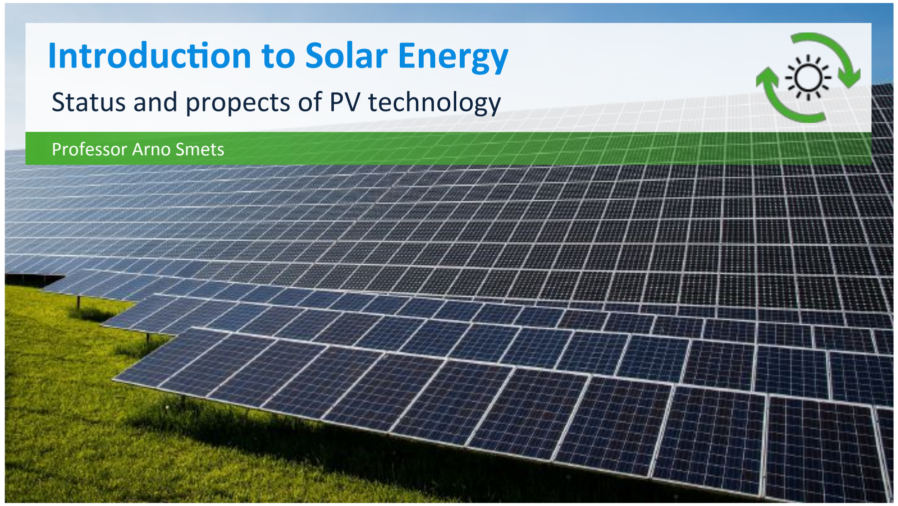
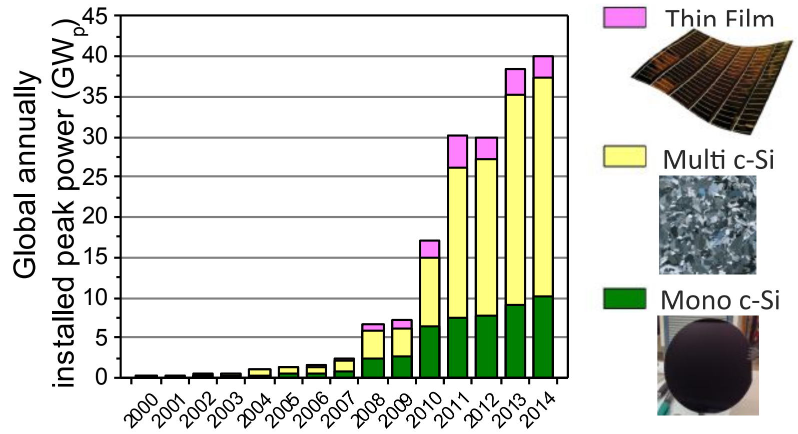
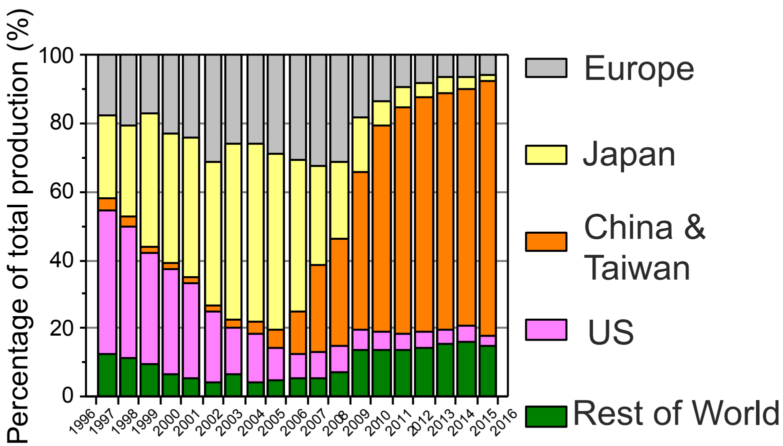
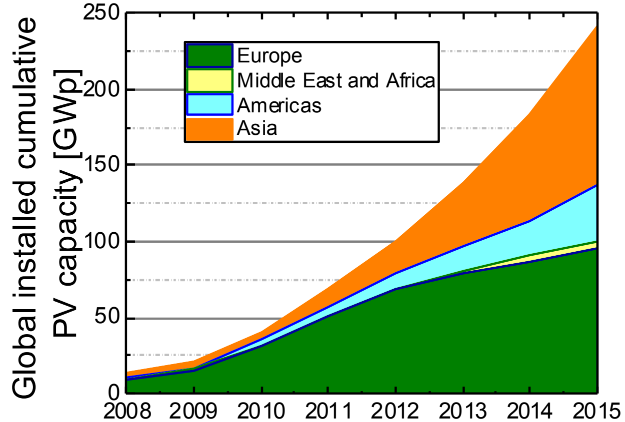
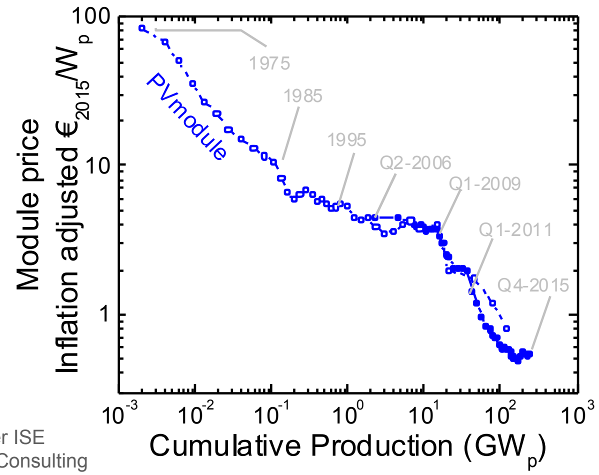

Introduction to Solar Energy
Status and propects of PV technology
Professor Arno Smets

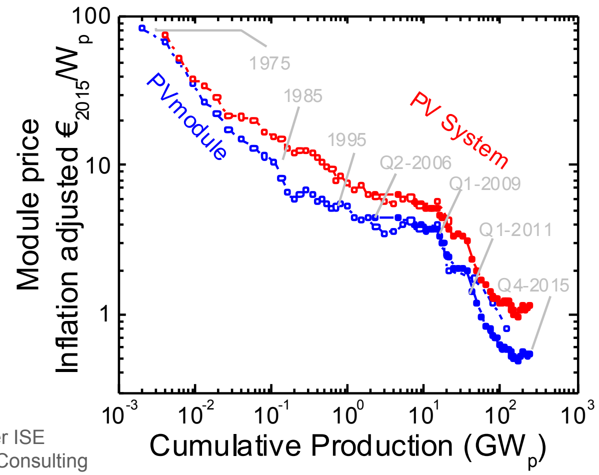

Global annually installed peak power (GW_p)
0
5
10
15
20
25
30
35
40
45
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Thin Film
Multi c-Si
Mono c-Si


Percentage of total production (%)
0
20
40
60
80
100
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
Europe
Japan
China & Taiwan
US
Rest of World

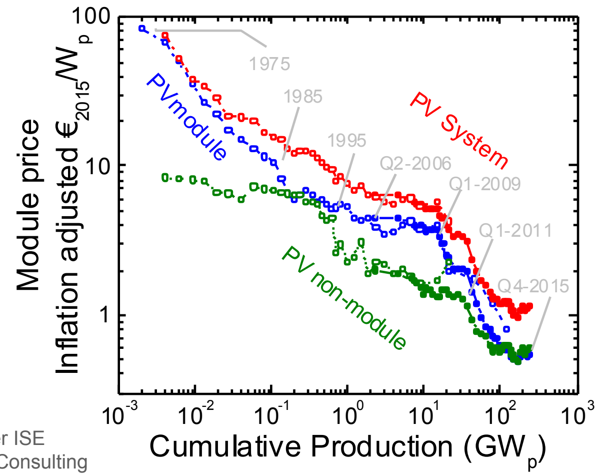

Global installed cumulative PV capacity [GWp]
0
50
100
150
200
250
2008
2009
2010
2011
2012
2013
2014
2015
Europe
Middle East and Africa
Americas
Asia



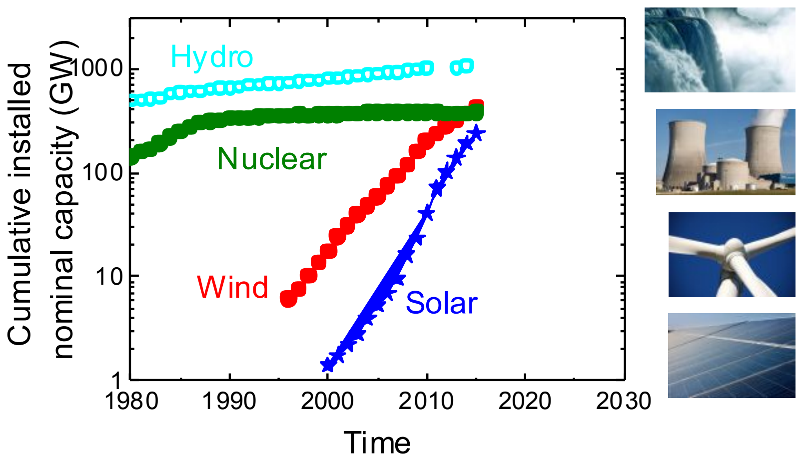
Source:
Fraunhofer ISE
Navigant Consulting

