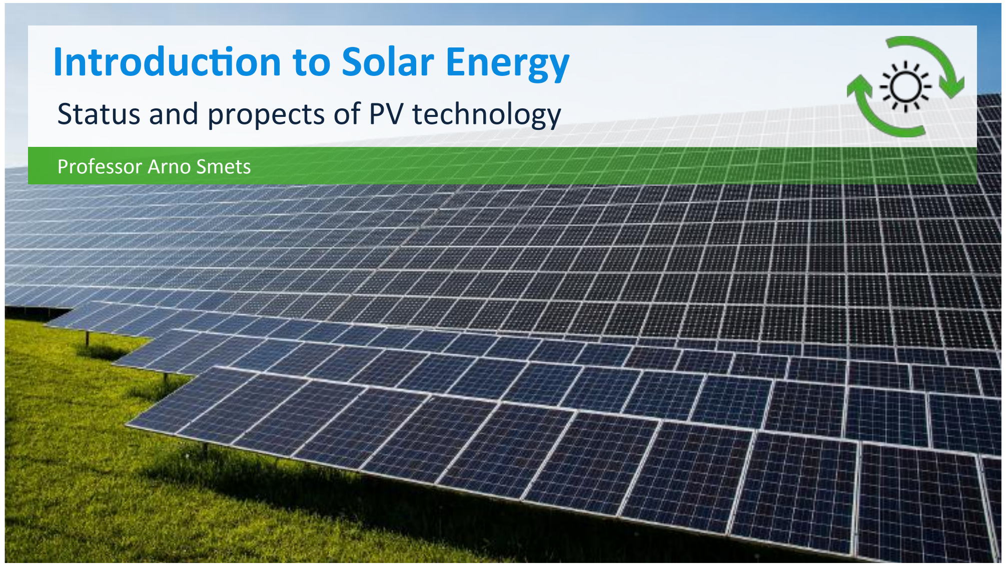
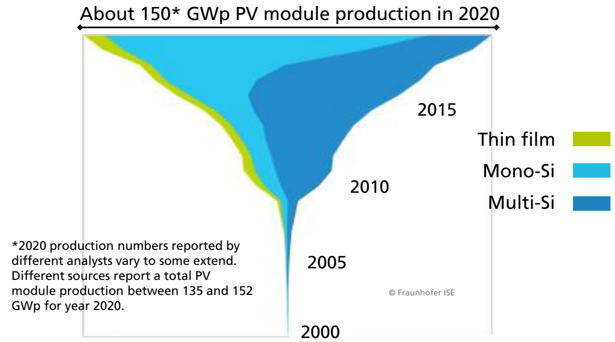
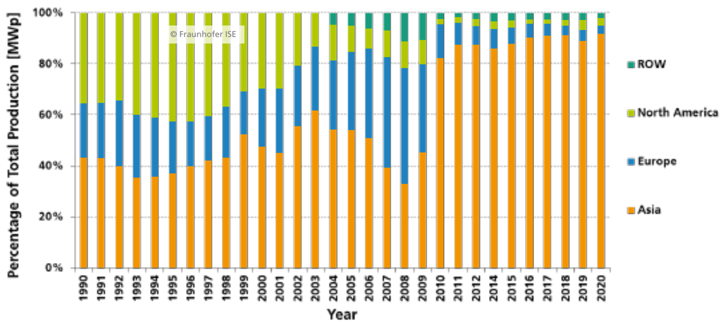


Annual PV Production by Technology
Worldwide (in GWp)



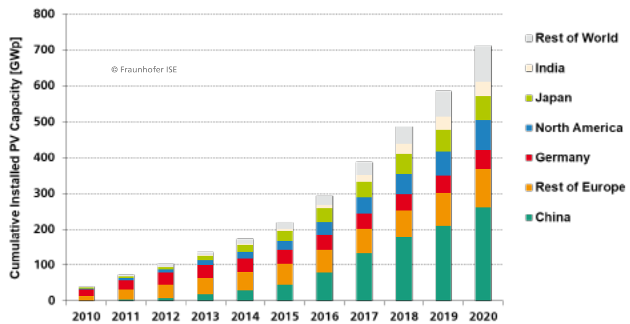
Data: from 2000 to 2009: Navigant; from 2010: IHS Markit. Graph: PSE Projects GmbH 2021

PV Module Production by Region 1990-2020
Percentage of Total MWp Produced

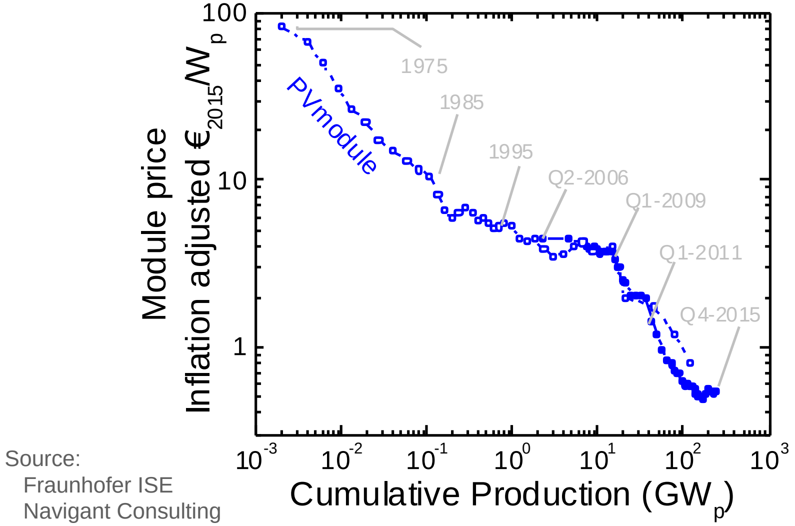


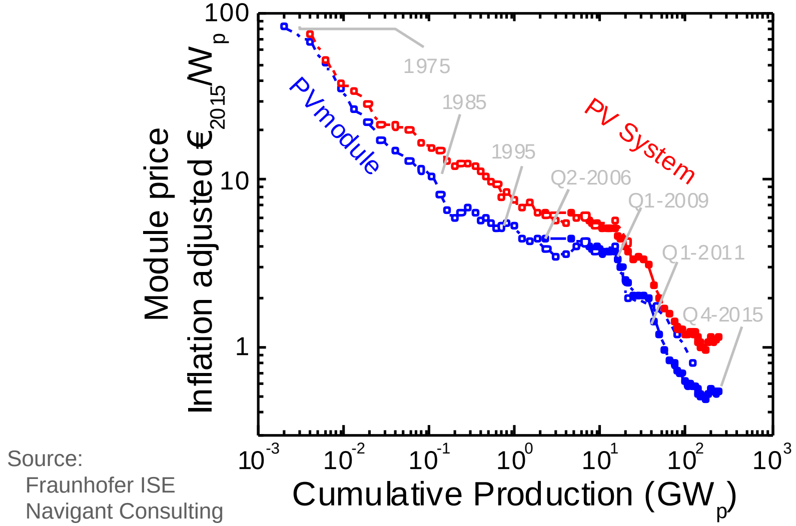
Data: Up to 2004 Strategies Unlimited; 2005 to 2009: Navigant Consulting; since 2010: IHS Markit. Graph: PSE Projects GmbH 2021

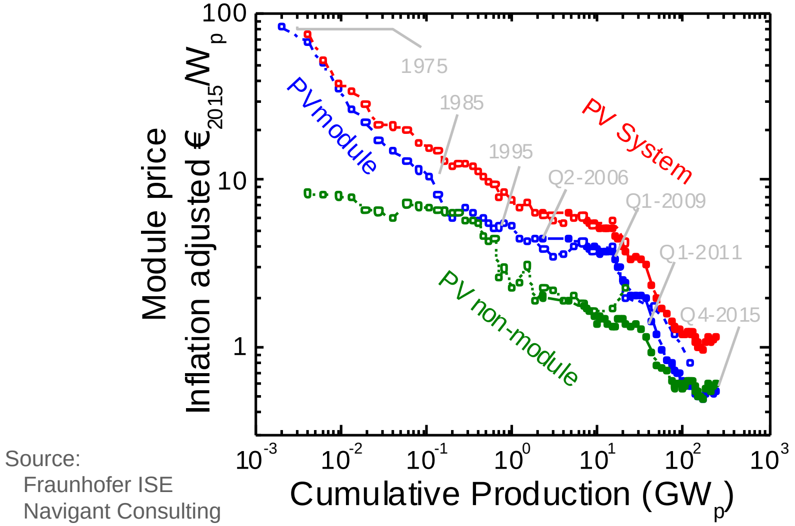
Global Cumulative PV Installation
From 2010 to 2020

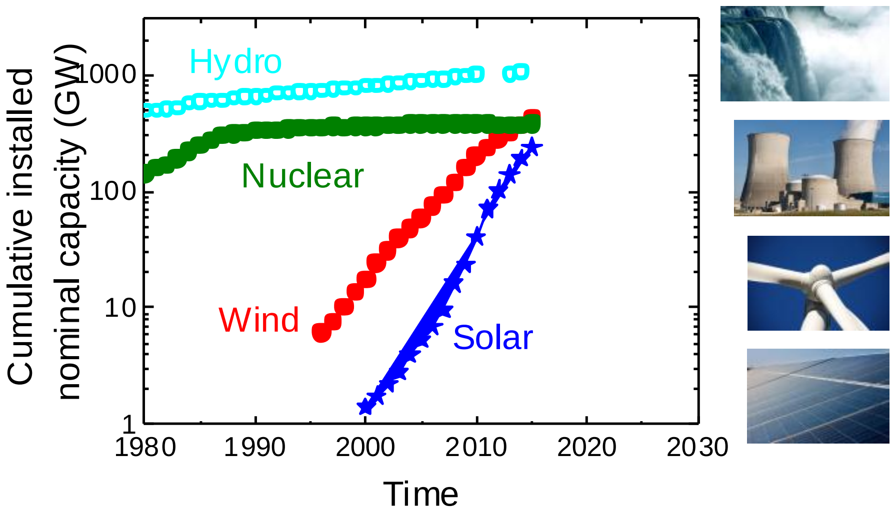


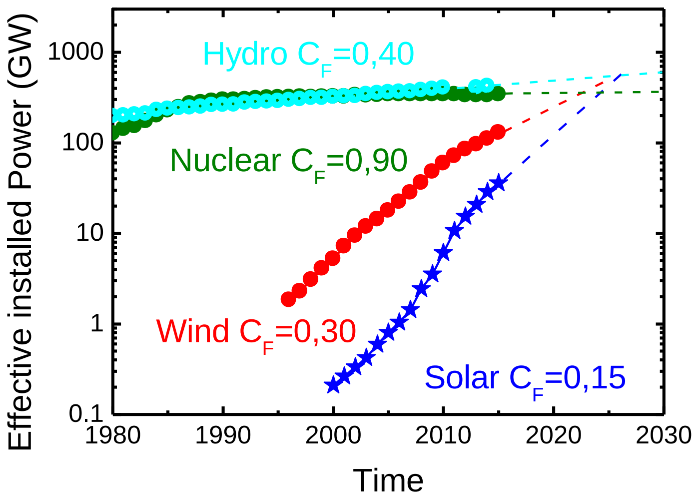
Data: IRENA 2021. Graph: PSE Projects GmbH 2021


Module price
Inflation adjusted €$_{2015}$/W$_p$
100
10
1
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
Cumulative Production (GW$_p$)
PV module
1975
1985
1995
Q2-2006
Q1-2009
Q1-2011
Q4-2015
Source:
Fraunhofer ISE
Navigant Consulting


Module price
Inflation adjusted €$_{2015}$/W$_p$
100
10
1
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
Cumulative Production (GW$_p$)
PV module
PV System
1975
1985
1995
Q2-2006
Q1-2009
Q1-2011
Q4-2015
Source:
Fraunhofer ISE
Navigant Consulting


Module price
Inflation adjusted €$_{2015}$/W$_p$
100
10
1
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
Cumulative Production (GW$_p$)
PV module
PV System
PV non-module
1975
1985
1995
Q2-2006
Q1-2009
Q1-2011
Q4-2015
Source:
Fraunhofer ISE
Navigant Consulting

