UNIVERSITÀ DI TRENTO

DEPARTMENT OF

INDUSTRIAL ENGINEERING

Renewable Energy Conversion Systems

Lecture 16

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MSc Degree in Mechatronic Engineering,

Academic Year 2024-2025

Lecture 16: Outline

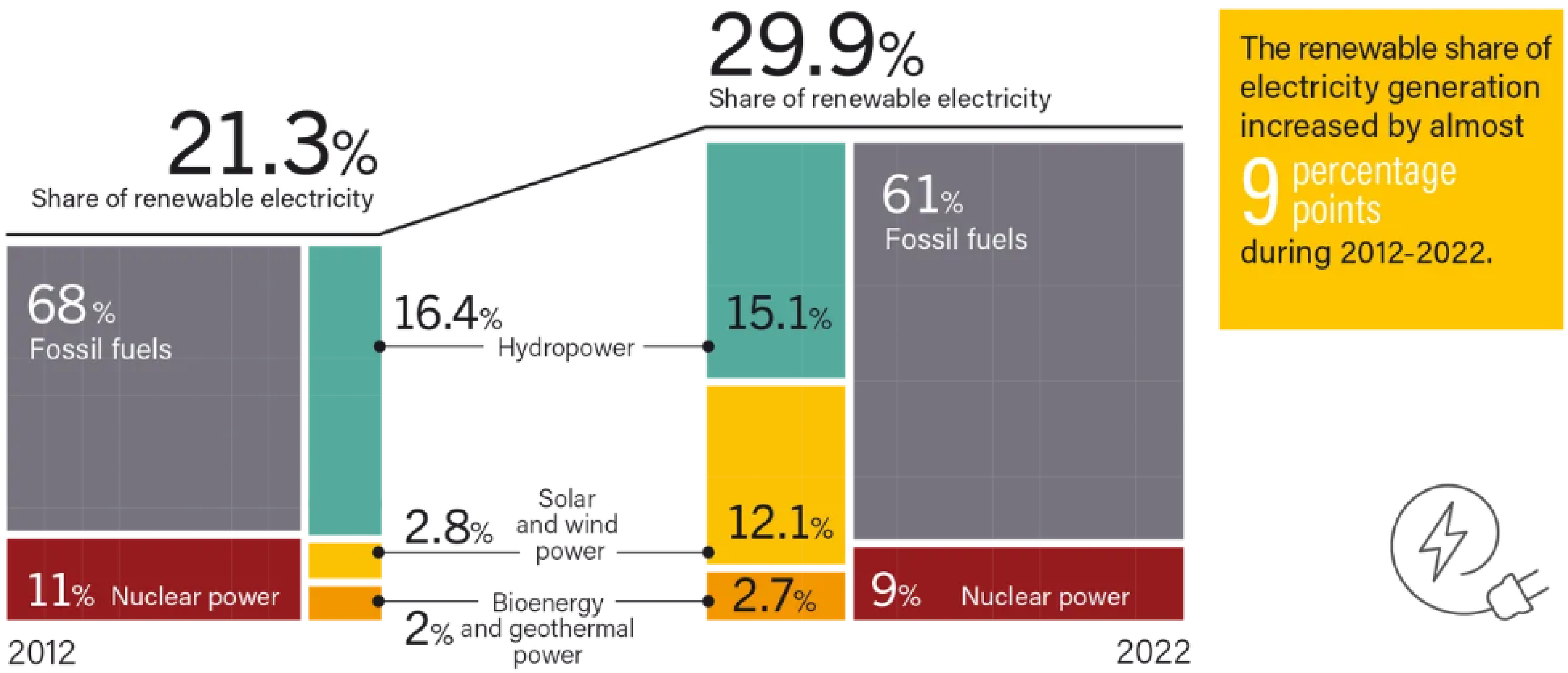
Main topic:

Photovoltaic Energy Conversion Systems

- Trends of development of Photovoltaic (PV) systems
- Main components of a PV energy conversion systems
  - PV cells/modules/arrays
  - Modeling of PV cells
  - Maximum Power Point Tracking (MPPT)
  - Power electronic converters for PV applications

Photovoltaic (PV) Systems - Outlook

Share of Renewable Electricity Generation, by Energy Source, 2012 and 2022



Source:REN21 (2023)

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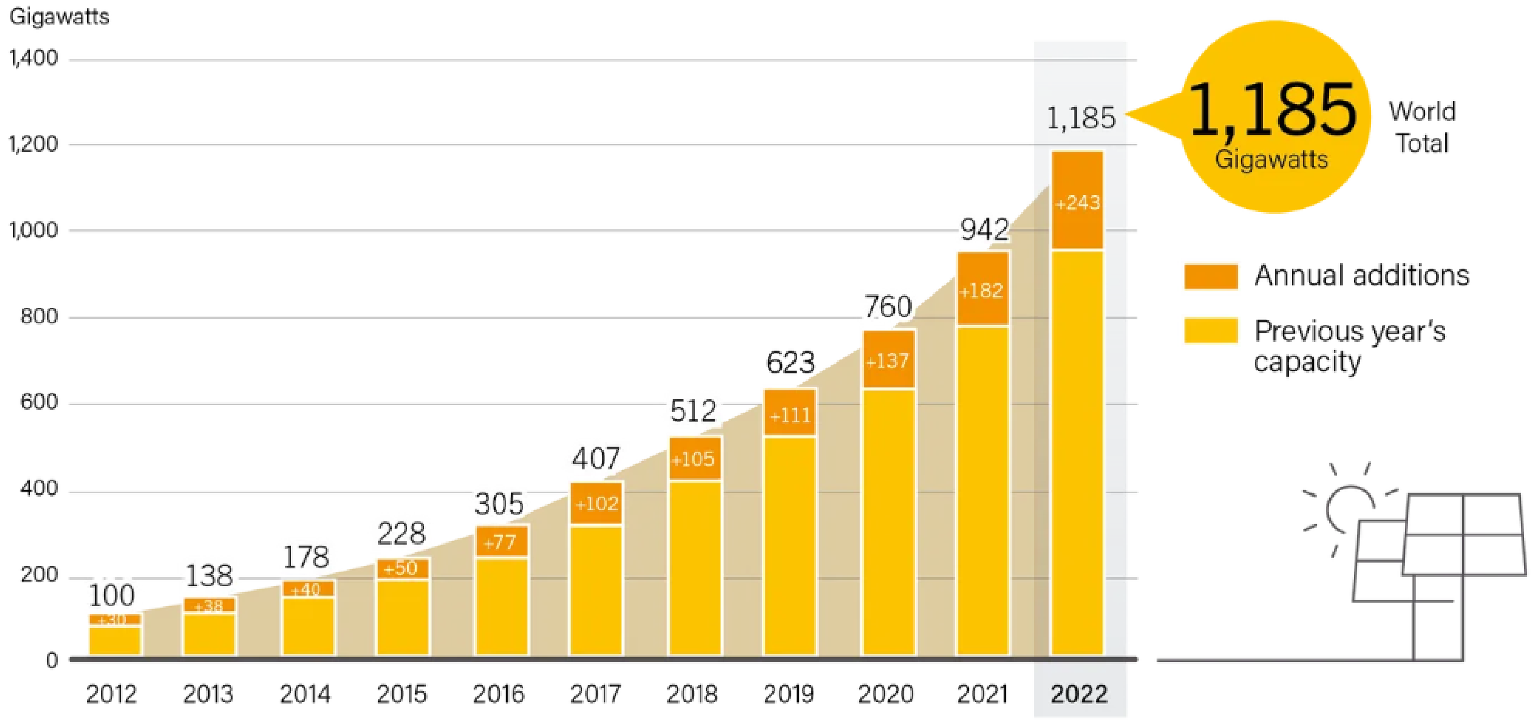
Photovoltaic (PV) Systems - Outlook

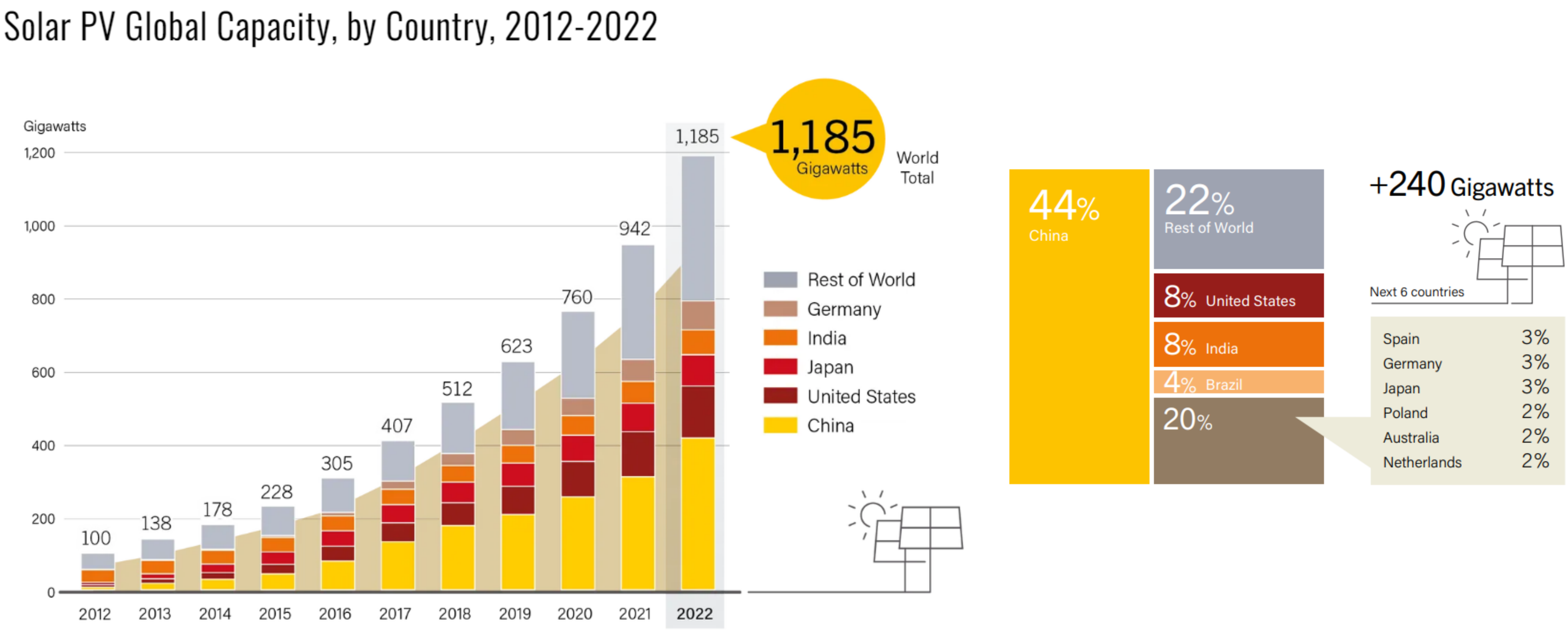
Solar PV Global Capacity and Annual Additions, 2012-2022



Source:REN21 (2023)

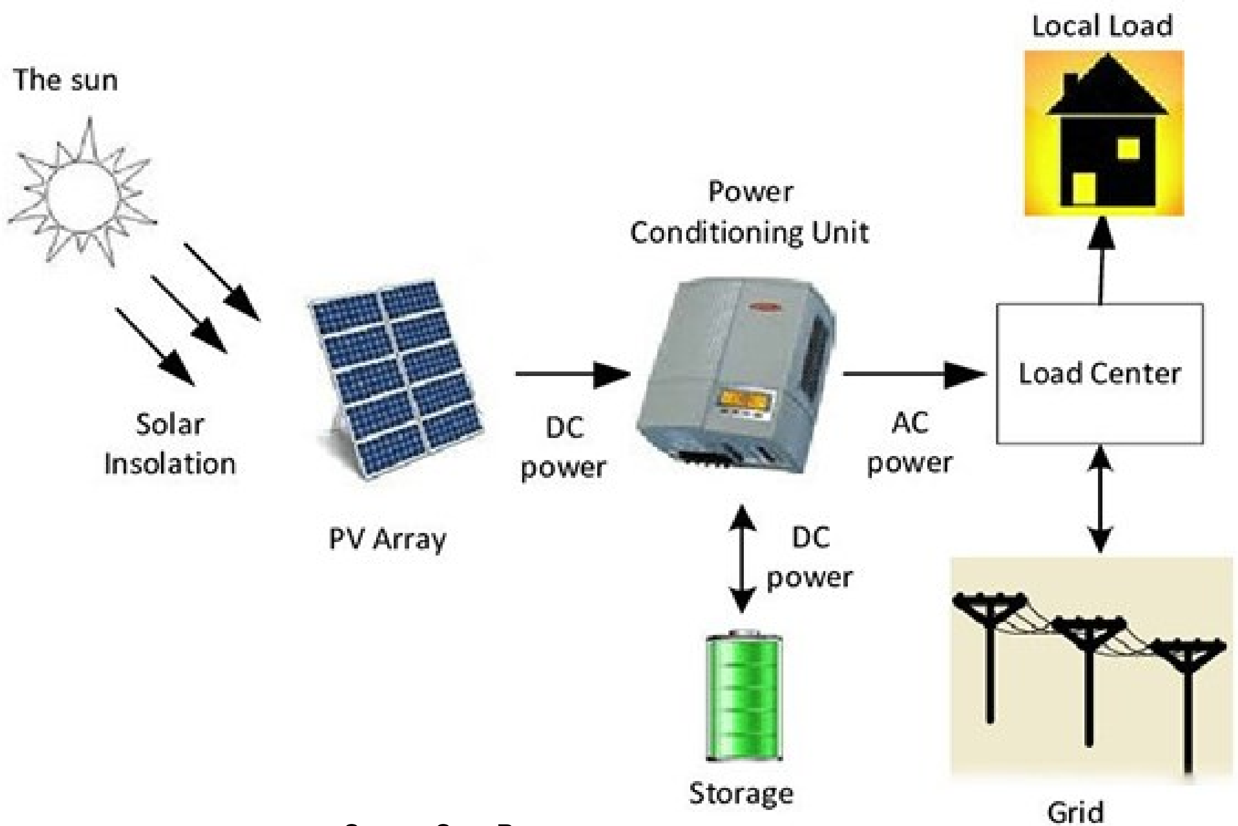
Most used renewable energy source to produce electricity, after hydro-power