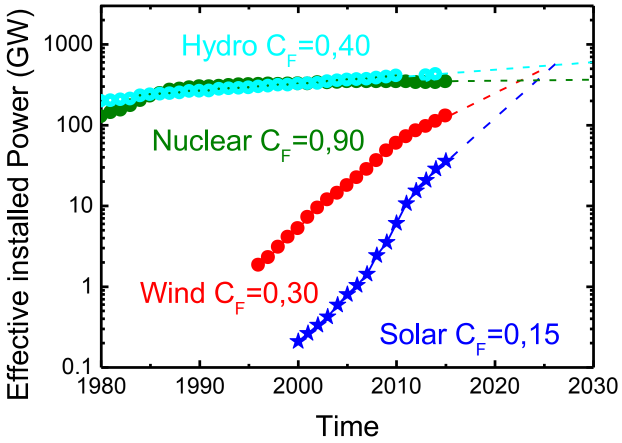


Source:
Fraunhofer ISE
Navigant Consulting



Source:
Fraunhofer ISE
Navigant Consulting

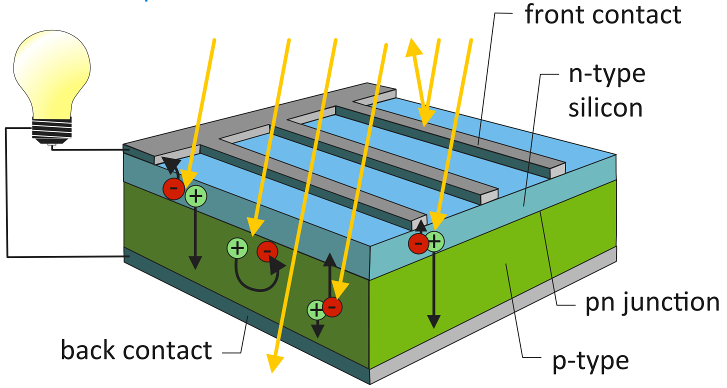


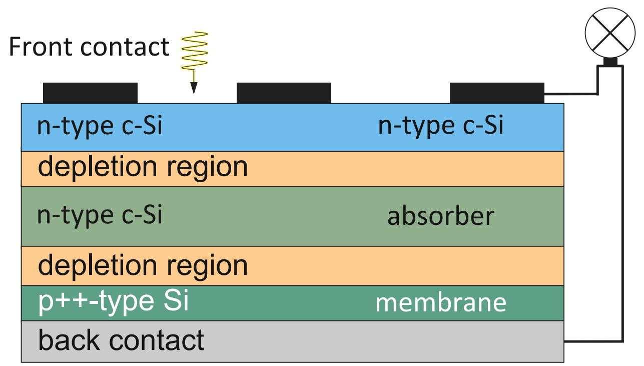


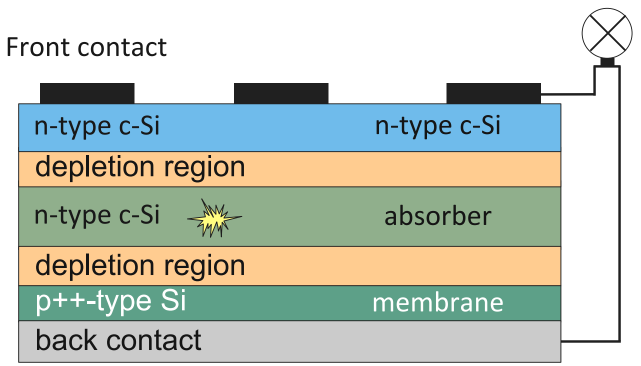
Silicon ingots

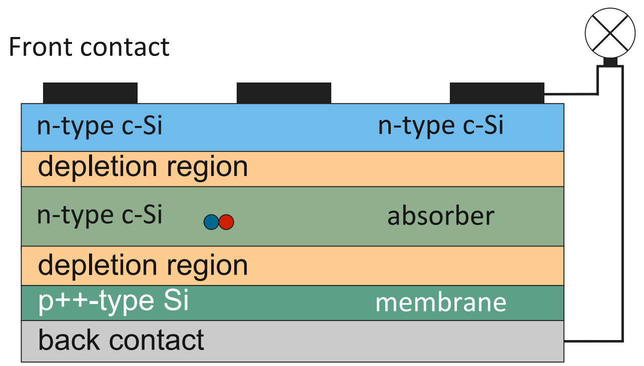
Solar Cell

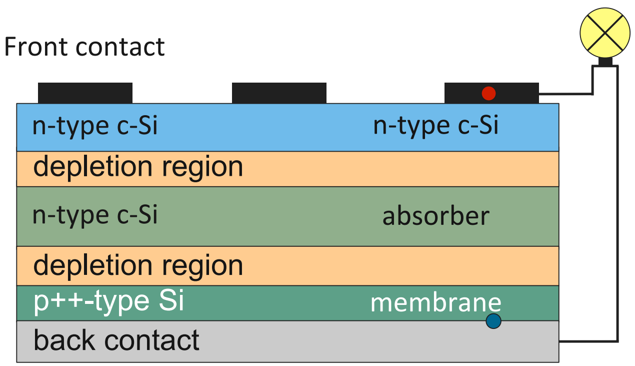
Solar cell operation



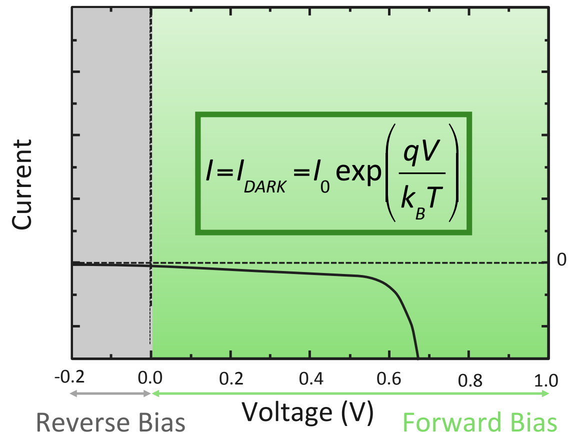




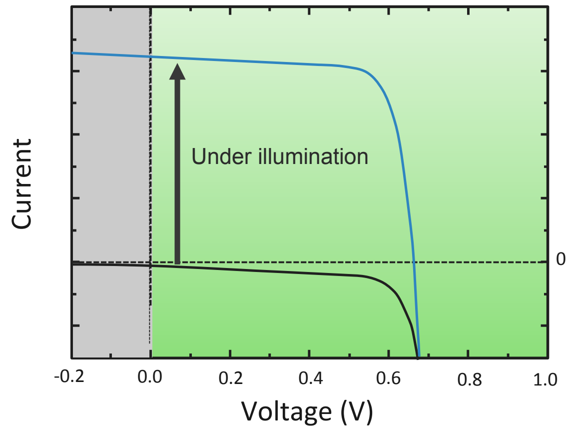




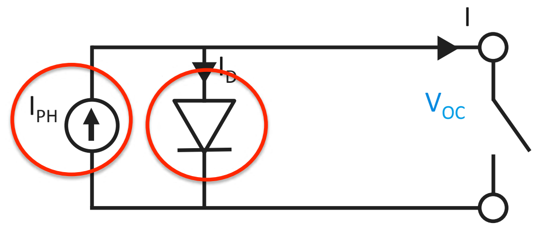
Basic IV-Curve

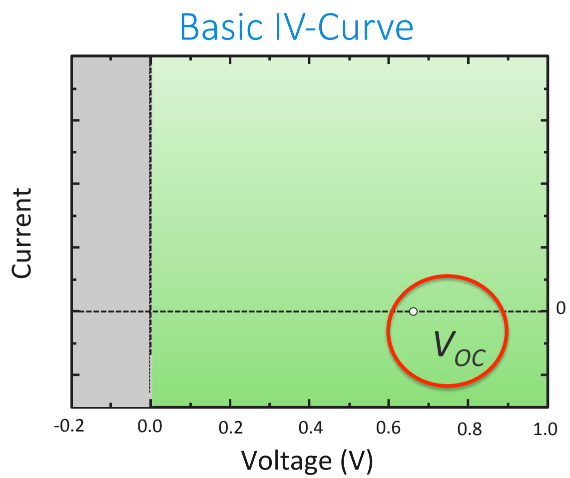


Basic IV-Curve

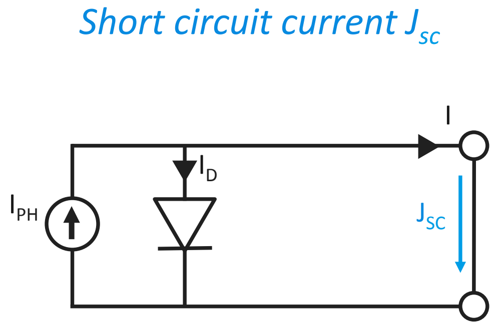


Open circuit voltage V_{OC}

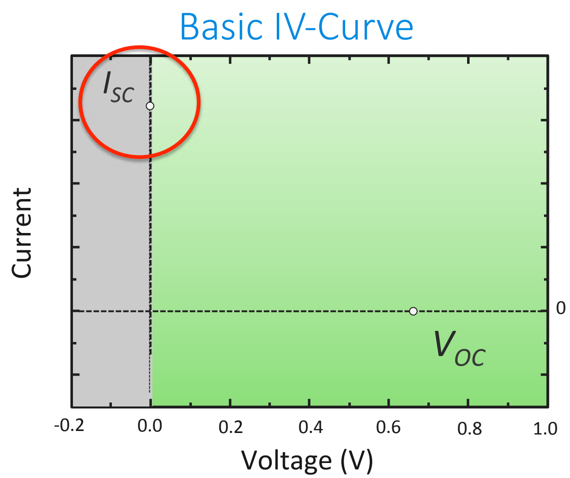




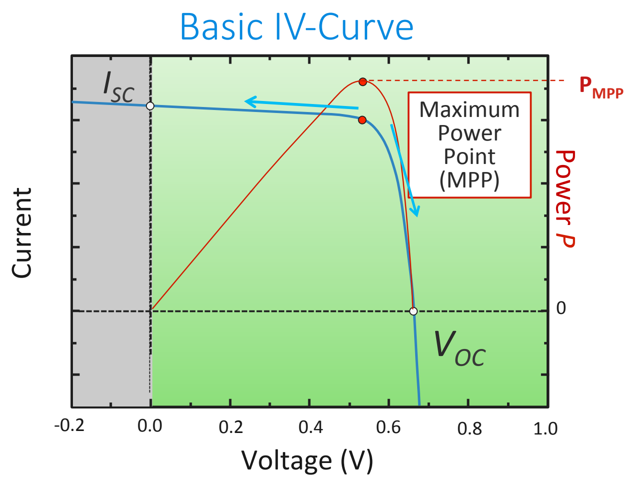
