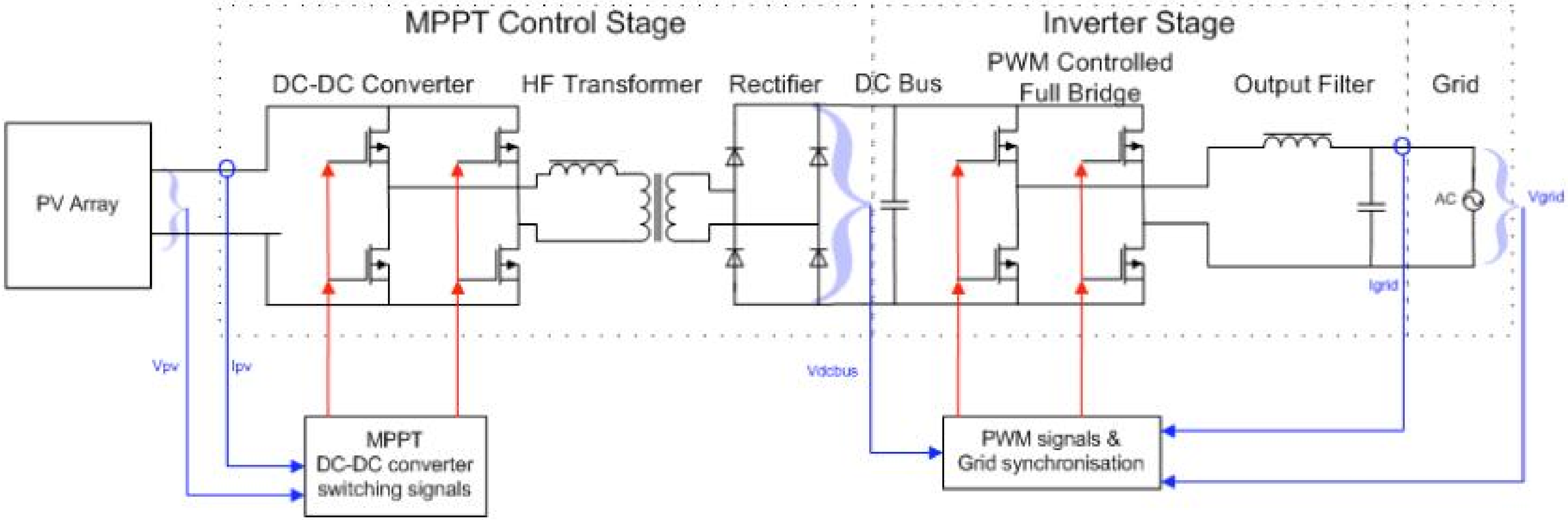
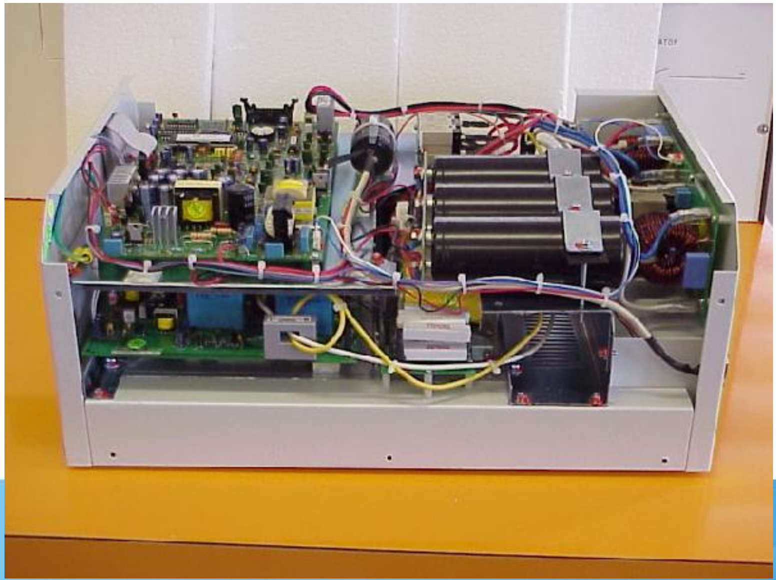
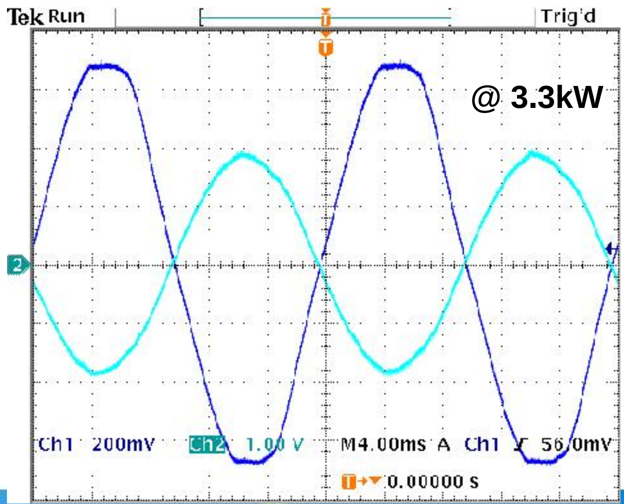
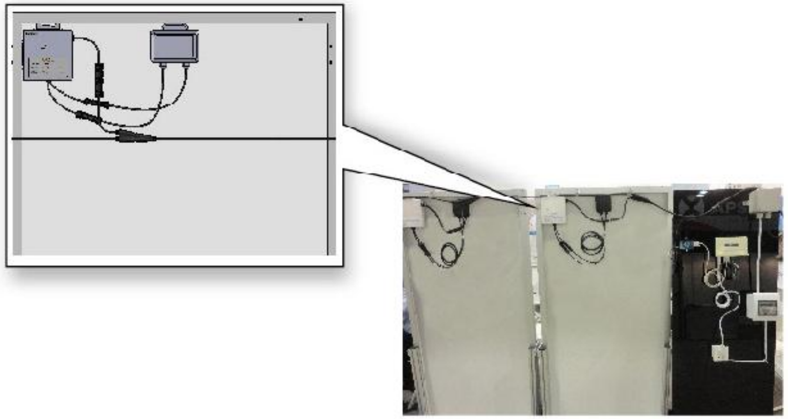
Grid-Connected PV Inverter (String Type)