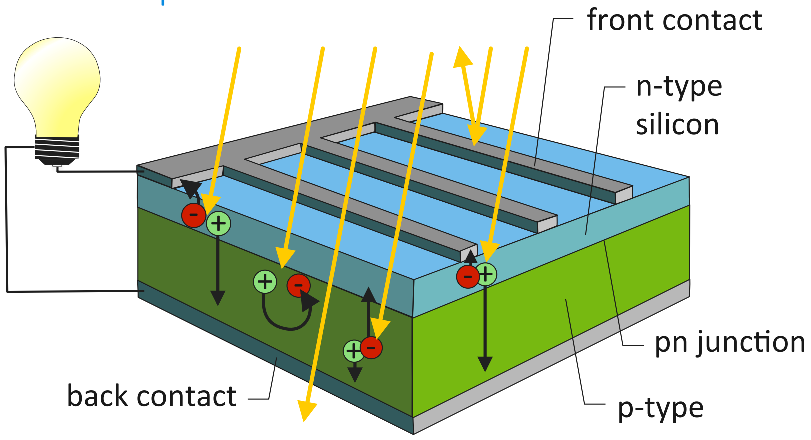

Cumulative installed
nominal capacity (GW)
1000
100
10
1
1980
1990
2000
2010
2020
2030
Time
Hydro
Nuclear
Wind
Solar