Basic IV-Curve
Current
0
V_{OC}
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
Voltage (V)



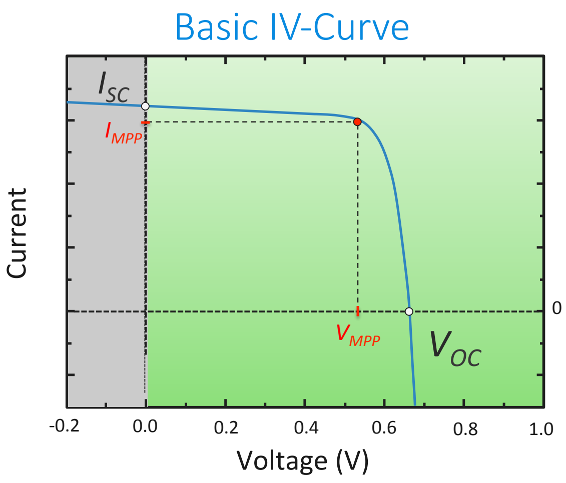
Short circuit current J_{sc}
I
I_D
I_{PH}
J_{SC}

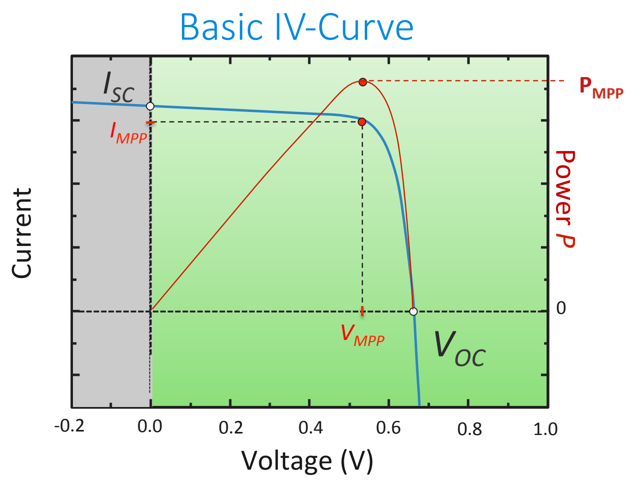


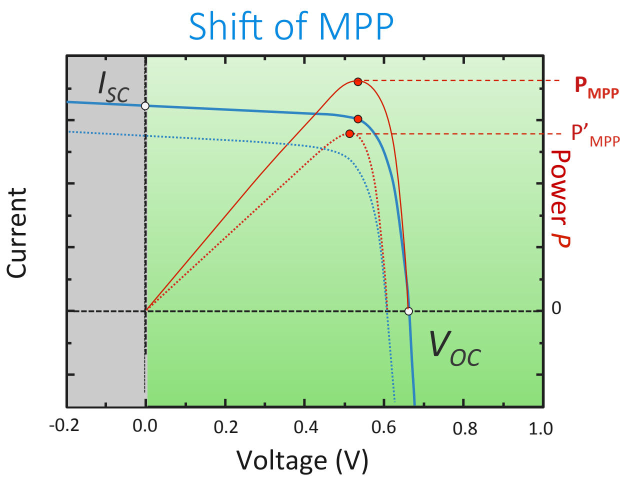
Basic IV-Curve
Current
I_{SC}
0
V_{OC}
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
Voltage (V)



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)

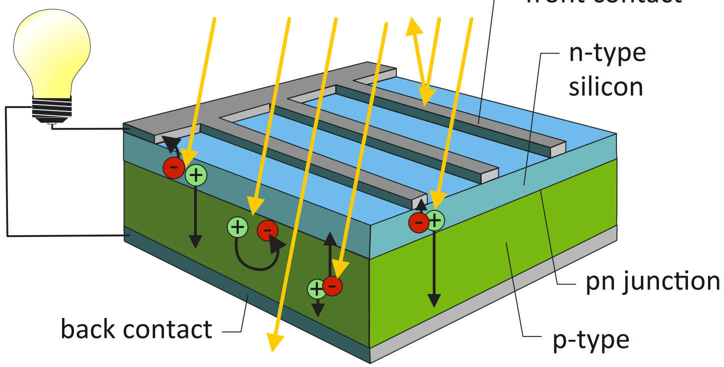


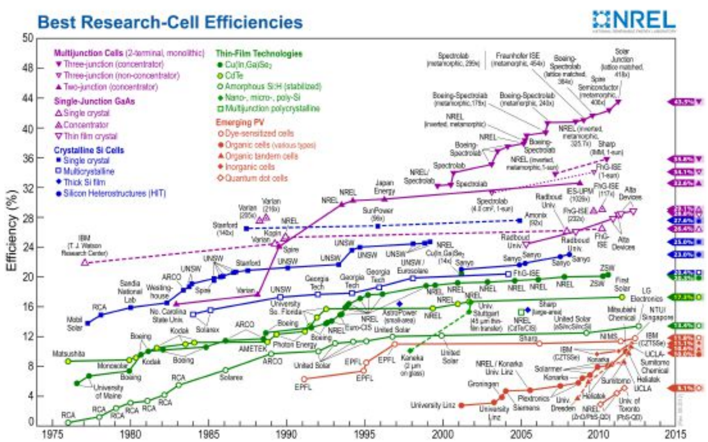




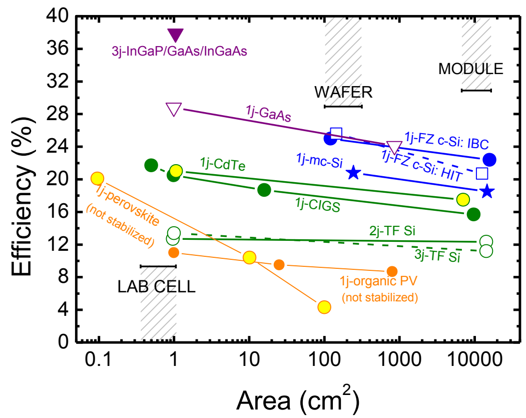
$$Efficiency = \frac{P_{mpp}}{P_{in}}$$

Solar cell operation

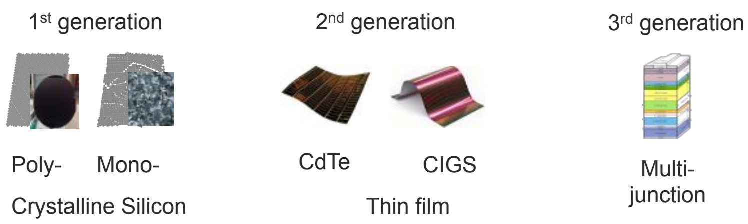




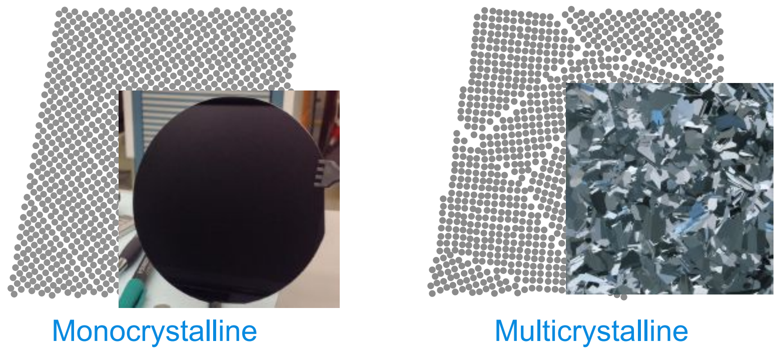
Records? Let's scale it up….



