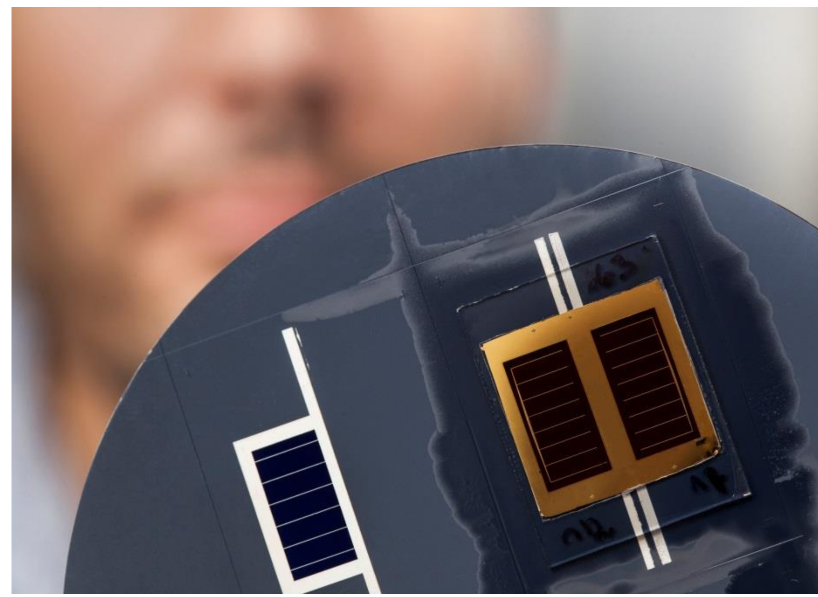
Second cool concept of the week

Nature Energy | **August 25**, 2017

New records for the solar cell of tomorrow

The U.S. Department of Energy's National Renewable Energy Laboratory (NREL), CSEM and EPFL have taken an important symbolic step forward. Working together, they were able to demonstrate the high potential of silicon-based multi-junction solar cells: they raised the one-sun record conversion efficiency of III–V/Si solar cells to **32.8%** for two junctions and **35.9%** for three junctions. These achievements, published today in Nature Energy, are a world first in the highly competitive race to improve silicon-based solar cells efficiency, confirming the potential of this approach.



UNIK 4450/9450 – Solar cells

Overview

- Solar cells and solar cell models
- Definition of important parameters
- Solar cell technologies
- The past and present of solar cells

Clever student question:

”What IS a solar cell, really?”

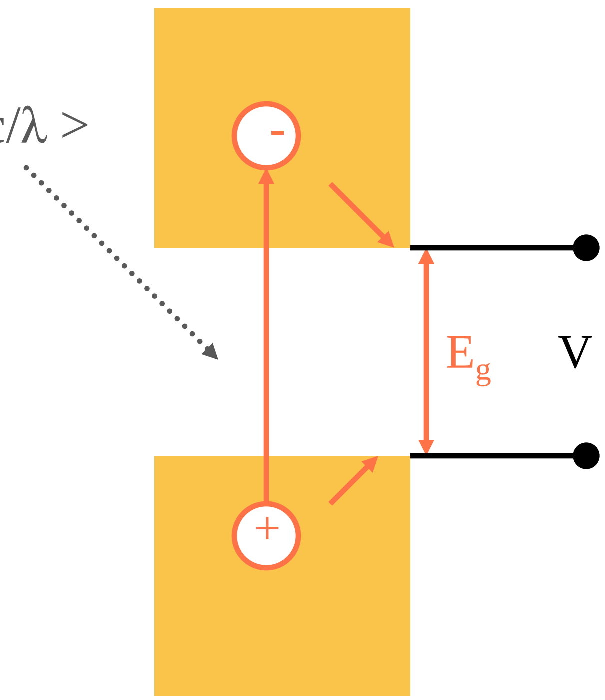
Q: WHAT IS A SOLAR CELL?

- A: ”Any device that uses solar radiation to drive an electric current”
  - A very general definition, which includes both photovoltaic devices and thermopiles, devices that comvert thermal energy into electric energy
- A: ”A semiconductor device that converts the energy of sunlight into electric energy. Also called *photovoltaic cell*.”
  - A narrow definition, which excludes several technologies not based on semiconductors
- A: “Any device that directly converts the energy in light into electrical energy by the process known as the photovoltaic effect.”
  - The definition, which will be used in this course

Photovoltaic energy conversion

- Photons with sufficient energy excite charge carriers to higher energy levels where they become mobile.
- A built-in asymmetry in the solar cell separates the carriers, thus creating a net current.
- Any energy difference between the charge carriers extracted at the external terminals will generate a potential difference, which can be used to drive the current through a load to do electrical work.

$E_{phot} = hc/\lambda > E_g$



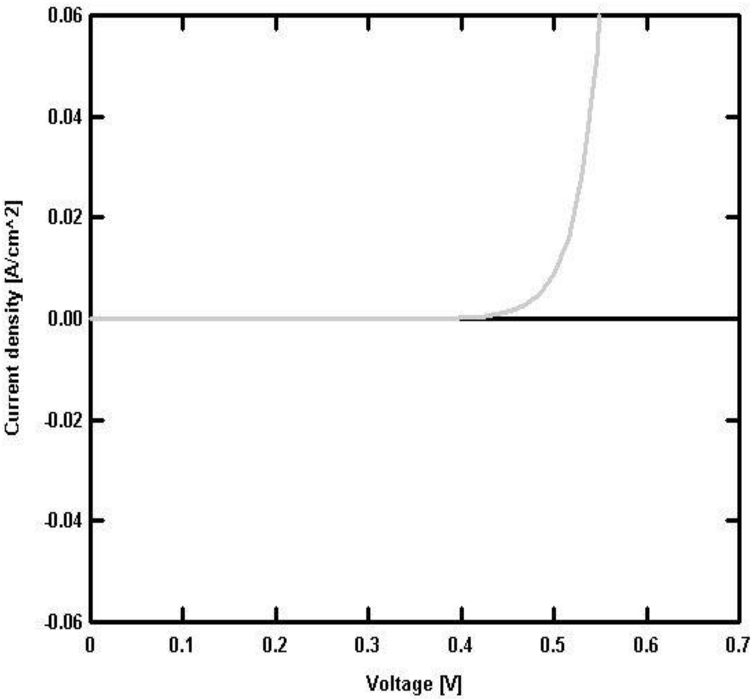
Solar cells and power generation

(The electrician's point of view)

- A solar cell is a two terminal device, which

  1. Acts as a diode in the dark.

Diode I-V characteristics



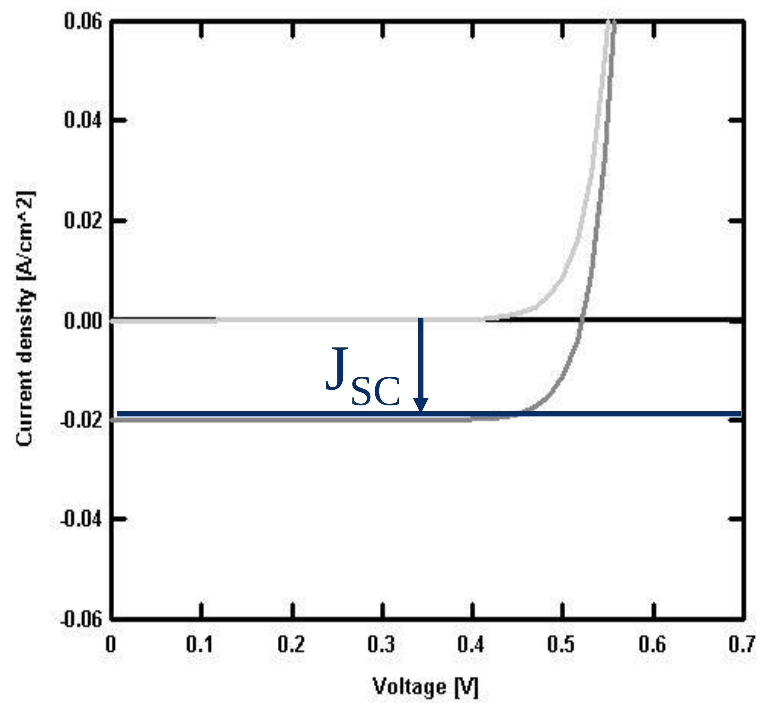
Solar cells and power generation

(The electrician's point of view)

- A solar cell is a two terminal device, which

  1. Acts as a diode in the dark.
  2. Generates photovoltage V and a photogenerated current I_{SC} when illuminated. The photocurrent is determined by the irradiance

Illuminated solar cell



Solar cells and power generation

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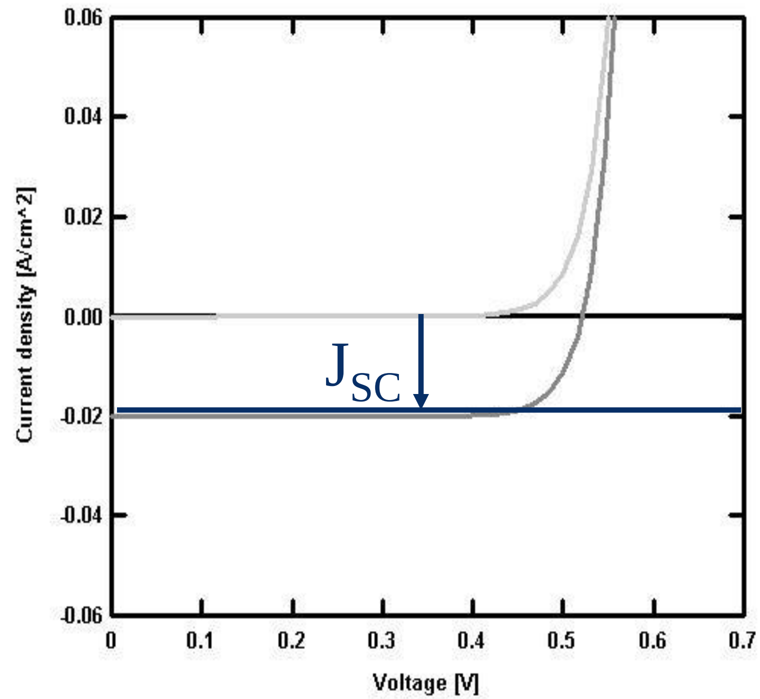
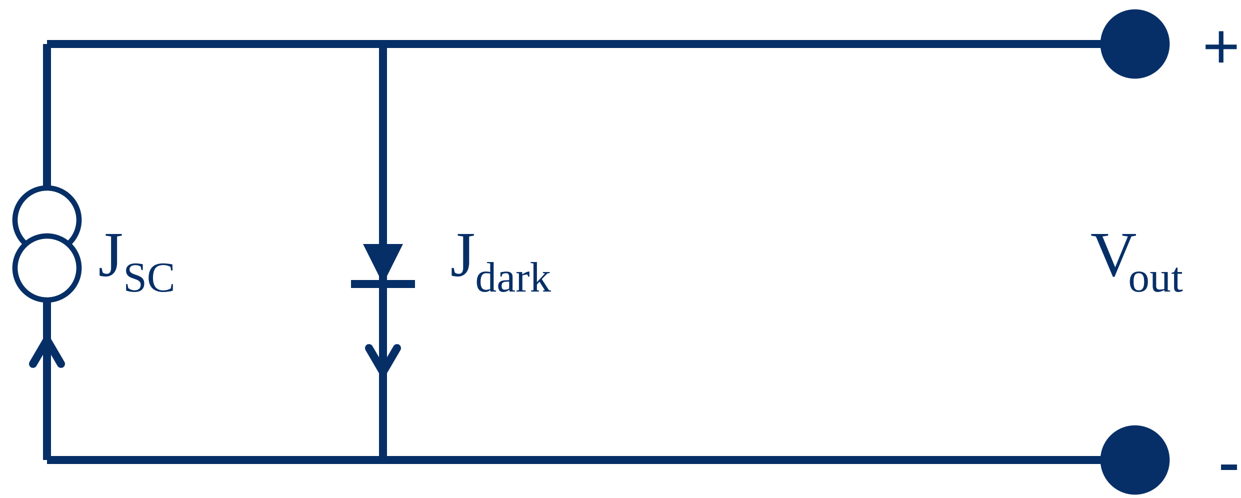
- The total current-voltage (I-V) relationship of an illuminated solar cell is a superposition of the I-V characteristics of the diode and the photocurrent.

Illuminated solar cell



Simple equivalent circuit diagram

- A good model for simple evaluation of solar cell efficiency



$$J_{TOT} = J_{dark} - J_{SC} = J_0(e^{eV/kT} - 1) - J_{SC}$$

Ideality factor

- Real diodes rarely exhibit an ideal diode behaviour described by

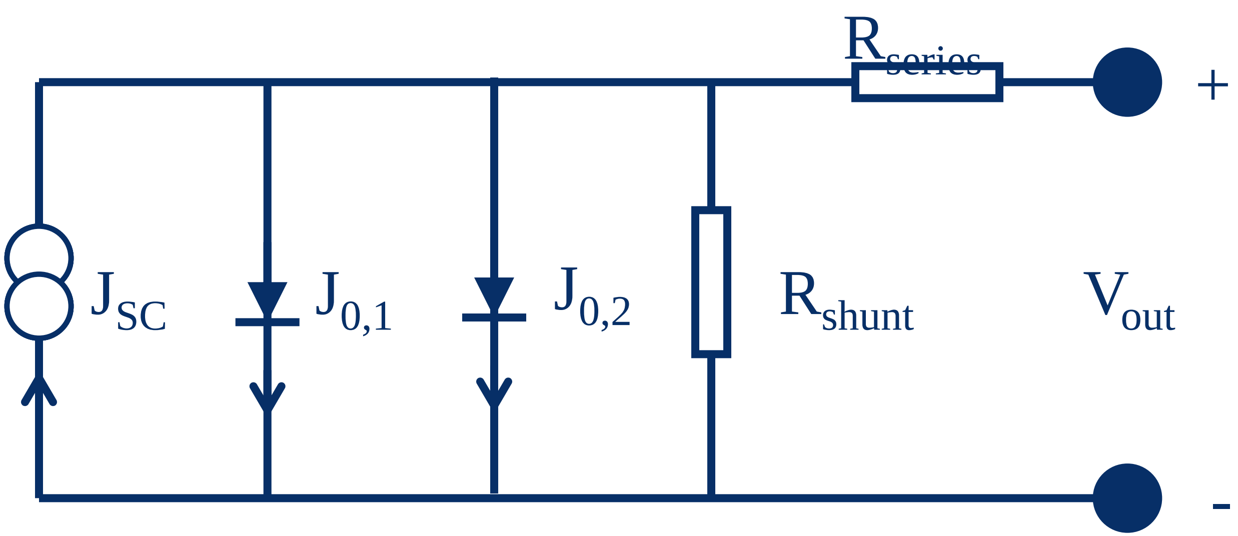
$$J_{TOT} = J_0(e^{eV/kT} - 1)$$

- A better description can be obtained by introducing an ideality factor (m)

$$J_{TOT} = J_0(e^{eV/mkT} - 1)$$

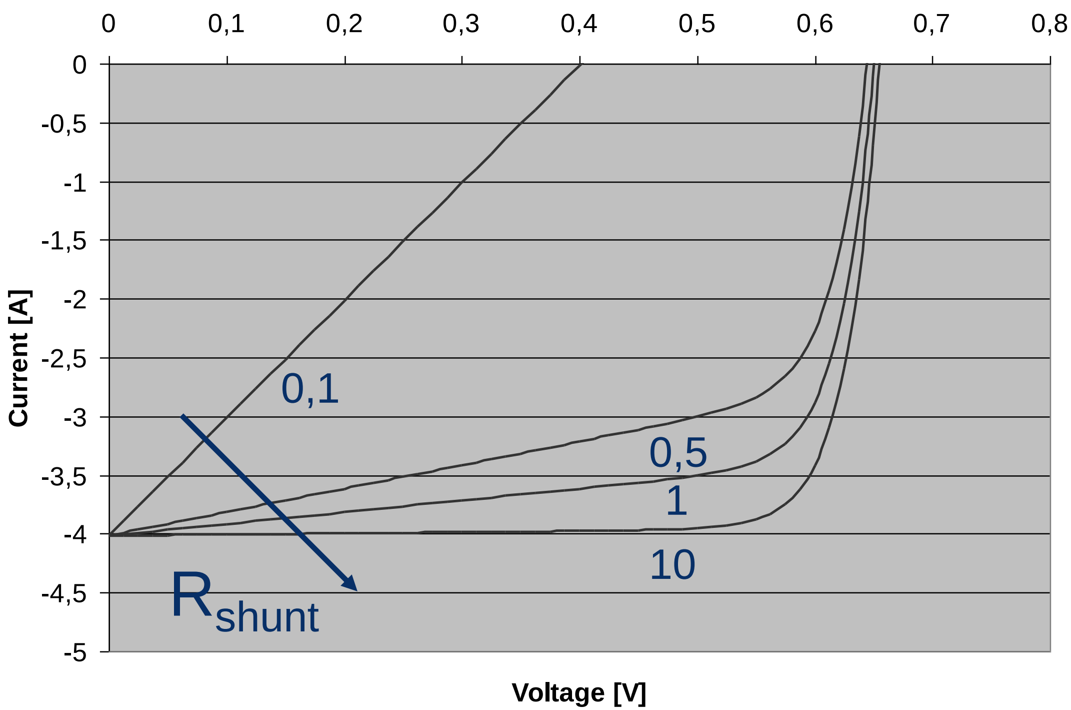
Two-diode model

- The most commonly used model in the solar cell research community and industry

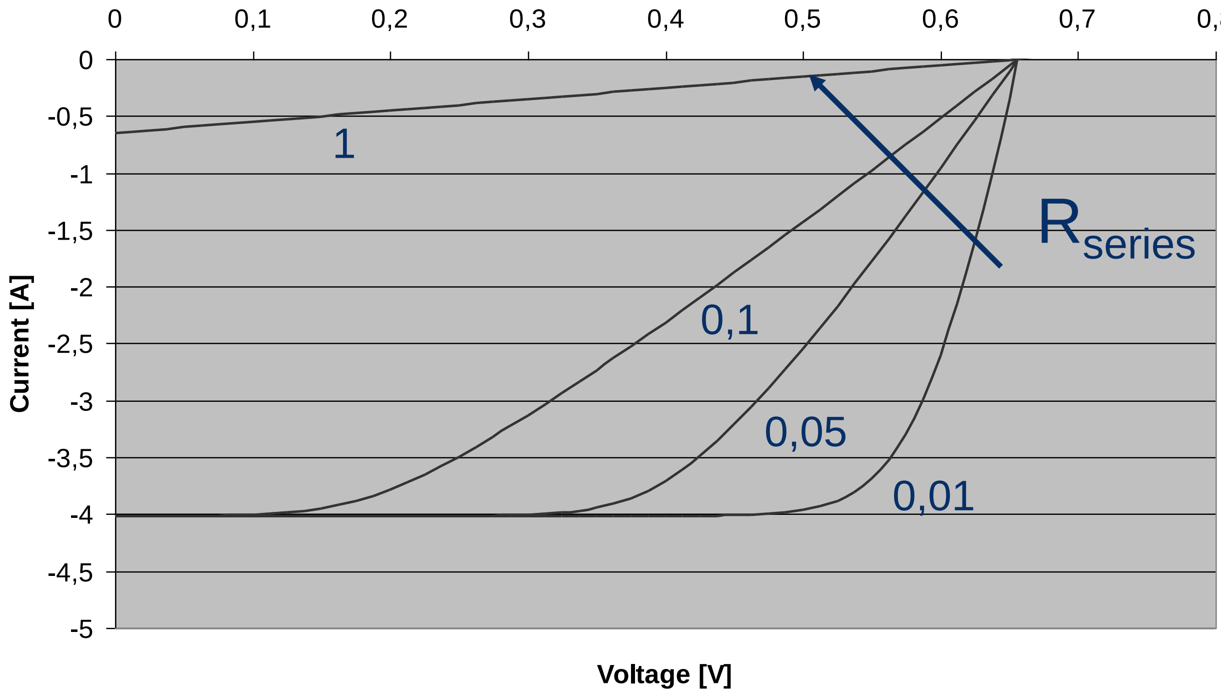


$$J_{TOT} = J_{0,1}(e^{q(V+JAR series)/kT} - 1) + J_{0,2}(e^{q(V+JAR series)/2kT} - 1) - J_{SC} + (V + JAR_{series})/R_{shunt}$$