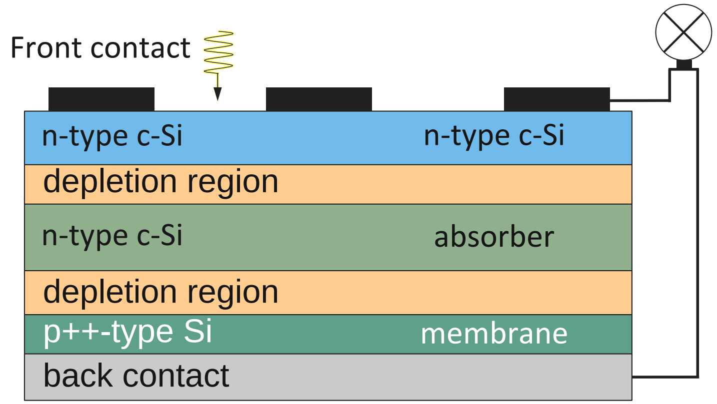


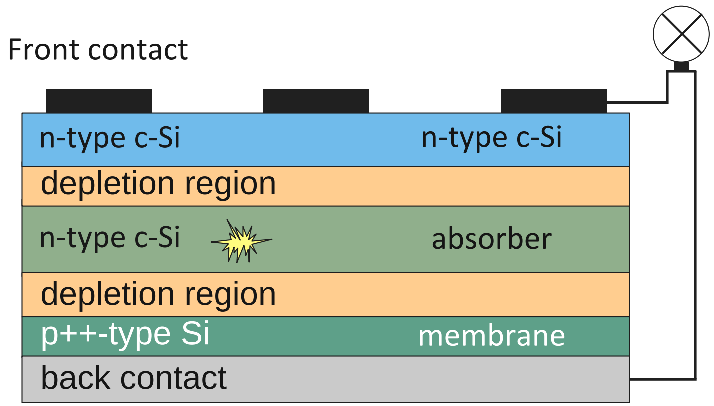
Silicon ingots

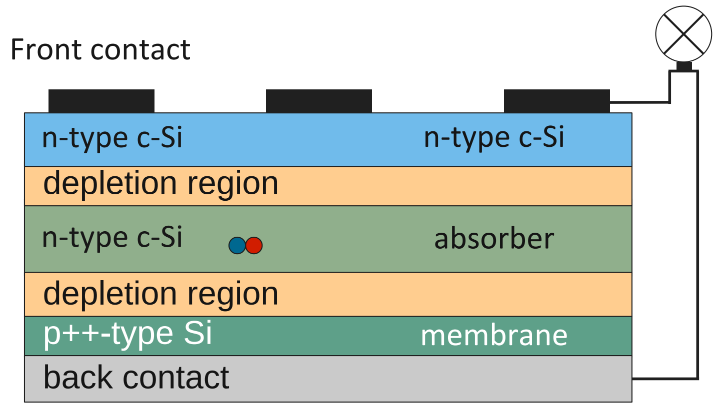
Solar Cell

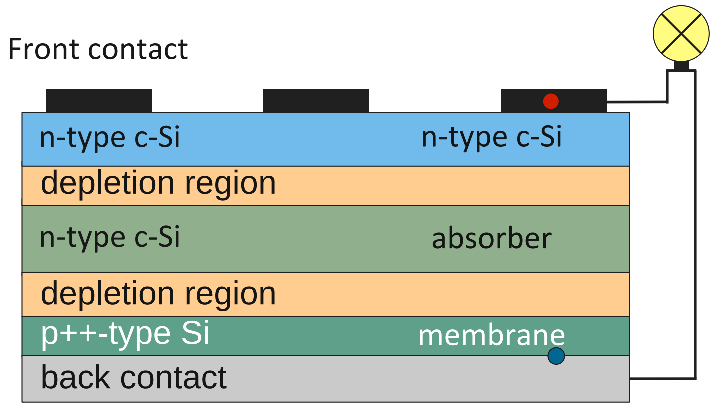
Solar cell operation



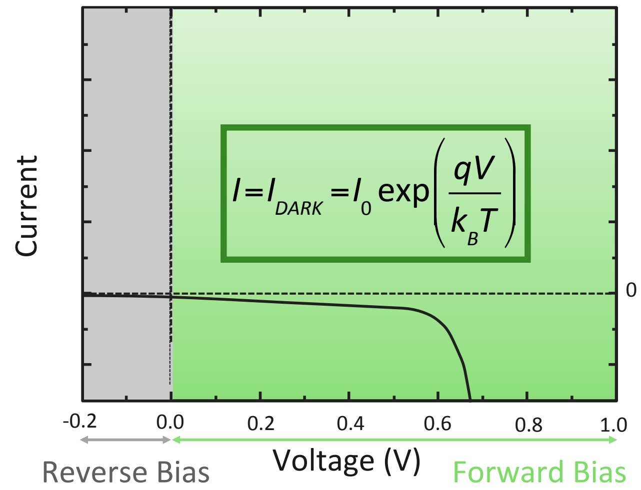




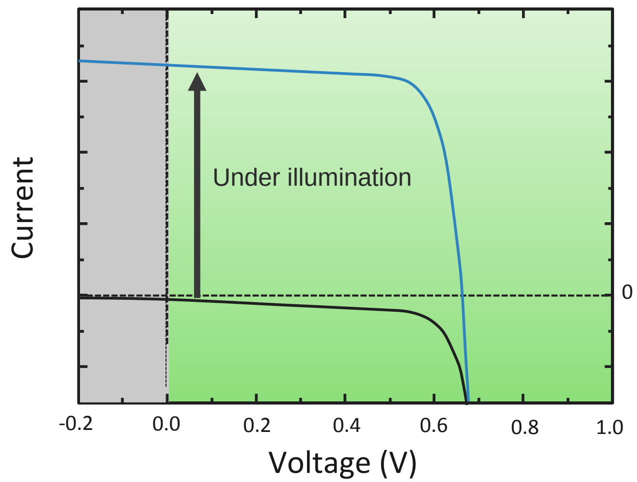




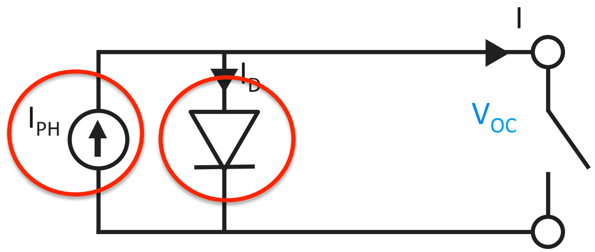
Basic IV-Curve

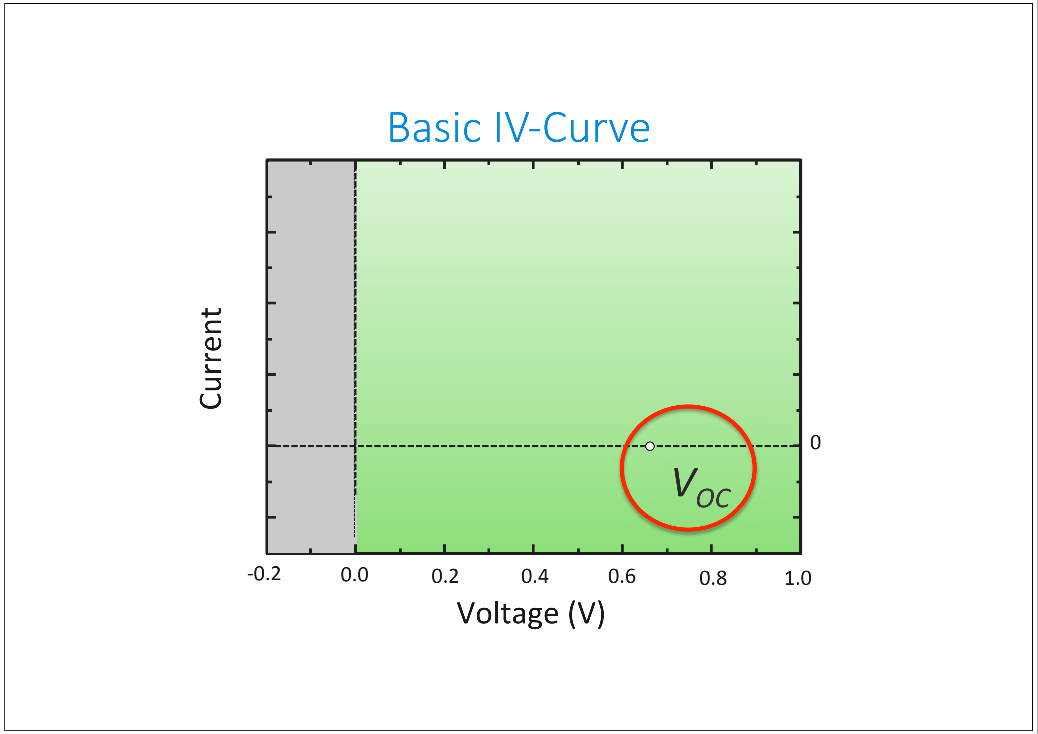


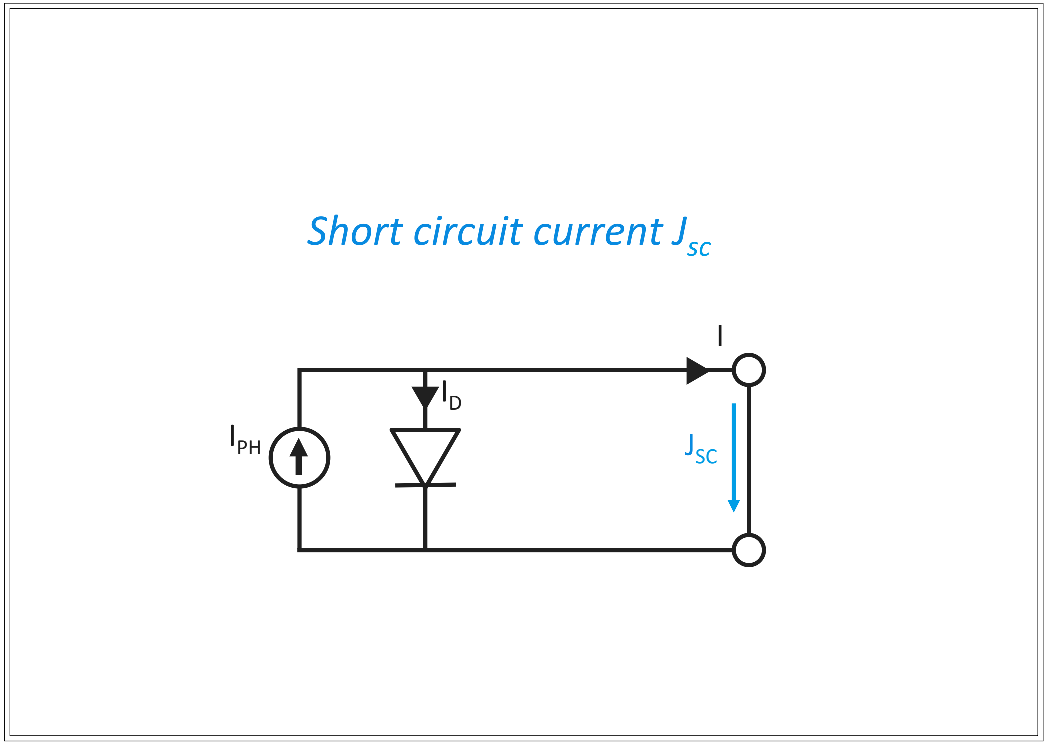
Basic IV-Curve

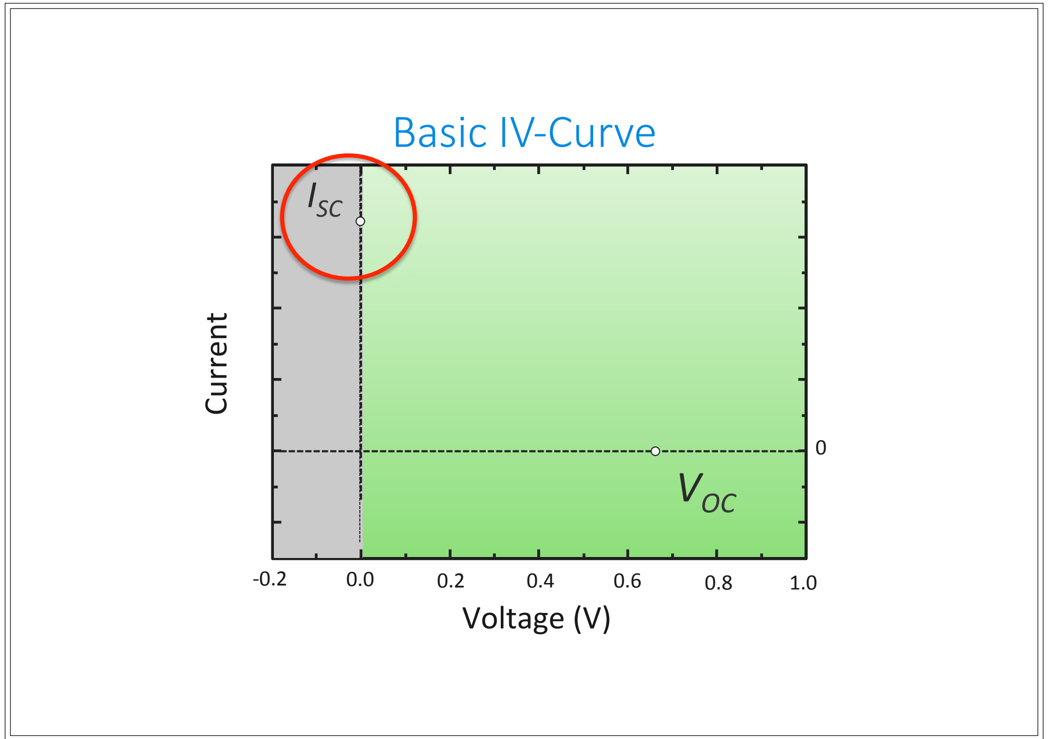


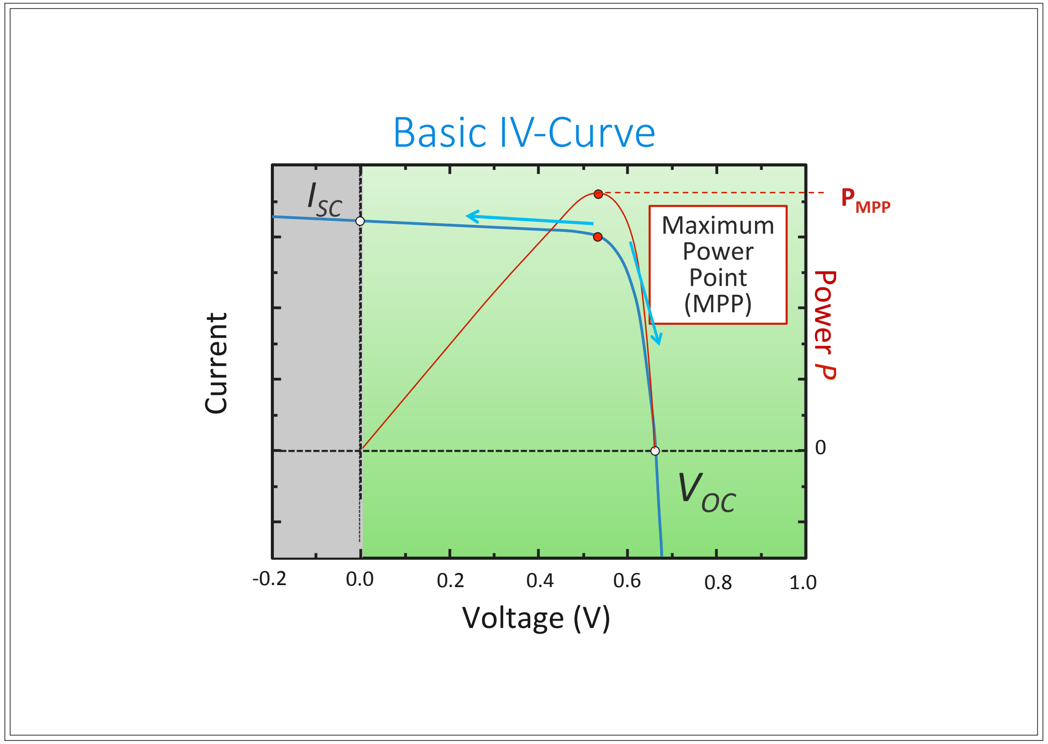
Open circuit voltage V_{OC}



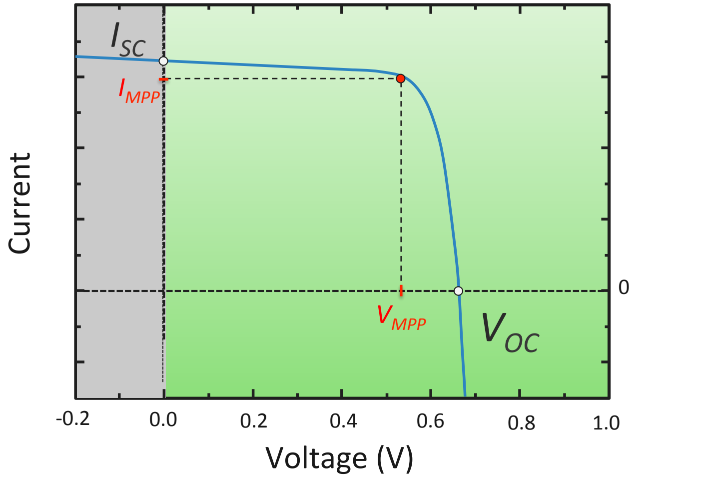

Basic IV-Curve
Current
0
V_{OC}
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
Voltage (V)


Short circuit current J_{sc}
I
I_D
I_{PH}
J_{SC}

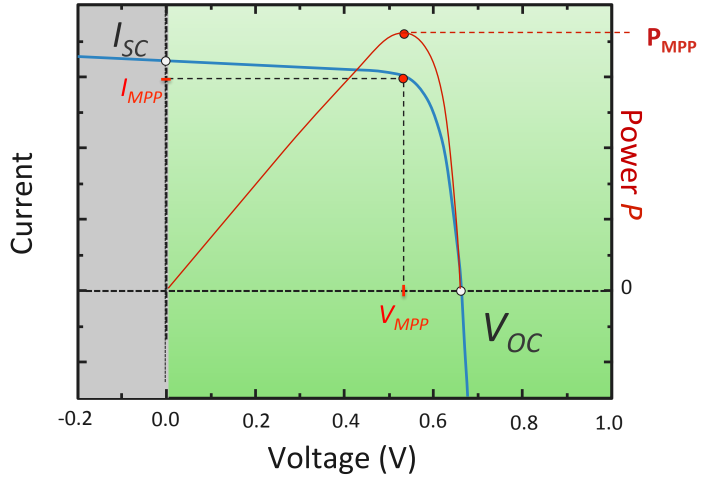

Basic IV-Curve
Current
I_{SC}
0
V_{OC}
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
Voltage (V)


Basic IV-Curve
Current
I_{SC}
P_{MPP}
Maximum Power Point (MPP)
Power P
0
V_{OC}
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
Voltage (V)

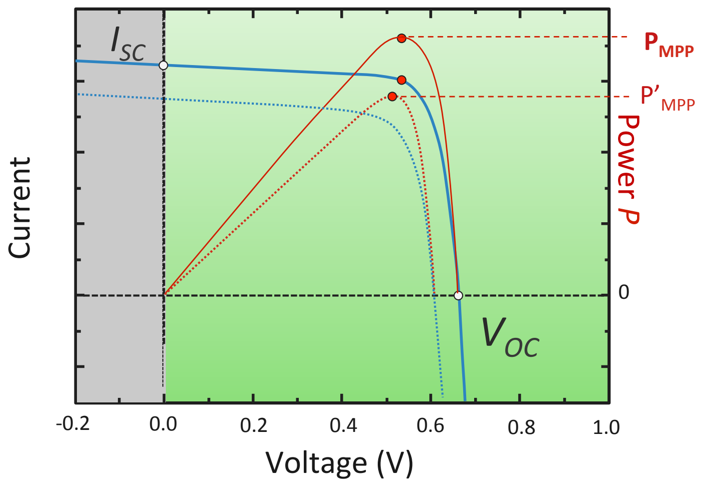
Basic IV-Curve



Basic IV-Curve

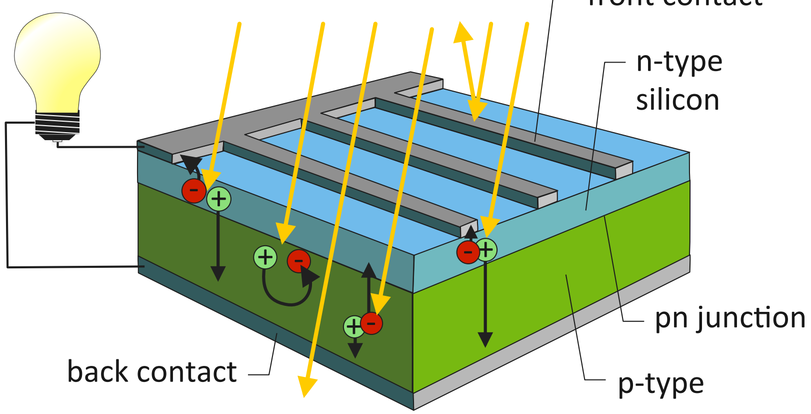


Shift of MPP



$$Efficiency = \frac{P_{mpp}}{P_{in}}$$

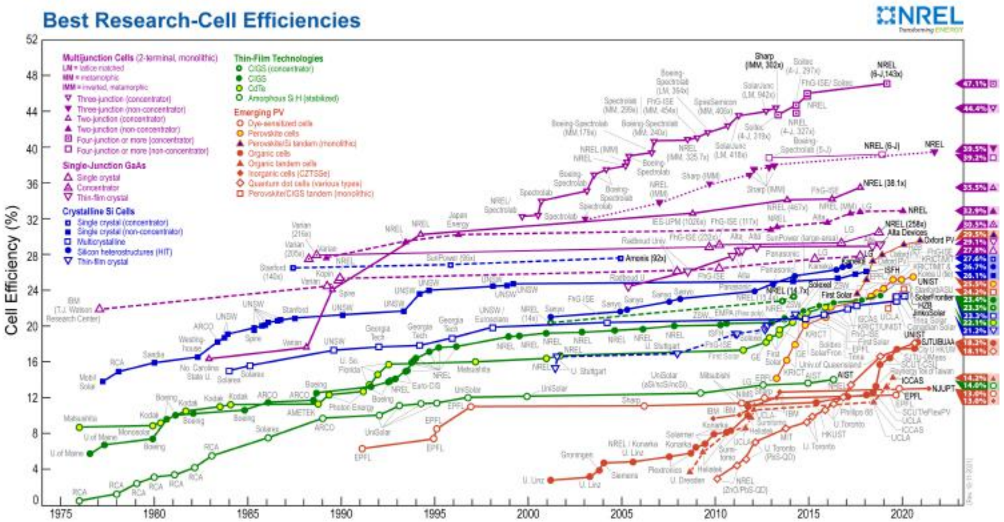
Solar cell operation



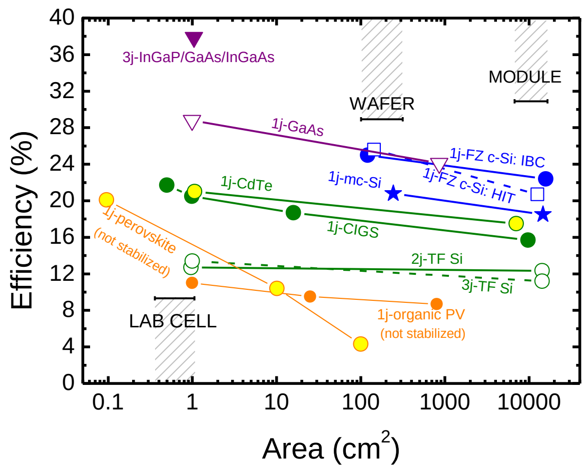
Introduction to Solar Energy

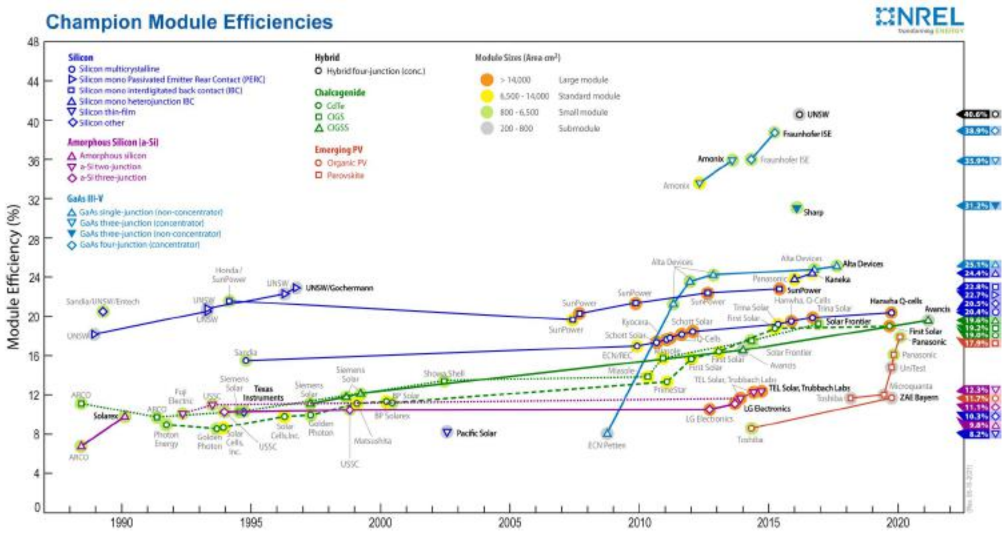
PV technologies

Professor Arno Smets



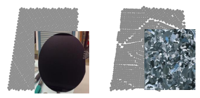
Records? Let’s scale it up….