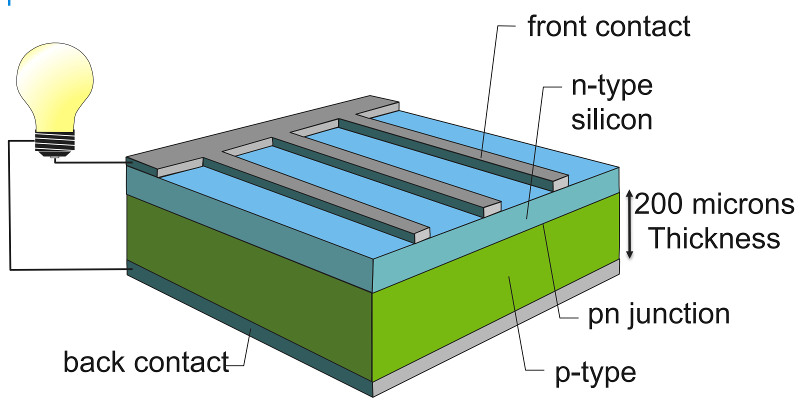
Main PV technologies



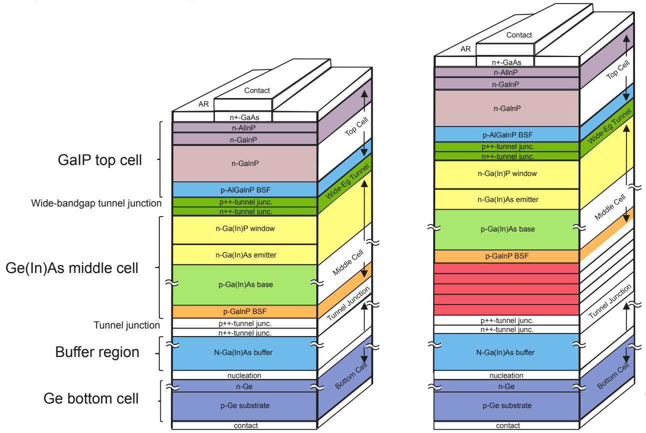
Crystalline silicon wafer-types



Typical silicon solar cell

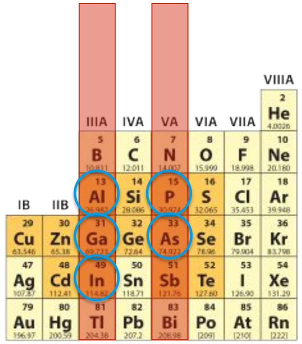


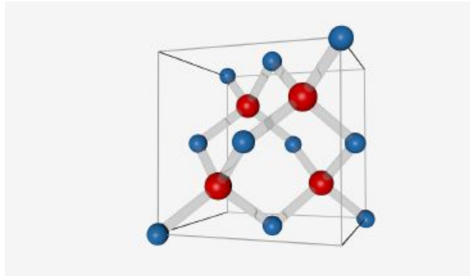
Top Efficiency Solar Cells – Multi Junction Devices



Courtesy: Richard King
Spectro Labs

III-V Semiconductor Materials





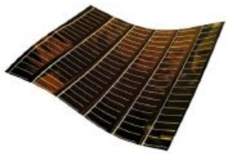
III – V PV Technology Application

Thin Film PV modules: *glass encapsulated*

CdTe (First Solar)

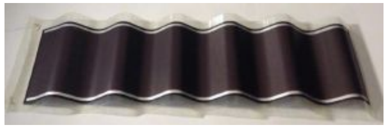
CIGS(Solar Frontier)

Thin Film PV modules: *Flexible*



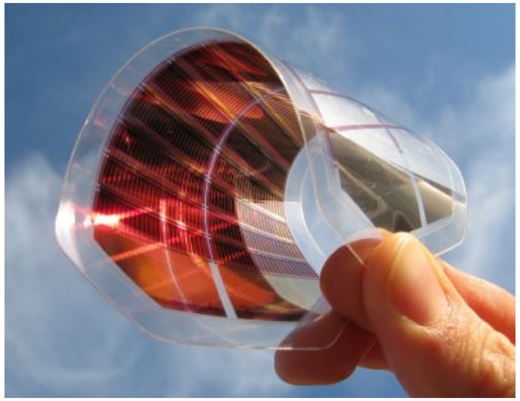
CdTe
EMPA Switzerland

CIGS
MiaSolé

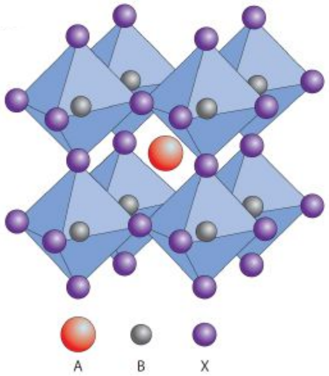


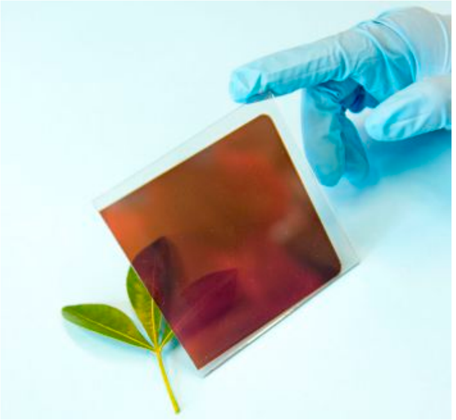
Thin-film silicon
HyET Solar

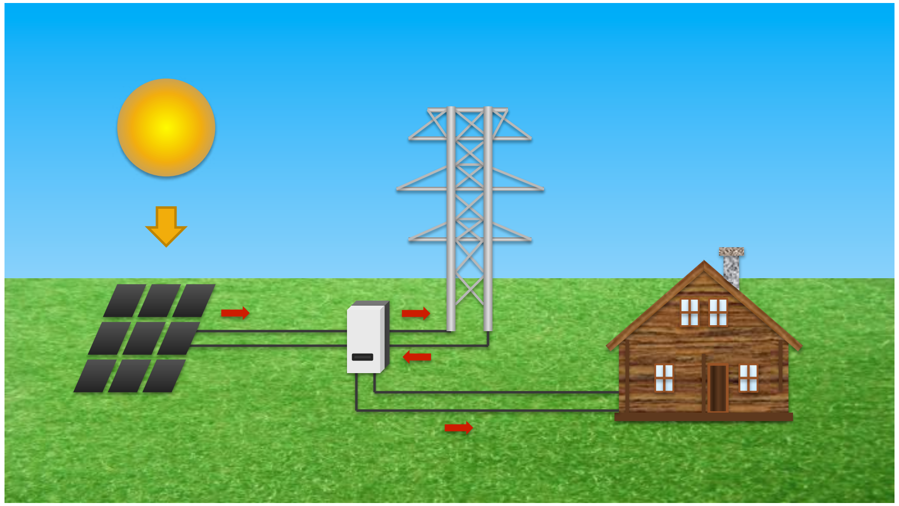
Organic Solar Cells



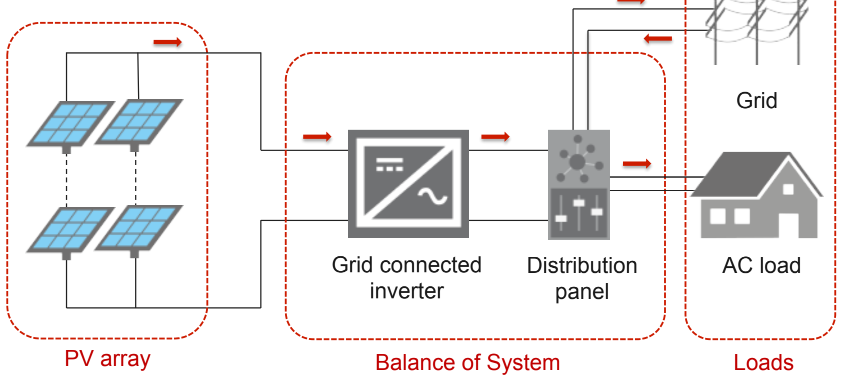
Perovskites







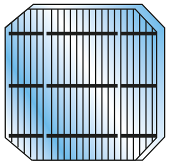
Grid connected system



Solar Cell

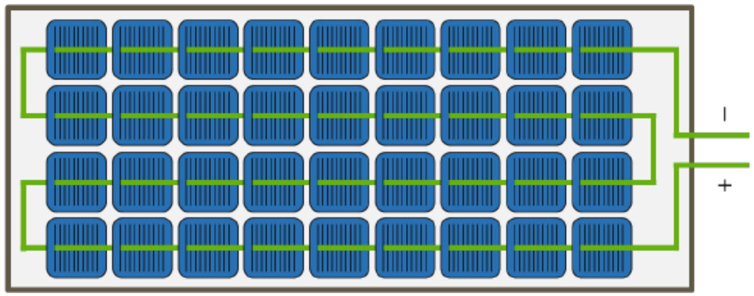
PV modules

From a solar cell to
an array: ‘modularity'