Shunt resistance

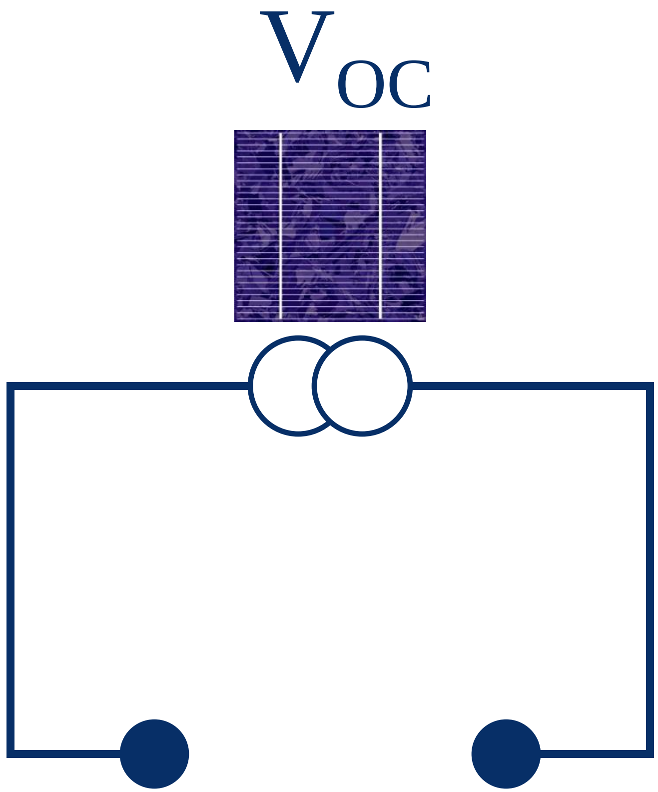


Series resistance



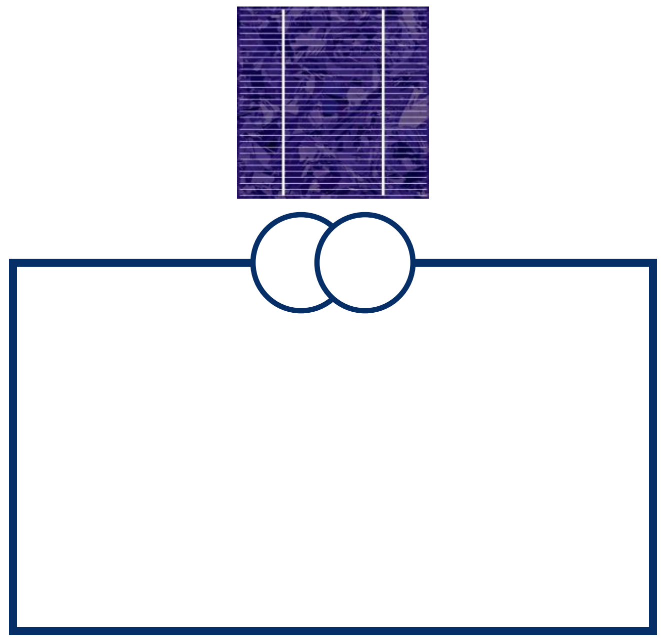
Important solar cell parameters

- Open circuit voltage V_{OC}
- Short circuit current J_{SC}
- Efficiency η
- Fill factor FF
- Quantum efficiency QE



Open circuit voltage

I_{SC}



Short circuit current

V_{oc}

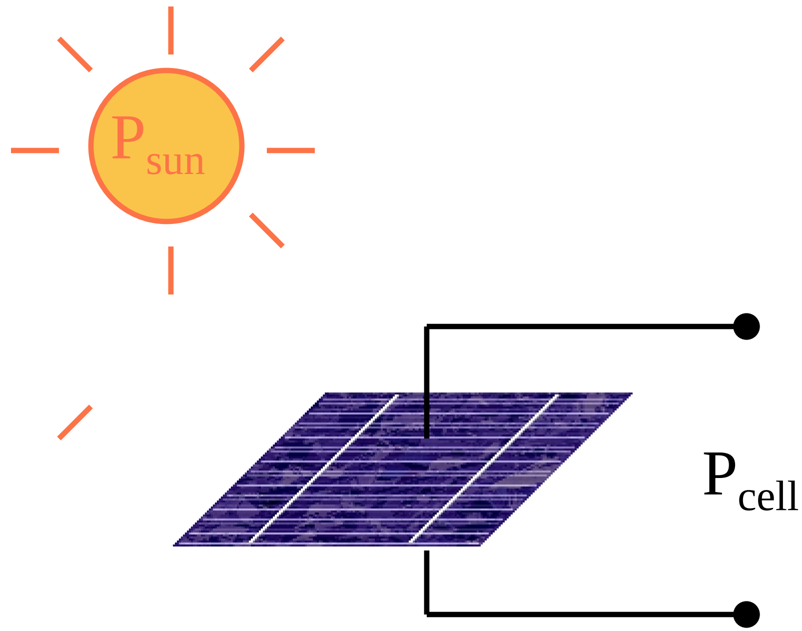
- From the diode equation, it can be shown that

$$V_{oc} = (kT/q) \cdot \ln(J_{sc}/ J_0 + 1)$$

η

- The efficiency (η) of a solar cell is defined as the ratio between the output electrical power and the power of the light falling upon it in the following manner:

$$\eta = P_{cell} / P_{sun}$$



- P_{cell} is given by

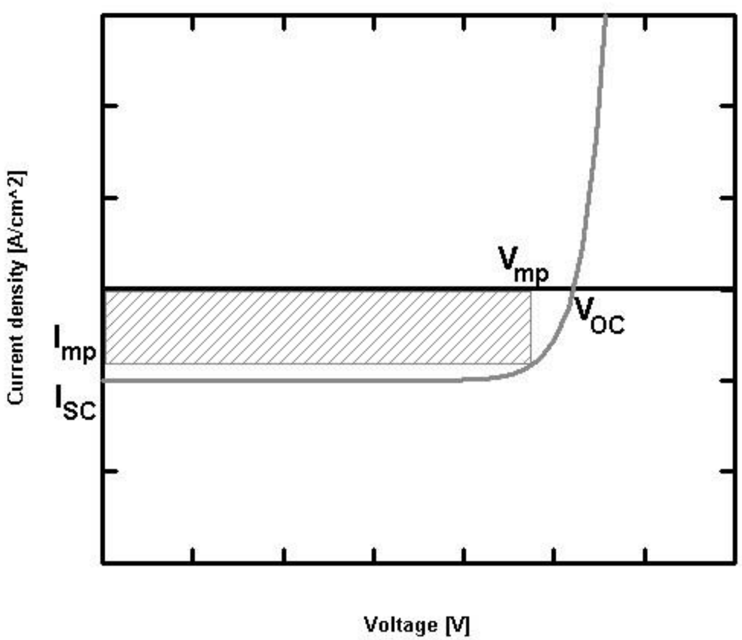
$$P_{cell} = I \cdot V$$

η

- η is defined at the maximum power point of the solar cell.

$$\eta = P_{mp}/P_{sun}$$
$$= I_{mp} \cdot V_{mp}/P_{sun}$$

- η is sometimes called the **conversion efficiency** of a solar cell.



Measuring η

- η is extracted from I-V measurements of illuminated solar cells.
- Solar cell characteristics depend on T and irradiance.
- Solar cell efficiency must be measured under standard testing conditions (STC) for comparison.
  - Spectrum = AM1.5
  - Irradiance = 1 Sun = 1 kW / m^2
  - Cell temperature (T_c) = 25 ^oC

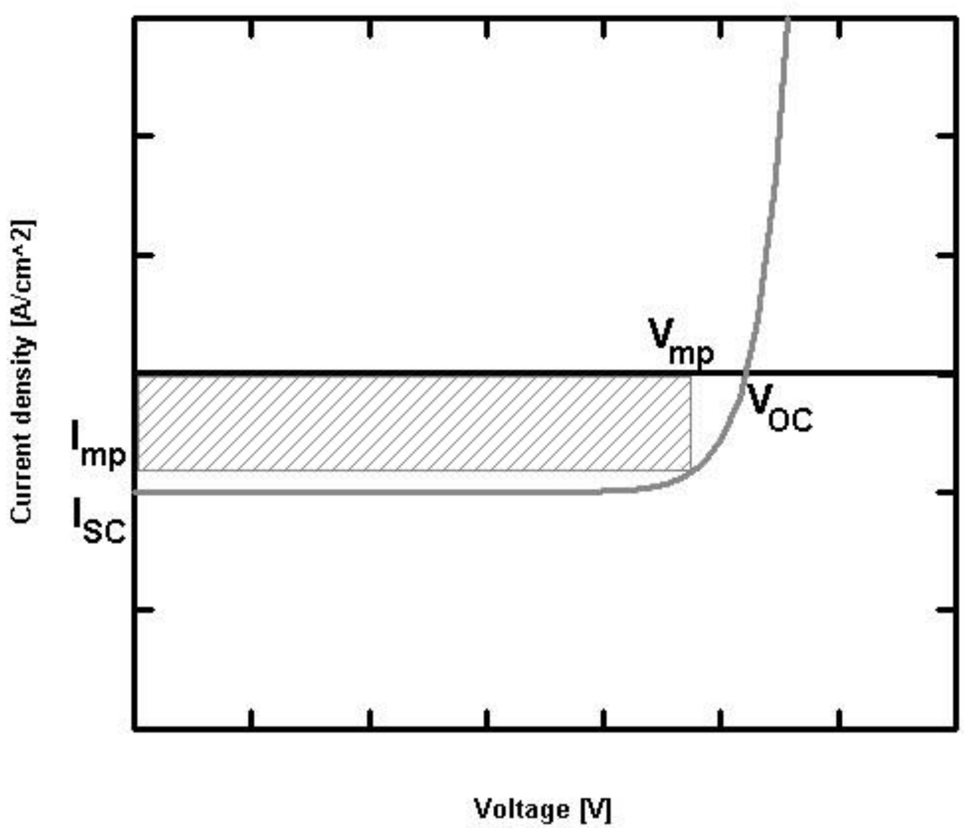
FF

- The fill factor (FF) is defined as the ratio

$$FF = I_m \cdot V_m / I_{SC} \cdot V_{OC}$$

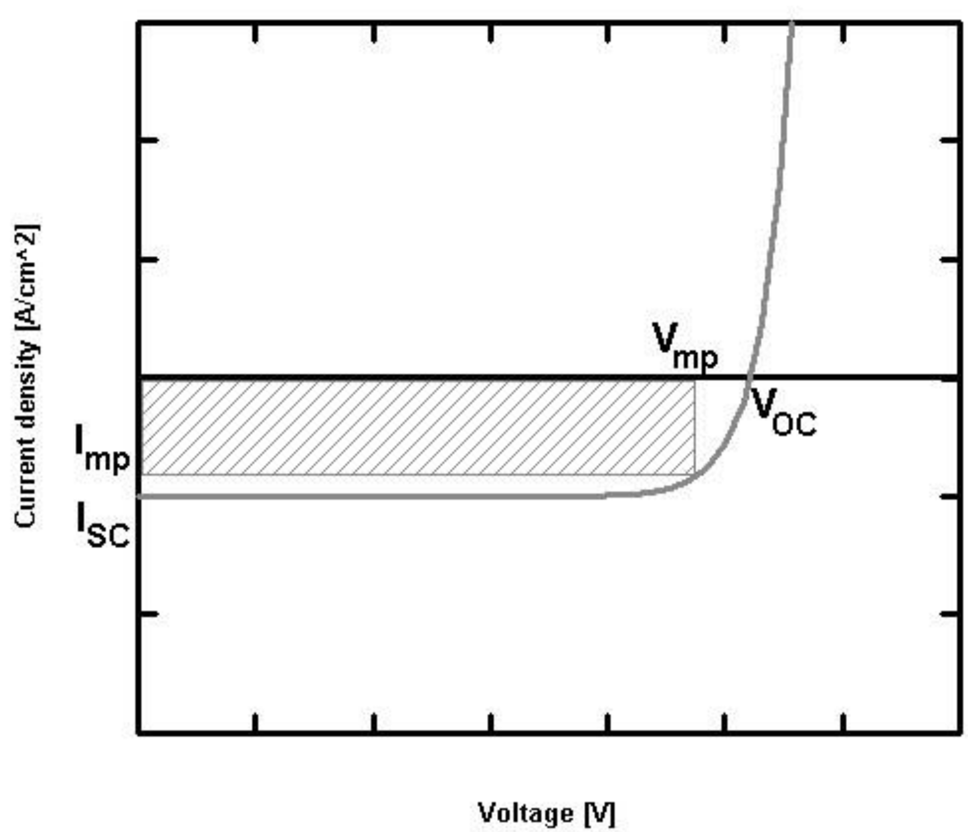
- η can be related to I_{SC} and V_{OC} through FF

$$\eta = I_{SC} \cdot V_{OC} \cdot FF / P_{sun}$$

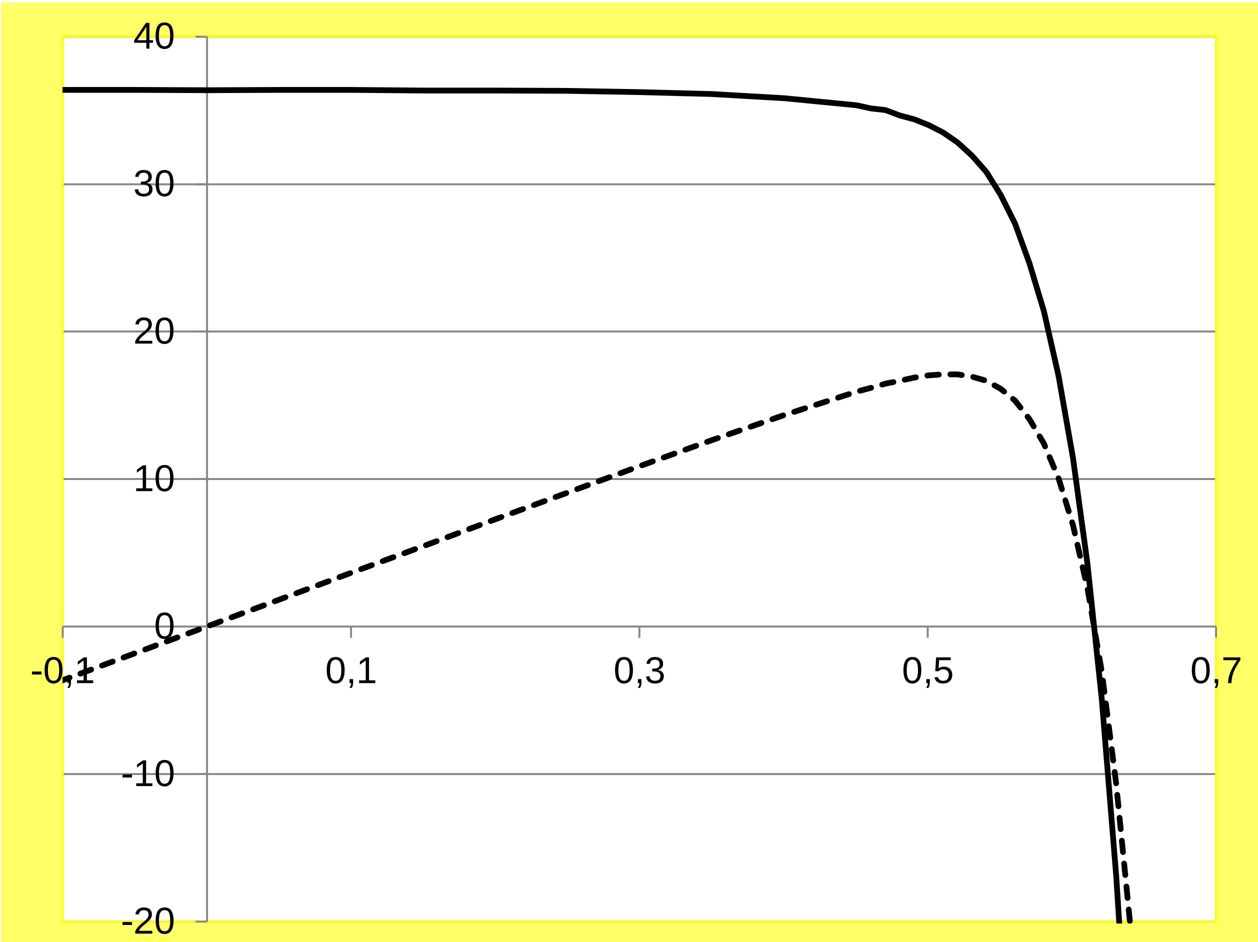


FF

- FF is determined by the shape of the I-V curve
  - Ideality factor
  - Series resistance
  - Shunt resistance
  - …