Main PV technologies

1st generation



Poly- Mono-

Crystalline Silicon

2nd generation

CdTe CIGS

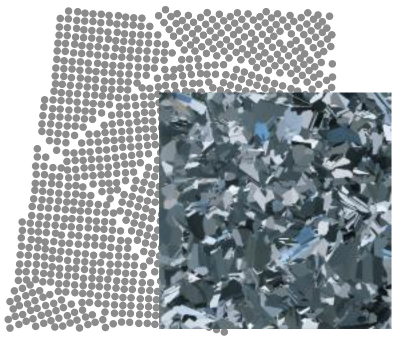
Thin film

3rd generation

Multi-junction

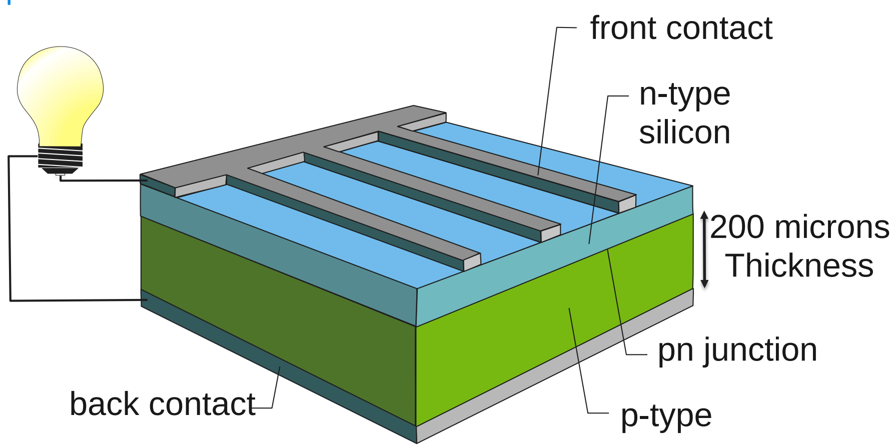
Crystalline silicon wafer-types

Monocrystalline

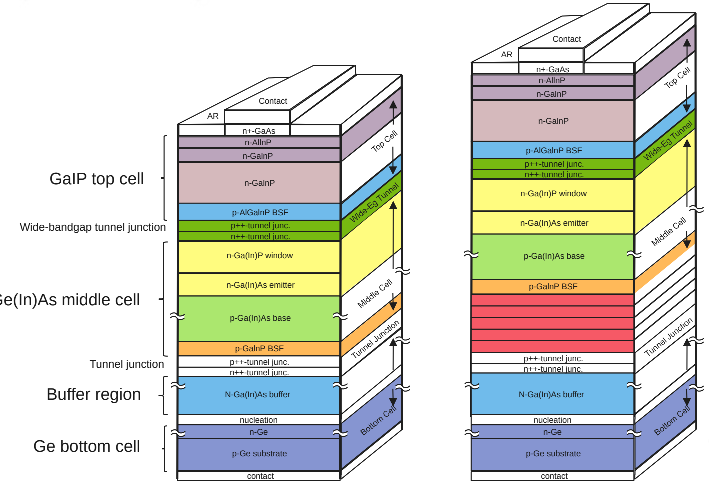


Multicrystalline

Typical silicon solar cell

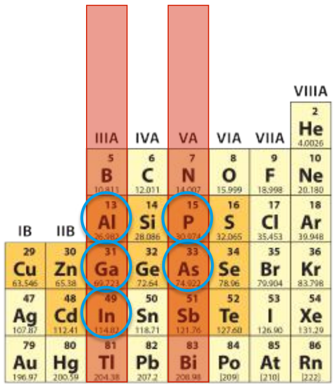


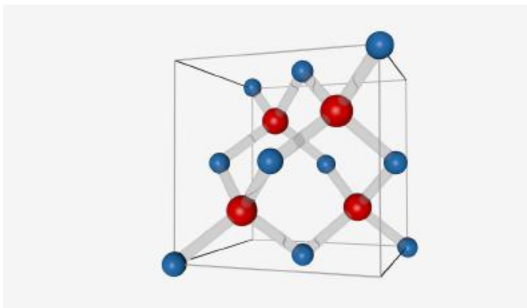
Top Efficiency Solar Cells – Multi Junction Devices



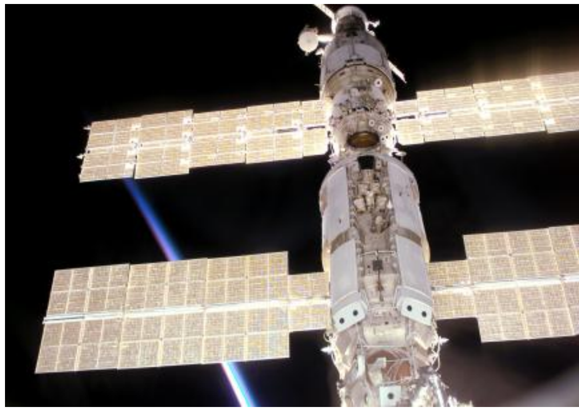
Courtesy: Richard King
Spectro Labs

III-V Semiconductor Materials



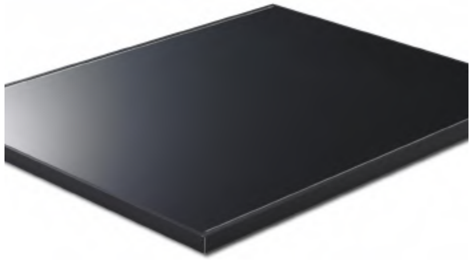


III – V PV Technology Application



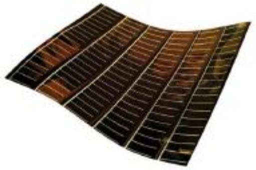
Thin Film PV modules: *glass encapsulated*

CdTe (First Solar)



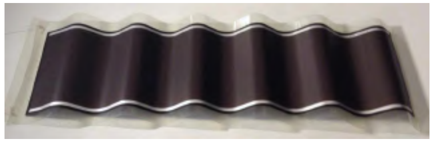
CIGS(Solar Frontier)