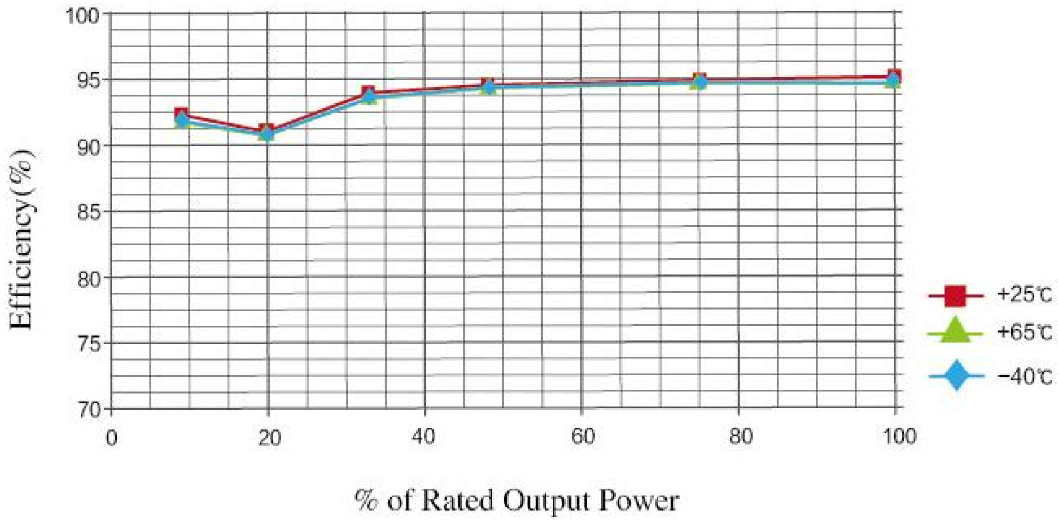






Micro Inverter



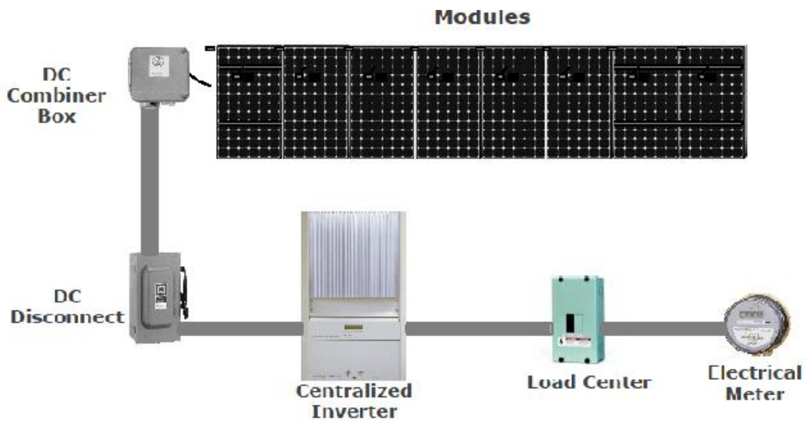


The Micro-inverter is small inverter which attached in the back of each panel in order to handle the output of a single panel. It produces grid-matching power directly at the back of the panel. Major advantage : a single failing panel or inverter will not take the entire string offline

Comparison between String And Micro Inverters

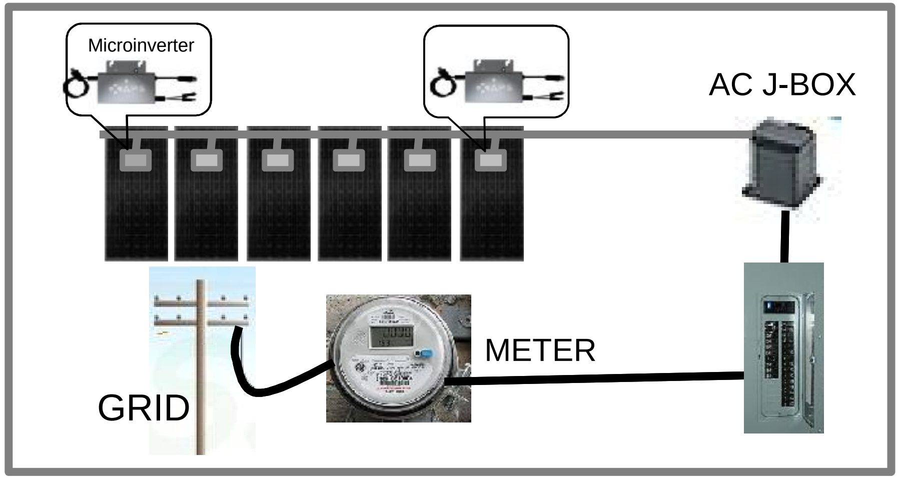
STRING INVERTER

PV panels connect in a series to form a string, which then connects to the string inverter.



MICROINVERTER

Each PV panel is connected to one microinverter, so each panel is independently controlled and monitored.