Typical solar cell characteristics



SETTINGS:

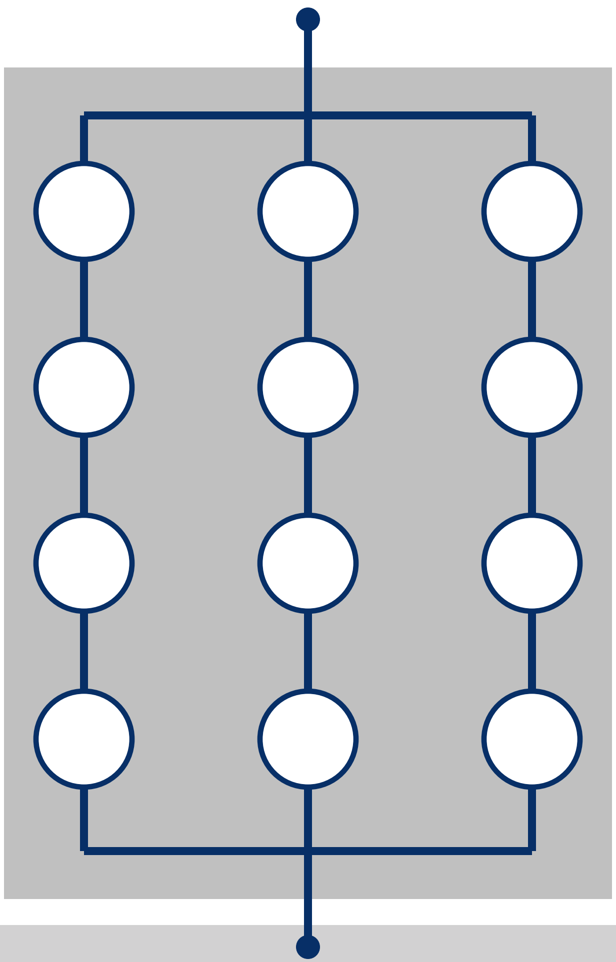
Cell Area: 156,25 cm^2
Temperature: 25 ^oC
Sun Intensity: 100 mW/cm^2

CELL PARAMETERS:

Efficiency:	17,1 %
Voc:	615 MV
Jsc:	36,4 mA/cm^2
FF:	76,4 %
V_{mp}:	511 MV
J_{mp}:	33,5 mA/cm^2
J_{01}:	$5{,}6\cdot10^{-10}$ mA/cm^2
J_{02}:	$1{,}3\cdot10^{-4}$ mA/cm^2
R_s	$2{,}5\cdot10^{-3}$ Ω
R_{sh}:	26,2 Ω

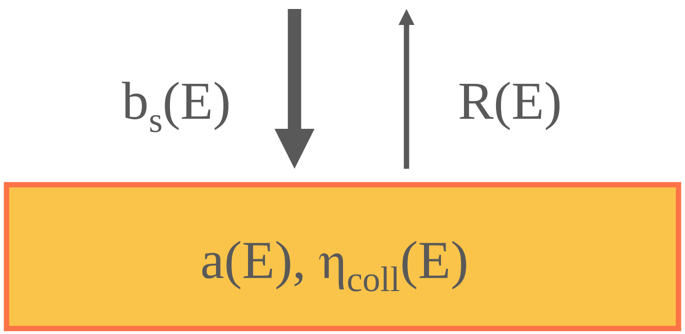
Intermezzo – solar modules

- The photovoltage of one solar cell is small (~0.5 V).
- Several solar cells are connected in series in a solar module in order to obtain useful output voltages.
- The output voltage of a string within a module equals the sum of the individual cell output voltages.
- The output current of a module is the sum of the individual string output currents.

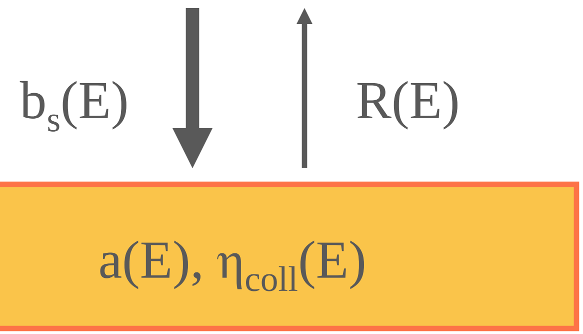


Photogenerated current

- The photocurrent depends on several factors
  - The incident irradiation ($b_s(E)$)
  - The amount of reflected light from the solar cell
    - Reflectance ($R(E)$)
  - The amount of light absorbed within the solar cell
    - Absorbance ($a(E)$)
  - The probability of collecting photogenerated charge carriers at an external terminal
    - Collection efficiency ($\eta_{coll}(E)$)
  - The area (A) of the solar cell



Photogenerated current



$$I_{SC}(E) = q \cdot A \cdot ([1 - R(E)] \cdot \eta_{coll}(E) \cdot a(E) \cdot b_s(E))$$

QE

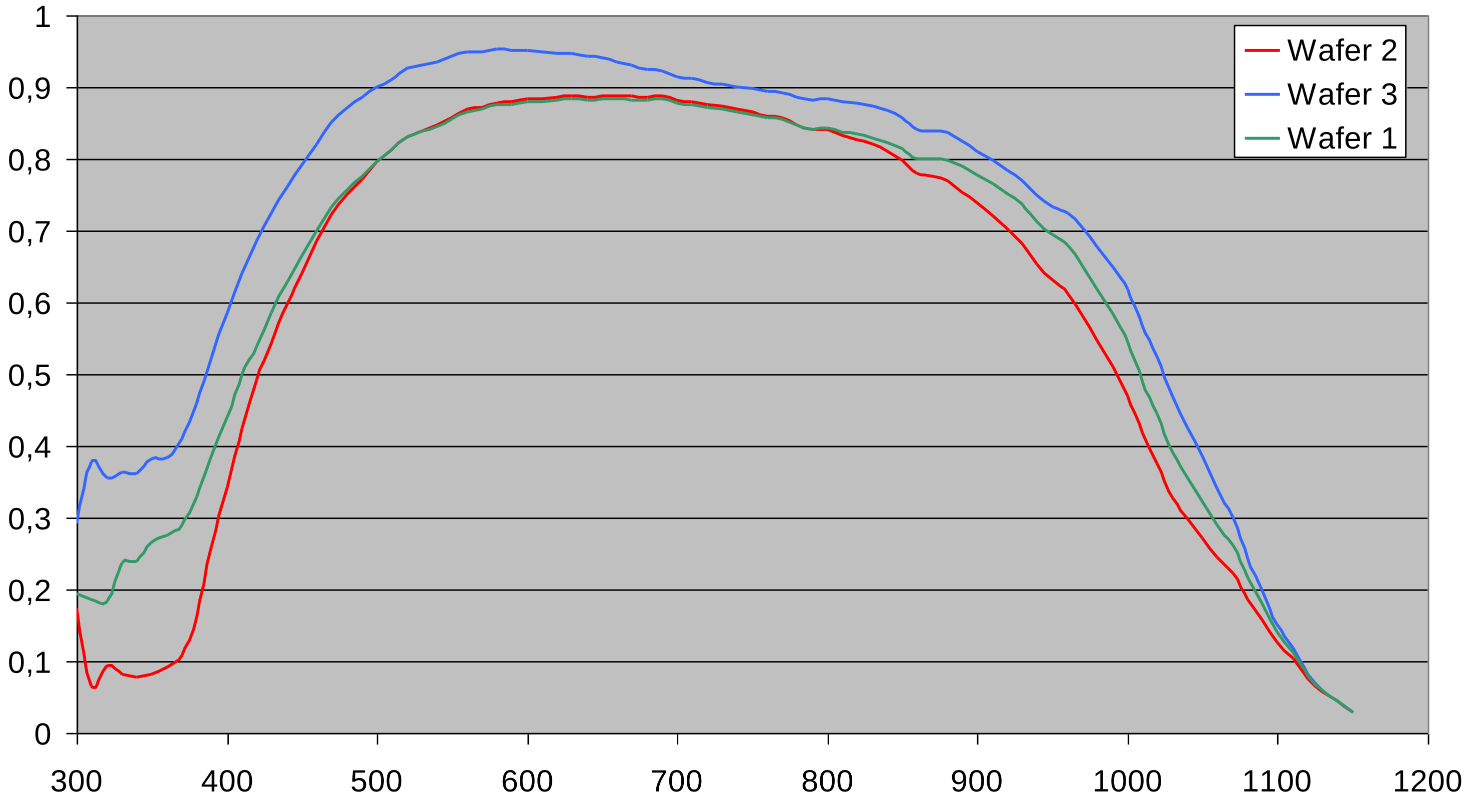
- The quantum efficiency ($QE(E)$) is a measure of the probability of an incident photon generating one electron that is successfully collected at the terminals
- The **external** quantum efficiency ($EQE(E)$) is given by

$$EQE(E) = [1 - R(E)] \cdot \eta_{coll}(E) \cdot a(E)$$
$$I_{SC}(E) = q \cdot A \cdot EQE(E) \cdot b_s(E)$$

- The **internal** quantum efficiency ($IQE(E)$) neglects reflective losses, and is given by

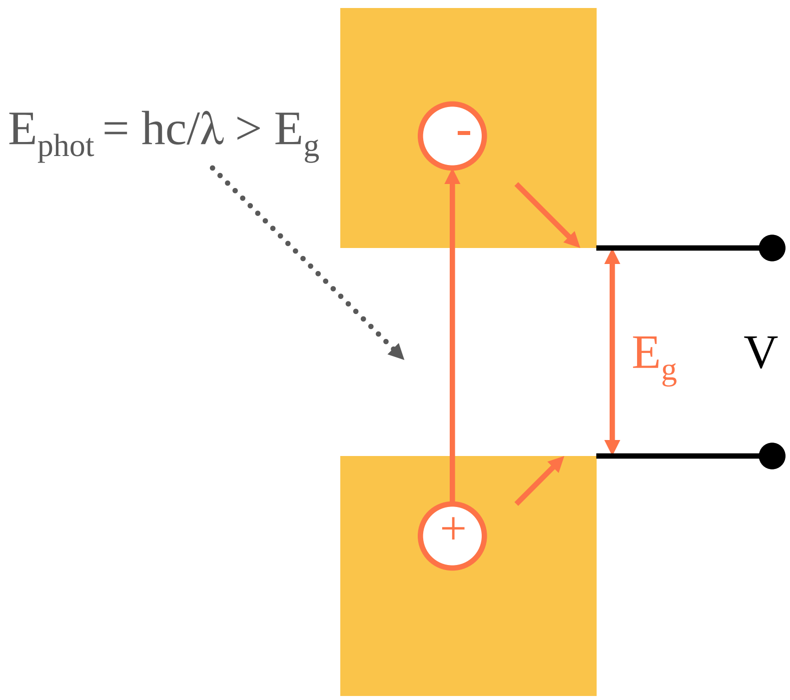
$$IQE(E) = \eta_{coll}(E) \cdot a(E)$$
$$I_{SC}(E) = q \cdot A \cdot [1 - R(E)]\, IQE(E) \cdot b_s(E)$$

EQE



1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
300
400
500
600
700
800
900
1000
1100
1200
Wafer 2
Wafer 3
Wafer 1

Solar cell operation



Solar cell operation

- The power generation in a solar cell can be divided into three steps

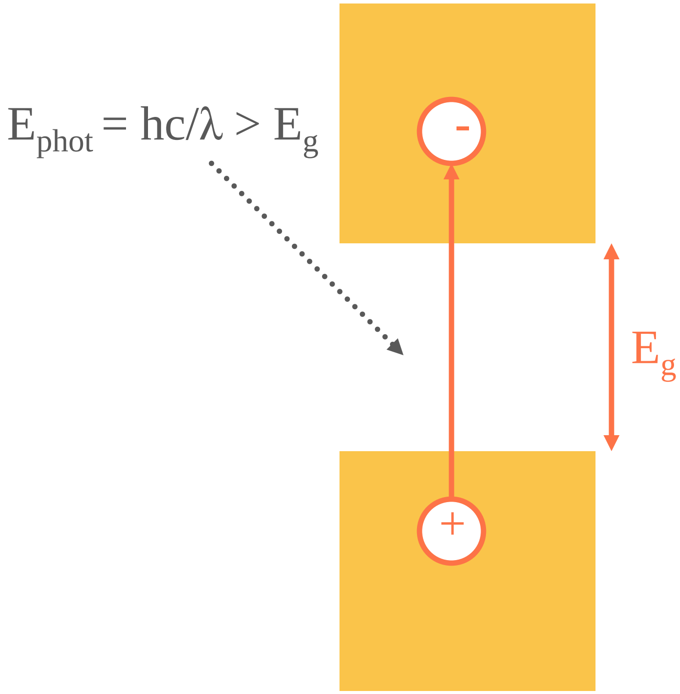
  1. Photogeneration of charge carriers
  2. Separation of charge carriers
  3. Transport of the charge carriers from the point of generation to the external electrical connections

- An efficient solar cell must perform all these tasks efficiently

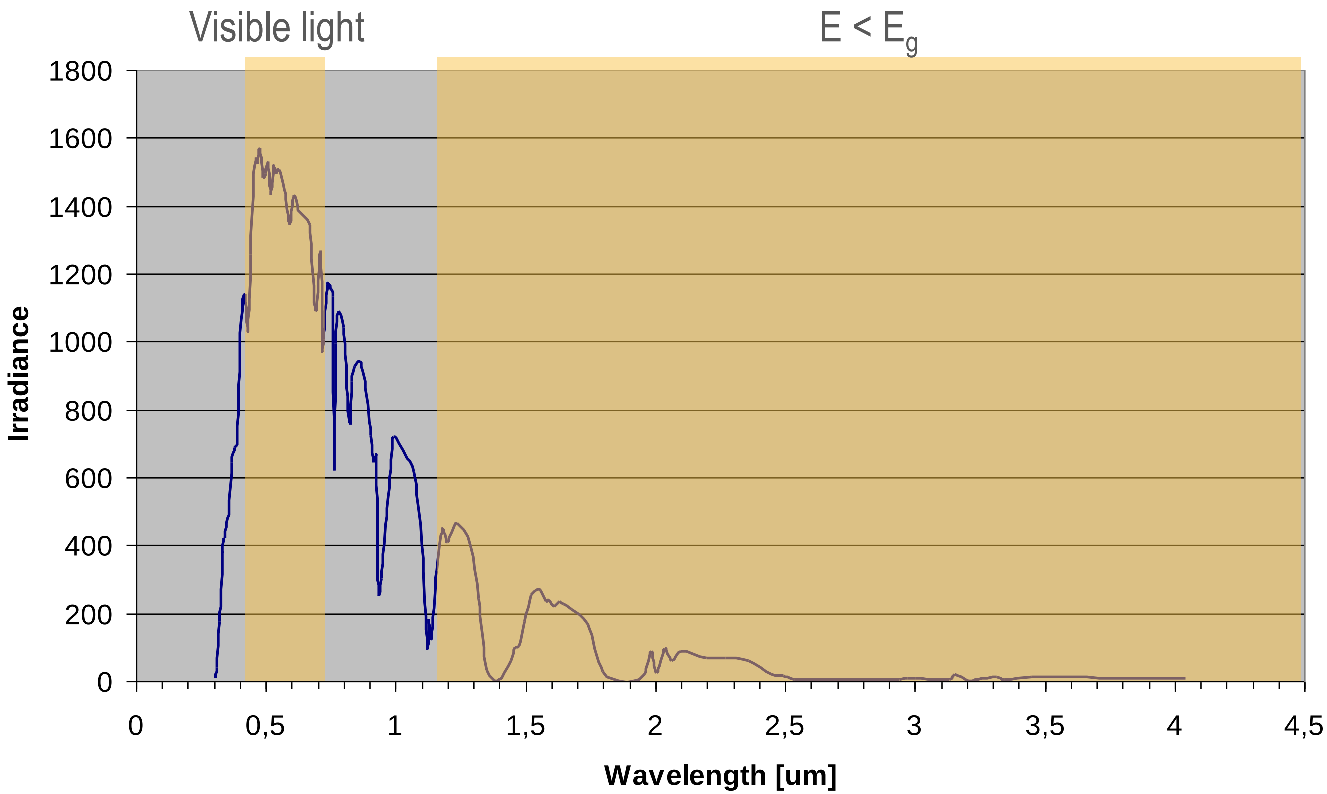
Photogeneration

<u>Design rules</u>

1. Use materials with several electronic energy levels
   - Semiconductors, polymers…
2. Trap as much sunlight as possible
   - Use anti-reflective coatings and texturing
   - Minimize contact shading
3. Avoid excessive transmission
   - Weakly absorbing materials require optically thick solar cells
   - Strongly absorbing materials can be used for thin film solar cells