Thin Film PV modules: *Flexible*



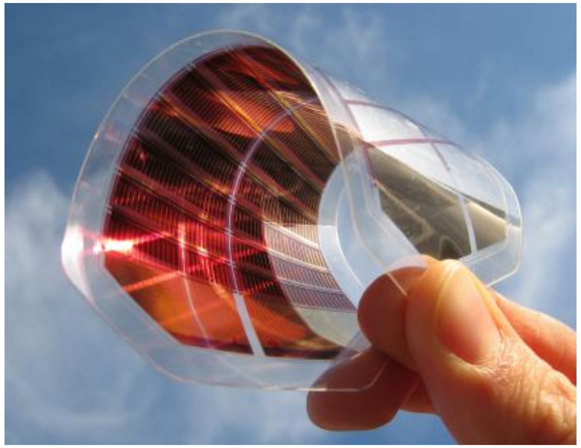
CdTe
EMPA
Switzerland

CIGS
MiaSolé

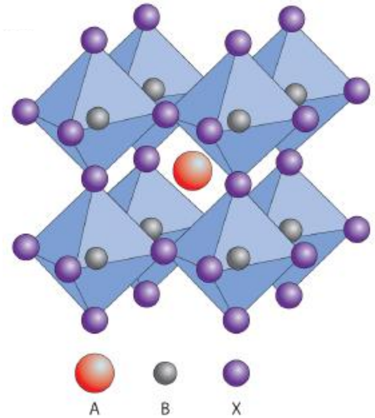


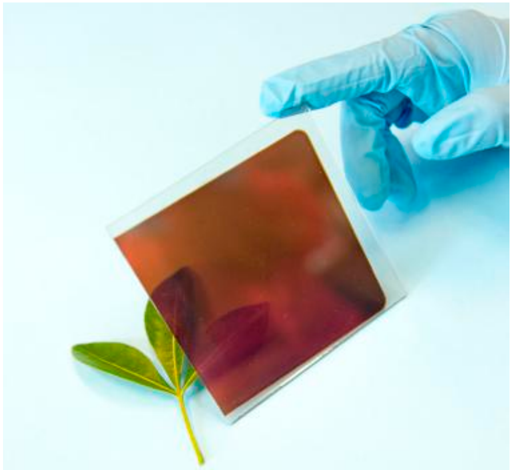
Thin-film silicon
HyET Solar

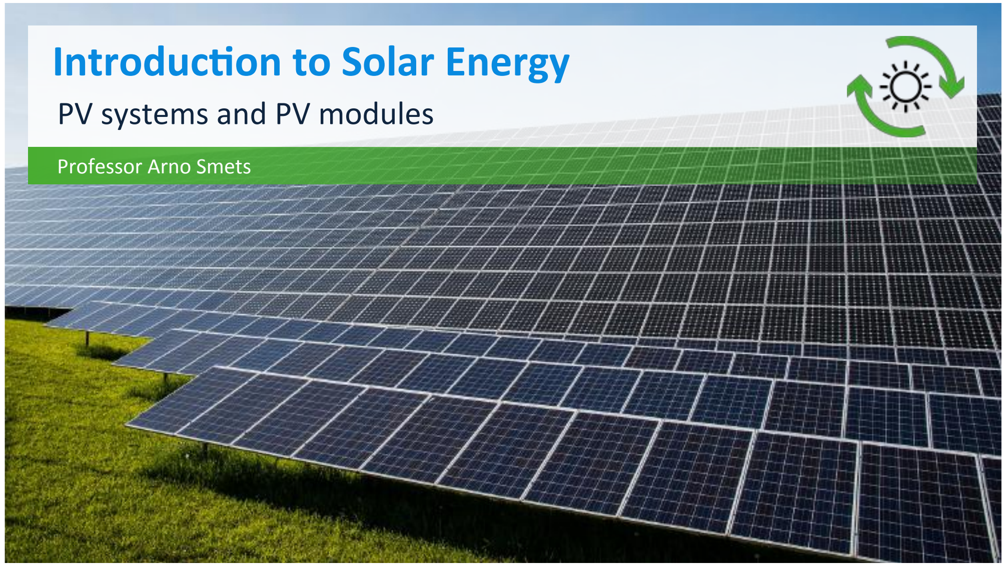
Organic Solar Cells

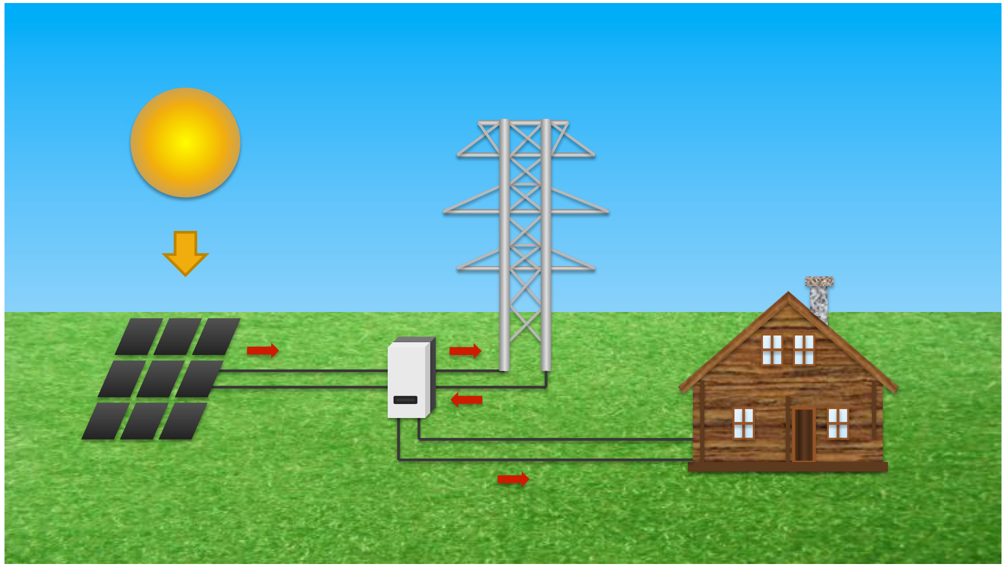


Perovskites

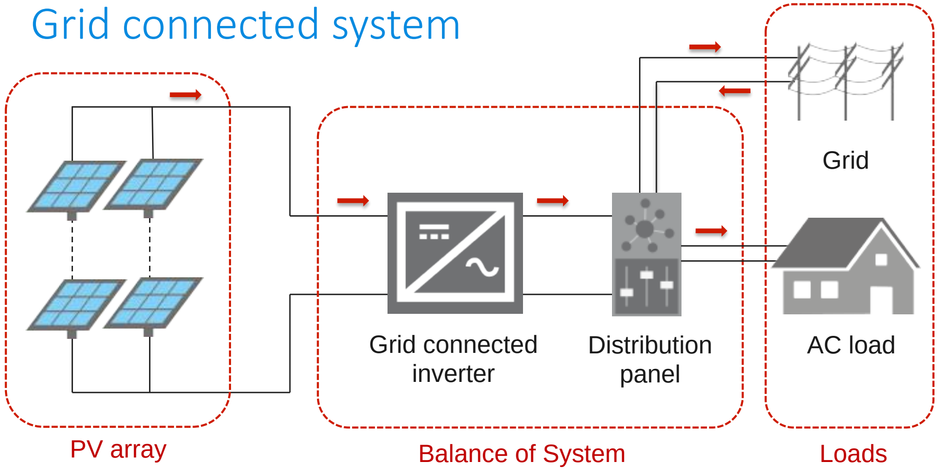








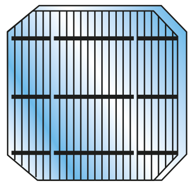
Grid connected system



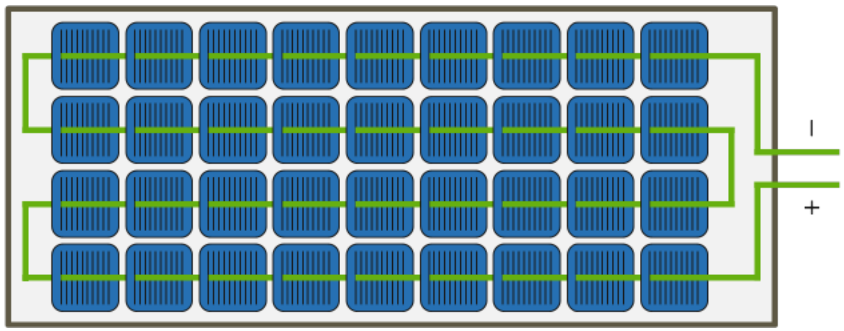
Solar Cell

PV modules

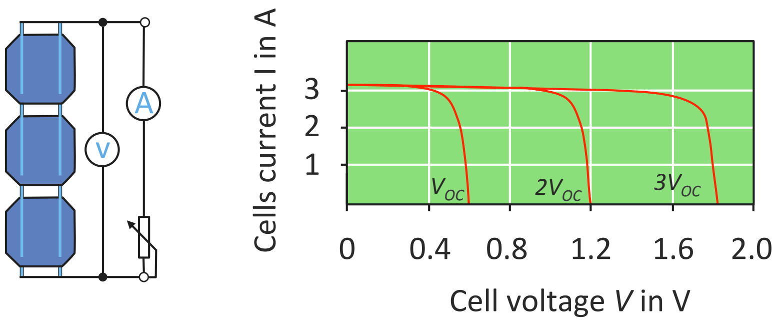
From a solar cell to
an array: 'modularity'

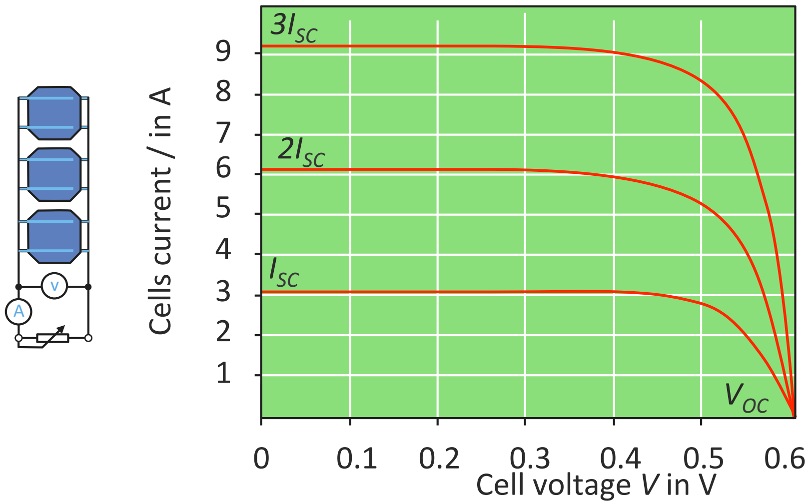


PV cell, module and array



Series connection

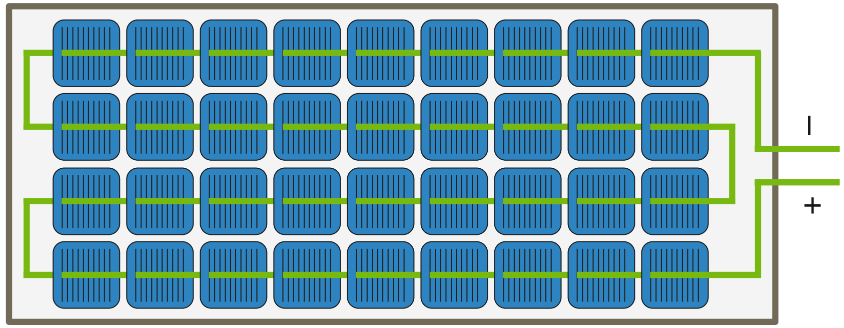




Modules

V_{OCcell} = 0.6 V
I_{SCcell} = 5 A

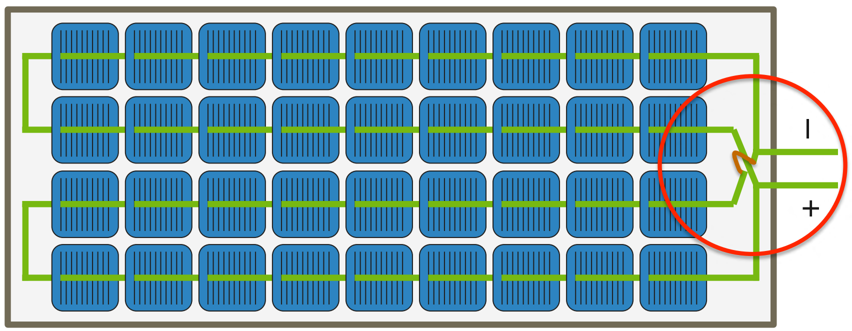
$V_{OCmodule}$ = 21.6 V
$I_{SCmodule}$ = 5 A