Photovoltaic (PV) Systems - Outlook



Source:REN21 (2022)

Grid-connected PV systems

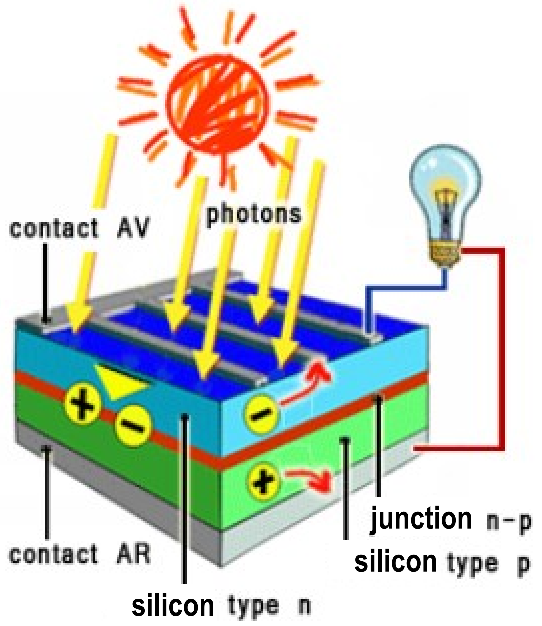


Source:SegaPower.com

Main components:
- PV array (power generator)
- Power electronic converter
- Local grid/load

Optional components:
- Energy storage system
- Low frequency or high frequency transformer

Photovoltaic Effect



The photovoltaic effect is a physical and chemical phenomenon consisting in the generation of voltage and electric current in a material upon exposure to light

Source: Bayeh and Moubayed; (2015)

PV cells

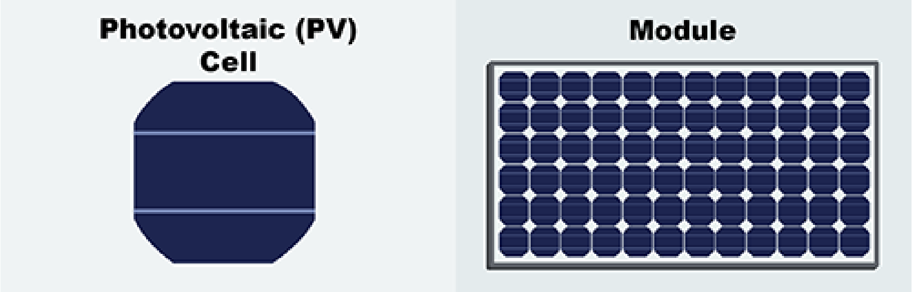
Source :Wikipedia

- A **photovoltaic cell** converts the energy of light directly into electricity by the photovoltaic effect
- It is a device whose **electrical characteristics,** such as current, voltage, or resistance, **vary** when **exposed to light**
- The common single-junction silicon **solar cell** can produce a **maximum** open-circuit **voltage** of approximately **0.5 - 0.6 V**

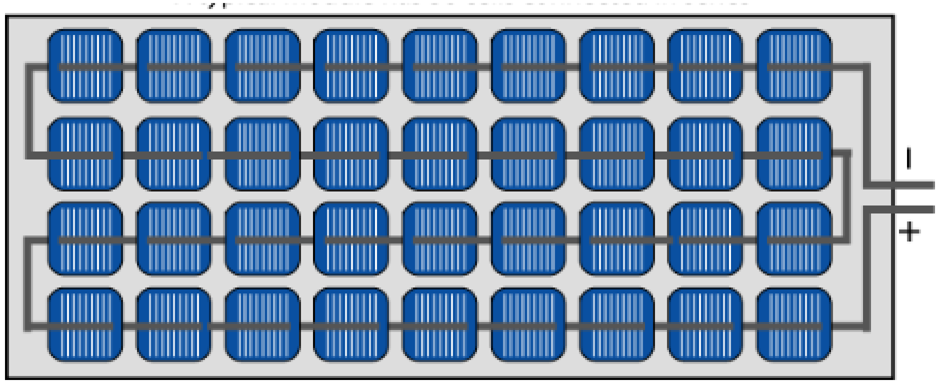
- The **output current** varies depending on **the size** of the cell. In general, a typical commercially-available silicon cell produces a current between **28 and 35 milliamps per square centimeter**

From PV cells to modules

Source :Florida Solar Energy Center



PV module with series connected cells

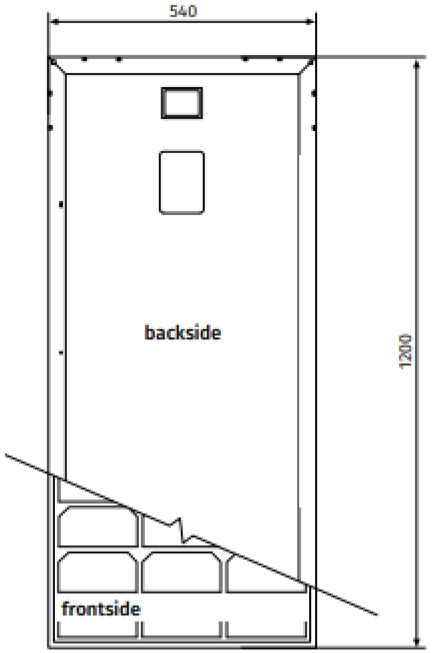


- **Photovoltaic cells** are connected electrically in series and/or parallel circuits to produce higher voltages, currents and power levels.
- **Photovoltaic modules** consist of PV cell circuits sealed in an environmentally protective laminate and are the fundamental building blocks of PV systems.

A solar module is made of photovoltaic cells arranged in a configuration that can contain 32, 36, 48, 60, 72 and 96 cells. A solar panel comprising 32 cells typically can produce 14.72 volts output (each cell producing about 0.46 volt of electricity).

PV module

Source :Offgridsun.com



Solar Module 100 W

Monocrystalline 36 cells

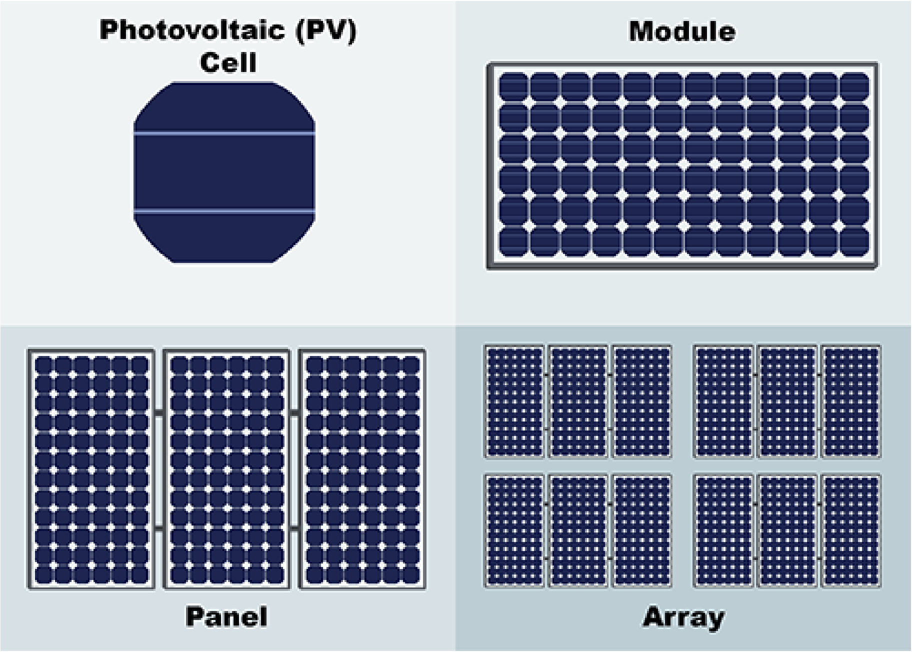
ELECTRICAL DATA		
MODULE		FU 100 M next
Standard Test Conditions STC 1000 W/sqm - AM 1.5 - 25 °C - measuring tolerance <3%		
Module power (Pmax)	W	100
Module efficiency	%	15.29
Maximum power voltage (Vmpp)	V	18.40
Maximum power current (Impp)	A	5.43
Open circuit voltage (Voc)	V	22.95
Short circuit current (Isc)	A	5.85
Maximum system voltage	V	1000

TEMPERATURE RATINGS		
Temperature coefficient (Isc)	%/°C	0.02
Temperature coefficient (Voc)	%/°C	-0.33
Temperature coefficient (Pmax)	%/°C	-0.48
NOCT *	°C	47
Operating temprature	°C	from -40 to +85

* Nominal Operating Cell Temperature

MECHANICAL SPECIFICATIONS	
Dimensions	1200 x 540 x 30 mm
Weight	6.7 kg
Glass	Tempered, transparent, 3.2 mm
Cell encapsulation	EVA (Ethylene Vinyl Acetate)
Cells	36 five bus-bar monocrystalline cutted-cells
Backsheet	Composite multilayer film
Frame	Anodized aluminium frame with mounting and drainage holes
Junction box	Junction box with or without cables