STRING INVERTER SYSTEMS

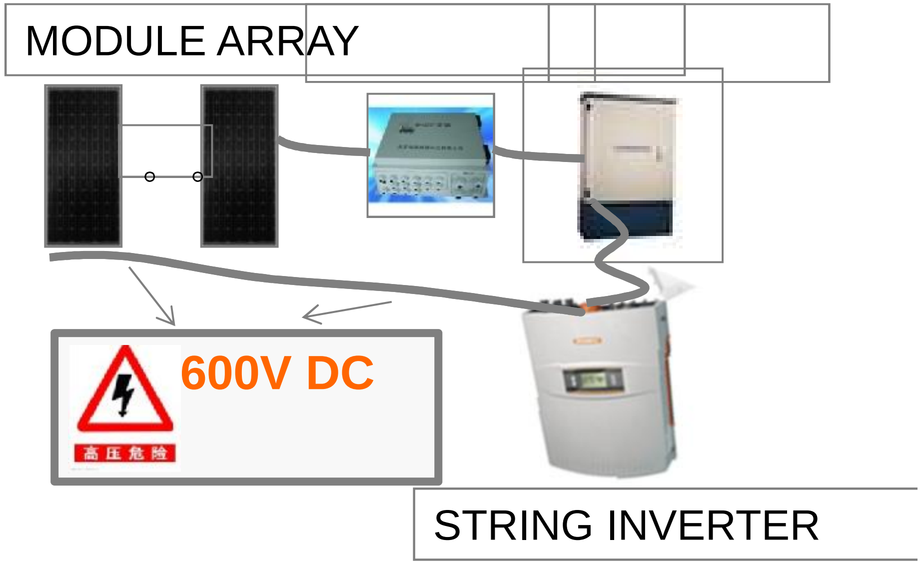
600V DC travels between the PV array and the inverter.

•Lethal to humans

•High risk of DC arc faults

➢ According to UL, almost all PV-related fire accidents are caused by arcing.

DC output is constant if the solar panels are exposed to sunlight.



MICROINVERTER SYSTEMS

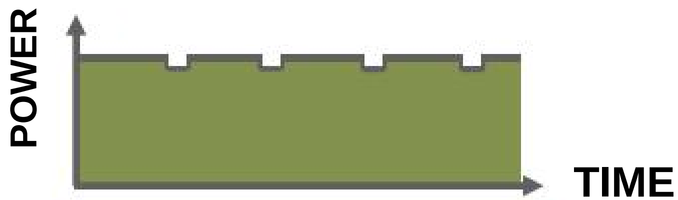
220V AC travels between the micro inverter and the electrical panel.

• No danger to humans

• Low risk of DC arc faults

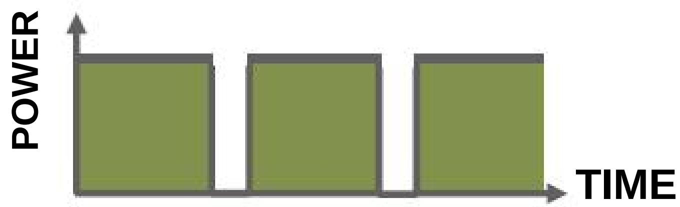
No DC output occurs until the unit is connected to the AC grid.

Comparison between String And Micro Inverters



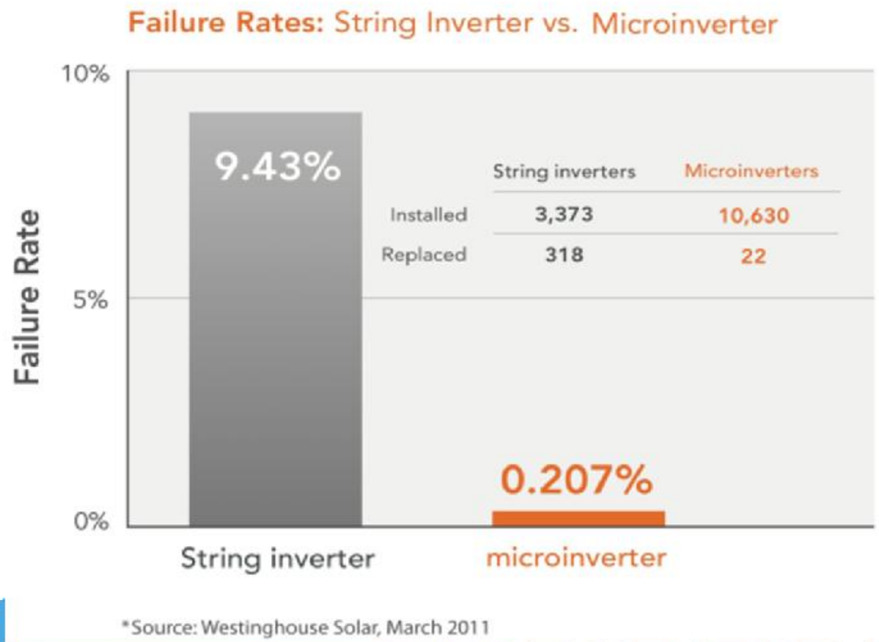
MICROINVERTER SYSTEM
Availability: >99.8%