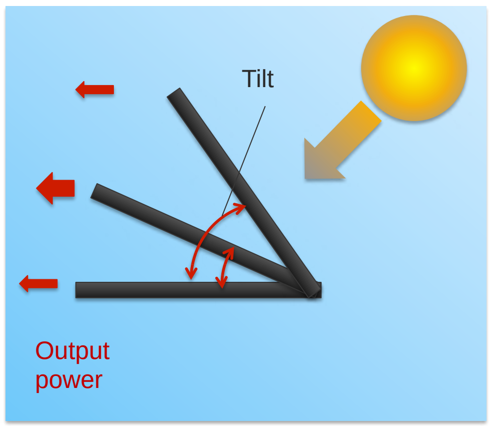
Modules

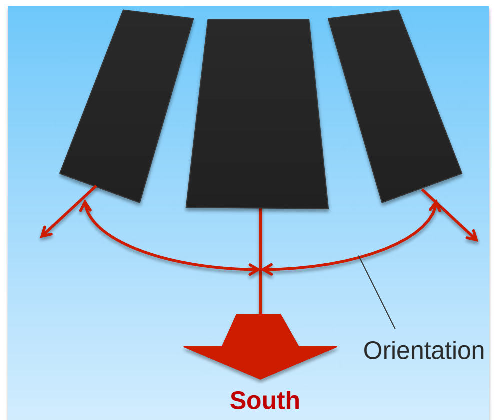
V_{OCcell} = 0.6 V
I_{SCcell} = 5 A

$V_{OCmodule}$ = 10.8 V
$I_{SCmodule}$ = 10 A

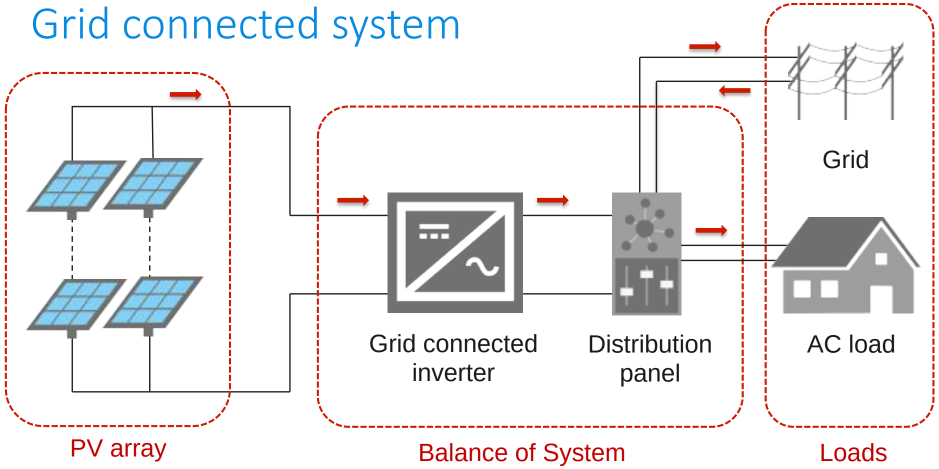


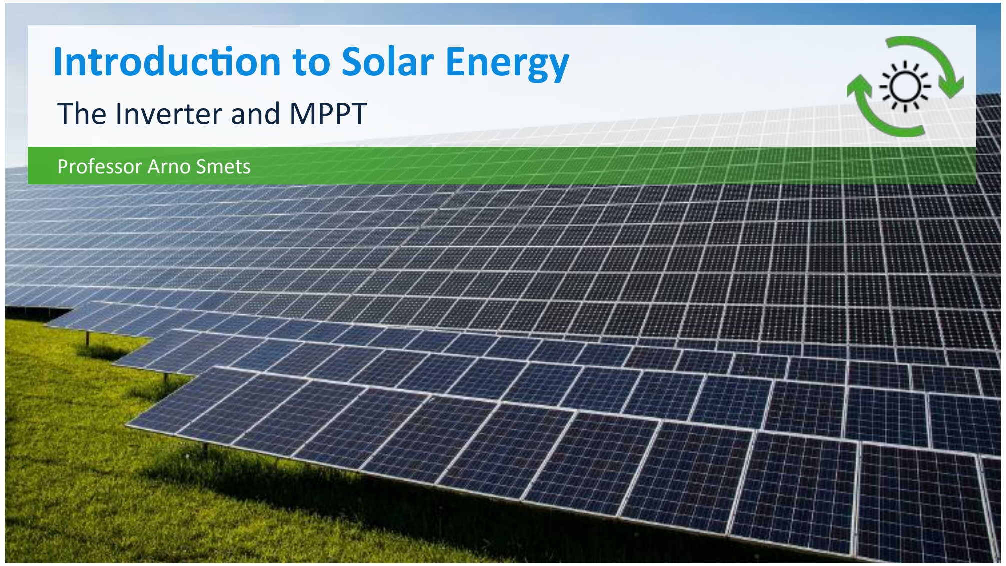
Tilt and orientation

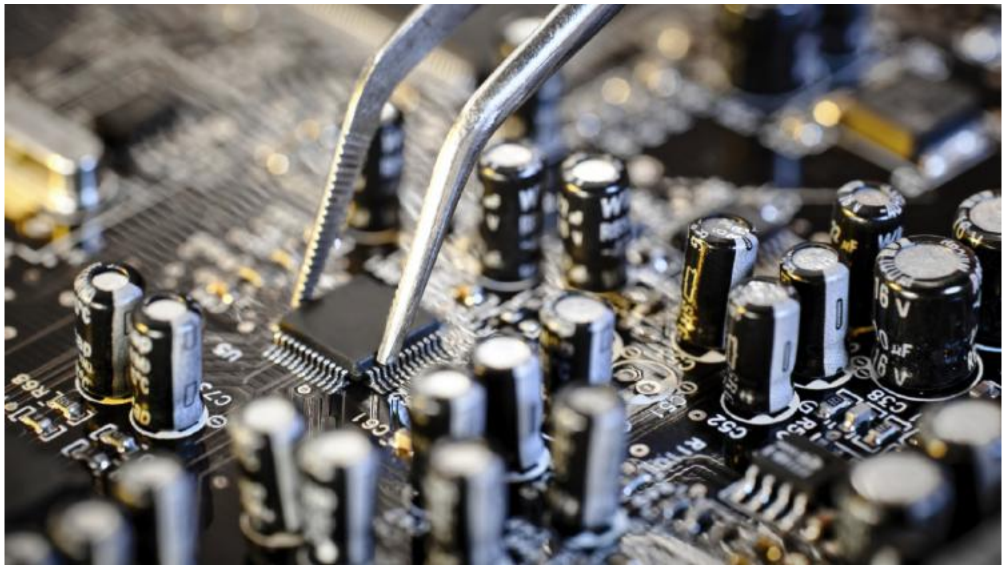




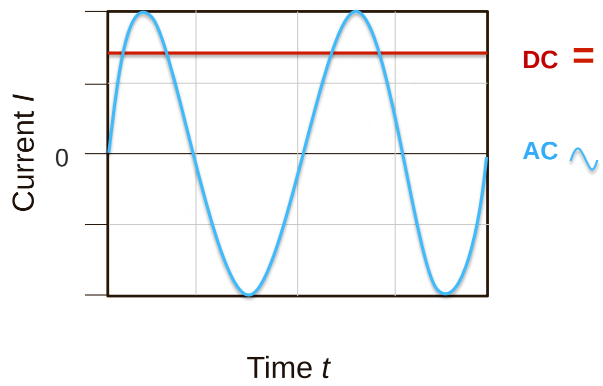
Grid connected system





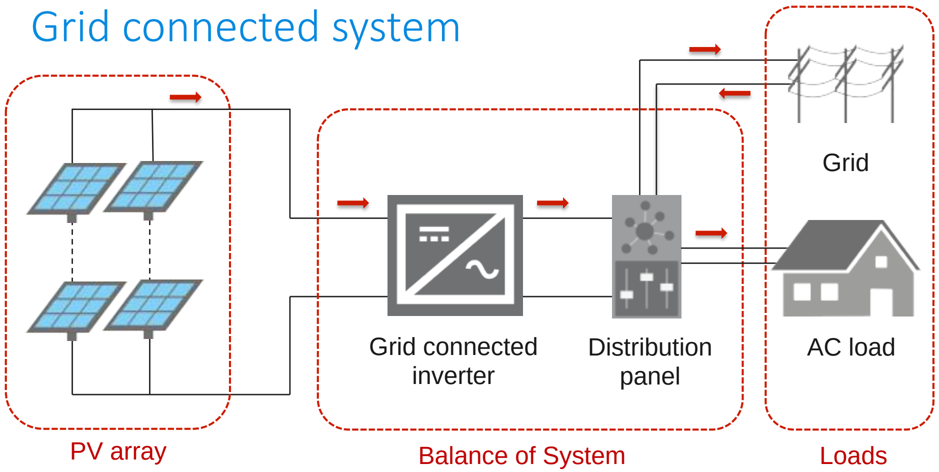


DC and AC current

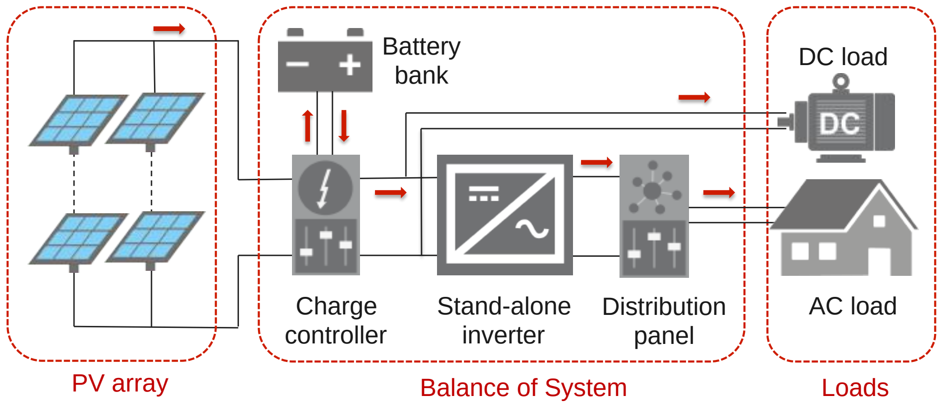


Inverter

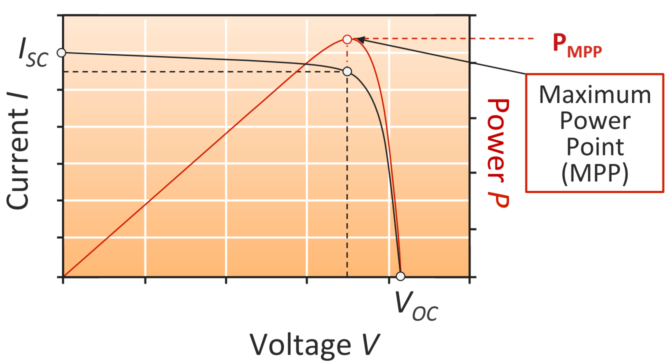
Grid connected system



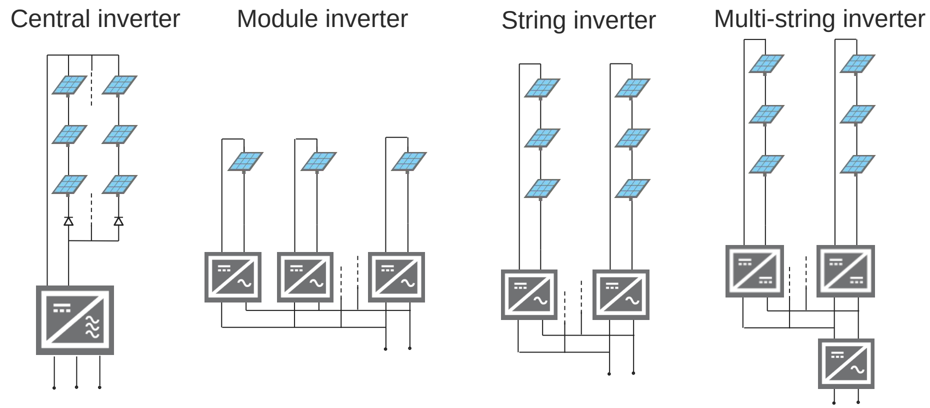
Off-grid system



Maximum Power Point Tracking



Implementation topologies



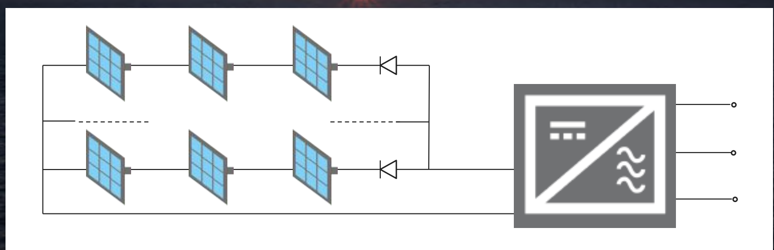
Central inverter

Pros

- Initial investment
- Maintenance
- Design and implementation

Cons

- DC wiring cost
- Shading performance loss



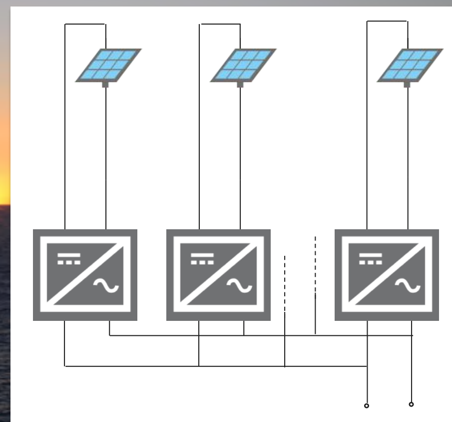
Module inverter

Pros

- Performance loss mitigation
- DC wiring cost
- Design

Cons

- Initial investment
- Maintenance



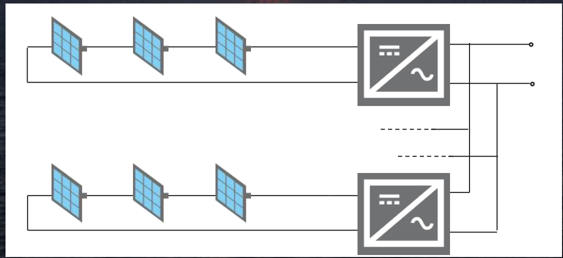
String inverter

Pros

- Performance loss mitigation

Cons

- Design and Implementation
- Initial investment
- Maintenance



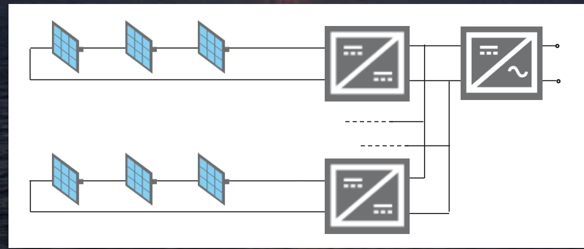
Multi-string inverter

Pros

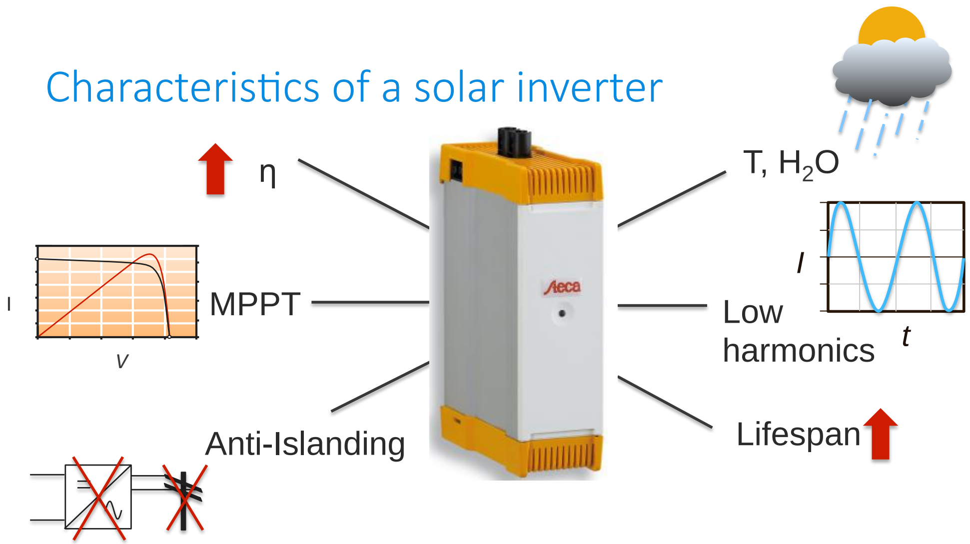
- Performance loss mitigation
- Initial investment