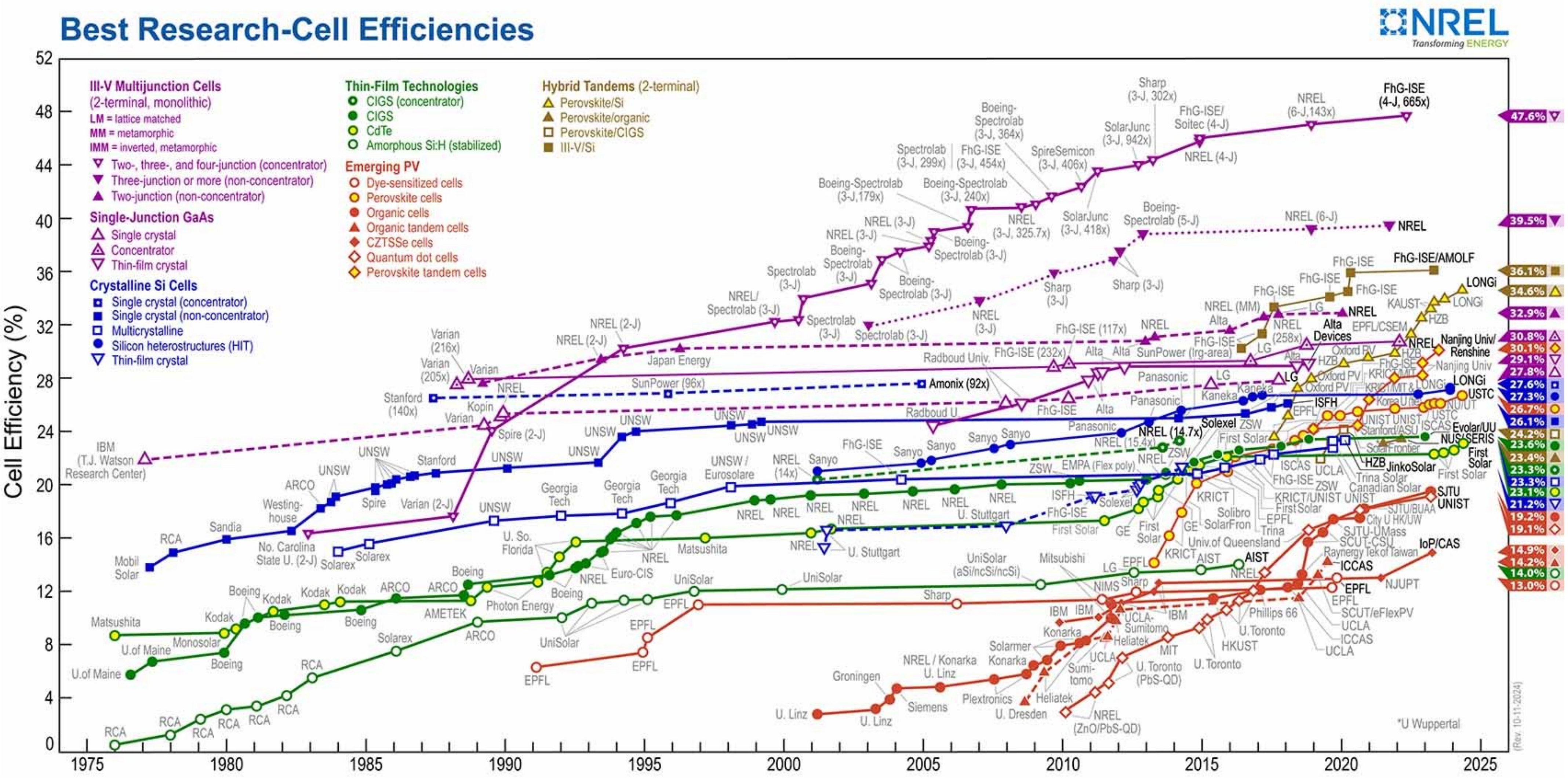
From PV cells to arrays



Source :Florida Solar Energy Center

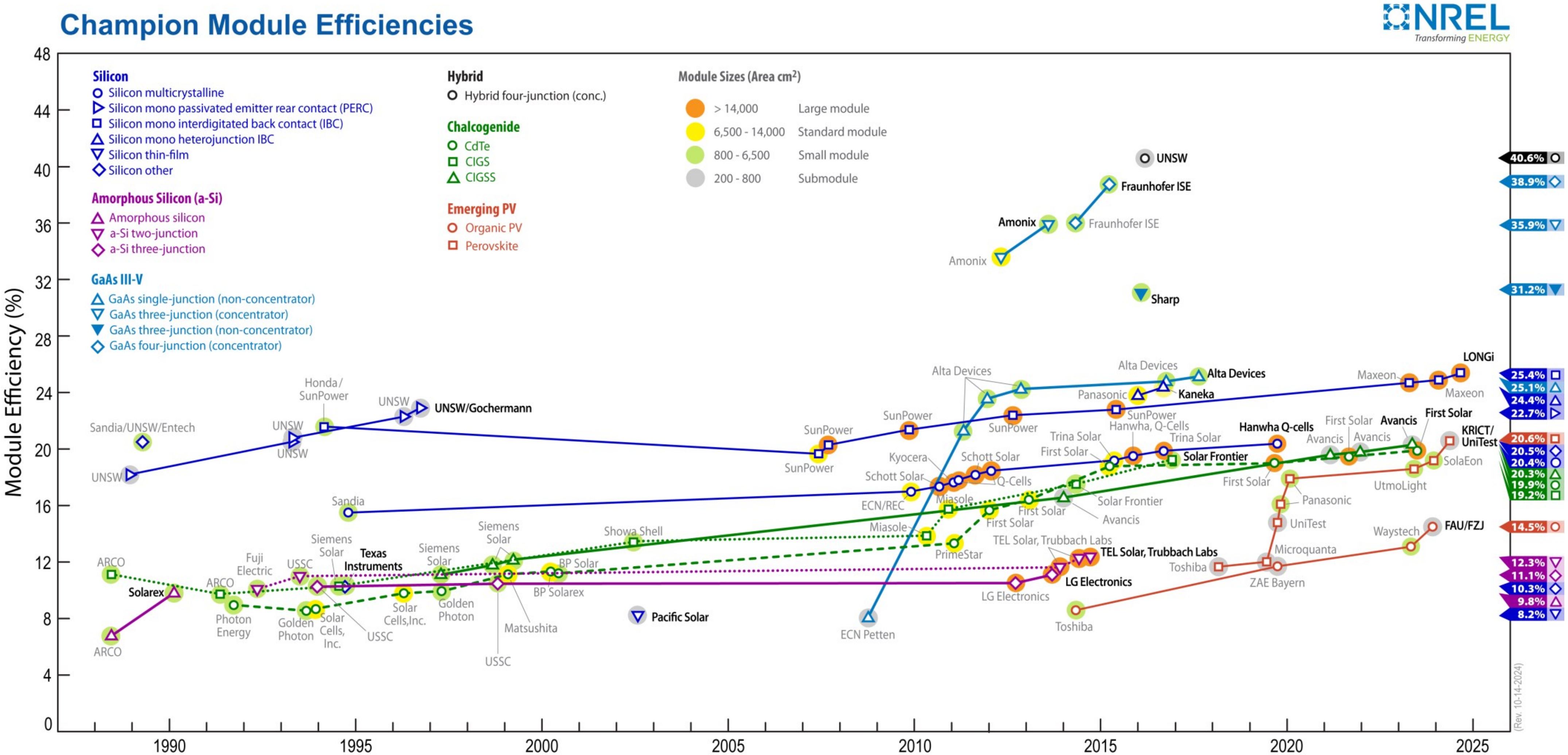
- **Photovoltaic cells** are connected electrically in series and/or parallel circuits to produce higher voltages, currents and power levels.
- **Photovoltaic modules** consist of PV cell circuits sealed in an environmentally protective laminate and are the fundamental building blocks of PV systems.
- **Photovoltaic panels** include one or more PV modules assembled as a pre-wired, field-installable unit.
- **A photovoltaic array** is the complete power-generating unit, consisting of any number of PV modules and panels.

PV cell efficiency



Source: NREL

PV module efficiency



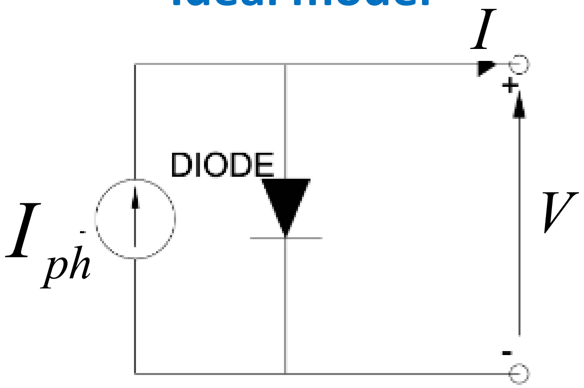
Source: NREL

Modeling of a PV cell

Models of different complexity have been elaborated

Many of them are based on a (single) diode

Ideal model



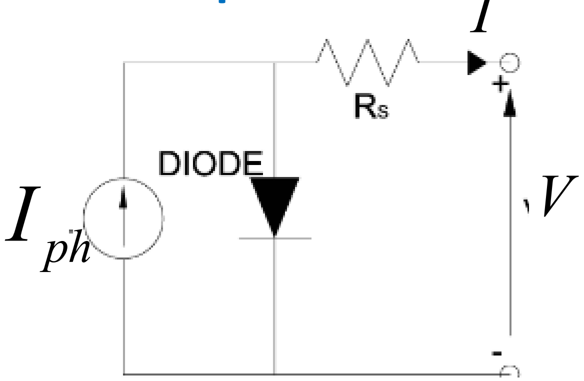
$$I = I_{ph} - I_s[e^{\frac{V}{AV_T}} - 1]$$

$$V_T = \frac{KT}{q}$$

Low accuracy

Simple & fast

Simple model



$$I = I_{ph} - I_s[e^{\frac{V+IR_s}{AV_T}} - 1]$$

$$V_T = \frac{KT}{q}$$

Better accuracy

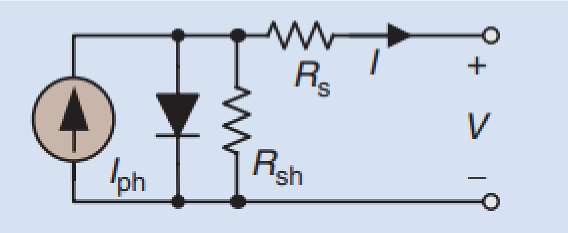
Iph= light-generated current
q= electron charge
K= Boltzmann constant

A=diode quality factor
T=temperature

Is= diode saturation current
V_T=thermal voltage

Modeling of a PV cell

Most used model for a PV cell

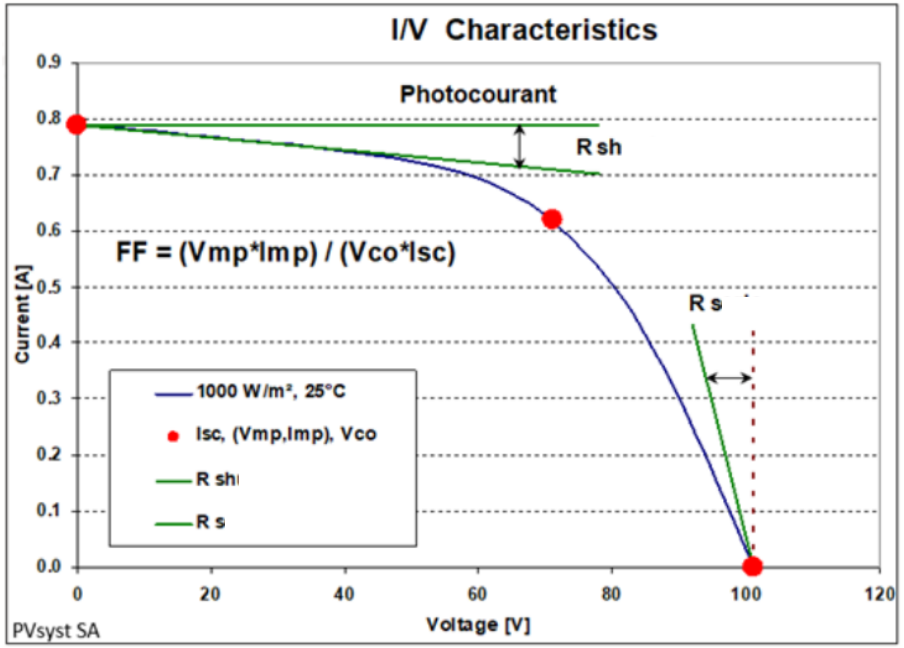


Source: Romreo-Cadaval et al.

$$I = I_{ph} - I_s[e^{\frac{(V+IR_S)}{AV_T}} - 1] - \frac{V + IR_s}{R_{sh}}$$

If ideal R_s=0, R_{sh}=∞

$$I_{ph} = (\frac{S}{S_{ref}})(I_{ph\_ref} + \mu_{ISC}(T - T_{ref}))$$



FF=filling factor Isc= short circuit current Voc=open circuit voltage S= irradiance μ_{ISC}=temperature coefficient of short circuit current

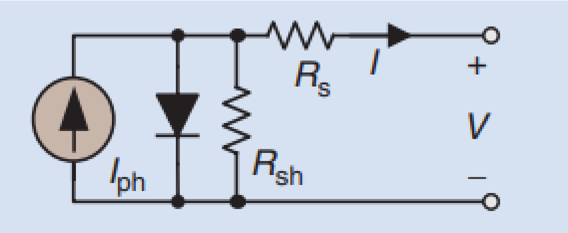
Vmp= Voltage at the maximulm power point Imp= Current at the maximulm power point

q= electron charge A=diode quality factor Is= diode saturation current

K= Boltzmann constant T=temperature V_T=thermal voltage

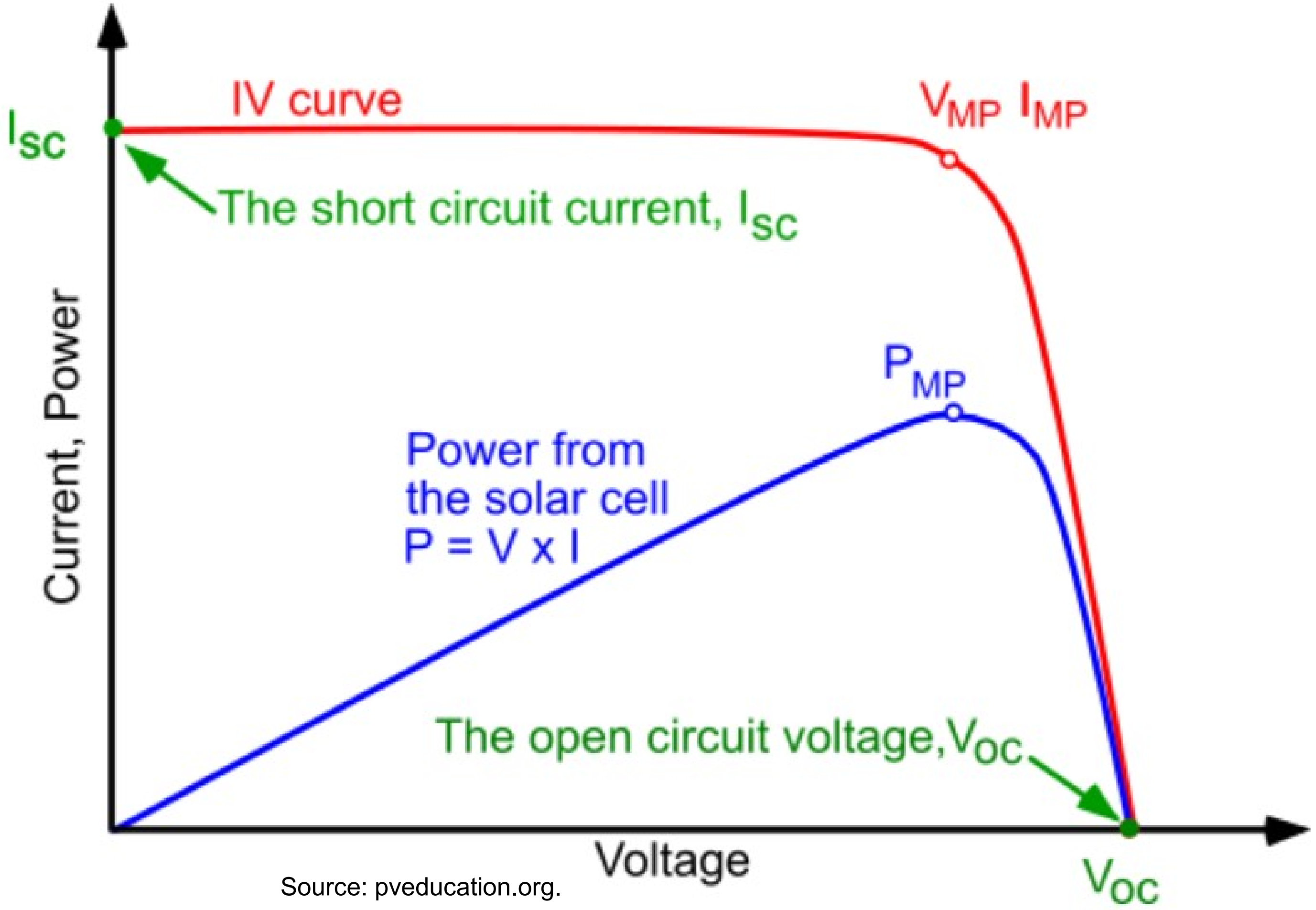
Modeling of a PV cell

Most used model for a PV cell



Source: Romreo-Cadaval et al.

$$I = I_{ph} - I_s\left[e^{\frac{(V+IR_S)}{AV_T}} - 1\right] - \frac{V + IR_s}{R_{sh}}$$



Source: pveducation.org.