Warranty: **10** years
Designed for 25 years of use



STRING INVERTER SYSTEM
Availability: >95%

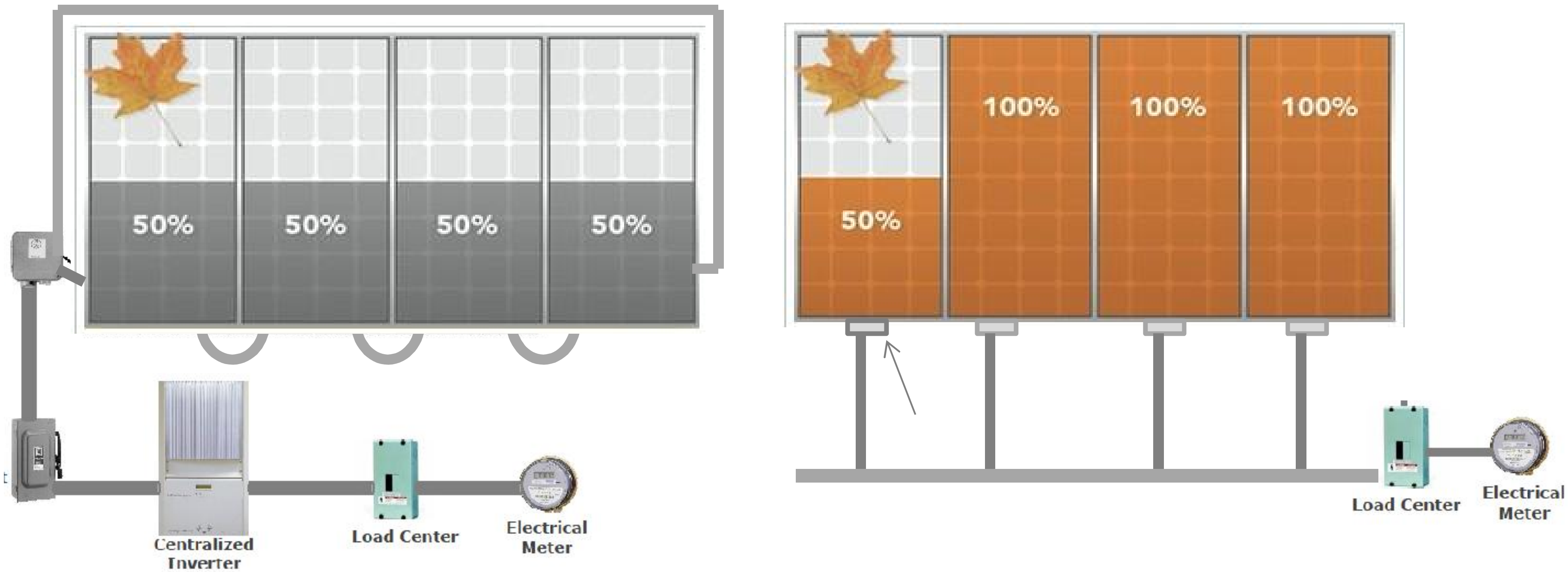
Warranty: **3-5** years



	String inverters	Microinverters
Installed	3,373	10,630
Replaced	318	22

Failure of a microinverter results in the loss of power output from one solar module, while failure of a central inverter results in the loss of power output from every solar module in the connected system.