Cons

- Design and Implementation
- Maintenance



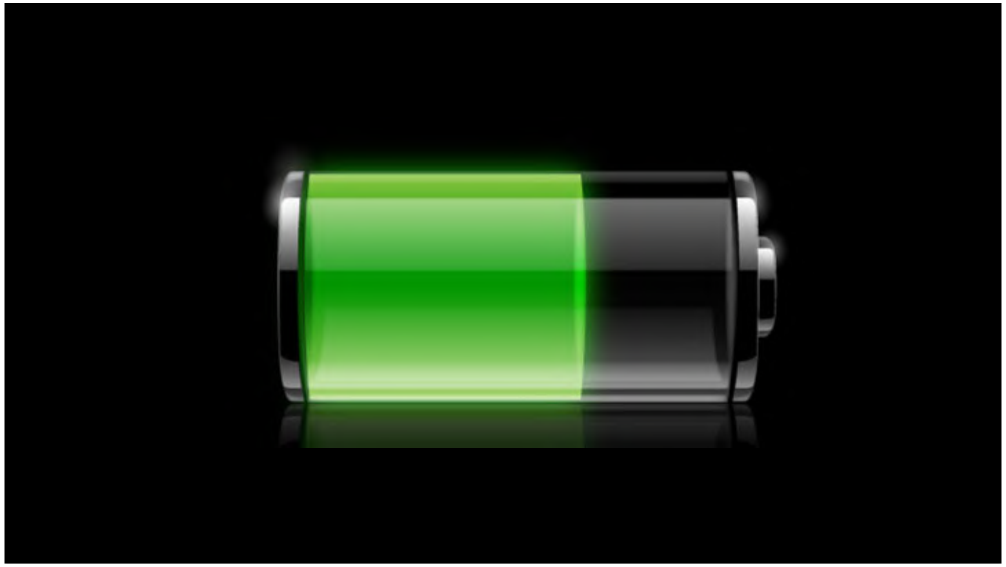
Characteristics of a solar inverter



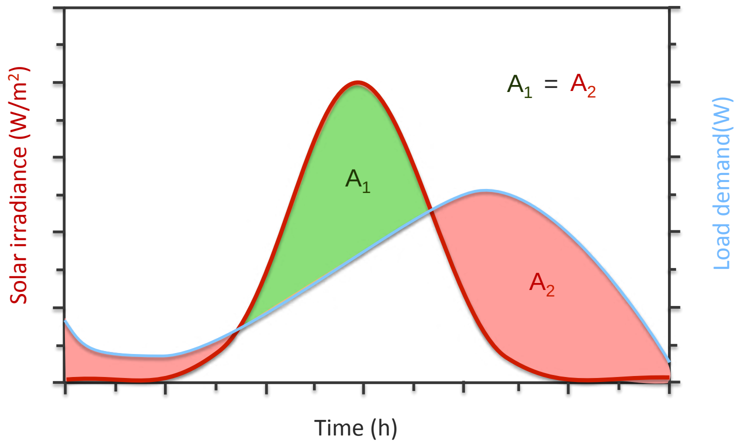
Introduction to Solar Energy

Batteries

Professor Arno Smets



Solar irradiance and demand profile



Types of batteries

Zinc carbon
Alkaline

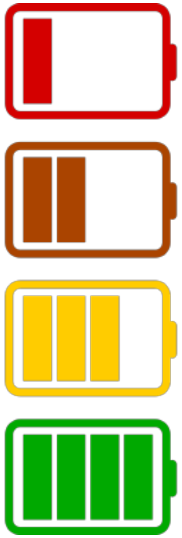
Primary

Lead Acid
Lithium ion

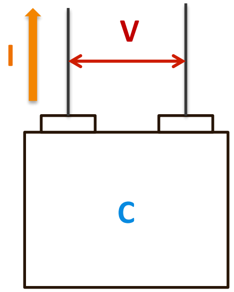
Secondary

Secondary batteries

Lead acid batteries	Lithium-ion batteries
	



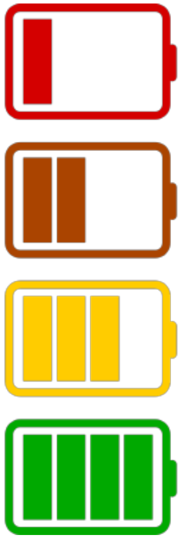
Battery characteristics



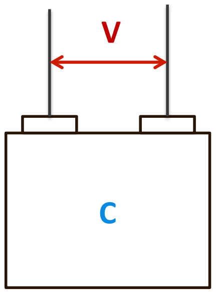
Rated voltage: 12V, 24V, 48V

Rated capacity: Ah, mAh

Rated current: A, mA

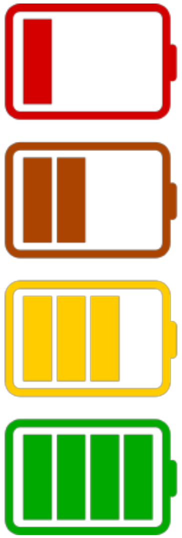


Battery characteristics

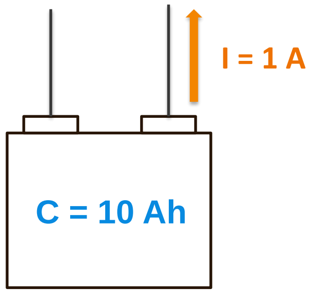


$$E_{battery} = C_{battery} \cdot V$$

$$[Wh] = [Ah] \cdot [V]$$

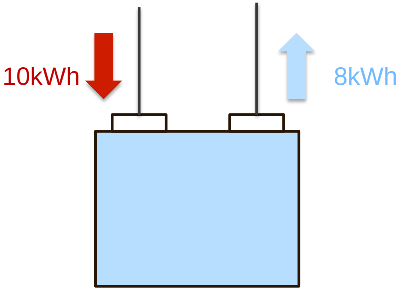


Significance of Amp hours



$$\frac{10\ Ah}{1\ A} = 10\ h$$

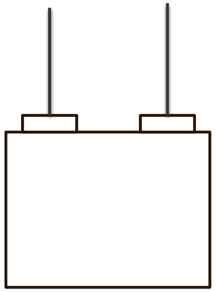
Efficiency of storage



$$\eta = \frac{E_{out}}{E_{in}} \cdot 100$$

$$\eta = \frac{8\ kWh}{10\ kWh} \cdot 100 = 80\%$$

Battery efficiency

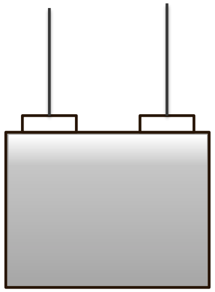


$$\eta_V = \frac{V_{discharge}}{V_{charge}} \cdot 100$$

$$\eta_C = \frac{Q_{discharge}}{Q_{charge}} \cdot 100$$

$$\eta_{batt} = \eta_V \cdot \eta_C = \frac{V_{discharge} \cdot Q_{discharge}}{V_{charge} Q_{charge}} \cdot 100$$

SOC and DOD

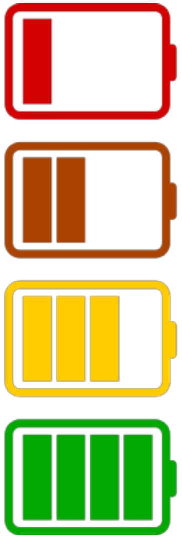


$$SOC = \frac{E_{battery}}{C_{battery} \cdot V}$$

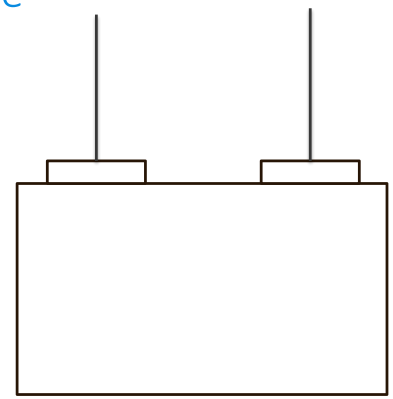
$$10\ Ah\ - 2\ Ah = 8\ Ah \longrightarrow SOC = 80\%$$

$$\longrightarrow DOD = 20\%$$

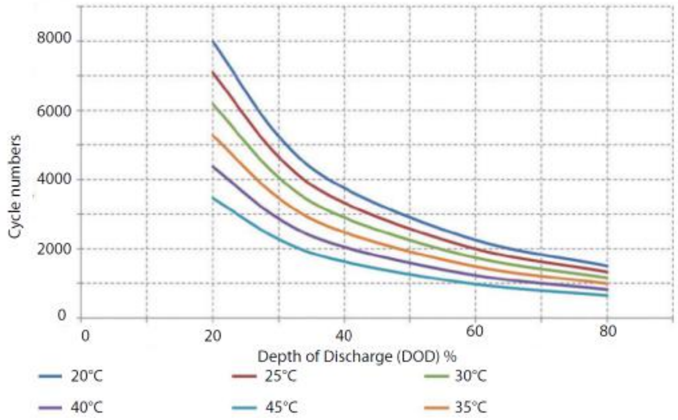
$$DOD = \frac{C_{battery} \cdot V - E_{battery}}{C_{battery} \cdot V}$$