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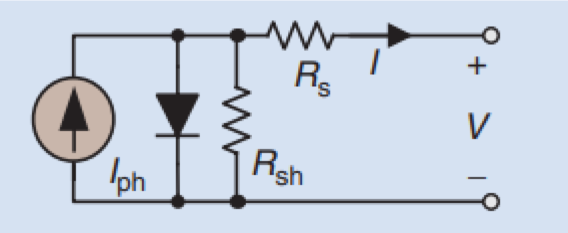
Modeling of a PV cell

Most used model for a PV cell

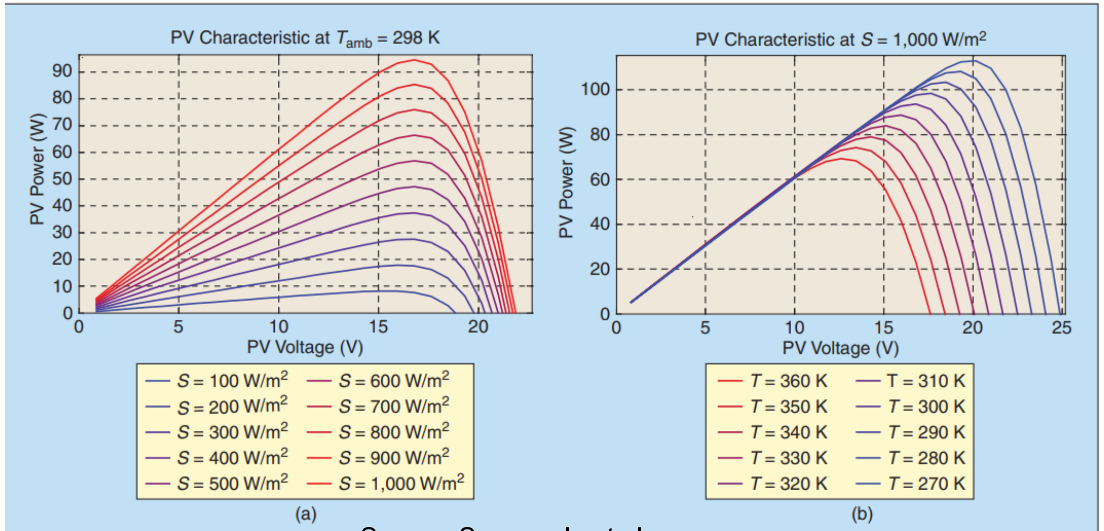


Source: Romreo-Cadaval et al.

$$I = I_{ph} - I_s[e^{\frac{(V+IR_S)}{AV_T}} - 1] - \frac{V+IR_s}{R_{sh}}$$

$$I_{ph} = (\frac{S}{S_{ref}})(I_{ph\_ref} + \mu_{ISC}(T - T_{ref}))$$

Irradiance variation **Temperature variation**

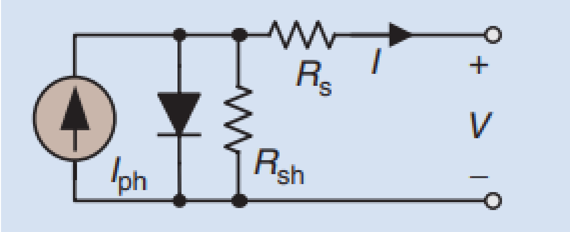


Source: Spagnuolo et al.

FF=filling factor
Isc= short circuit current
Voc=open circuit voltage
S= irradiance
μ_{ISC}=temperature coefficient of short circuit current
Vmp= Voltage at the maximulm power point
Imp= Current at the maximulm power point
q= electron charge
A=diode quality factor
Is= diode saturation current
K= Boltzmann constant
T=temperature
V_T=thermal voltage

Modeling of a PV cell

Derivation of PC cell model from manufacturer information



$$I = I_{ph} - I_s[e^{\frac{(V+IR_S)}{AV_T}} - 1] - \frac{V+IR_s}{R_{sh}}$$

5 parameters need to be determined: I_{ph}, I_s, A, R_s, R_{sh}

As 4 conditions can be found, one parameter needs to be assumed, which is normally A (e.g. A=1.2 for monocrystalline silicon). Some simplifications can also be applied

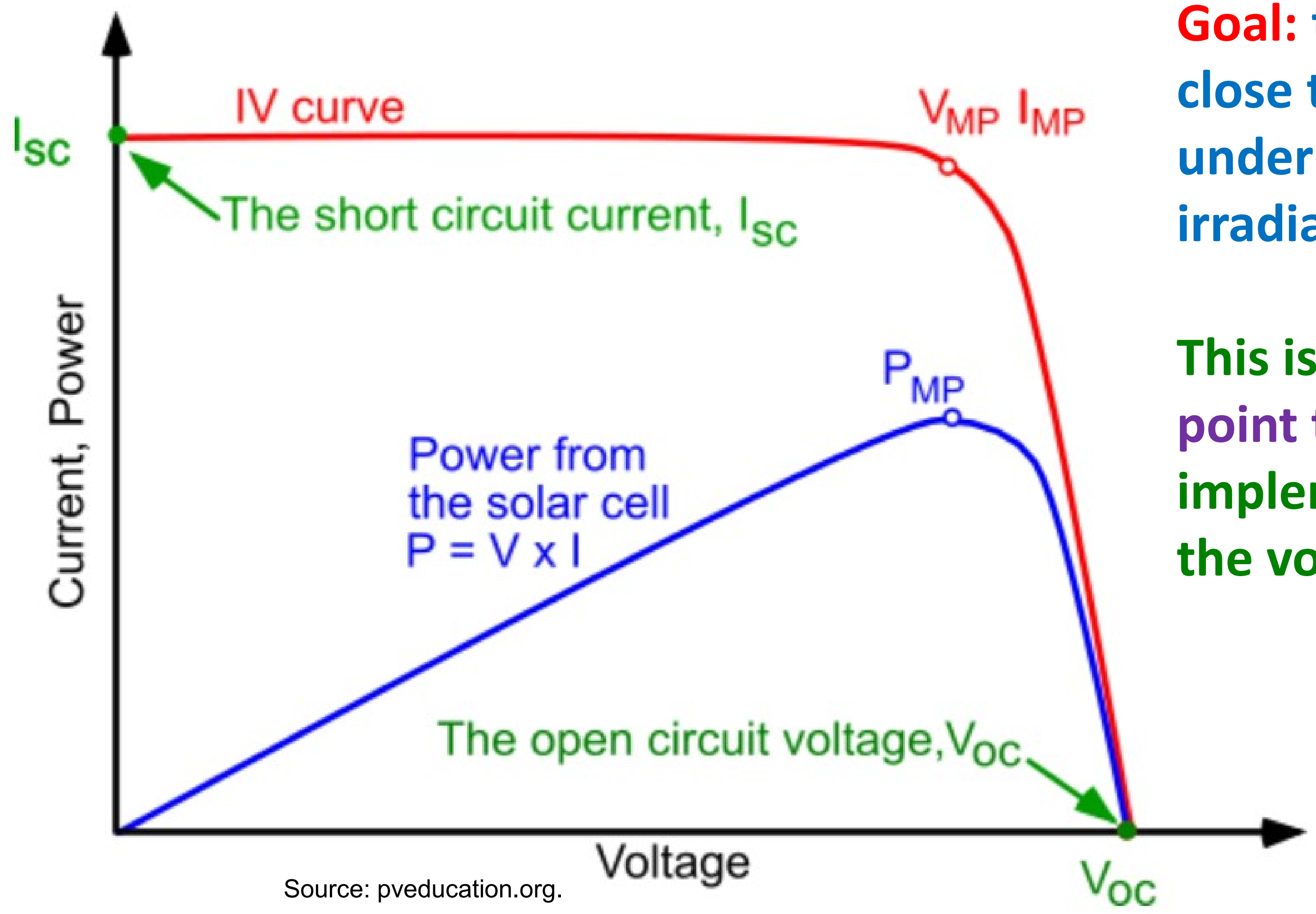
R_s and R_{sh} can be obtained from the MPPT conditions, applying simplifications of non-linear equations

I_s can be obtained from the open-circuit operation I=0 V=V_{oc}

I_{ph} can be obtained considering that I_{diode}~0 under short-circuit condition (I_{ph}=I_{sc})

Source: Romreo-Cadaval et al.

Maximum Power Point Tracking (MPPT)



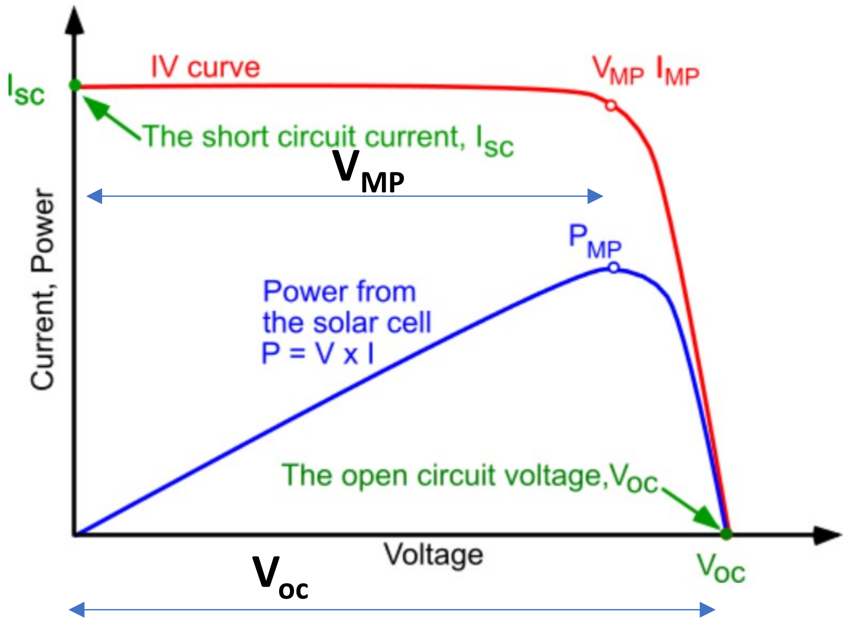
Source: pveducation.org.

Goal: to keep the PV system operating at, or close to, the peak power point of the PV panel under changing conditions, like varying solar irradiance/shading, temperature, and load.

This is performed through the Maximum power point tracking (MPPT), i.e., an algorithm implemented in PV systems to continuously adjust the voltage, such that the PV works at P_{MP}

Multiple MPPT exist, the most common being 1) Fractional open circuit voltage 2) Perturb & Observe, 3) Incremental Conductance method;

MPPT: Fractional Open Circuit Voltage

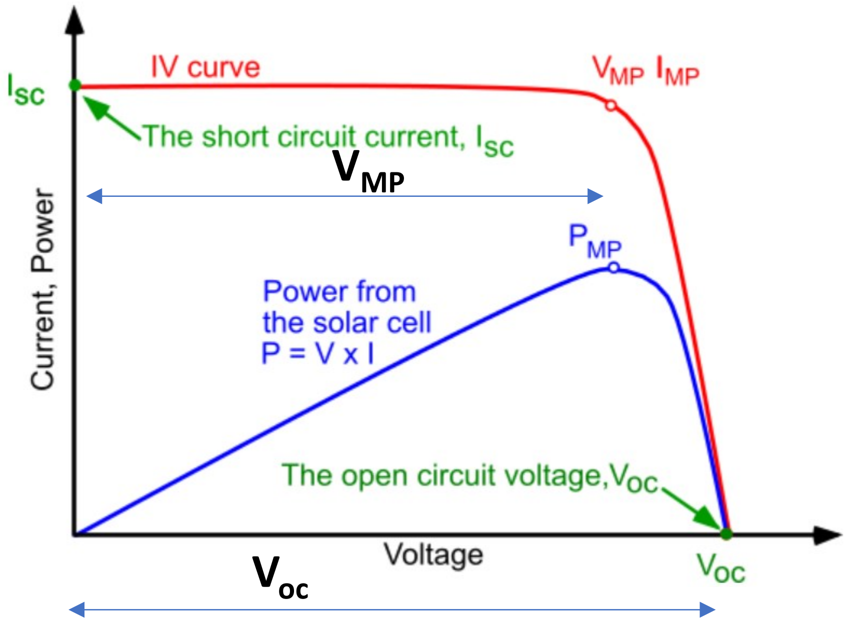


This algorithm is based on the principle that the maximum power point voltage is always a constant fraction (k= 0.6-0.93) of the open circuit voltage. The open circuit voltage of the cells needs to be periodically measured to be used as controller's input

$$k = \frac{V_{MP}}{V_{OC}}$$

Source: Matlab.