The solar spectrum

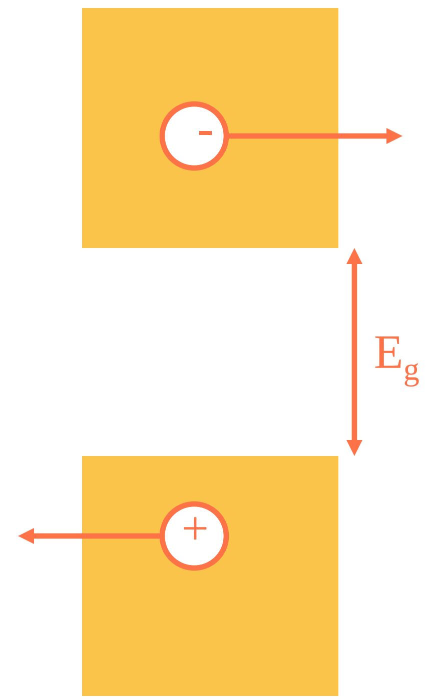


Separation

Design rules

1. Asymmetry must be built into the solar cell in order to obtain a net current
   - Built-in electrical fields
   - Combinations of hole and electron conductors
   - …

2. In order to obtain a high V_{oc}, the energy separation of the electrons and holes should be maintained as large as possible until the carriers are collected

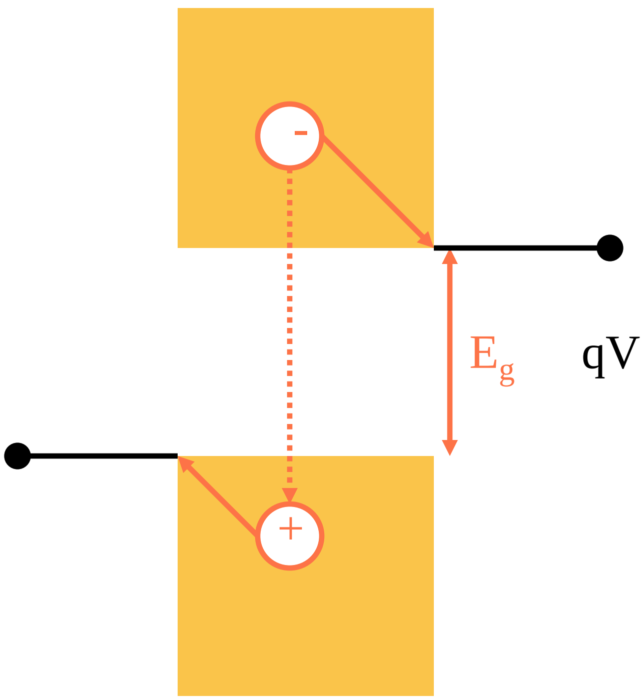


Transport

<u>Design rules</u>

1. Minimize resistive losses
   - Series resistance
   - Shunt resistance

2. Avoid recombination of charge carriers
   - Material (bulk) recombination
   - Surface (interface) recombination

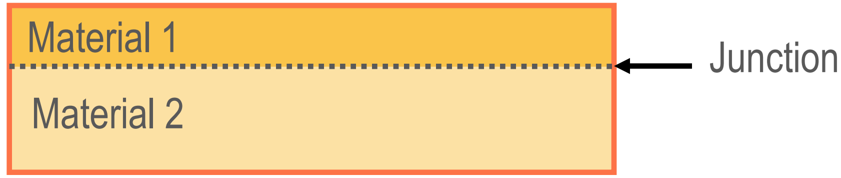


Solar cell terminology

Solar cell technologies – junction types

- **Homojunction:** the junction acting as a driving force in the solar cell is made from one material
- Examples: almost all wafer-based silicon solar cells

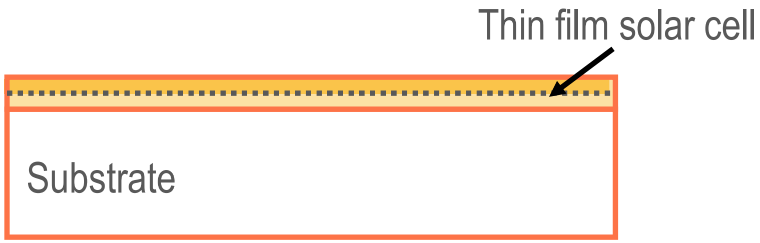
- **Heterojunction:** the junction acting as a driving force is made by depositing one material atop another material
- Examples: Many thin film solar cells, the wafer-based HIT solar cell from Panasonic (Sanyo)…



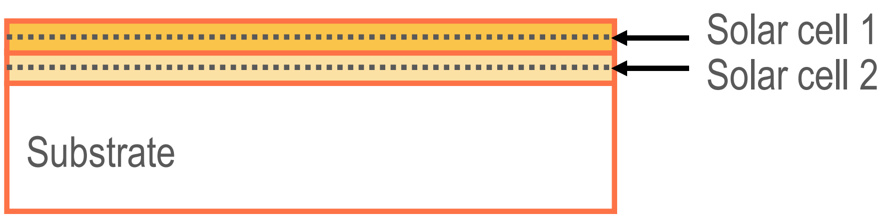
Solar cell technologies – generations

- **1st generation solar cells:** solar cells where the substrate acts as the absorbing material
- Examples: all industrial, wafer-based silicon solar cells

- **2nd generation solar cells:** potentially more cost-effective technologies
- Examples: thin film solar cells, electrochemical solar cells, …



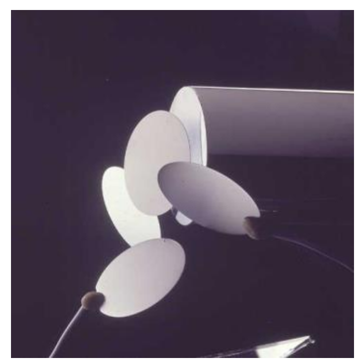
- **3rd generation solar cells:** Solar cells with enormous efficiency potential
- Examples: tandem solar cells, …



Wafer-based solar cells

- The most common type of solar cells by far

- Mostly homo-junction solar cells
  - Main exeption: HIT (Sanyo)
- Substrate materials
  - Silicon
    - Monocrystalline (sc-Si)
    - Multicrystalline (mc-Si)
  - Compound semiconductors
    - GaAs…


sc-Si


mc-Si

Image: Topsil, IFE

Wafer-based solar cells

- Advantages
  - Efficient
  - Relatively cost-efficient
  - Mature technology
  - Abundant materials

- Disadvantages
  - Material and energy consumption

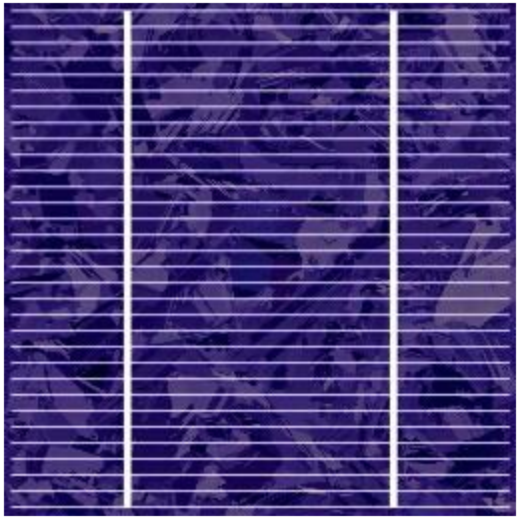
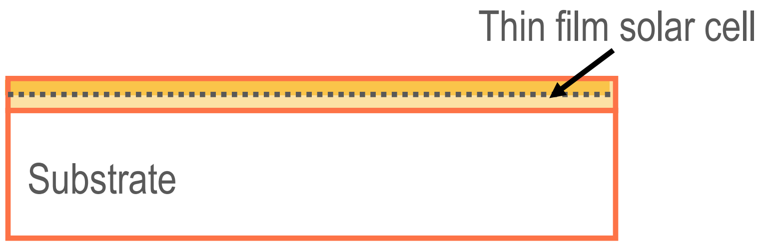


Image: Topsil, IFE

Thin film solar cells



- Thin film solar cells are slowly growing into the solar cell market

- Materials
  - Silicon
    - Amorphous
    - Nano, micro and monocrystalline
  - Compound semiconductors
    - CIGS, CdTe, …
  - Perovskites!

Thin film solar cells

- Advantages
  - Low material and energy consumption
  - Potentially very efficient
- Disadvantages
  - Material issues
  - Immature technology

Other solar cell concepts

- Electrochemical cells
  - Grätzel cells
  - Dye-sensitized solar cells
- Advantages
  - Potentially cost-effective
  - Potentially low-tech
- Disadvantages
  - Efficiency
  - Stability

- Organic solar cells
- Advantages
  - Potentially cost-effective
- Disadvantages
  - Efficiency
  - Stability
  - Immature technology

The past and present of solar cells

Solar cell history

Year	Event
1839	Photovoltaic effect in electrolyte (Becquerel, F)

Image: Wikipedia

Solar cell history

Year	Event
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1873	Photovoltaic effect in solid state - Se (Smith, UK)

Smith, Willoughby
Nature **7**, 303 (20 February 1873) |
doi:10.1038/007303e0
Effect of Light on Selenium During the Passage of An Electric Current
BEING desirous of obtaining a more suitable high resistance for use at the Shore Station in connection with my system of testing and signalling during the submersion of long submarine cables, I was induced to experiment with, bars of selenium, a known metal of very high resistance...

Image: Wikipedia

Solar cell history

Year	Event
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1883	Large area solar cell – thin film Se (Fritts, USA)

The current, if not wanted immediately, can be either stored where produced, in storage batteries, . . . or transmitted a distance and there used"

Fritts 1883

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Image: Wikipedia

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1954	6% Si solar cell (Chapin/Bell Lab, USA)


Bell System Solar Battery Converts Sun's Rays into Electricity!

Bell Telephone Laboratories invention has great possibilities for telephone service and for all mankind

Images: Wikipedia

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1958	Vanguard I – first solar powered satelite

Image: Wikipedia

Inhabitat

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1973	Global oil crisis

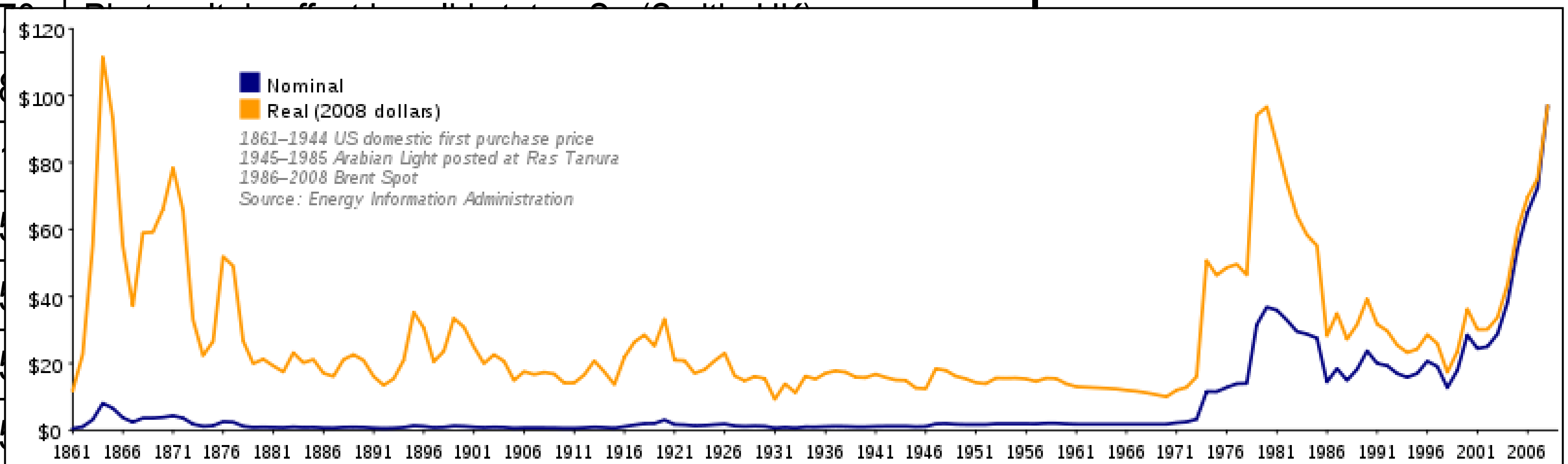

Image: Wikipedia

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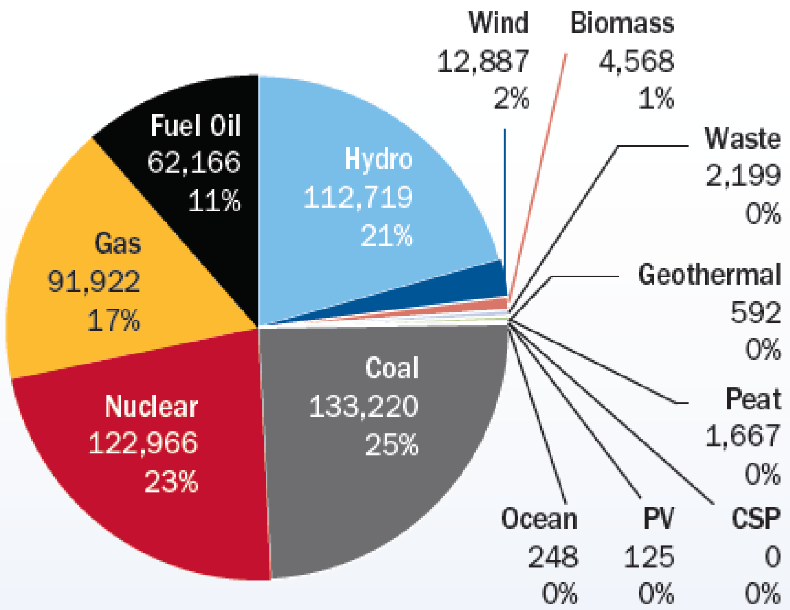
1973	Global oil crisis
1994	ScanWafer AS established

European power production capacity 2000…

FIGURE 2.3: EU POWER MIX 2000



Data: EWEA (2014)