- MPPT for each solar module
- No module mismatch power losses
- No variation effect from tile angle or installation orientation
- Minimized shading effect
- Independently-controlled solar modules



Inverter characteristics

- Efficiency
- Response times
- Harmonic output
- Fault current contribution
- Synchronisation
- Frequency control
- Power factor
- DC injection

Requirement	Standard	Details
General	AS/NZS 3100	Electrical Safety Requirement
Compatibility with electrical installation	AS 60038	A.C. Voltage and frequency ratings
Power flow direction	N/A	Power flow between energy source and grid may be in either direction
Power factor	AS 4777.2	Range between 0.8 leading to 0.95 lagging between all outputs from 20% to 100% of rated volt-amperes
Harmonic Currents	AS 4777.2	Harmonic current shall not exceed the limits in Table 1.
EMC	Radio Communications Act	
Voltage fluctuation and flicker	AS/NZS 61000.3.3 AS/NZS 61000.3.5	Rated less that or equal to 16A per a phase Rated more than 16A per a phase
Impulse protection	IEC 60255-5	Withstand a standard lightning impulse of 0.5J, 5kV with 1.2/50 waveform
Transient voltage limits	AS 4777.2	Voltage-duration curve derived from measurements taken at a.c. terminal shall Not exceed the limits listed in Table 2.
Direct current injection	N/A	Single-phase inverter: the dc output current of the inverter at the a.c. terminals shall not exceed 0.5% of its rated output or 5mA which ever is greater Three-phase inverter: the dc output current of the inverter at the a.c. terminals measured between any two phases or between any phase and neutral shall not exceed 0.5% of its rated output or 5m which ever is greater
Data logging and communication devices	AS/NZS 60950	Any electronic data logging or communications equipment incorporated in the inverter requires to comply with the appropriated requirements

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DC-AC ELECTRICAL CONVERSION EFFICIENCY

- Efficiency is the most important parameter for grid-connected PV generation
- Depends on whether galvanic insulation transformer is used between the AC on the grid side and the DC generated on the PV side or not.
- Transformer can be either 50 Hz LF transformers, or HF transformers.
- The presence or absence of LF or HF transformers in the inverters influences not only the size, weight, ease of installation and material costs, but also the earthing and safety measures to be adopted in the PV system, and the control of DC injection feed into the grid.
- Inverters with an LF transformer can achieve DC-AC efficiency of 92%,while those with an HF transformer typically achieve a maximum efficiency of 96%.

European Efficiency

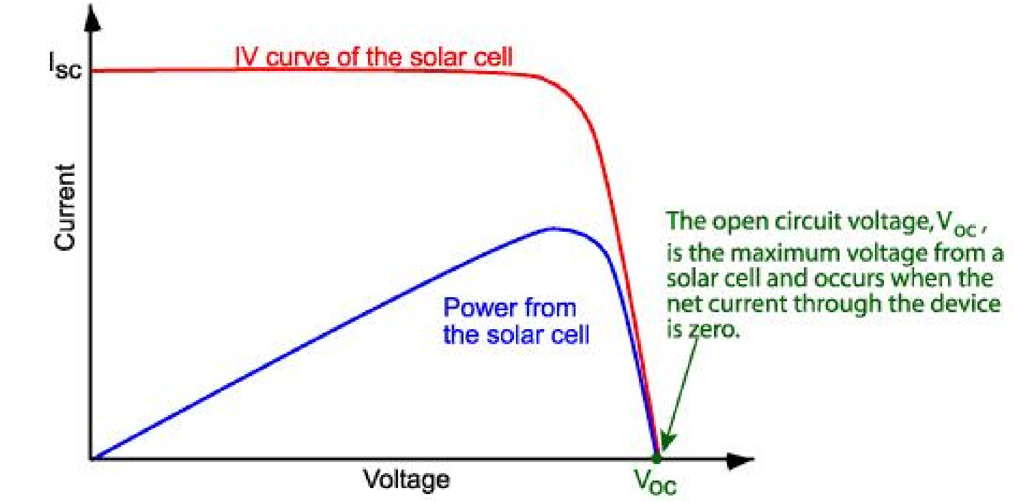
Normalized efficiency, ηE, and is valid for irradiance levels in central Europe. It is defined as a function of the efficiency at defined percentage values for nominal AC power. This is shown in the following equation:

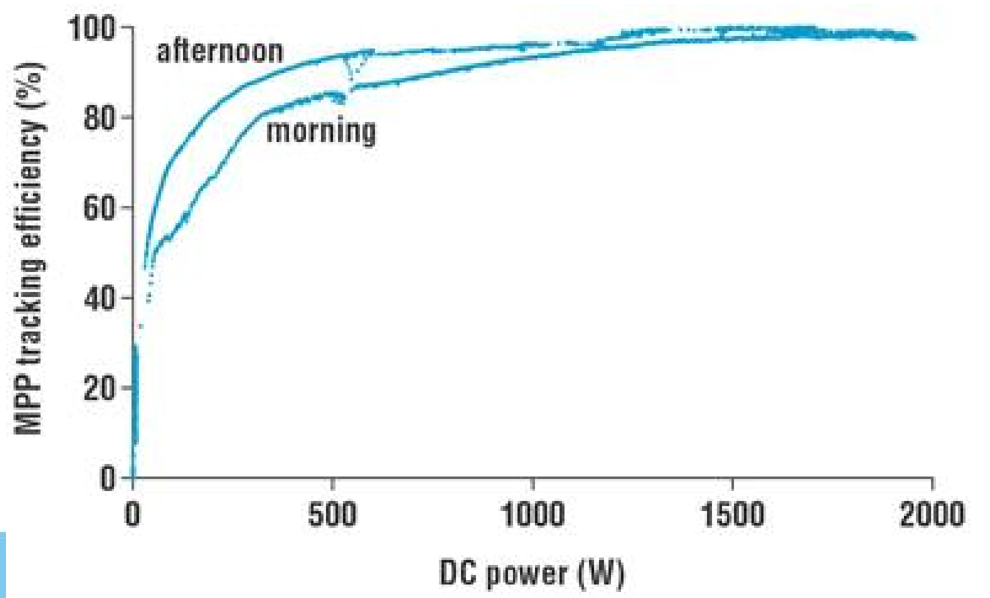
$\eta E = 0.03\eta 5\% + 0.06\eta 10\% + 0.13\eta 20\% + 0.1\eta 30\% + 0.48\eta 50\% + 0.2\eta 100\%$

Experimental inverter efficiencies for different string inverters; values used are representative of state-of-the-art technology

	Efficiency by inverter type (%)			
AC power (% of nominal)	**HF**	**LF (old technology)**	**LF (new technology)**	**Transformerless**
5	77.5	84.8	85.1	86.7
10	85.8	90.4	88.9	91.5
20	91.0	92.0	92.3	94.2
30	93.1	92.5	93.1	94.6
50	93.8	90.9	93.4	95.0
100	93.3	90.0	92.8	94.2
η_E	92.3	90.8	92.6	94.2

MAXIMUM POWER POINT TRACKING EFFICIENCY





- The DC power input to an inverter depends on which point in the current-voltage (I-V) curve of the PV array it is working at.
- Ideally, the inverter should operate at the maximum power point (MPP) of the PV array.
- The MPP is variable throughout the day, mainly as a function of environmental conditions such as irradiance and temperature, but inverters directly connected to PV arrays have an MPP tracking algorithm to maximize energy transfer.
- The MPP tracking efficiency, η_{MPPT}, can be defined as the ratio of the energy obtained by the inverter from a PV array, to the energy obtained with ideal

Total Harmonic Distortion

- Inverters for grid-connected PV systems must generate energy at a defined quality
- The standards (example: international Standard IEC 61000-3-2) above require a THD of ≤ 5% for the harmonic spectra of the current waveform. nominal.

$$\%THD = 100x\frac{I_{dis}}{I_{s1}}$$

$$= 100x\frac{\sqrt{I_s^2 - I_{s1}^2}}{I_{s1}}$$

$$= 100x\sqrt{\sum_{h\neq 1}\left(\frac{I_{sh}}{I_{s1}}\right)^2}$$

Table 1 - Harmonic current limits [2]

Harmonic order number	Limit for each individual harmonic based on percentage of fundamental
2-9	4%
10-15	2%
16-21	1.50%
22-33	0.60%
Even harmonics	25% of equivalent odd harmonics
Total harmonic distortion (to the 50th harmonic)	5%

AS 4777

Islanding

- Grid fails but section ('island') remains energised
- Highly dangerous
- Anti-islanding protection required by AS 4777
- Automatic shut-down within two seconds of grid failure