MPPT: Fractional Open Circuit Voltage



Pros

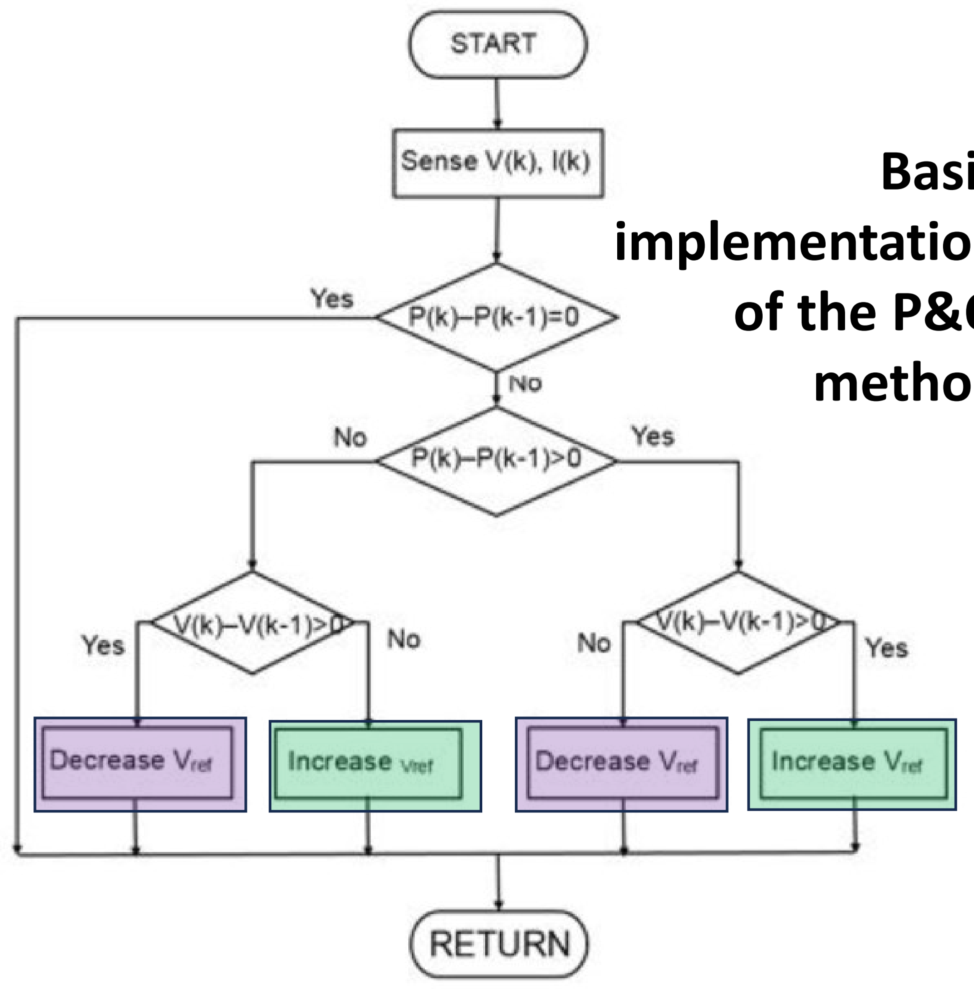
- Simplest MPPT algorithm

Cons

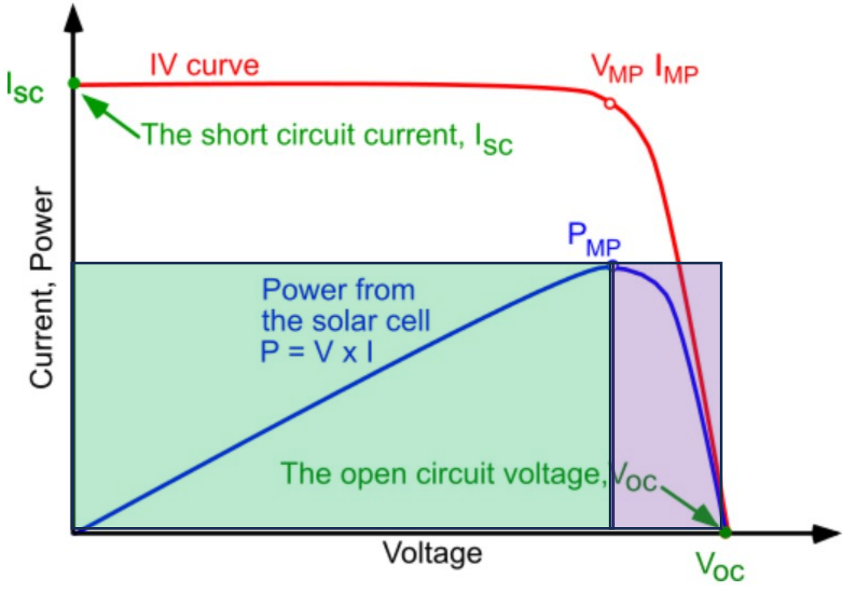
- Needs to periodically measure the Voc, which cannot be measured on a running plant

Source: Matlab.

MPPT: Perturb & Observe (P&O) method



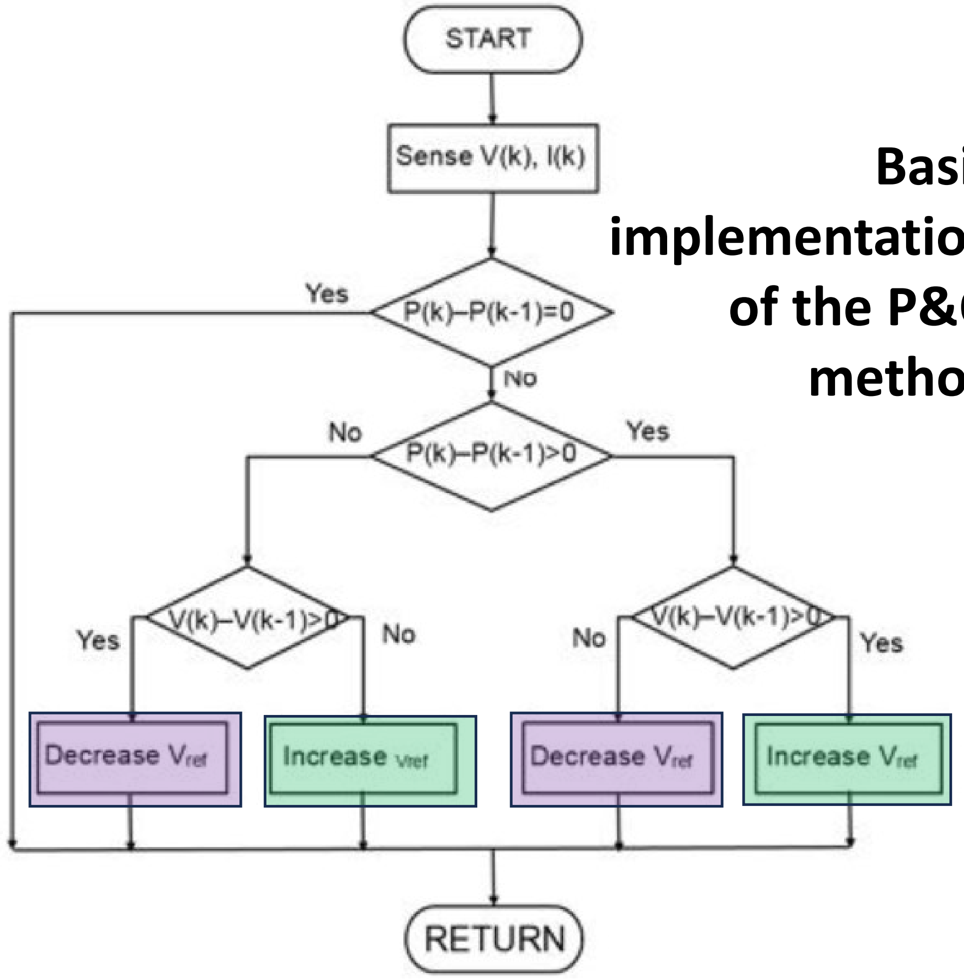
Basic implementation of the P&O method



In "peturb and observe" the operating voltage (V) is perturbed (by modifying the corresponding reference V_{ref}) to ensure maximum power output. Voltage is continuously varied

Source: Matlab.

MPPT: Perturb & Observe (P&O) method



Basic implementation of the P&O method

Pros

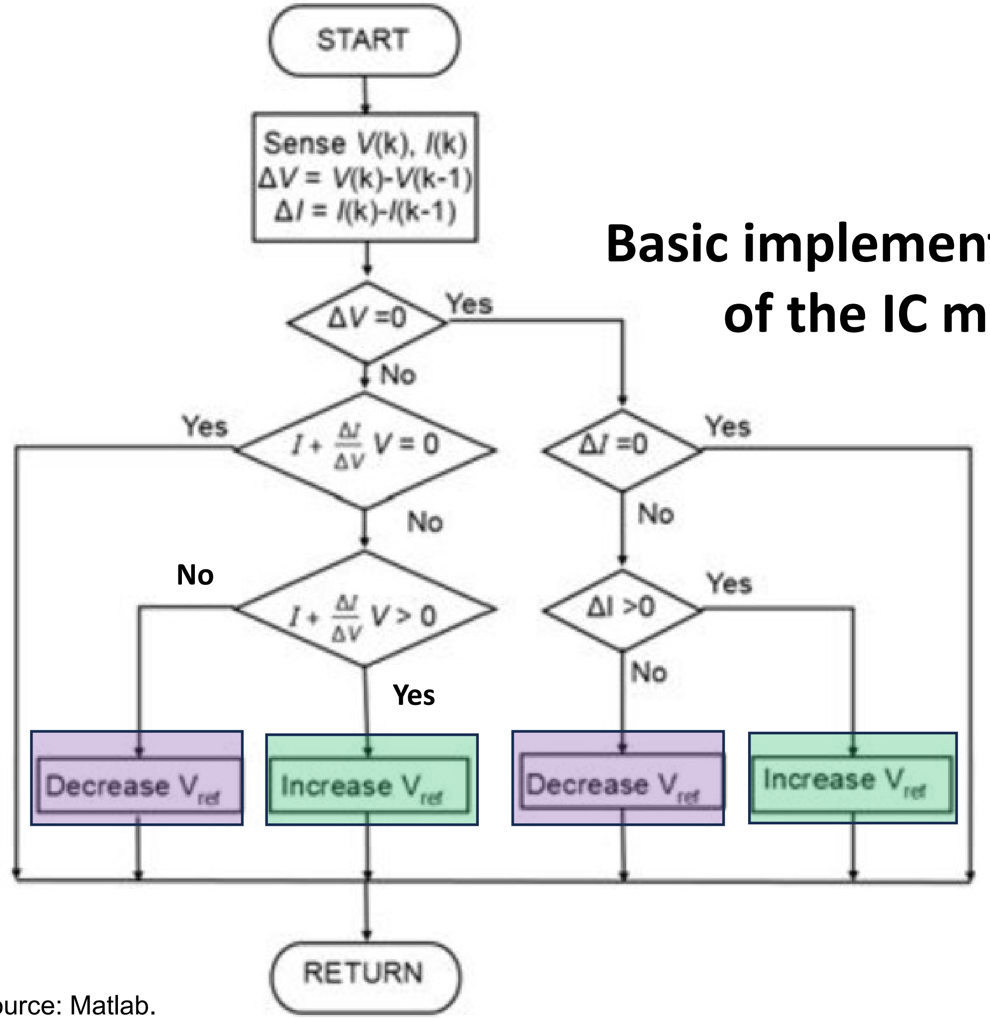
- Simple implementation
- Most used in commercial PV panels

Cons

- Continuous oscillation around the operating (MPPT) point
- If DV is small: long convergence time, if DV is large it will never reach the MPP
- Can just find a local maximum

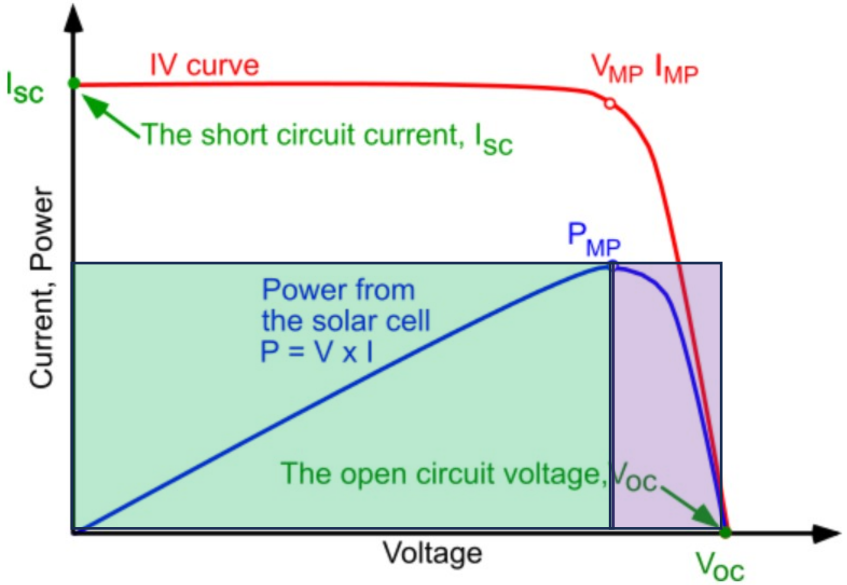
Source: Matlab.