…and in 2013

FIGURE 2.3: EU POWER MIX 2000

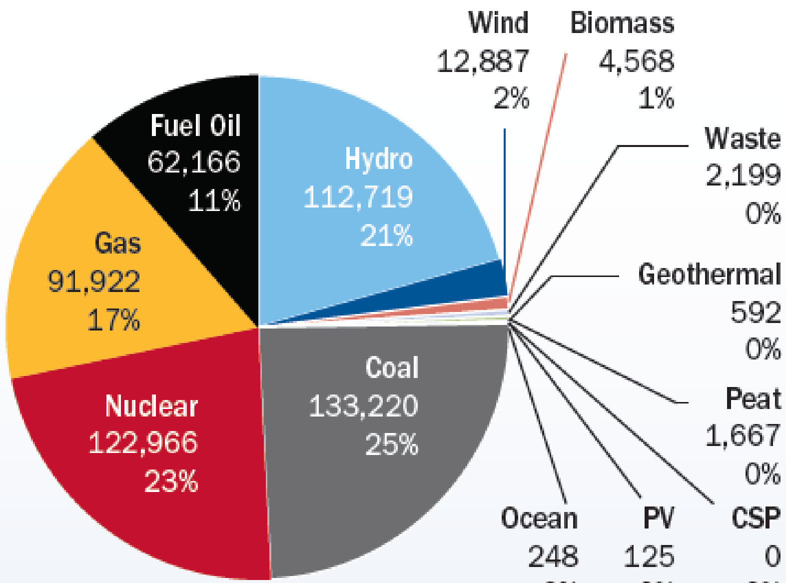
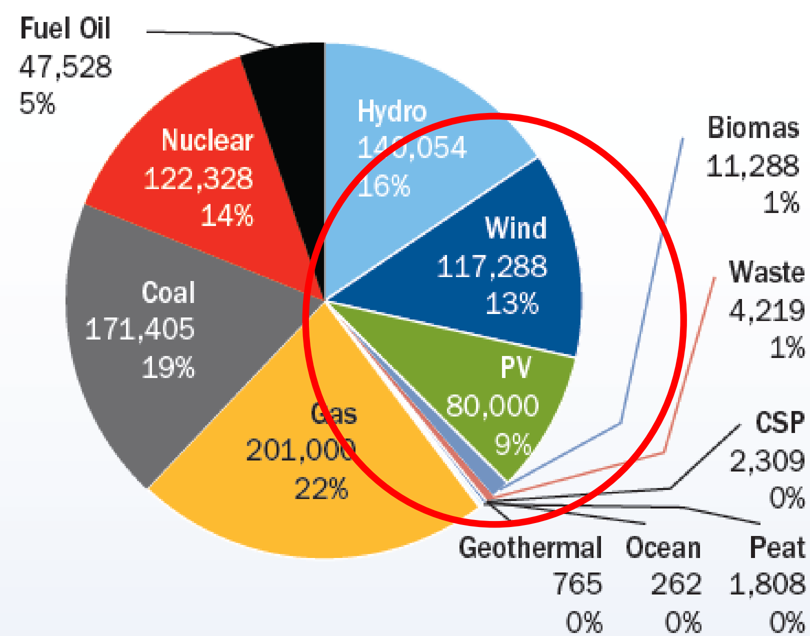
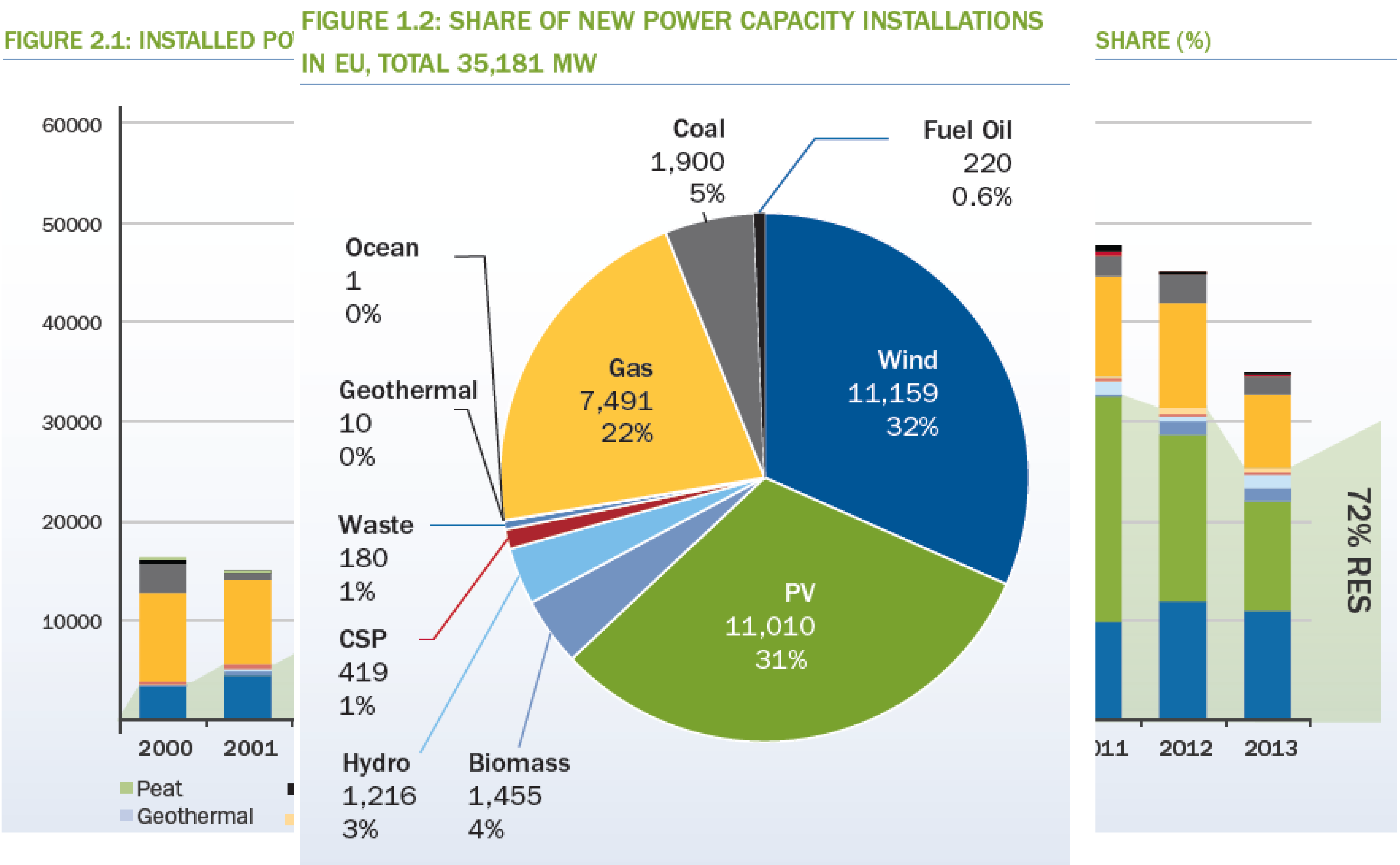


FIGURE 2.4: EU POWER MIX 2013



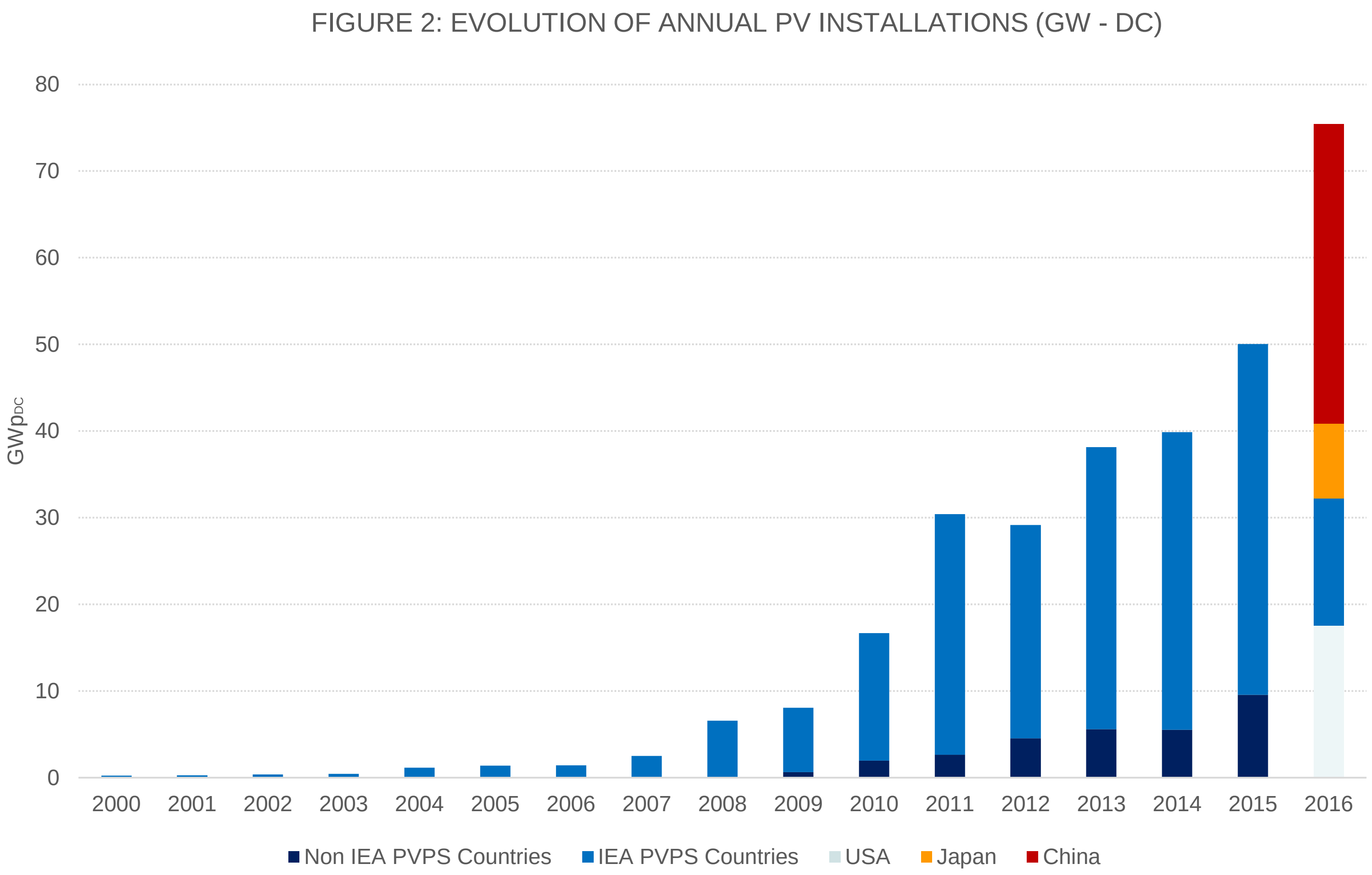
Data: EWEA (2014)

What is new?



Data: EWEA (2014)

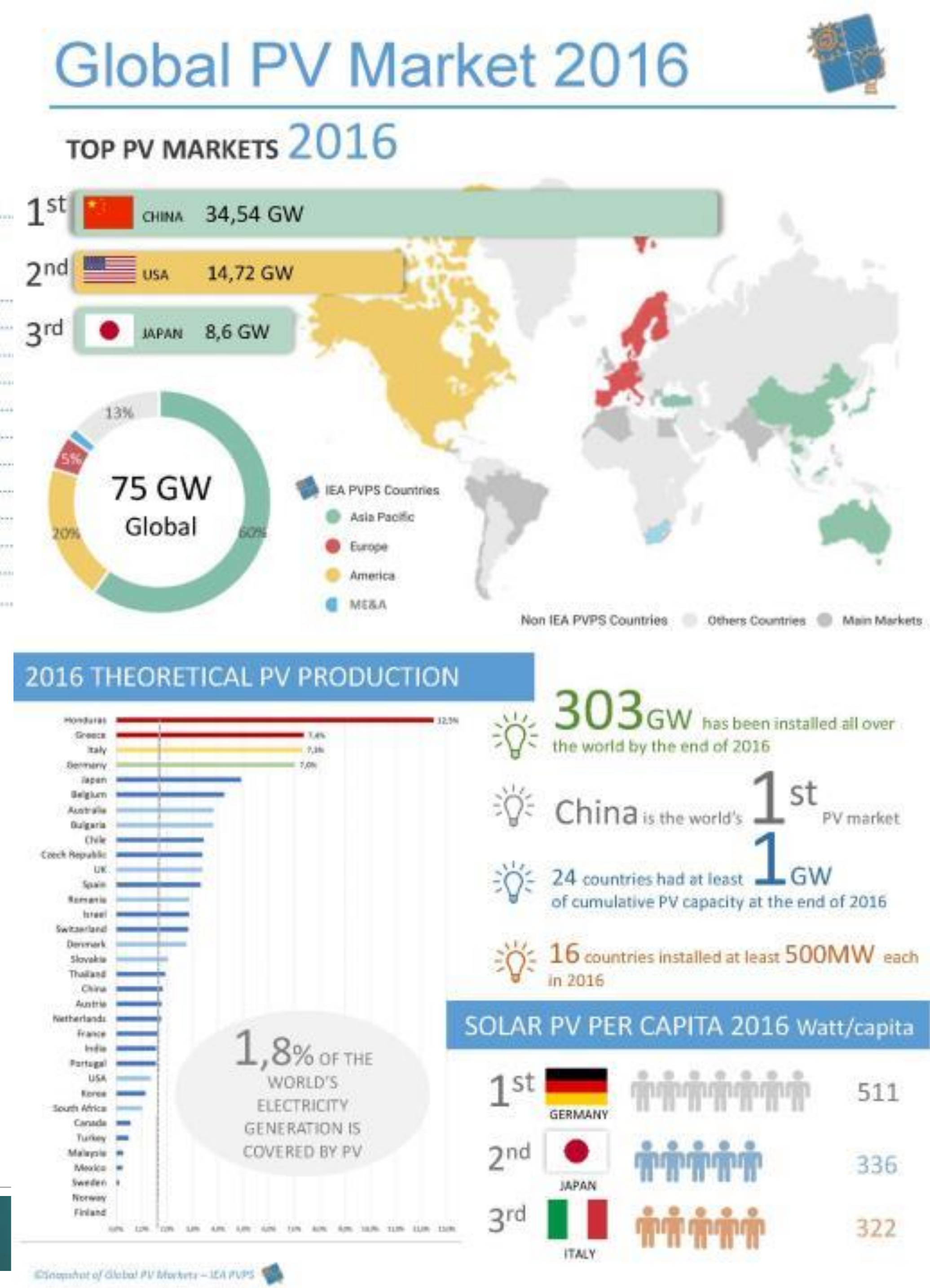
The world of solar cells 2017 – a snapshot



IEA-PVPS 2017

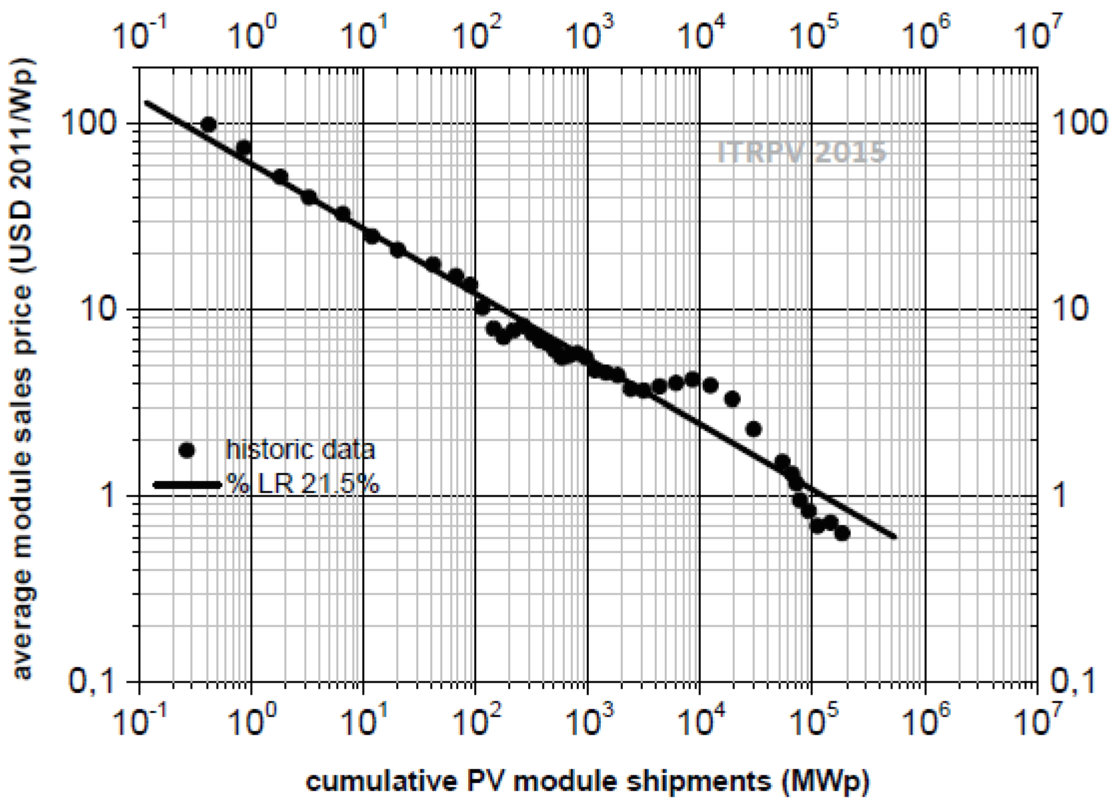
TABLE 1: TOP 10 COUNTRIES FOR INSTALLATIONS AND TOTAL INSTALLED CAPACITY IN 2016

TOP 10 COUNTRIES IN 2016 FOR ANNUAL INSTALLED CAPACITY			TOP 10 COUNTRIES IN 2016 FOR CUMULATIVE INSTALLED CAPACITY		
1	China	34,5 GW	1	China	78,1 GW
2	USA	14,7 GW	2	Japan	42,8 GW
3	Japan	8,6 GW	3	Germany	41,2 GW
4	India	4 GW	4	USA	40,3 GW
5	UK	2 GW	5	Italy	19,3 GW
6	Germany	1,5 GW	6	UK	11,6 GW
7	Korea	0,9 GW	7	India	9 GW
8	Australia	0,8 GW	8	France	7,1 GW
9	Philippines	0,8 GW	9	Australia	5,9 GW
10	Chile	0,7 GW	10	Spain	5,5 GW



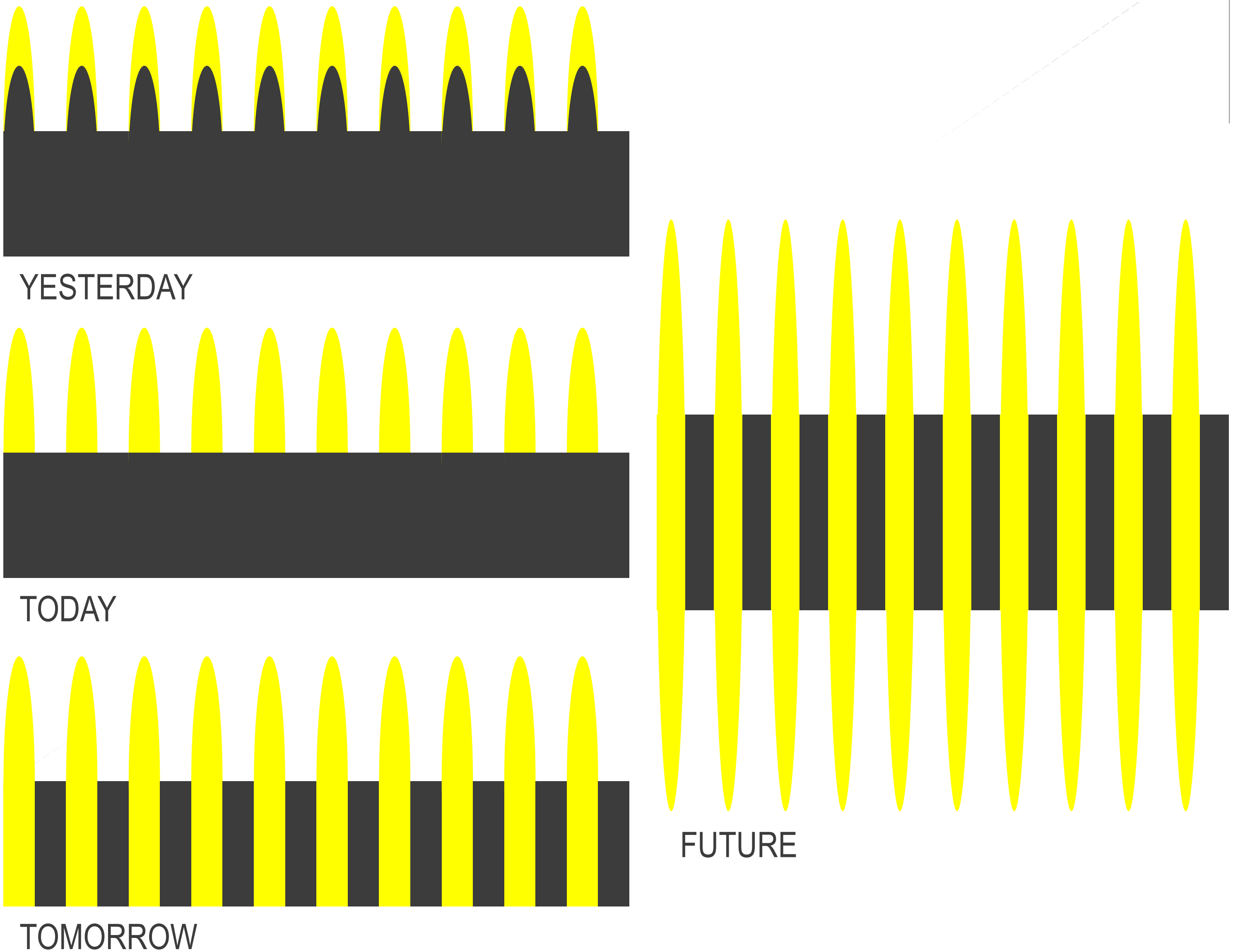
IEA-PVPS 2017/Scatec Solar

The solar revolution – cost



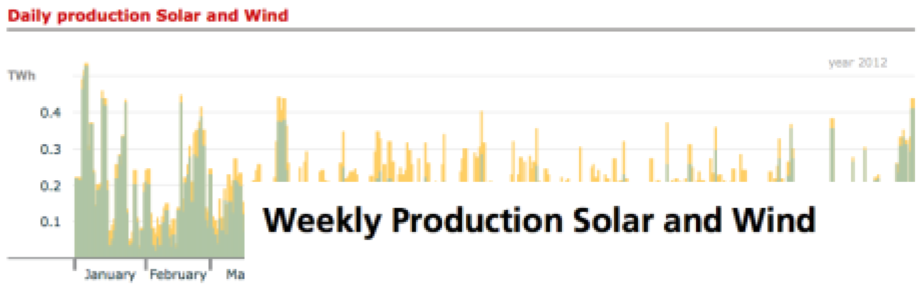
ITRPV 2015

How to think big enough?

