"Solar Energy" WS 2021/2022

Lecture 13: PV System Economics, Environmental Aspects and Energy Yield

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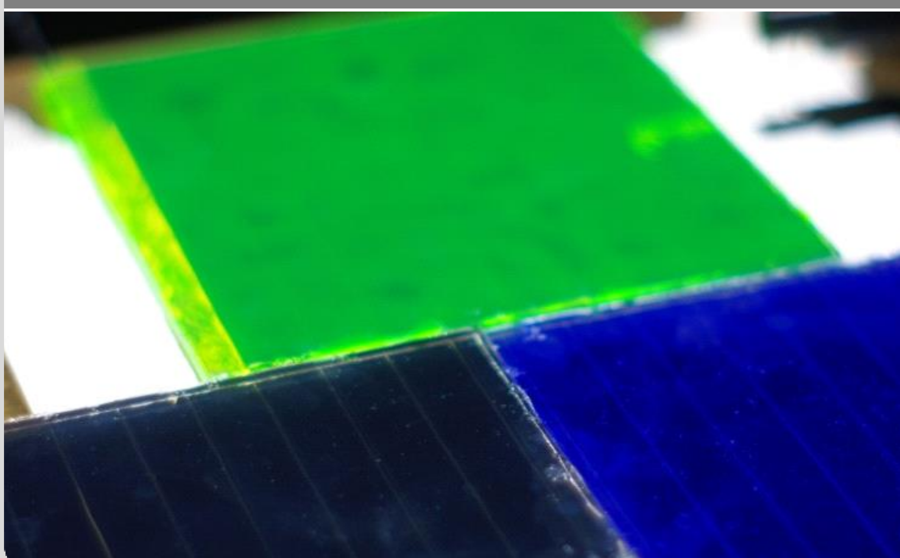
KIT Focus Optics & Photonics



Parts of the material used here have been kindly provided by Prof. T. Kirchartz, and Dr. D. Cheyns.

Part I: PV System Economics

- Payback Time
- Energy Payback Time
- Compensation Schemes
- Levelized Cost of Electricity
- Grid and Socket Parity

Payback time

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Payback time: Time required to recover the cost of an investment.

$$payback\ time = \frac{initial\ investment}{annual\ return}$$

Translated to the consumer level, the payback time is the time it takes to recover the initial investment of the PV system as the system continuously reduces the electricity bill.

The payback time is strongly influenced by:

- the annual solar radiation on the PV system (orientation, location)
- grid electricity costs: the higher these costs, the shorter the EPT
- Initial costs of the PV system. This can vary strongly!
- Capital costs
- Maintenance costs
- …

Source: textbook

Payback time

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<u>**Payback time:**</u> Time required to recover the cost of an investment.

$$payback\ time = \frac{initial\ investment}{annual\ return}$$

<u>SIMPLE EXAMPLE:</u> *Let us assume that the Smith family has installed a PV system with a* ***power of 1 kWp*** *on their rooftop. The* ***initial investment was €2000****. Family Smith has an* ***annual electricity bill of €2,000****. The installation of the PV system leads to an* ***average annual reduction of the electricity bill of €250****.*

Hence, the average annual return on their PV system is €250. As a consequence, the Smith’s have earned the final investment back after 8 years; the payback time is 8 years.

Source: textbook

Energy Payback Time

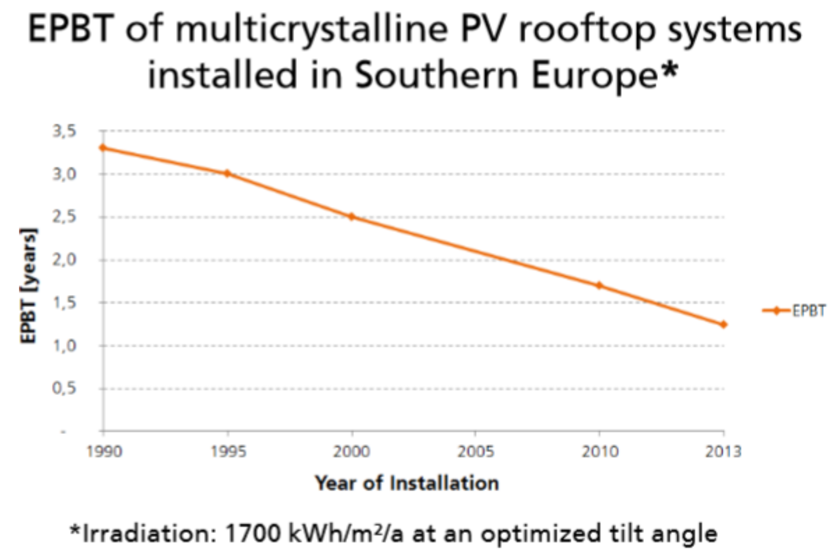
Same concept as financial payback time, but for the „invested energy“.