MPPT: Incremental Conductance (IC) method



Source: Matlab.

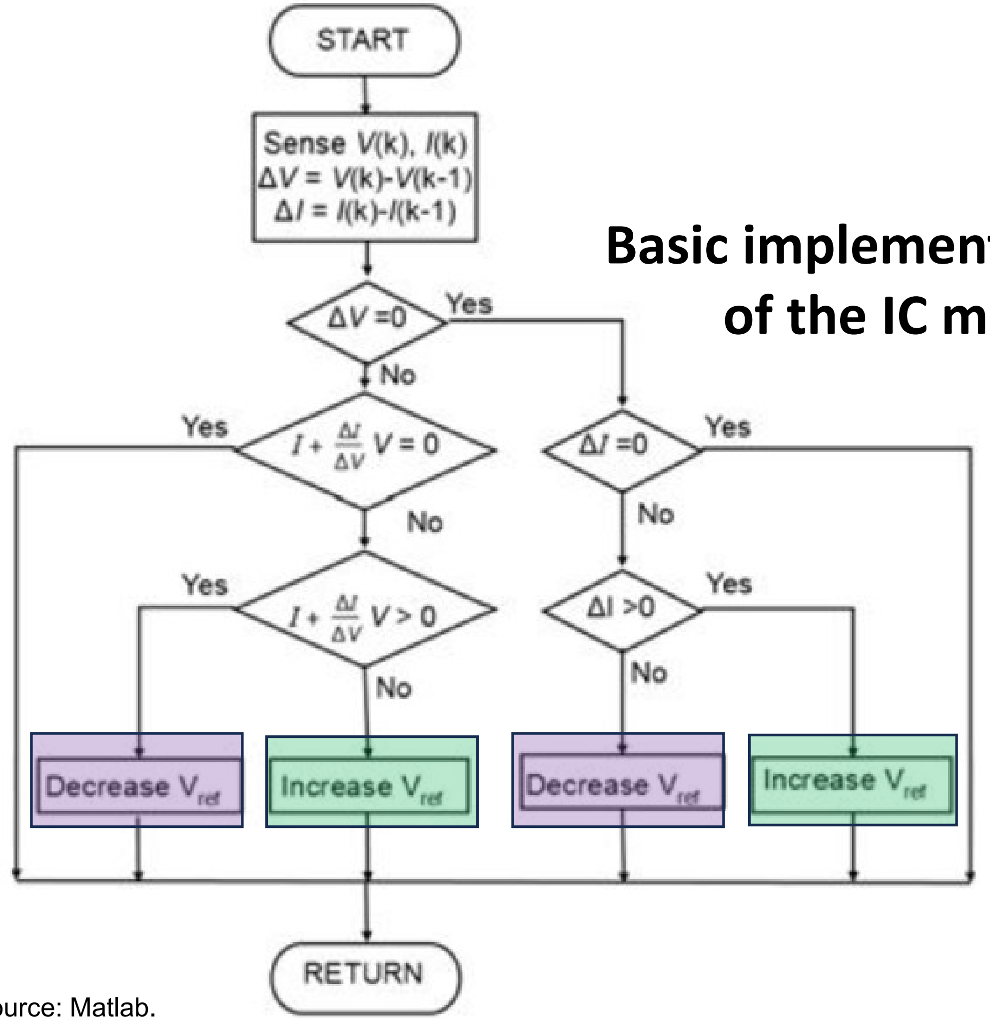
Basic implementation of the IC method



The incremental conduction method compares the incremental conductance and the instantaneous conductance of the system and acts on the voltage accordingly based on:

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} = I + V\frac{dI}{dV} \qquad \frac{dP}{dV} = 0$$

MPPT: Incremental Conductance (IC) method



Basic implementation of the IC method

Pros

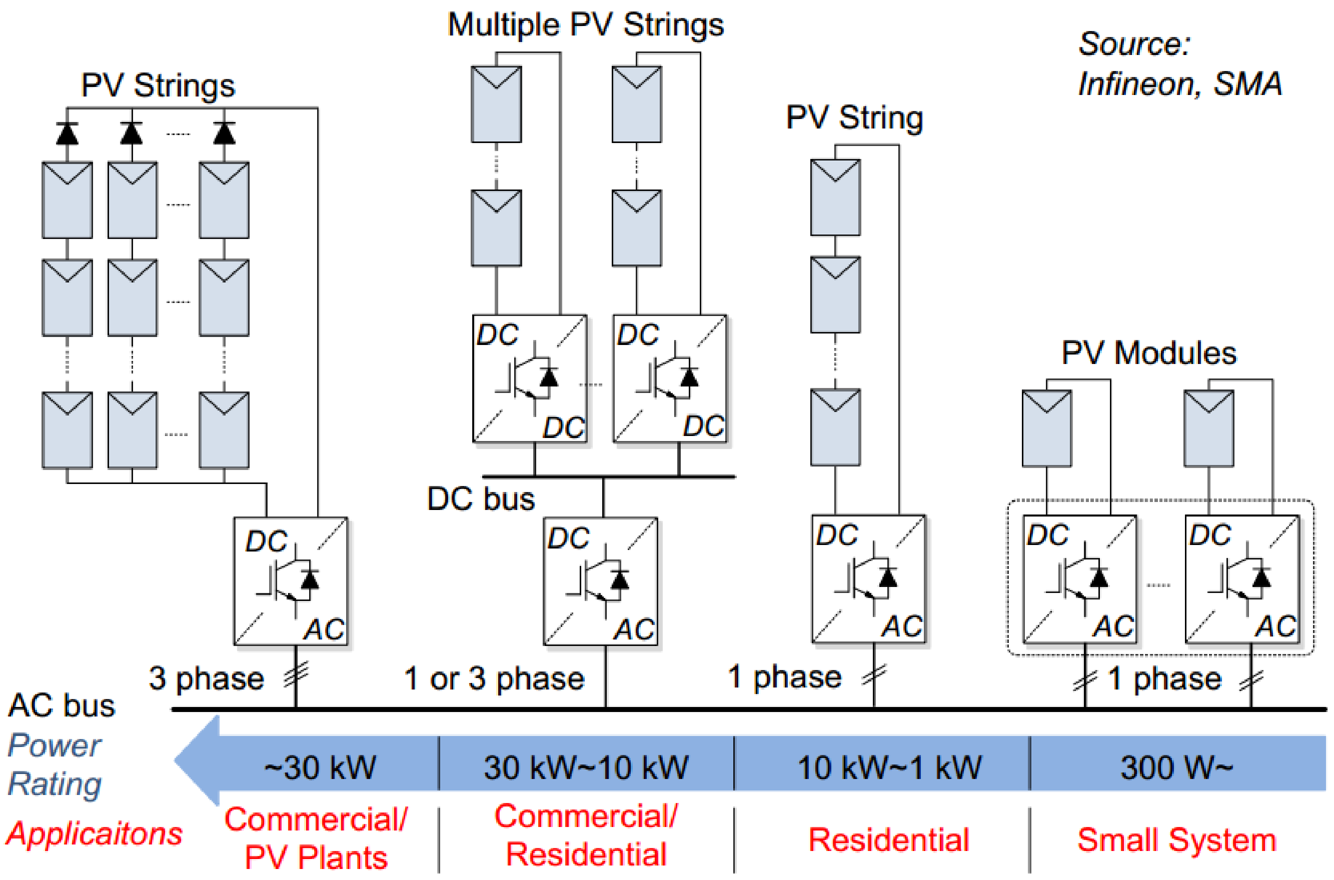
- Short time-response
- High accuracy
- Reaches steady-state operation

Cons

- Complex algorithm
- Increased costs
- Can just find a local maximum

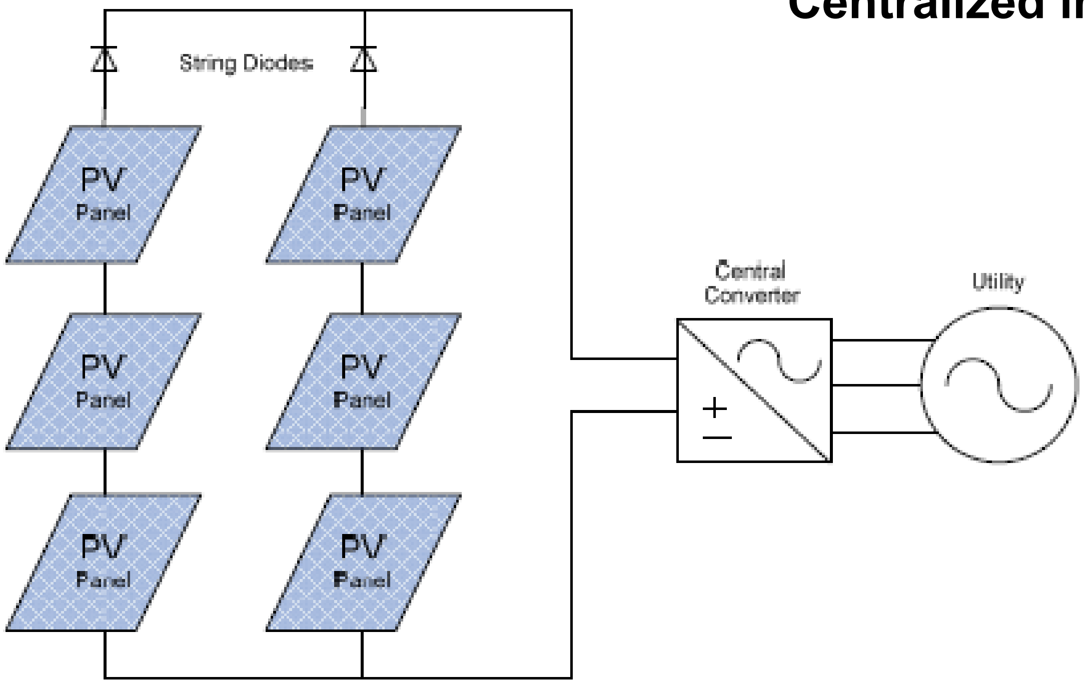
Source: Matlab.

Power electronic converters for PV - Overview



Source: Blaabjerg *et al.*

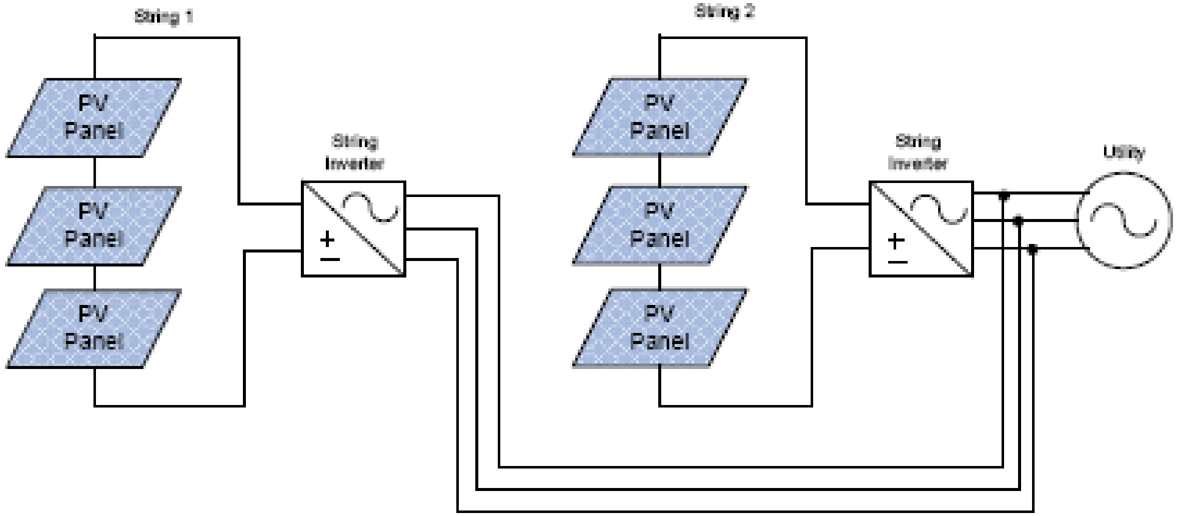
Power electronics for PV – PV systems configurations