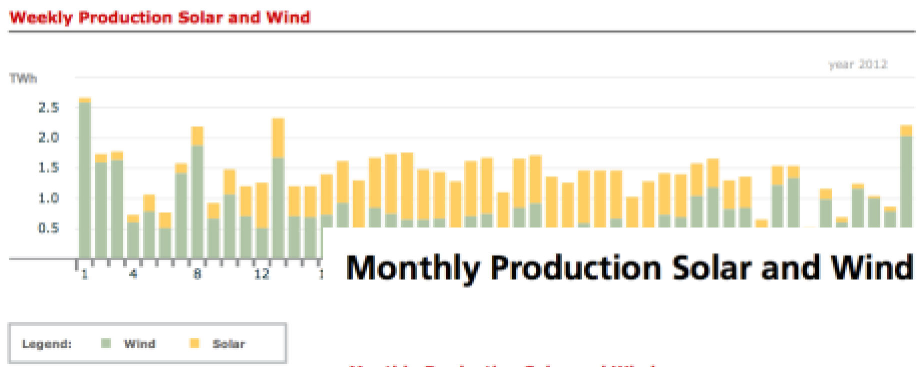


How to think big enough?

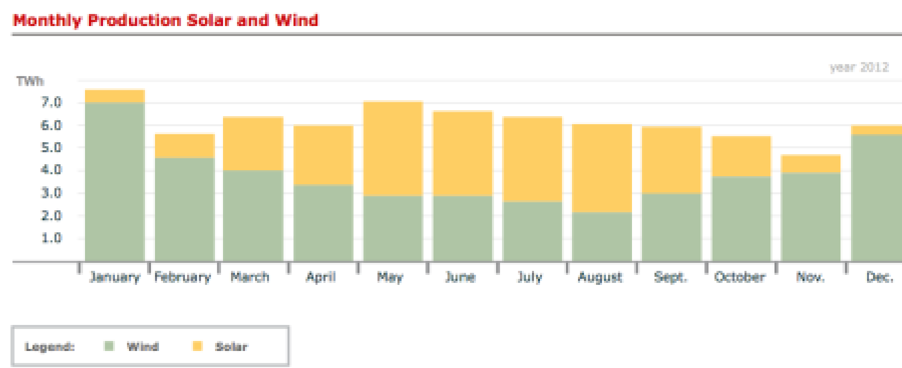
Daily production Solar and Wind



Weekly Production Solar and Wind



Monthly Production Solar and Wind



How to think big enough?

- Forecasting
- Demand side management
- Interconnection/infrastructure
  - Markets, geographical spread
- Storage and energy conversion
  - Batteries
  - Hydrogen
- Backup

TESLA

The solar revolution – 1

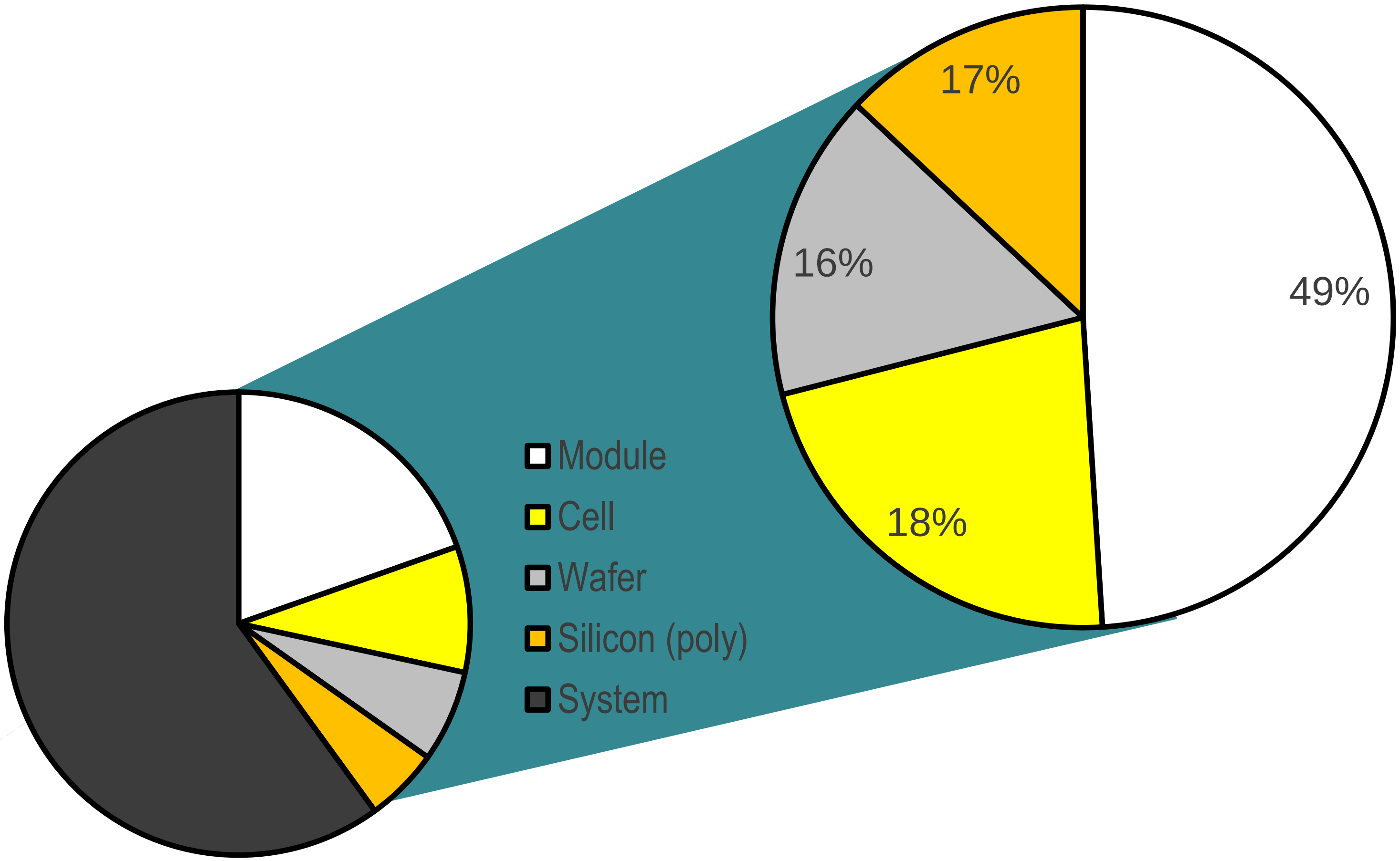
- The global solar cell industry is suddenly quite important
  - <0.1 % of global electricity production as late as in 2009
  - 1% in 2014
  - 2% in 2017
  - 5% in mid 2020s, depending on growth rates
  - …

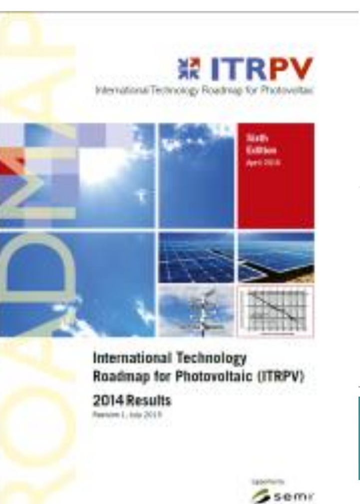
- The rapid growth continues!
  - ~56 GW_p in 2015
  - ~75 GW_p in 2016
  - ~80? GW_p in 2017 (2* production in 2013/2014)
  - …

The solar revolution – 2

- Important topics ahead
  - Solar cell and module technology
    - Increased efficiency
    - Reduced production costs along the entire production value chain
    - Reduced environmental footprint and recyclability
    - Improved field performance
    - Extended system lifetime
  - System operation and maintenance becomes increasingly important
    - High performance producers must demonstrate benefits in a system setting
  - The potential for radical breakthroughs remains significant
    - Still, evolutionary developments remain tremendously powerful!

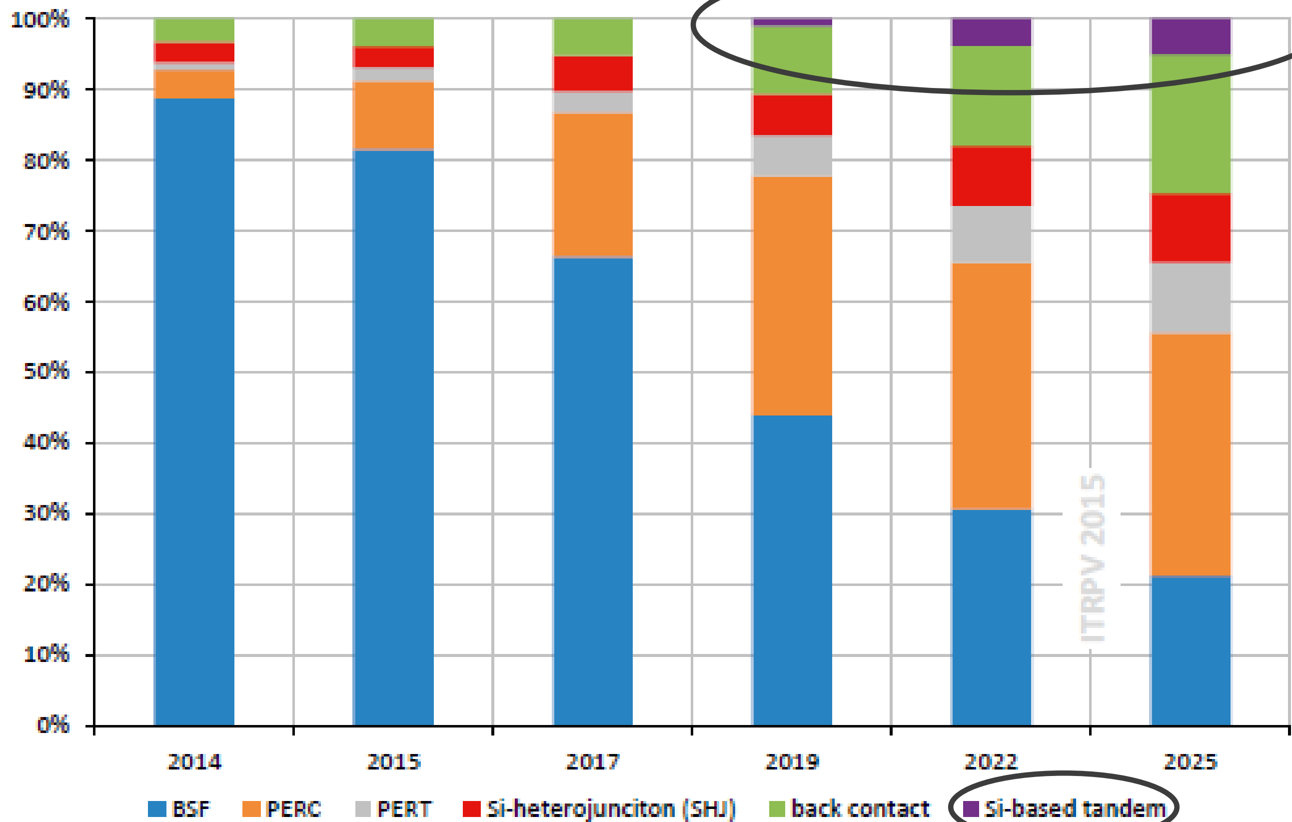
Efficiency *really* matters!

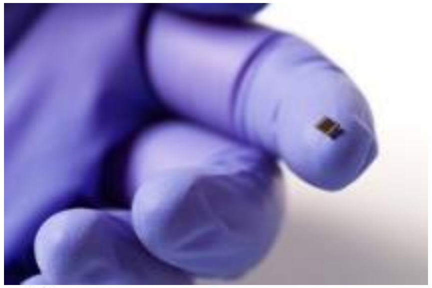


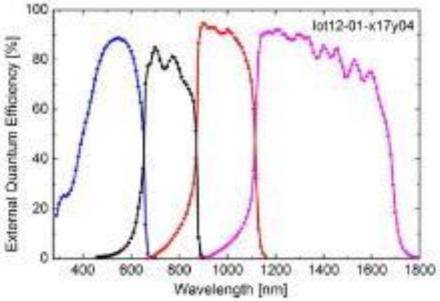


ITRPV Q2 2015

Evolution or revolution?







ITRPV 2015, FhG ISE 2015

Silicon-based solar cell technology

- Crystalline Si technology completely dominate today
  - Rapid roll-out demonstrated!
  - Decent efficiencies
  - Robust technology
  - Extra PRO: this is a Norwegian speciality!

- Efficiency is requried to balance the BOS costs
  - At least in «normal» use, many niche opportunities also exist

- Efficiencies on the rise!
  - Evolutionary developments are extremely effective
    - Good tradition for evolutionary developments in Norway!
  - Revolutionary concepts have hitherto struggled to grow with the market

What do the numbers mean?

75 000 MW_p/y ~ 400 – 500 km^2/y

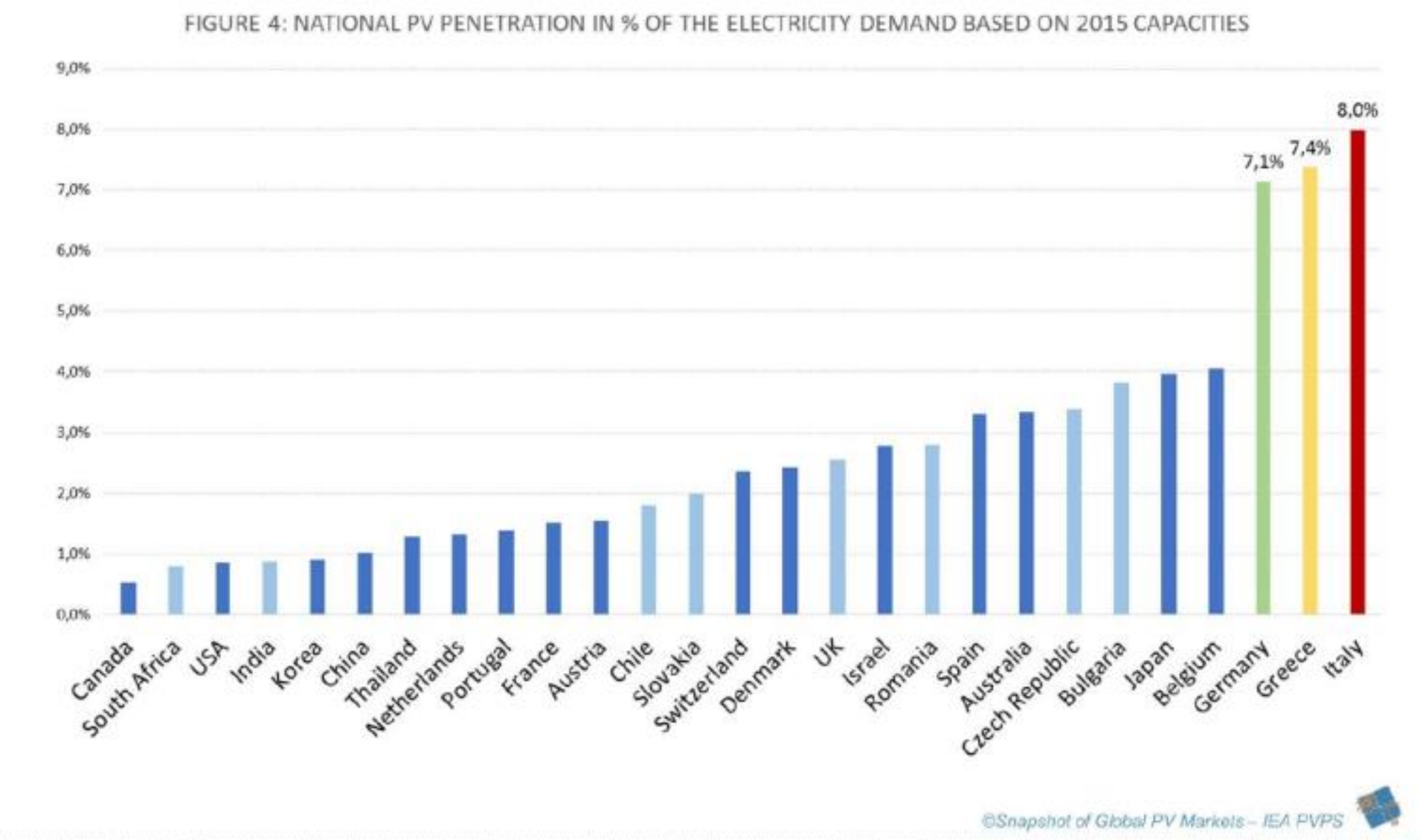
300 million solar panels/y

5 billion solar cells/y

~ 1 unit/production line/second(-ish)