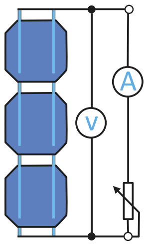


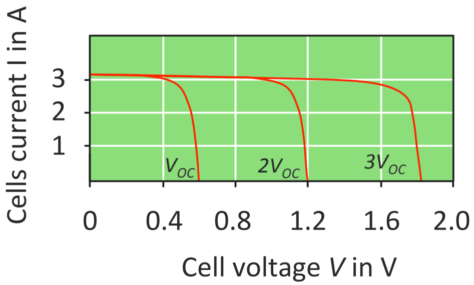
Cell

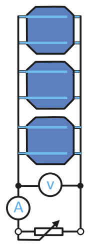
PV cell, module and array

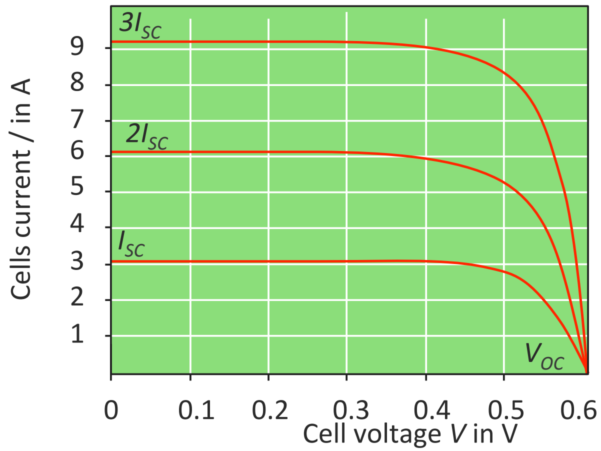


Series connection



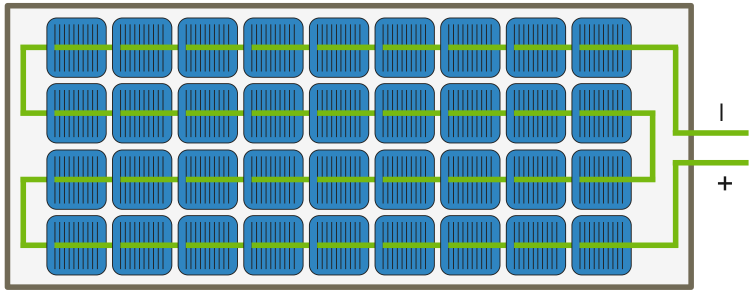






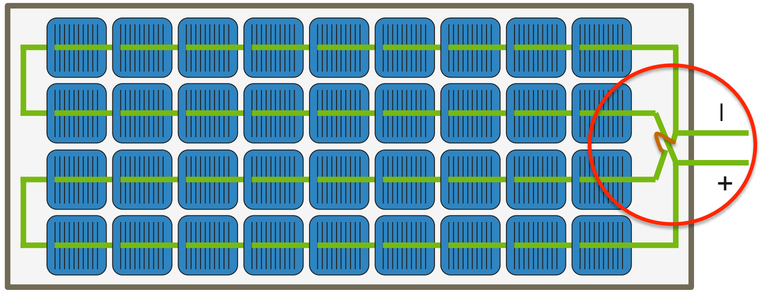
Modules

V_{OCcell} = 0.6 V
I_{SCcell} = 5 A
$V_{OCmodule}$ = 21.6 V
$I_{SCmodule}$ = 5 A

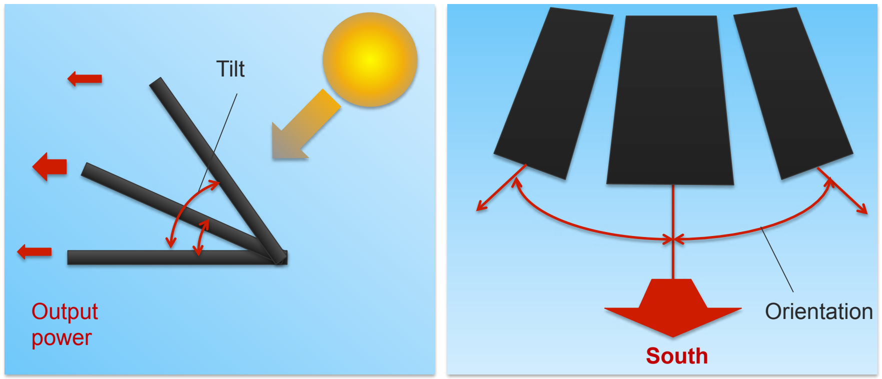


Modules

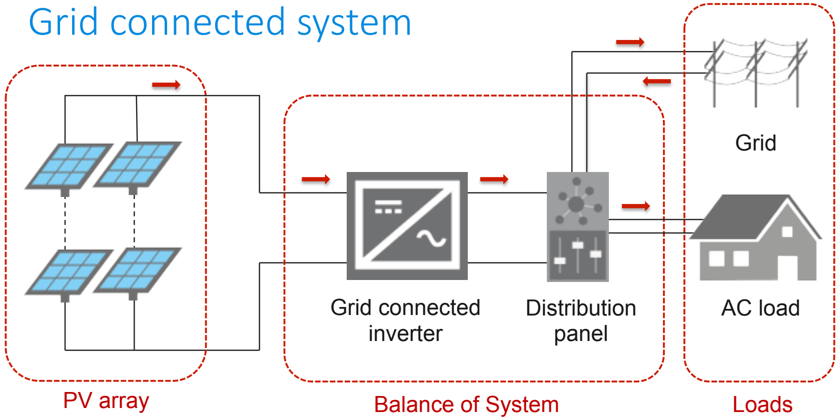
V_{OCcell} = 0.6 V
I_{SCcell} = 5 A
$V_{OCmodule}$ = 10.8 V
$I_{SCmodule}$ = 10 A