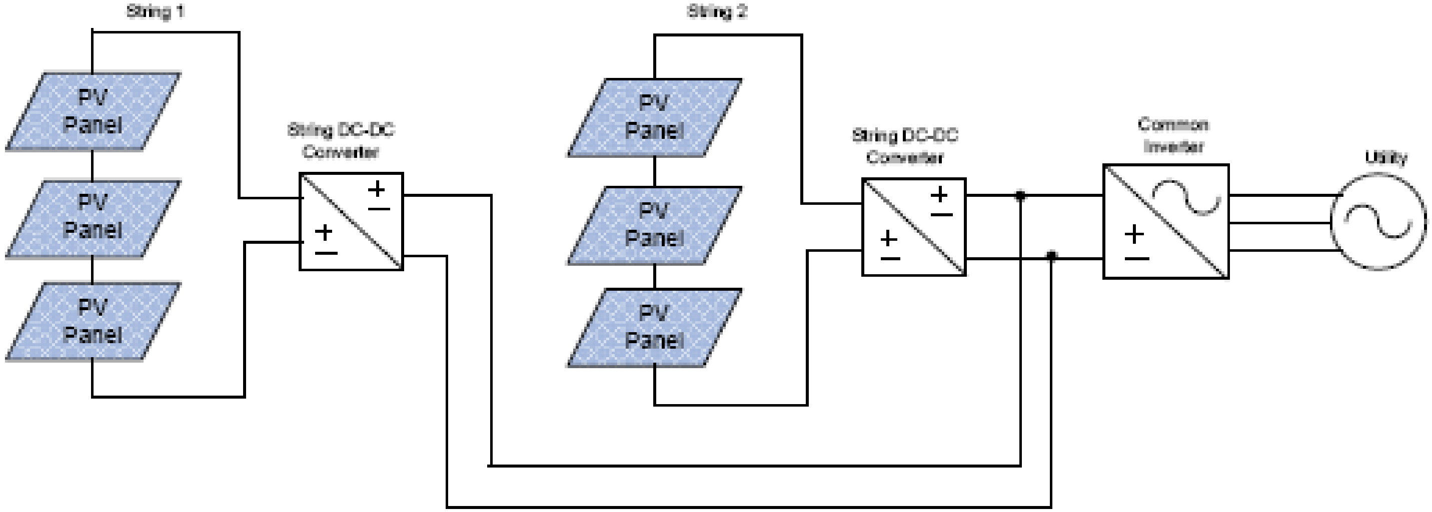
Centralized inverter

- DC power production
- Needs power conditioning
- String systems
- Maximum power point tracking possible with PE

Power electronics for PV – PV systems configurations

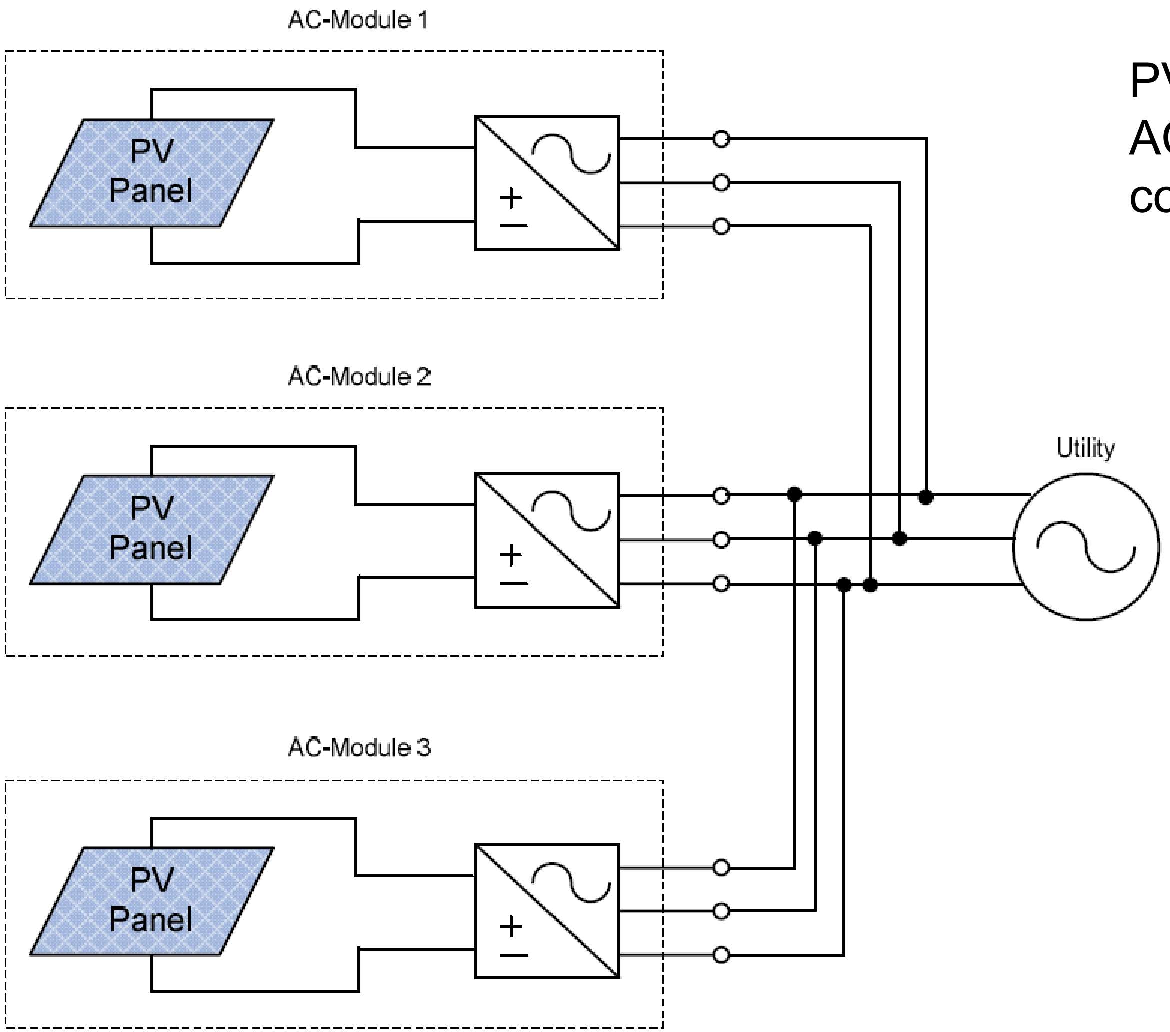


PV panels in string with individual inverters



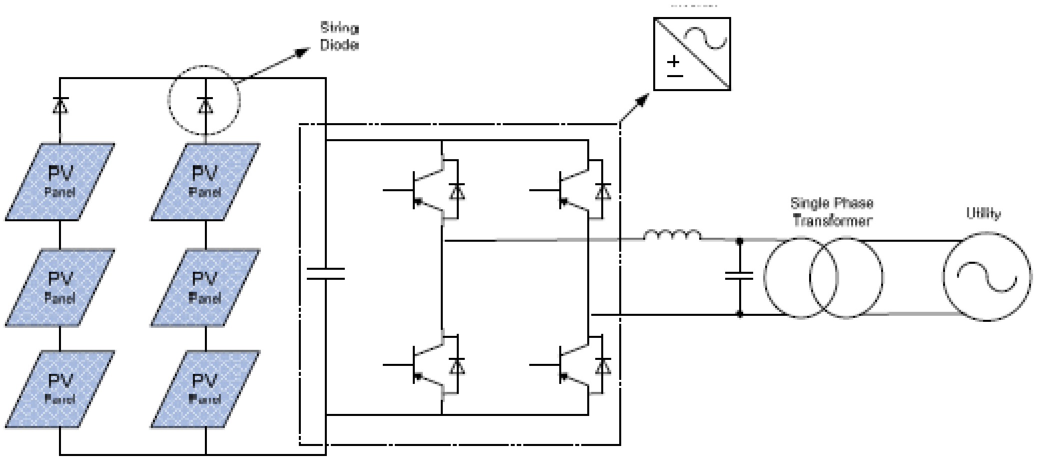
PV panels in multi-string inverter configuration

Power electronics for PV – PV systems configurations

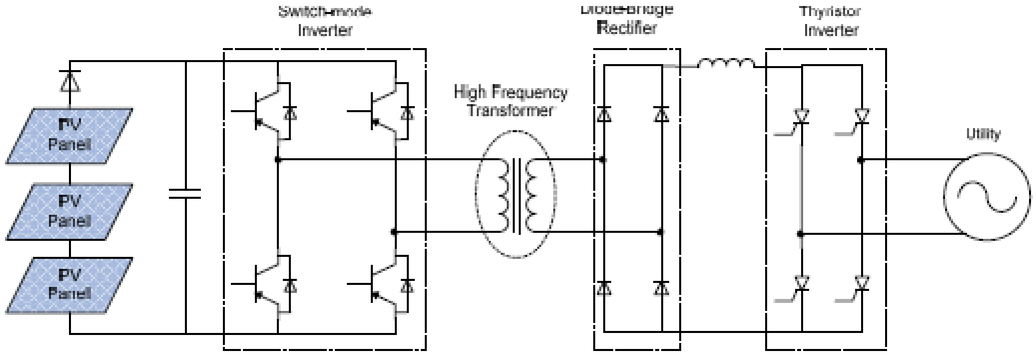


PV panels in AC-module configuration

Power electronics for PV – PV systems configurations

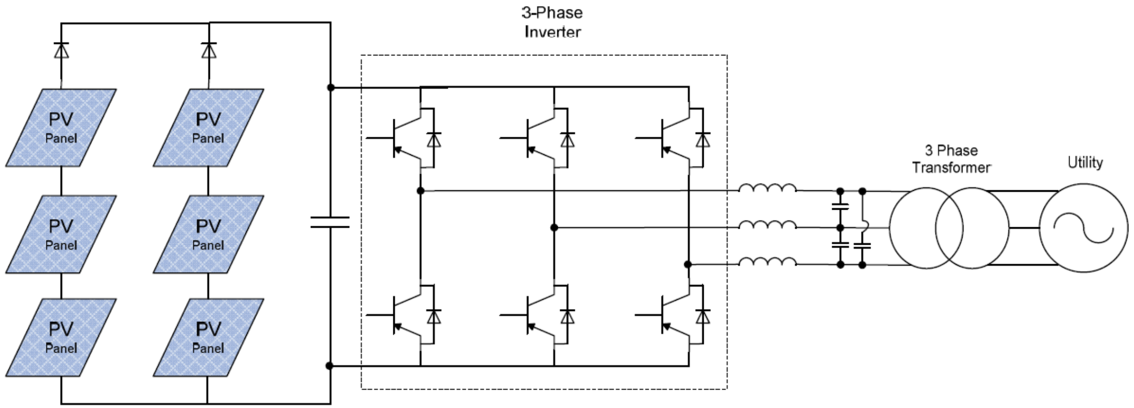


Single-phase,
single-stage

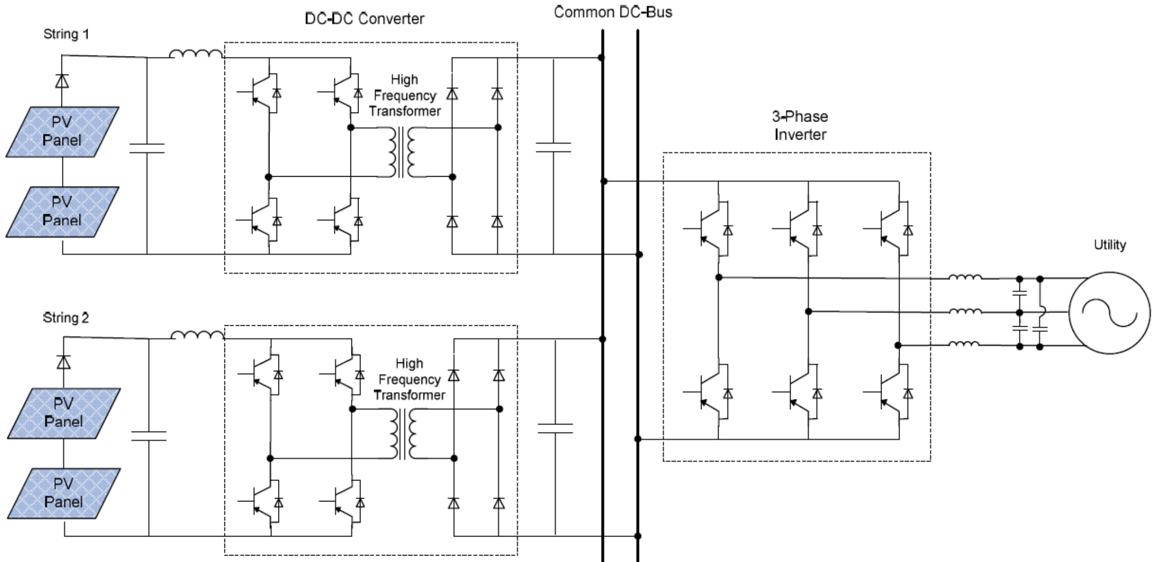


Single-phase,
multiple-stage

Power electronics for PV – PV systems configurations



Three-phase, line transformer



Three-phase, high frequency transformer

PV configuration features

TABLE 2 – A GRID-CONNECTED PV ENERGY CONVERSION SYSTEMS CONFIGURATIONS OVERVIEW.

	SMALL SCALE	MEDIUM SCALE	LARGE SCALE	
	AC MODULE	**STRING**	**MULTISTRING**	**CENTRAL**
Power range	<350 W	<10 kW	<500 kW	<850 kW (<1.6 MW for dual)
Devices	MOSFET	MOSFET, IGBT	MOSFET, IGBT	IGBT
MPPT efficiency	Highest (one module–one MPPT)	Good (one large string–one MPPT)	High (one small string–one MPPT)	Good (one array–one MPPT)
Converter efficiency	Lowest (up to 96.5%)	High (up to 97.8%)	High (up to 98%)	Highest (up to 98.6%)
Features	• Flexible/modular • Highest MPPT efficiency • Easy installation • Higher losses • Higher cost per watt • Two stage is mandatory	• Good MPPT efficiency • Reduced dc wiring • Transformerless (very common) • High component count • One string, one inverter	• Flexible/modular • High MPPT efficiency • Low cost for multiple string system • Two stage is mandatory	• Simple structure • Highest converter efficiency • Reliable • Needs blocking diodes (for array) • Poor MPPT performance • Not flexible
Examples	Power One Aurora MICRO-0.3-I and Siemens SMIINV215R60	Danfoss DLX 4.6 and ABB PVS 300	SMA SB5000TL and SATCON Solstice	SMA MV Power Platform and 1.6 Siemens SINVERT PVS630

Green dots indicate positive features, and red dots indicate negative features.