75 000 MW_p/y ~ 75 TWh/y ~ >2 entire Denmark/y

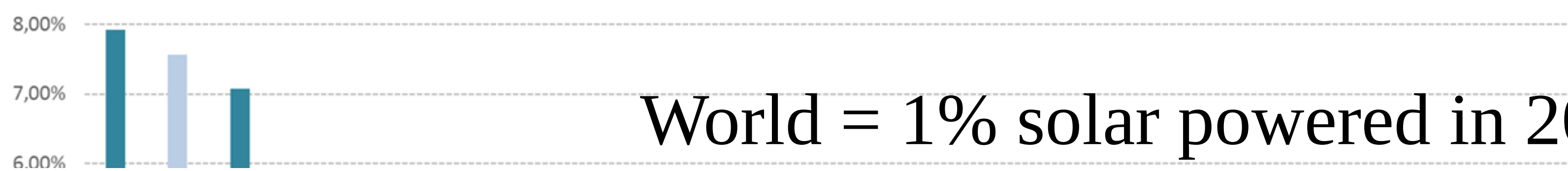
Making a real difference



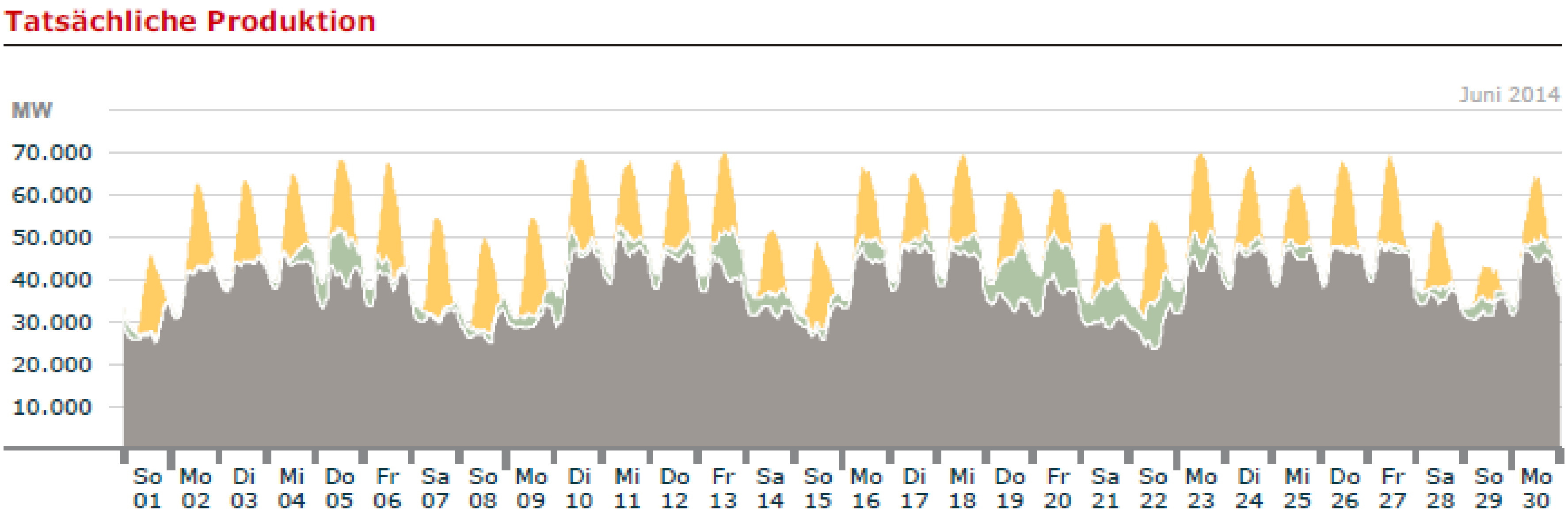
Data: IEA-PVPS (2016)

Modern solar cell history

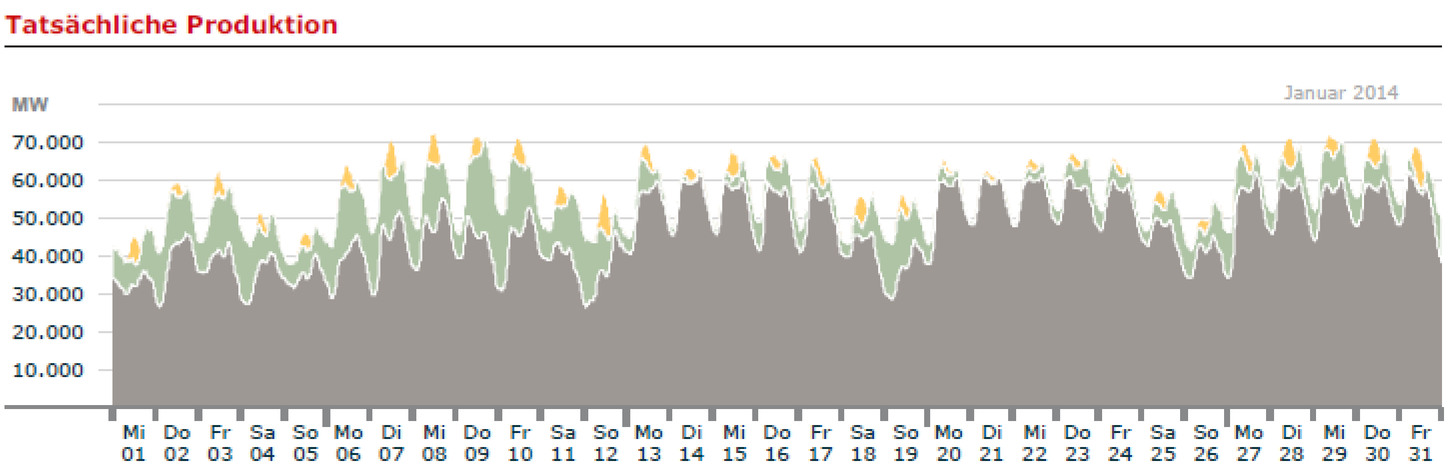
FIGURE 4: 2014 THEORETICAL PV PRODUCTION



World = 1% solar powered in 2014!

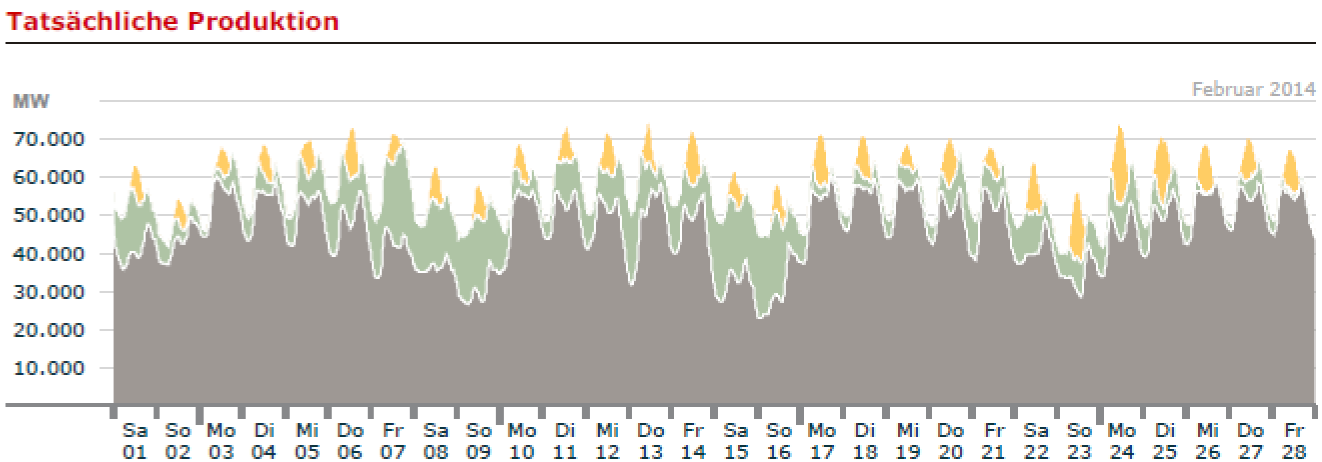


Data: IEA-PVPS (2015), Fraunhofer ISE (2015)



Fraunhofer ISE

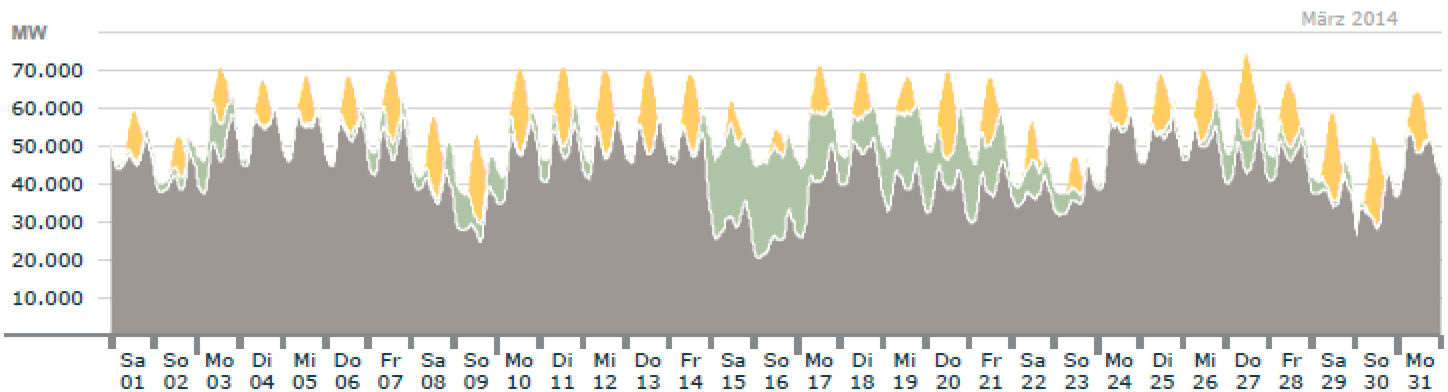
Data: Fraunhofer ISE (2015)



Fraunhofer ISE

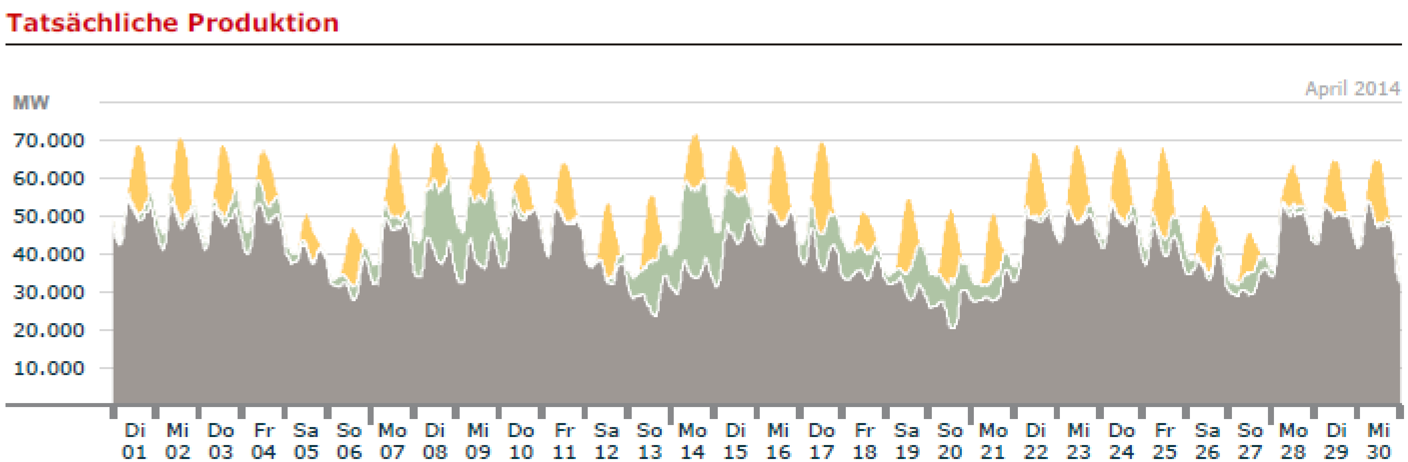
Data: Fraunhofer ISE (2015)

Tatsächliche Produktion

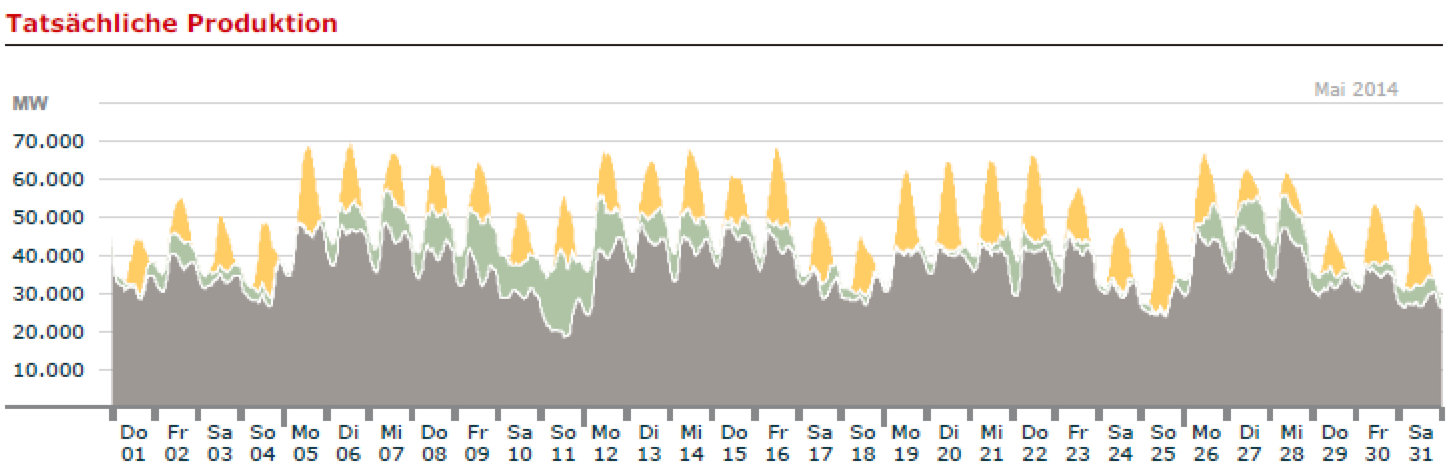


Fraunhofer ISE

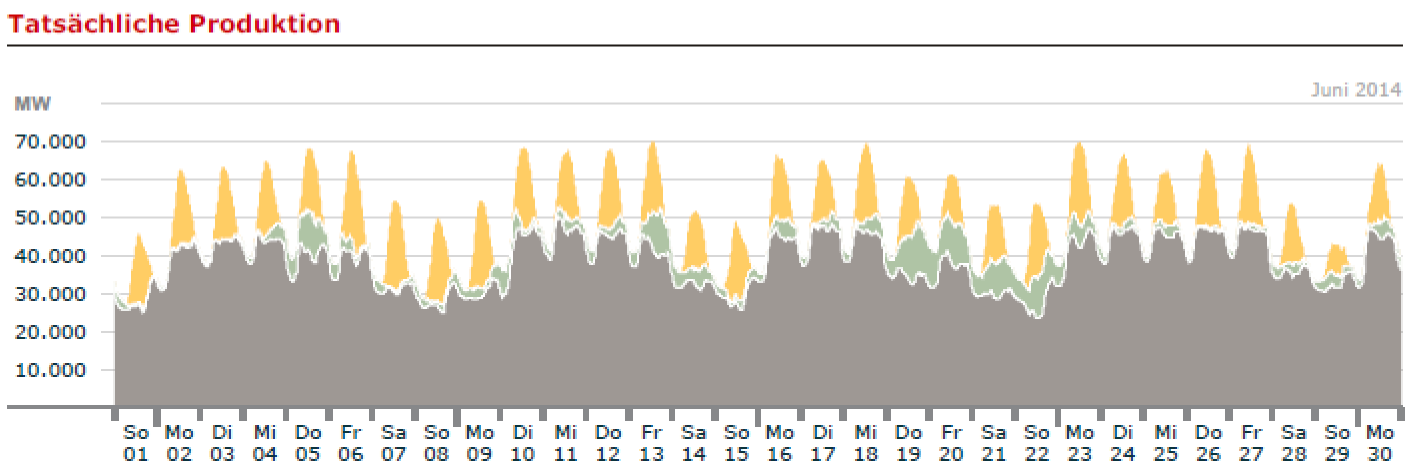
Data: Fraunhofer ISE (2015)



Data: Fraunhofer ISE (2015)