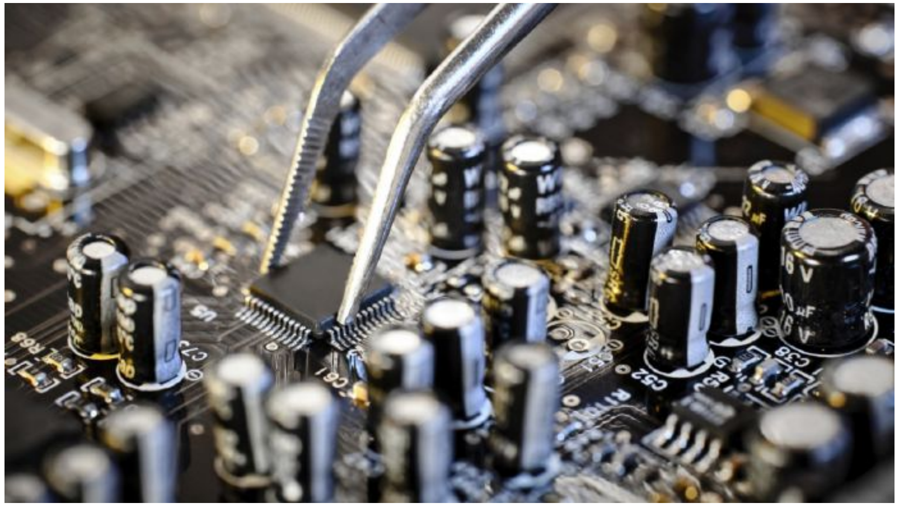
Tilt and orientation

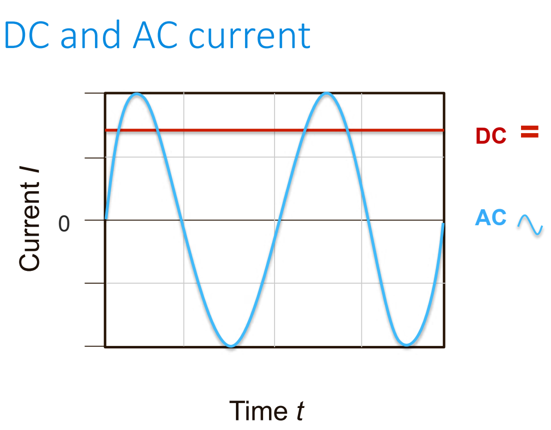


Grid connected system



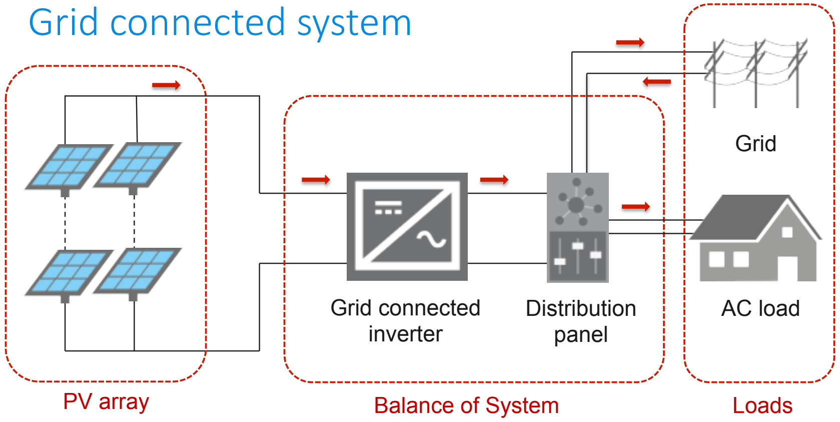

Introduction to Solar Energy
The Inverter and MPPT
Professor Arno Smets



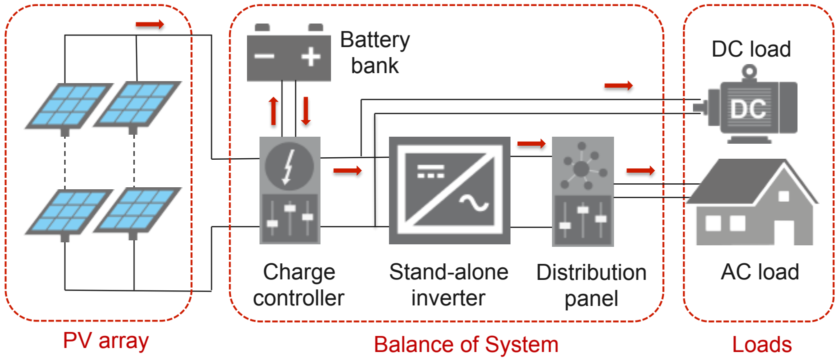

DC and AC current
Current I
0
Time t
DC =
AC ∿

Inverter

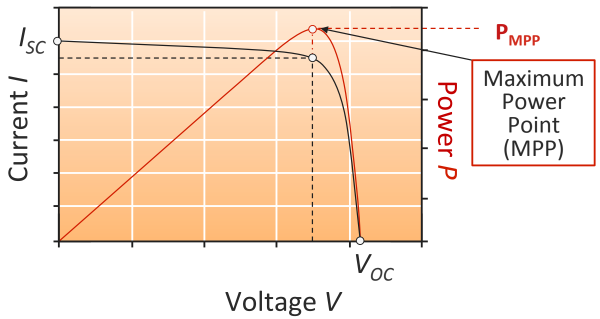
Grid connected system



Off-grid system

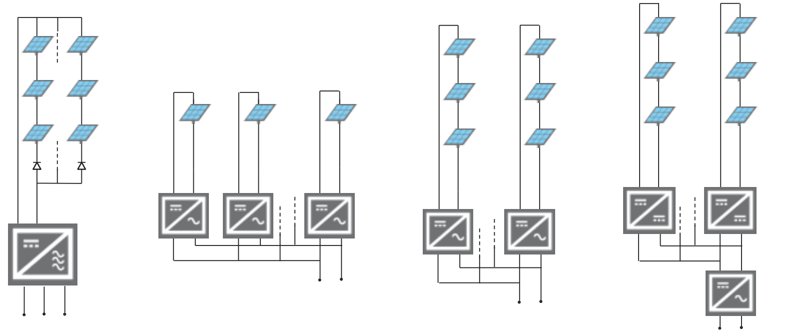


Maximum Power Point Tracking



Implementation topologies

Central inverter | Module inverter | String inverter | Multi-string inverter



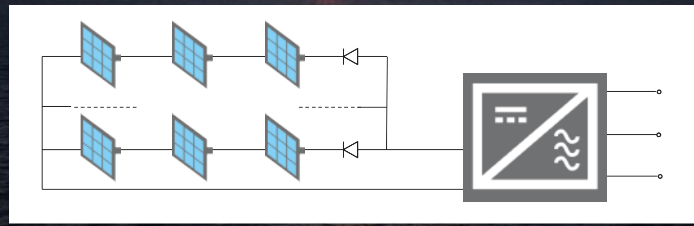
Central inverter

Pros

- Initial investment
- Maintenance
- Design and implementation

Cons

- DC wiring cost
- Shading performance loss



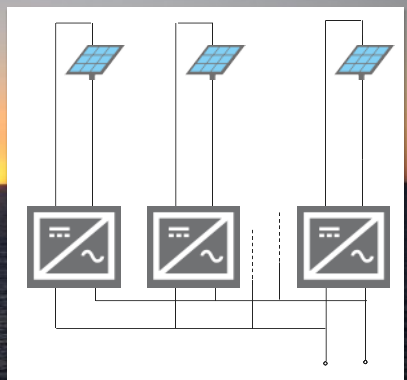
Module inverter

Pros

- Performance loss mitigation
- DC wiring cost
- Design

Cons

- Initial investment
- Maintenance



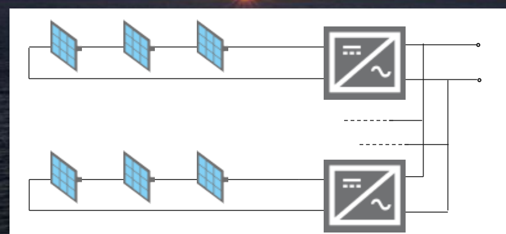
String inverter

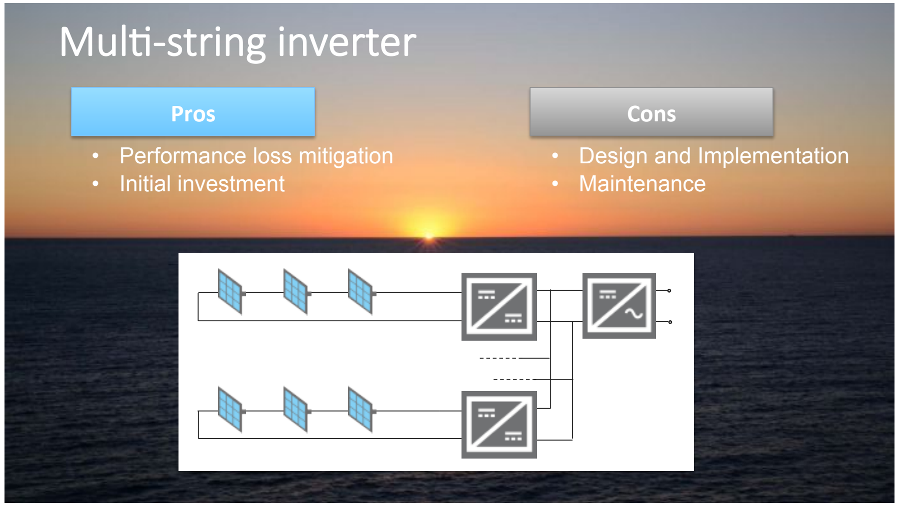
Pros

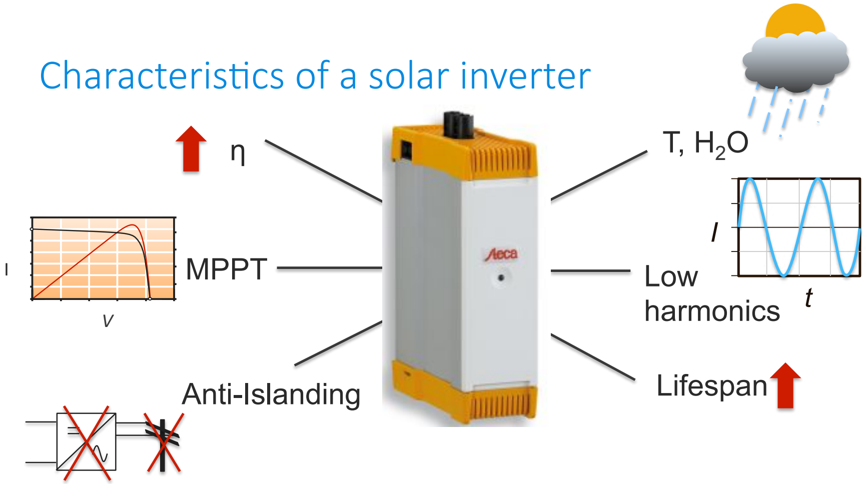
- Performance loss mitigation

Cons

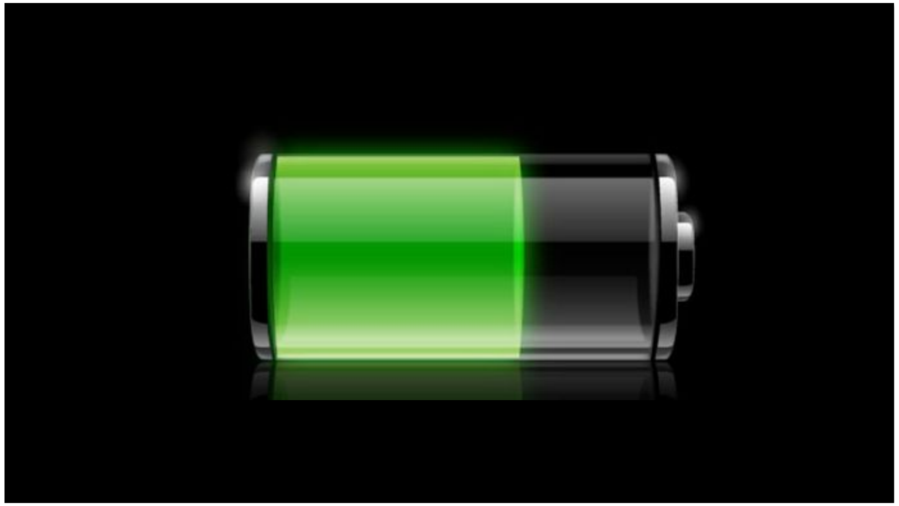
- Design and Implementation
- Initial investment
- Maintenance



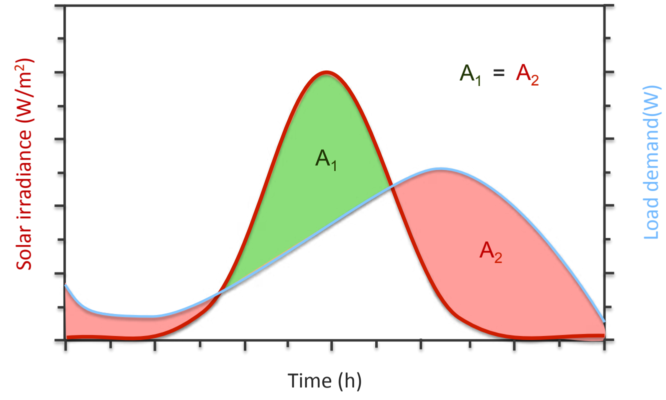

Multi-string inverter
Pros
Performance loss mitigation
Initial investment
Cons
Design and Implementation
Maintenance