Source: Kouro *et al.*

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Inverter configurations

Inverter topologies characteristics:

- Variable transistor/switch number

- With or without voltage transformer

- Single or three-phase

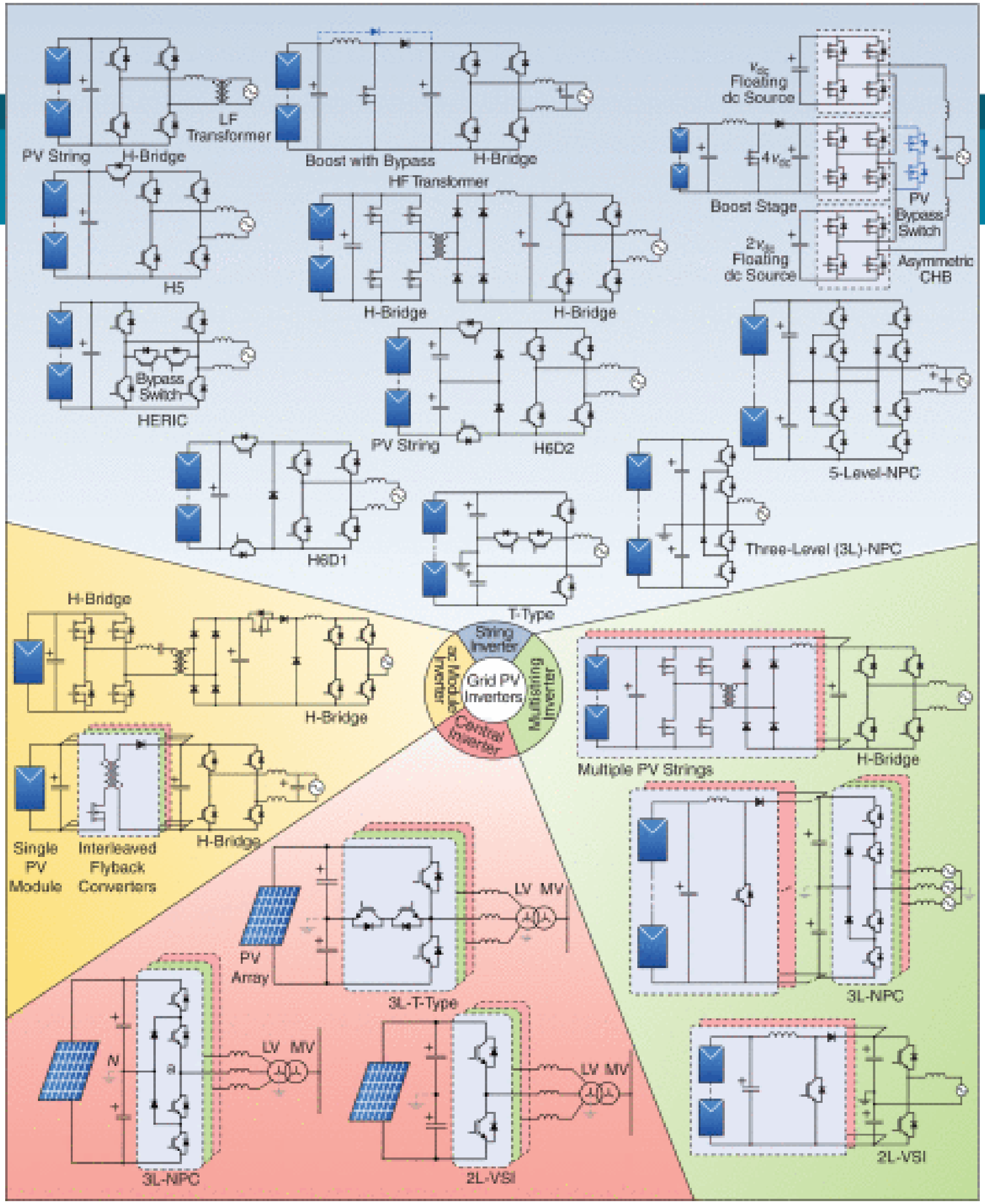
- Single or multi-stage

Drivers for PV converter evolution:

- Higher efficiency

- Higher compactness

- Higher reliability



Source: Kouro *et al.*

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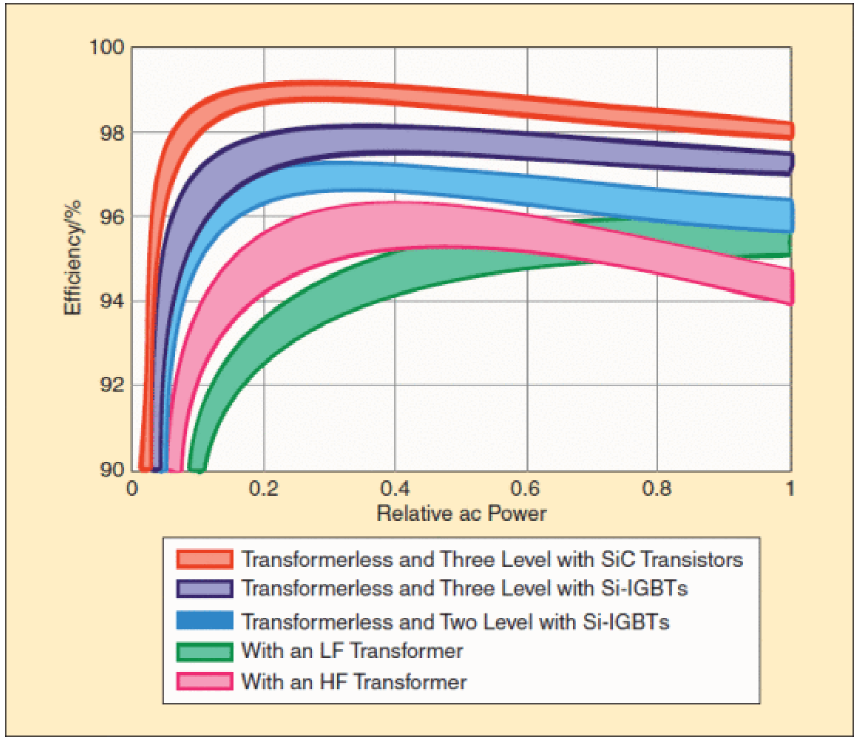
Inverter efficiency



Source: Bacha *et al.*

Main factors affecting inverter efficiency:

- Inverter topology

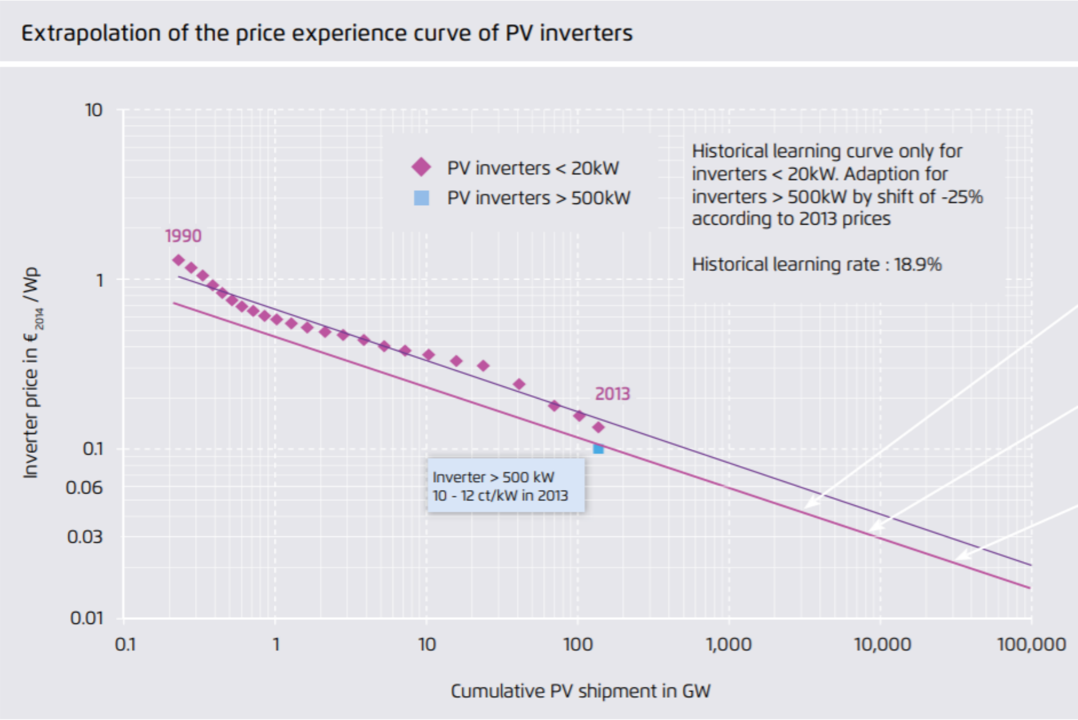
- Switching frequency (linked to the type of semiconductors used)

- Presence of voltage transformer

$$\eta_{EU} = 0.03\eta_{5\%} + 0.06\eta_{10\%} + 0.13\eta_{20\%} + \\ + 0.1\eta_{30\%} + 0.48\eta_{50\%} + 0.2\eta_{100\%}$$

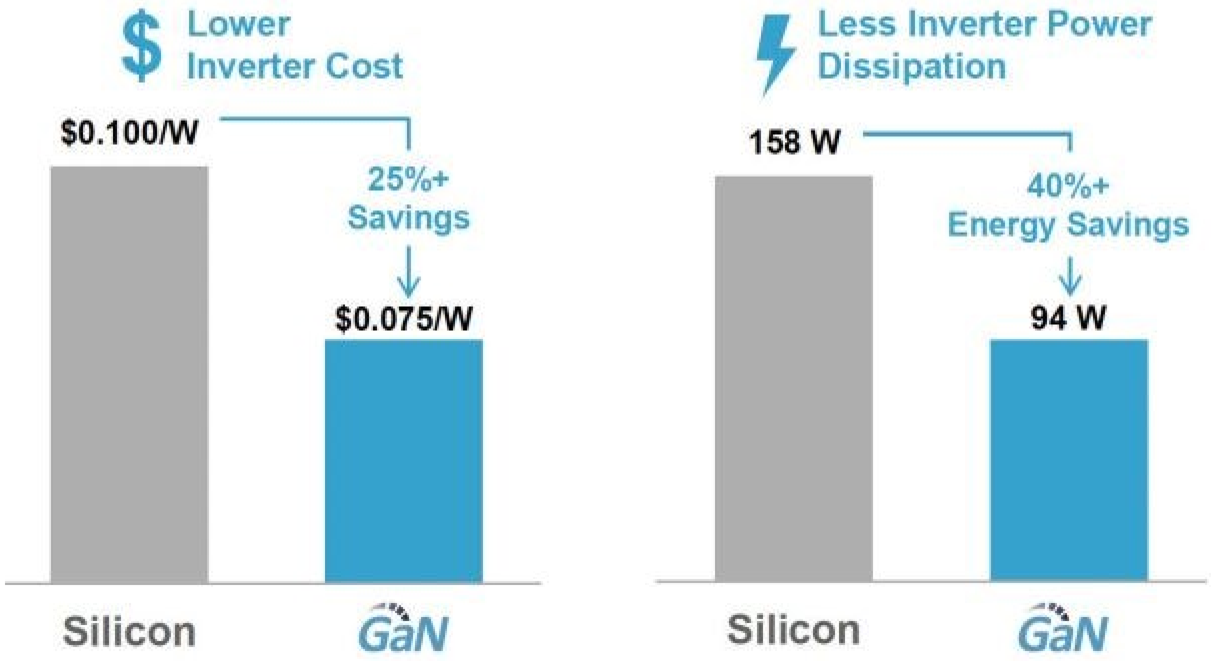
Efficiency weights performance in different operating conditions

Power electronics for PV – Cost outlook



Source: Fraunhofer ISE.

Power electronics for PV – Expected evolution



Source:
https://www.powerelectronicsnews.com/.

Conclusions

- **PV represents the largest share of renewable sources (after hydro) in electricity generation (~5% worldwide)**
- **Technology is rapidly evolving, aiming at higher efficiency and reduced costs**
- **Control through MPPT algorithms is crucial to increase energy harvesting**
- **Power electronic interfaces (with multiple topologies) are key components to enable the grid injection of produced power**

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Lecture 16: Reference material

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Z. Tang, Y. Yang and F. Blaabjerg, "Power electronics: The enabling technology for renewable energy integration," in CSEE Journal of Power and Energy Systems, vol. 8, no. 1, pp. 39-52, Jan. 2022, doi: 10.17775/CSEEJPES.2021.02850.

E. Romero-Cadaval, G. Spagnuolo, L. G. Franquelo, C. A. Ramos-Paja, T. Suntio and W. M. Xiao, "Grid-Connected Photovoltaic Generation Plants: Components and Operation," in IEEE Industrial Electronics Magazine, vol. 7, no. 3, pp. 6-20, Sept. 2013

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