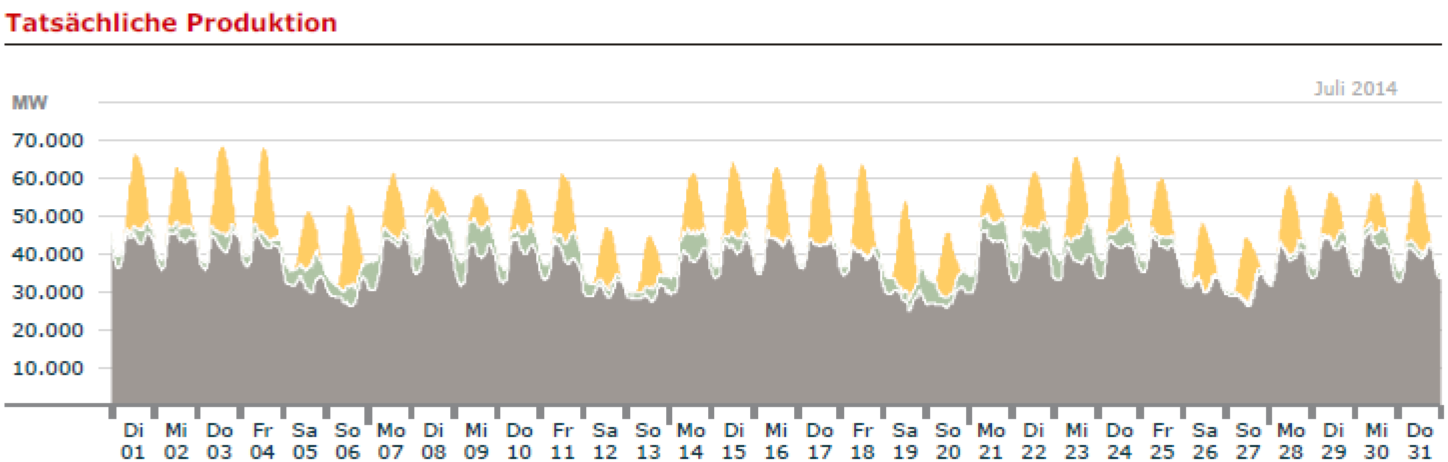


Data: Fraunhofer ISE (2015)



Fraunhofer ISE

Data: Fraunhofer ISE (2015)



Data: Fraunhofer ISE (2015)

W_p

- Most people use $/kWh as a measure of energy costs
- Solar cell output depends on local irradiation
  - The photovoltaic community uses $\$/W_p$
  - A 1 W_p cell is a cell delivering 1 W at STC
    - STC = 1 kW per 1 m^2
  - Solar cell production data are given in W_p
- Current price of solar modules: < 1 $\$/W_p$

Solar cell history

Year	Event
1839	Photovoltaic effect in electrolyte (Becquerel, F)
1873	Photovoltaic effect in solid state - Se (Smith, UK)
1883	Large area solar cell – thin film Se (Fritts, USA)
1914	1% Se solar cell – self-powered photometer for photography
1954	6% Si solar cell (Chapin/Bell Lab, USA)
1954	6% Cu_2S/CdS solar cell (Reynolds/US Air Force, USA)
1956	6% GaAs solar cell (Jenny/RCA Lab, USA)
1958	Vanguard I – first solar powered satelite
1970	GaAlAs/GaAs heterostructure solar cell (Alferov/Ioffe, SSSR)
1973	Global oil crisis
1994	ScanWafer AS established
2012	~100 GW_p solar cells installed, ~40 GW_p production capacity

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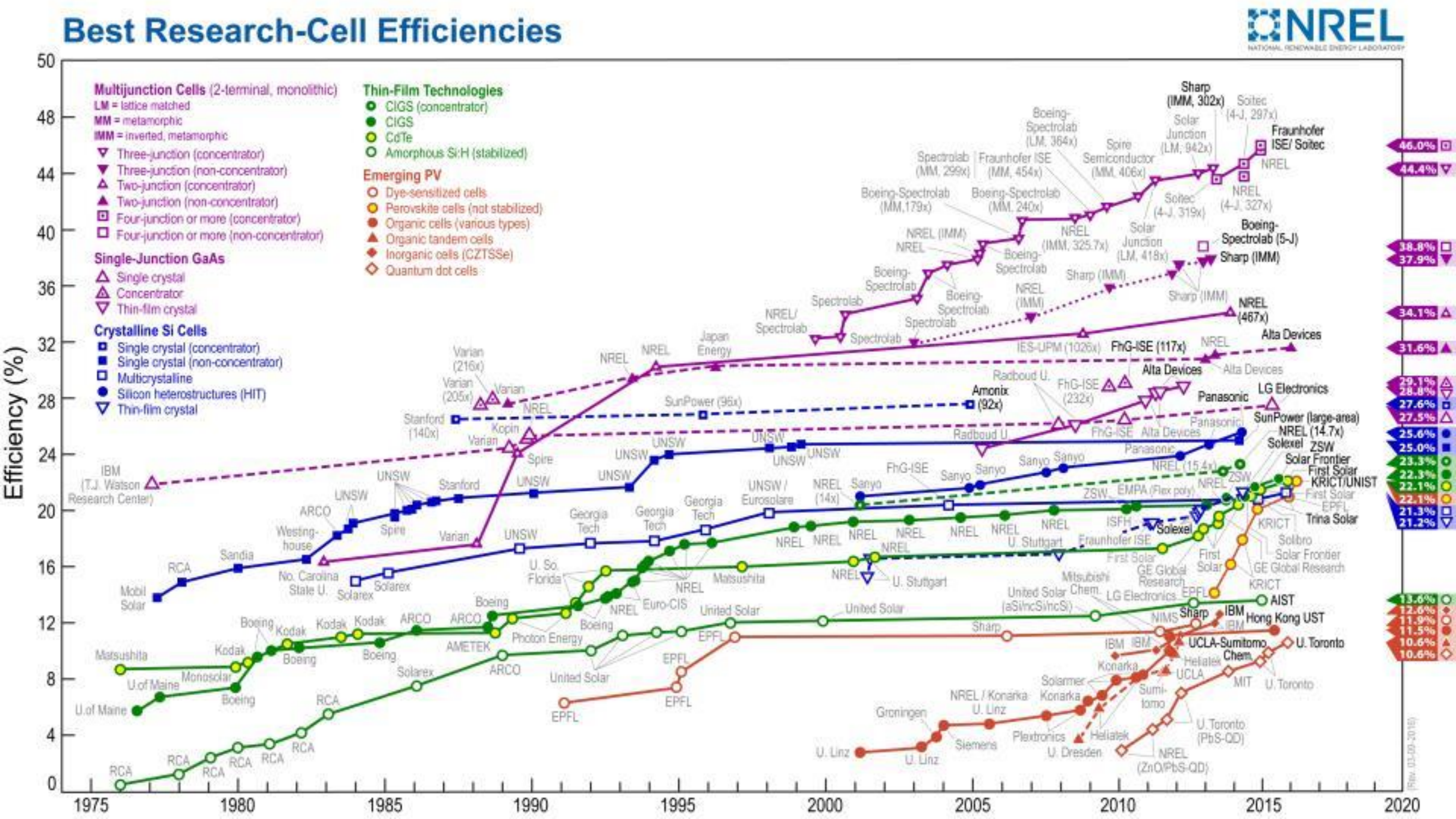
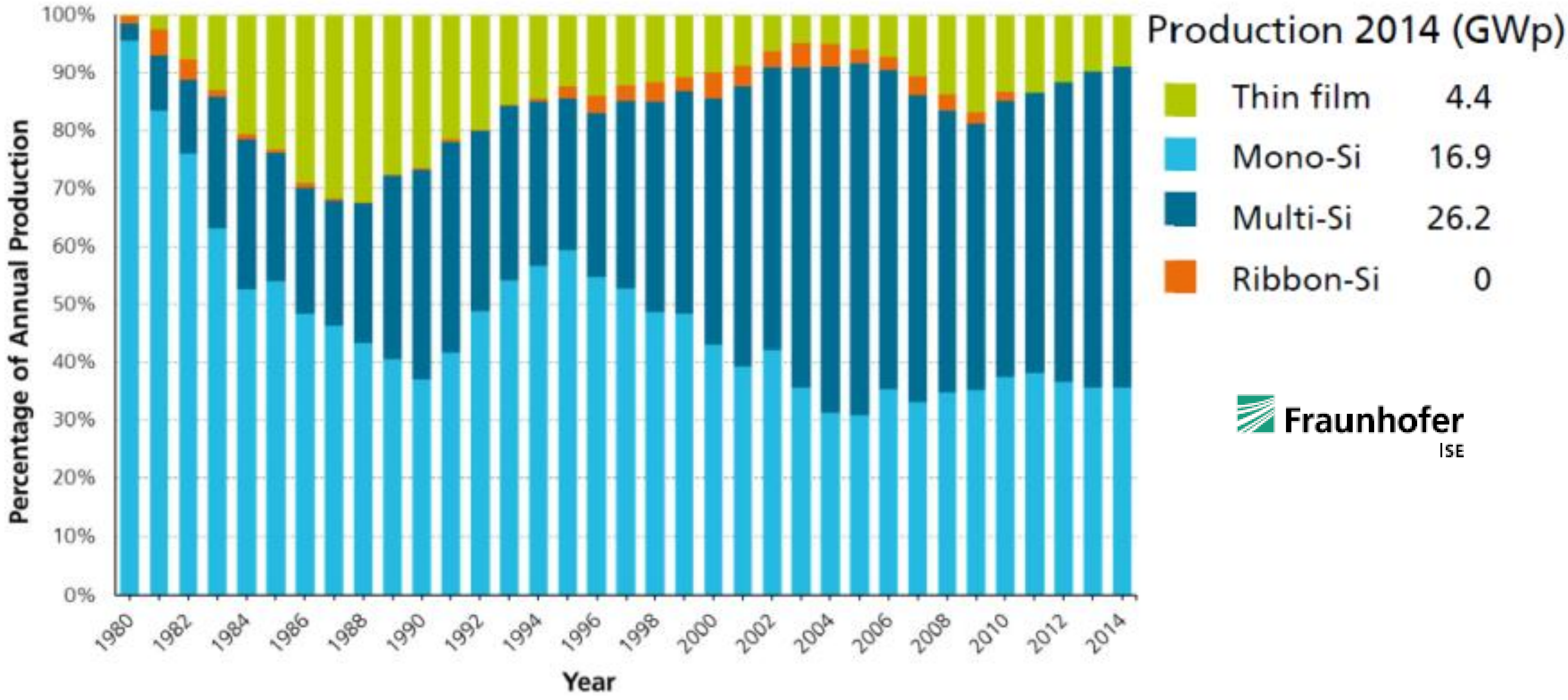
2012	REC Wafer closes all production in Norway

There are many solar cell technologies…



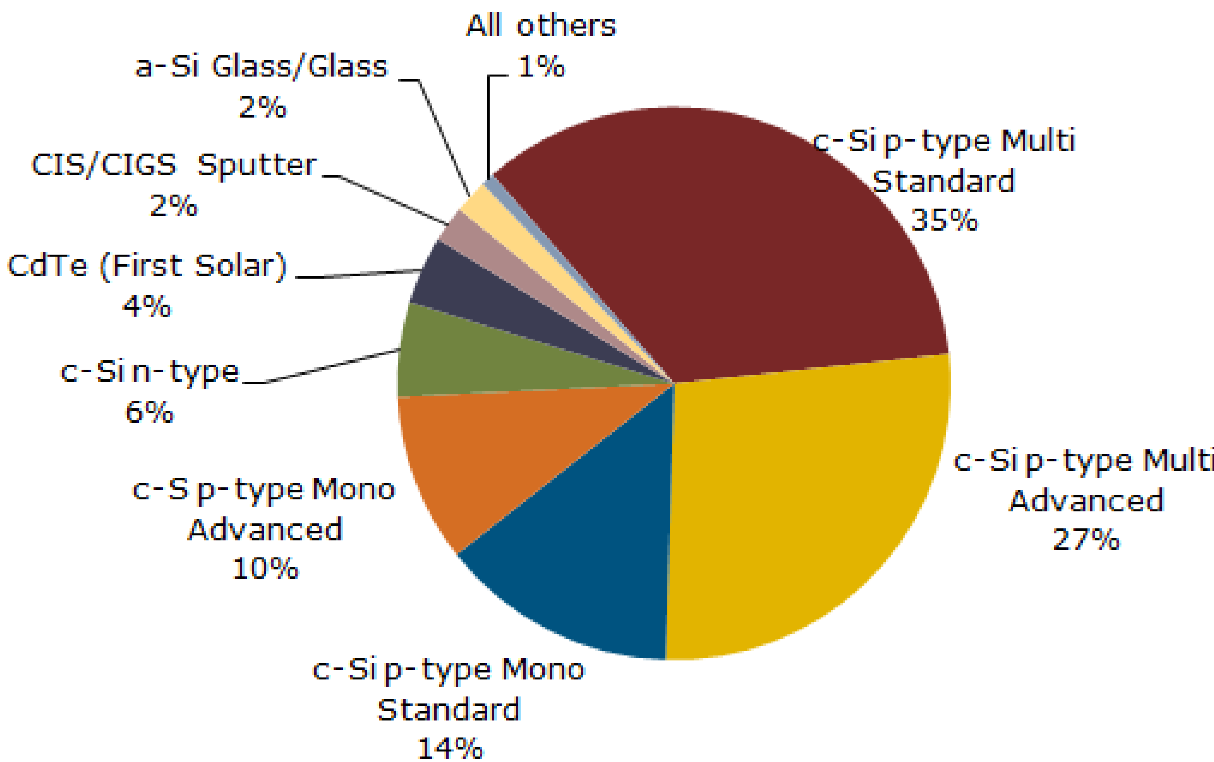
Silicon-based solar cell technology



Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi- proportion by Paula Mints). Graph: PSE AG 2015

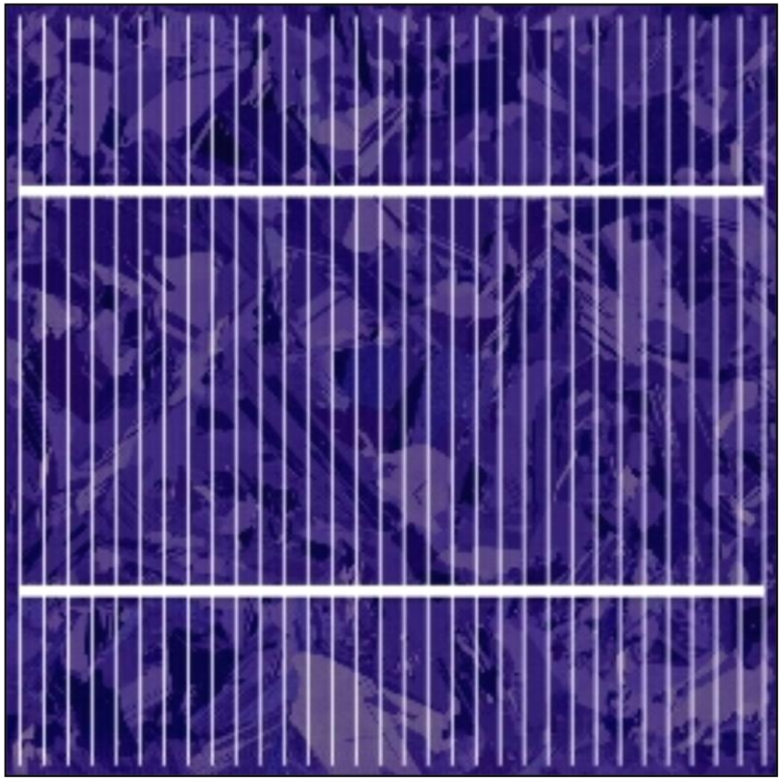
FhG ISE 2015

Technology shares

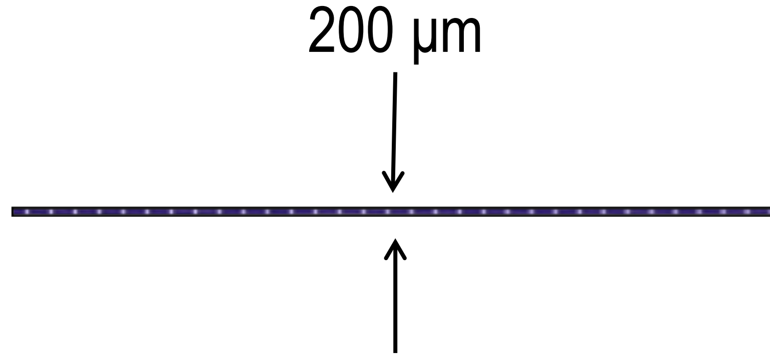


Data: NPD Solarbuzz forecast for 2014

The common solar cell



6”

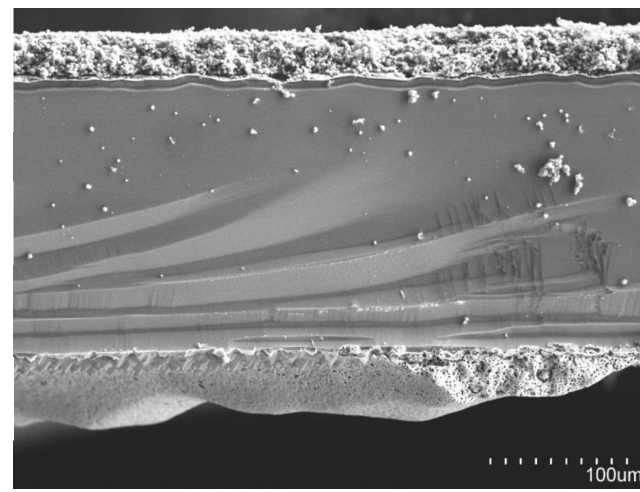


Al contact

Al BSF

Si wafer

Ag contact



Images: IFE (Kløw)

Oseana

Summary

SOLAR CELL THEORY

- Important solar cell parameters: V_{OC}, J_{SC}, η, FF, IQE and EQE
- The one diode equation is a good model for efficiency limit calculations
- The two diode model is a more realistic model often used when characterizing solar cells

SOLAR CELL TECHNOLOGY

- Silicon solar cells dominate the industry with a 90% market share
- Efficiencies are on the increase
- Solar electricity is currently the fastest growing renewable energy technology