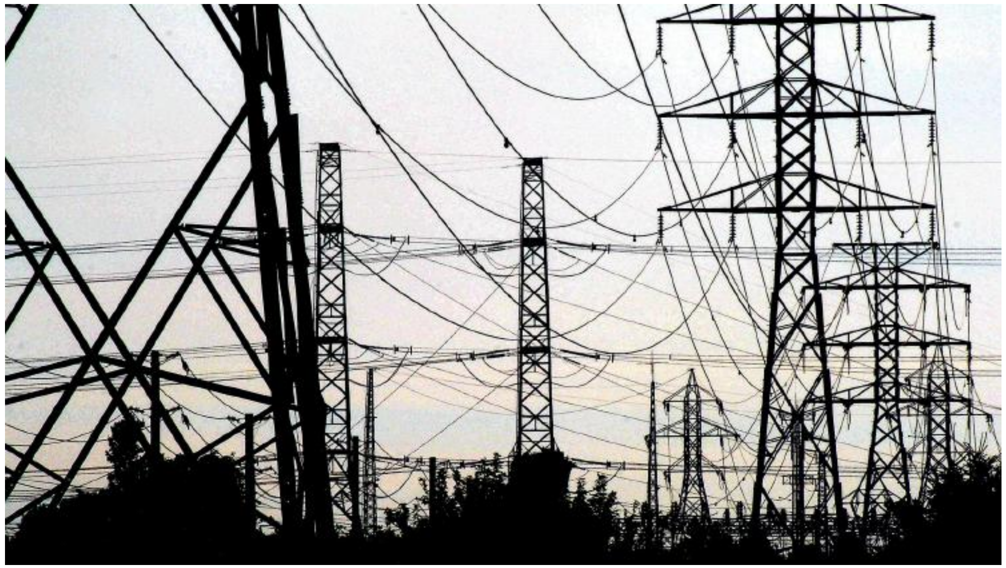


Cycle life

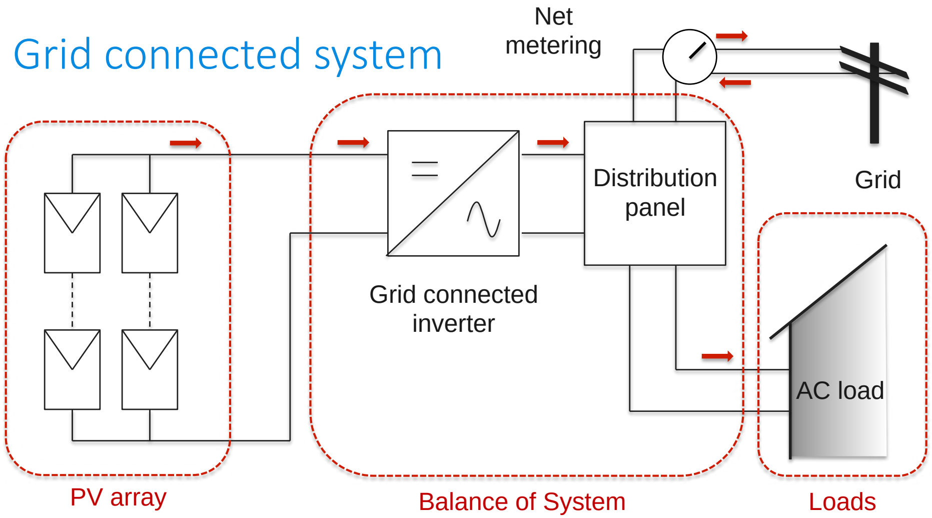


Cycle life vs. DOD

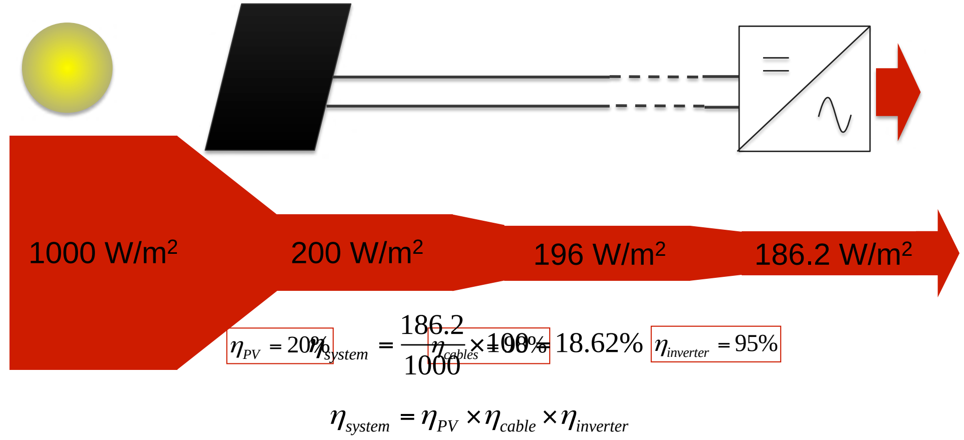




Grid connected system



Grid connected system



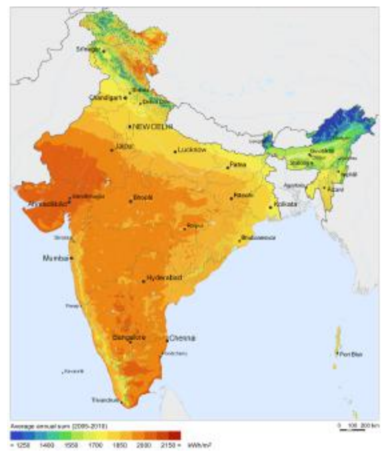
Sizing Example – Load

Item	Quantity	Power per item (W)	Total power (W)	Time of use (h)	Total energy (Wh)
Light	4	25	100	4	400
TV	1	100	100	5	500
Desktop	1	100	100	9	900
TOTAL			**300**		**1800**

Sizing example - Irradiation

Equivalent sun hours

~4.5 h/day



Sizing example – PV panels

Panel specifications	
Power output (Wp)	240
V_{MPP} (V)	48
I_{MPP} (A)	5
V_{OC} (V)	60
I_{SC} (A)	6

?

Sizing example – PV panels

MPPT

Total energy demand

$$Minimum\ W_p = 1800\,Wh / 4.5\,h/day \times 1.2 = 480\,W$$

Equivalent sun hours

Account for System losses

$$Number\ of\ Panels = 480\,W / 240\,W_p = 2\ panels$$

Sizing example – Grid connection

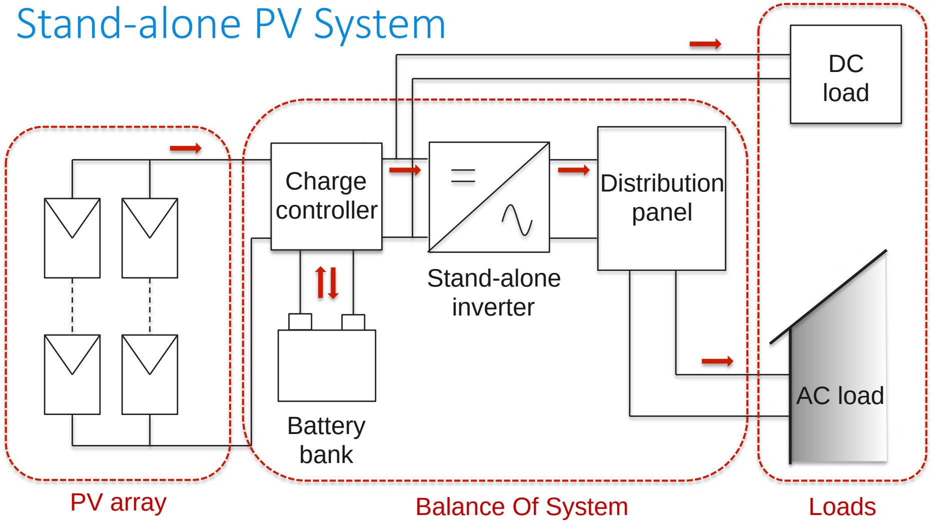
Sizing example - Inverter

$$Minimum\ Nominal\ Power\ Rating = 480\,W \times 1.2 = 576\,W$$

Total power from the panels

Safety margin

Stand-alone PV System



Sizing example – Charge controller

Steca Solarix MPPT Charge Controller

Short circuit current

Parallel

$$Maximum\ current = 6A \times 2 = 12A$$

Series

$$Maximum\ Voltage = 60V \times 2 = 120V$$

Open circuit voltage

Sizing example – Charge controller

Steca Solarix MPPT Charge Controller

Charge controller specifications	
Maximum voltage (V)	140
Maximum current (A)	10
Operational voltage	12V/24V
MPPT	Yes

< Max I

Operational Voltage

Panels in Series

Sizing example – Battery sizing

Batteries : Hoppeke

Battery specifications	
Depth of discharge	60%
Battery voltage (V)	12
Battery capacity (Ah)	100

?

Sizing example – Battery sizing


Batteries: Hoppeke

$$Minimum\ C_{batt} = \frac{1800Wh}{0.6 \times 24V} \times 1.2 \times 2 = 300Ah$$

Total energy demand
Days of autonomy
Depth of discharge
Operational voltage of the system
Account for System losses

$$Number\ of\ batteries\ in\ series = \frac{24V}{12V} = 2\ batteries$$

$$Number\ of\ batteries\ in\ parallel = 300Ah/100Ah = 3\ batteries$$

$$Number\ of\ batteries = 3 \times 2 = 6\ batteries$$

Sizing example - Inverter

Inverter specifications	
Efficiency	96%
Operational voltage	12V/24V

?

Sizing example - Inverter

Inverter specifications	
Efficiency	96%
Operational voltage	12V/24V

Total power demand

$$\text{Minimum Nominal Power Rating} = \frac{300W}{0.96} = 312.5W$$

Inverter efficiency

Introduction to Solar Energy

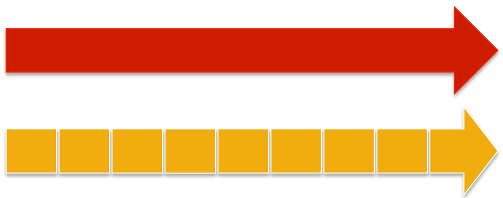
Policy and Price

Professor Arno Smets

Payback period

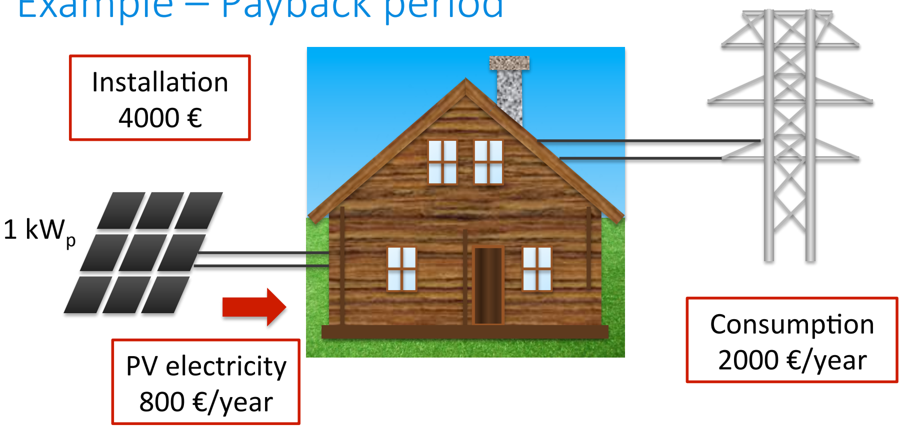
Investment cost

Returns



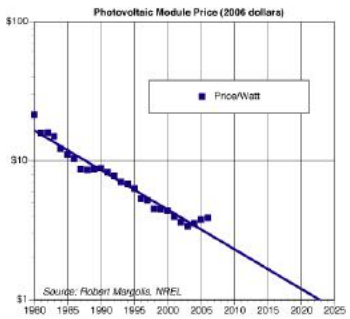
$$\text{Payback period} = \frac{\text{Investment cost}}{\text{Returns/year}}$$

Example – Payback period

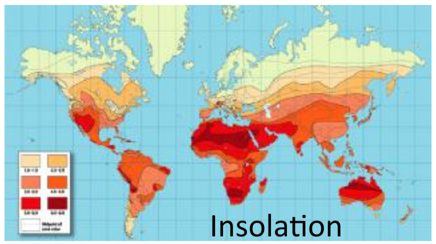


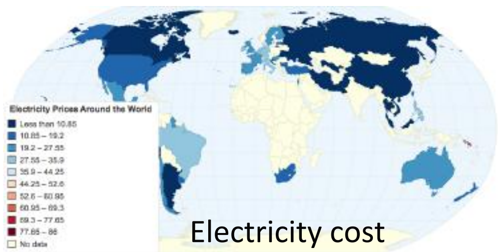
Example – Payback period

Location dependency

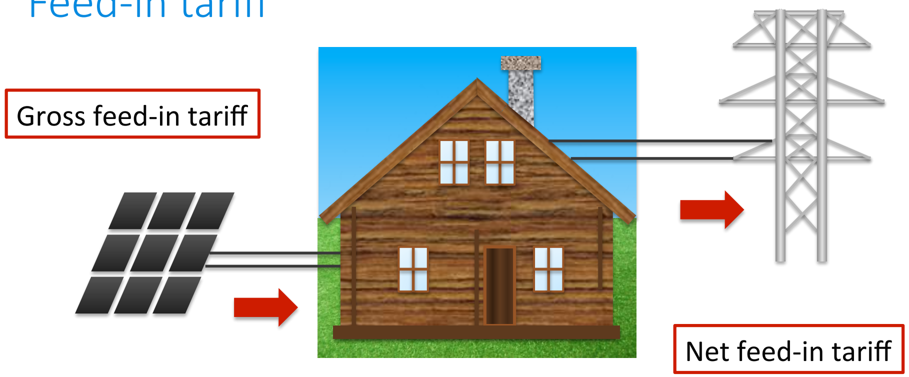


PV system cost

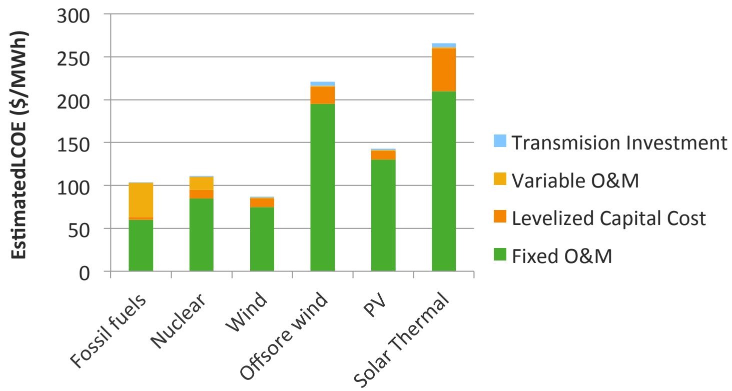




Feed-in tariff



Levelized cost of electricity (LCOE)



Energy Information Administration

Levelized cost of electricity (LCOE)

$$LCOE = \frac{I_0 + \sum_{t=1}^{N} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1+i)^t}}$$

A_t = Total annual cost in year t

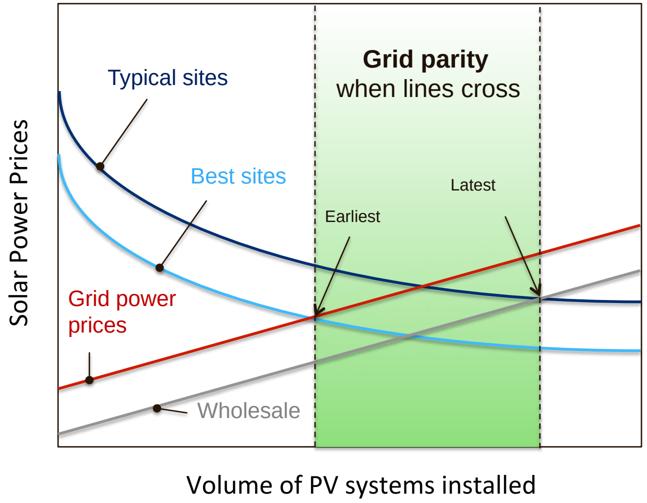
I_0 = Initial investment

E_t = Annual energy yield

i = Discount rate

Grid parity

Grid parity



Practical Handbook of Photovoltaics