Characteristics of a solar inverter
η
MPPT
I
V
Anti-Islanding
T, H_2O
I
t
Low harmonics
Lifespan


Introduction to Solar Energy
Batteries
Professor Arno Smets



Solar irradiance and demand profile



Types of batteries

Zinc carbon
Alkaline

Primary

Lead Acid
Lithium ion

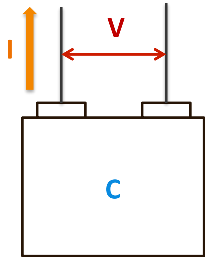
Secondary

Secondary batteries

Lead acid batteries

Lithium-ion batteries

Battery characteristics

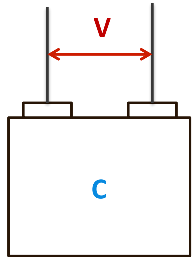


Rated voltage: 12V, 24V, 48V

Rated capacity: Ah, mAh

Rated current: A, mA

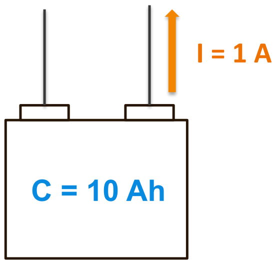
Battery characteristics



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

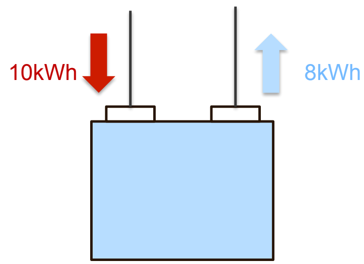
$$[Wh] = [Ah] \cdot [V]$$

Significance of Amp hours



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

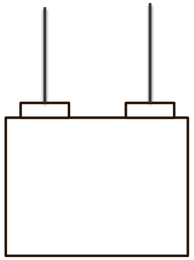
Efficiency of storage



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

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

Battery efficiency

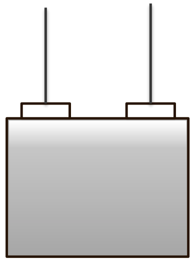


$$\eta_V = \frac{V_{discharge}}{V_{charge}} \cdot 100$$

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

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

SOC and DOD

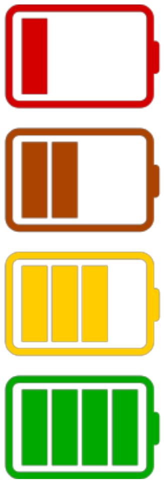


$$SOC = \frac{E_{battery}}{C_{battery} \cdot V}$$

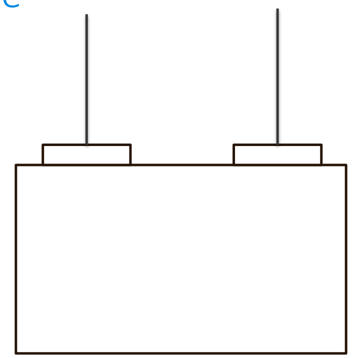
$$10\ Ah\ - 2\ Ah = 8\ Ah \longrightarrow SOC = 80\%$$

$$\longrightarrow DOD = 20\%$$

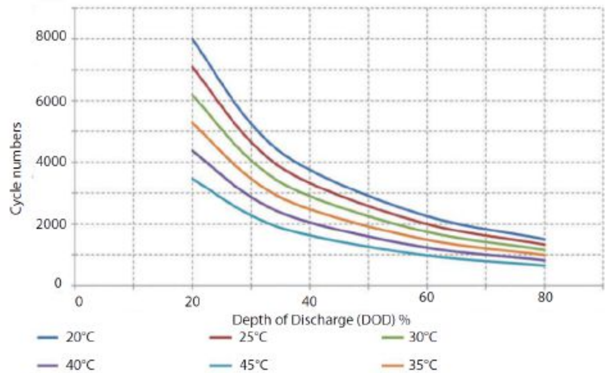
$$DOD = \frac{C_{battery} \cdot V - E_{battery}}{C_{battery} \cdot V}$$



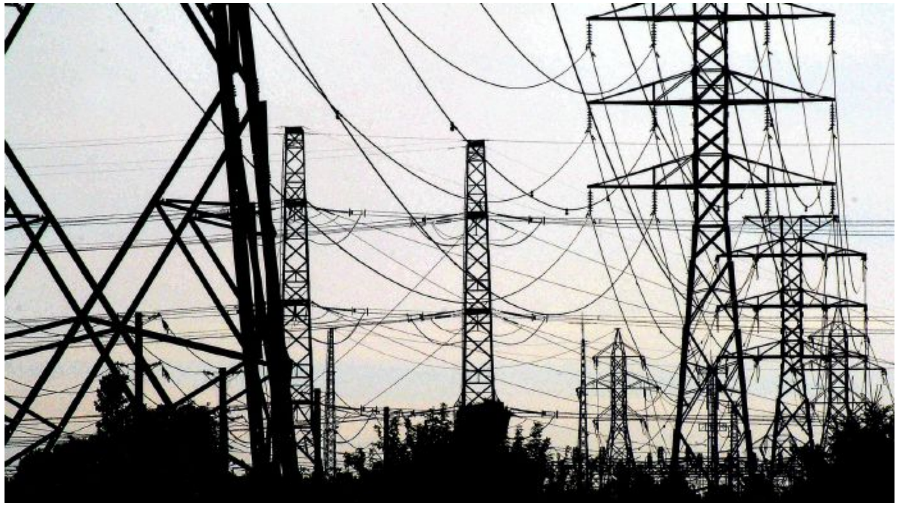
Cycle life

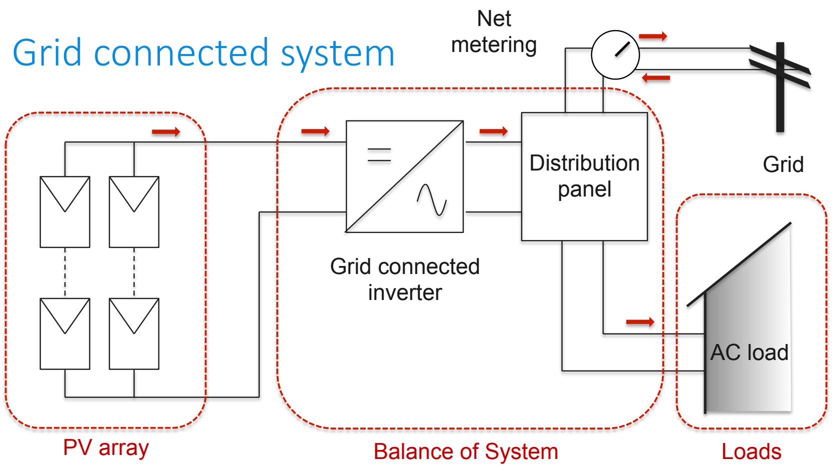


Cycle life vs. DOD

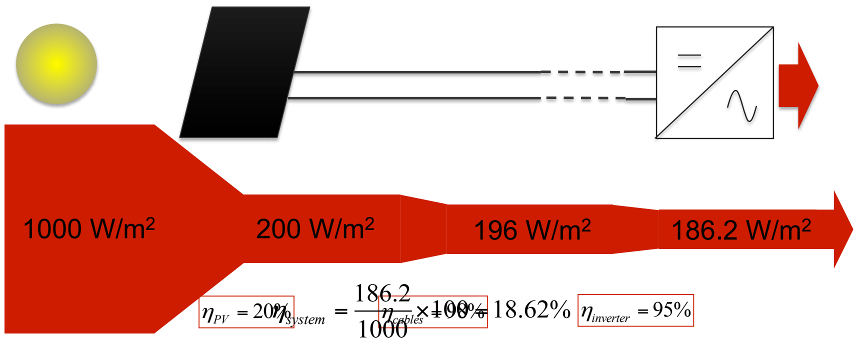



Introduction to Solar Energy
Design rules
Professor Arno Smets




Grid connected system
Net metering
Distribution panel
Grid
Grid connected inverter
AC load
PV array
Balance of System
Loads

Grid connected system



$\eta_{PV} = 20\%$ $\eta_{cables} = 98\%$ $\eta_{inverter} = 95\%$

$$\eta_{system} = \frac{186.2}{1000} \times 100\% = 18.62\%$$

$$\eta_{system} = \eta_{PV} \times \eta_{cable} \times \eta_{inverter}$$

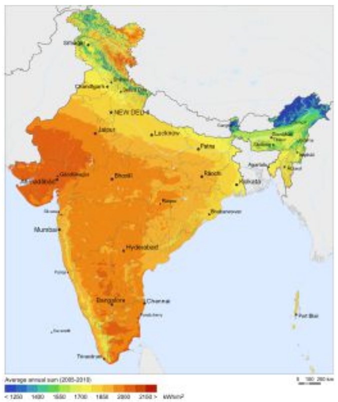
Sizing Example – Load

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

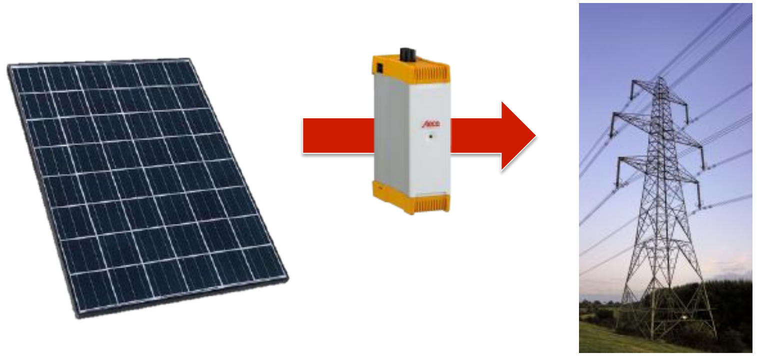
$$Minimum\ W_p = 1800\,Wh / 4.5\,h/day \times 1.2 = 480\,W$$

Equivalent sun hours

Account for System losses

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

Sizing example – Grid connection



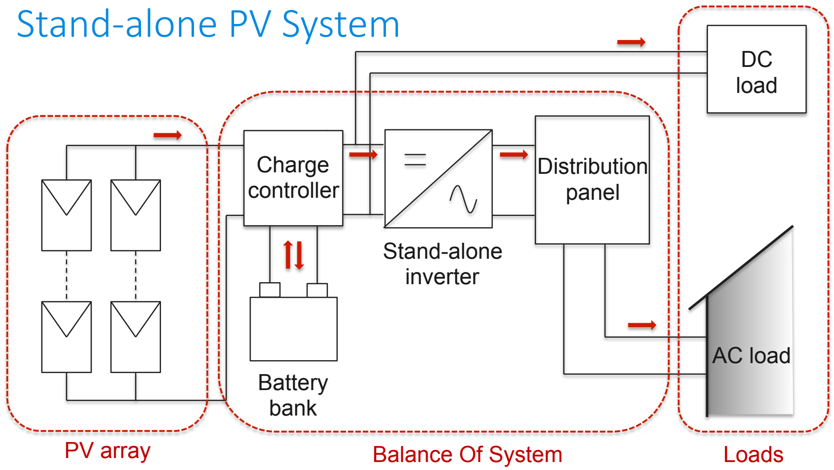
Sizing example - Inverter

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

Total power from the panels

Safety margin

Stand-alone PV System



Sizing example – Charge controller

Steca Solarix MPPT Charge Controller

Parallel

Short circuit current

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

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

Total energy demand

Days of autonomy

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

Depth of discharge

Account for System losses

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

Operational voltage of the system

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

$$\boxed{Number\ of\ batteries = 3 \times 2 = 6\ batteries}$$

Sizing example - Inverter

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

?

Sizing example - Inverter

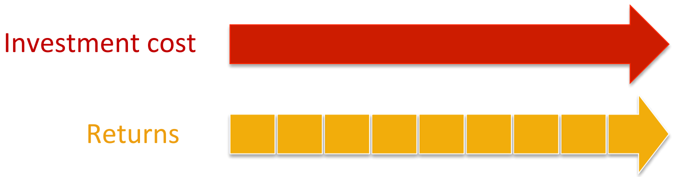
Inverter specifications	
Efficiency	96%
Operational voltage	12V/24V

Total power demand

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

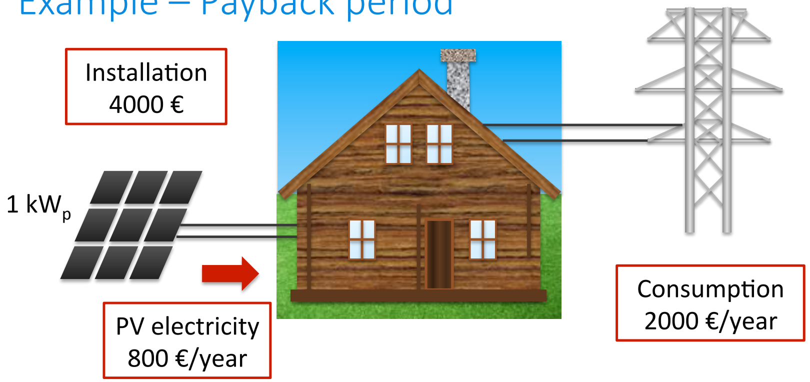
Inverter efficiency

Payback period

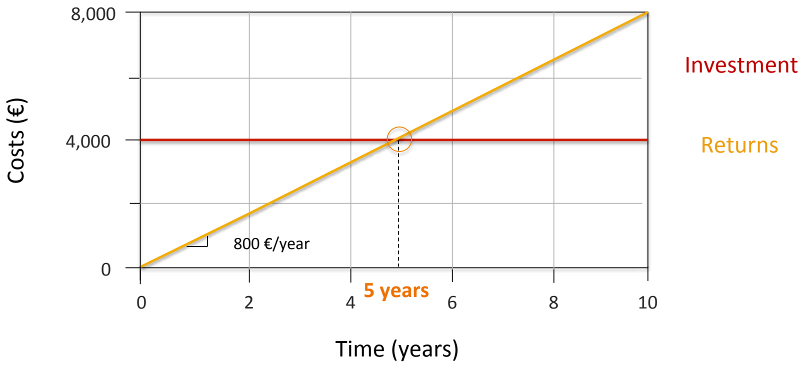


$$\text{Payback period} = \frac{\text{Investment cost}}{\text{Returns/year}}$$

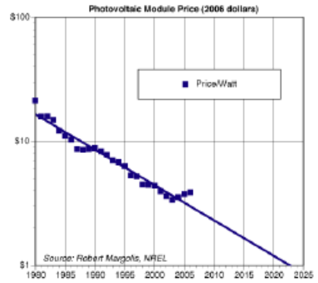
Example – Payback period



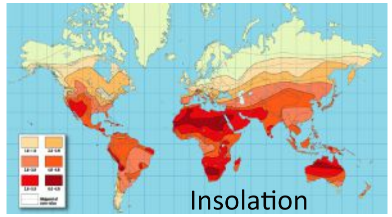
Example – Payback period

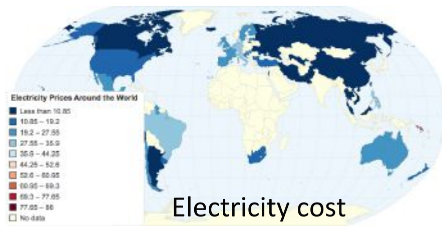


Location dependency

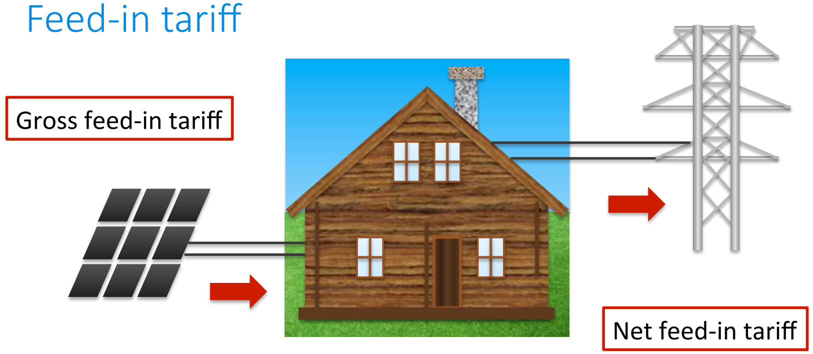


PV system cost

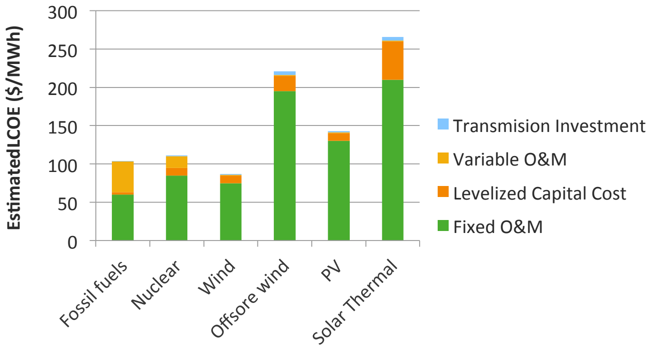




Feed-in tariff



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

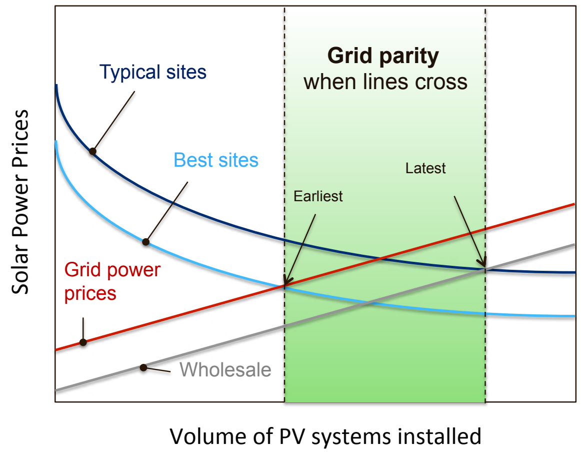
I_0 = Initial investment

E_t = Annual energy yield

i = Discount rate

Grid parity

Grid parity



Practical Handbook of Photovoltaics


Thank you for your attention!