Energy Payback Time (EPT): *Time required to recover the all the energy invested during extraction of raw materials, production, shipment, installation operation … .*

$$Energy\ payback\ time\ (EPT) = \frac{total\ energy\ invested}{averyge\ annual\ energy\ yield}$$

The energy payback time of typical PV systems is between 0.7 and 3 years and depends on location, orientation of the PV array as well as the solar irradiance throughout the year.

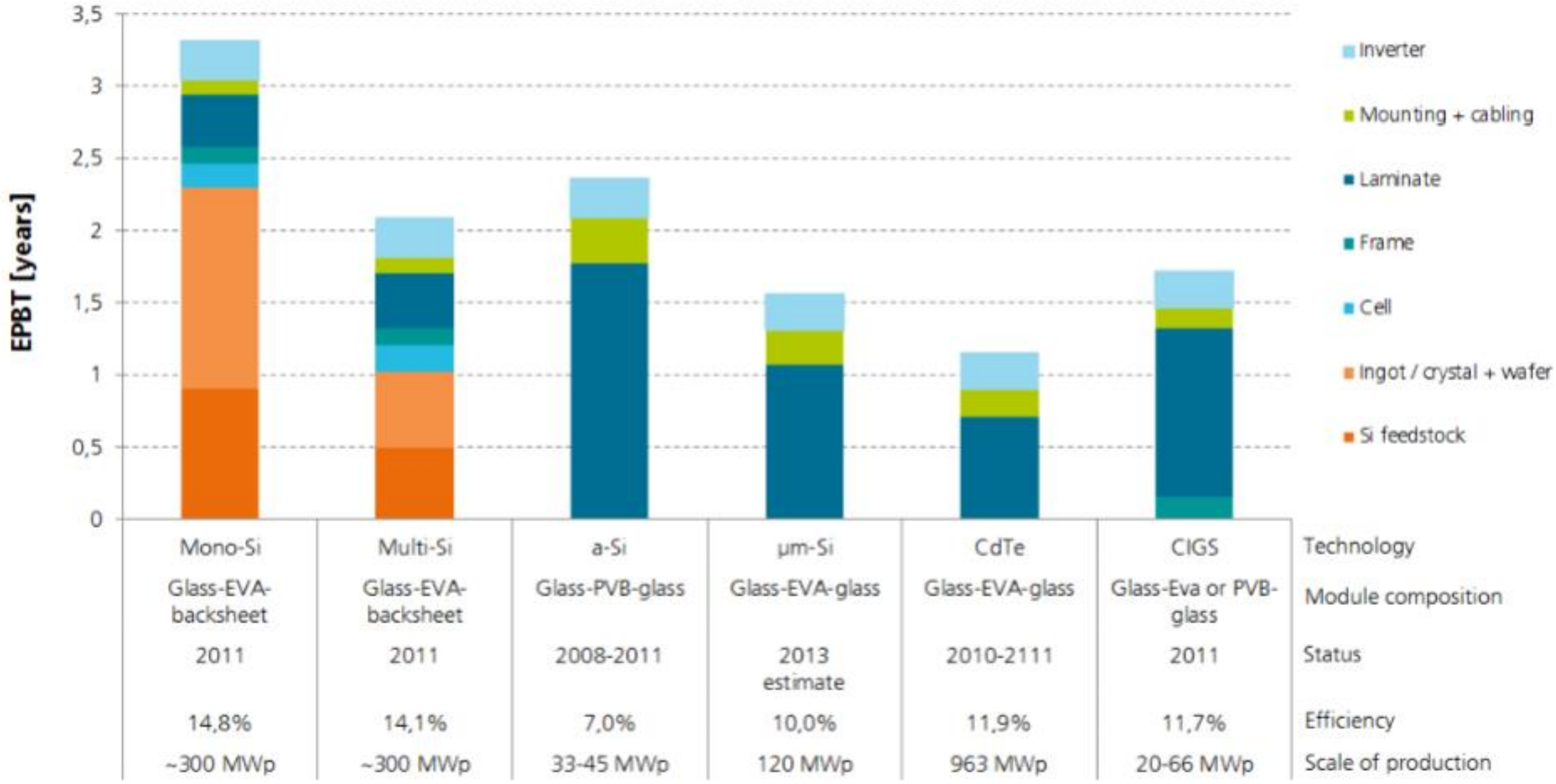
Rooftop PV systems produce net clean energy for ~95% of their life span (30 years) or more.



Source: http://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf

Energy Payback Time

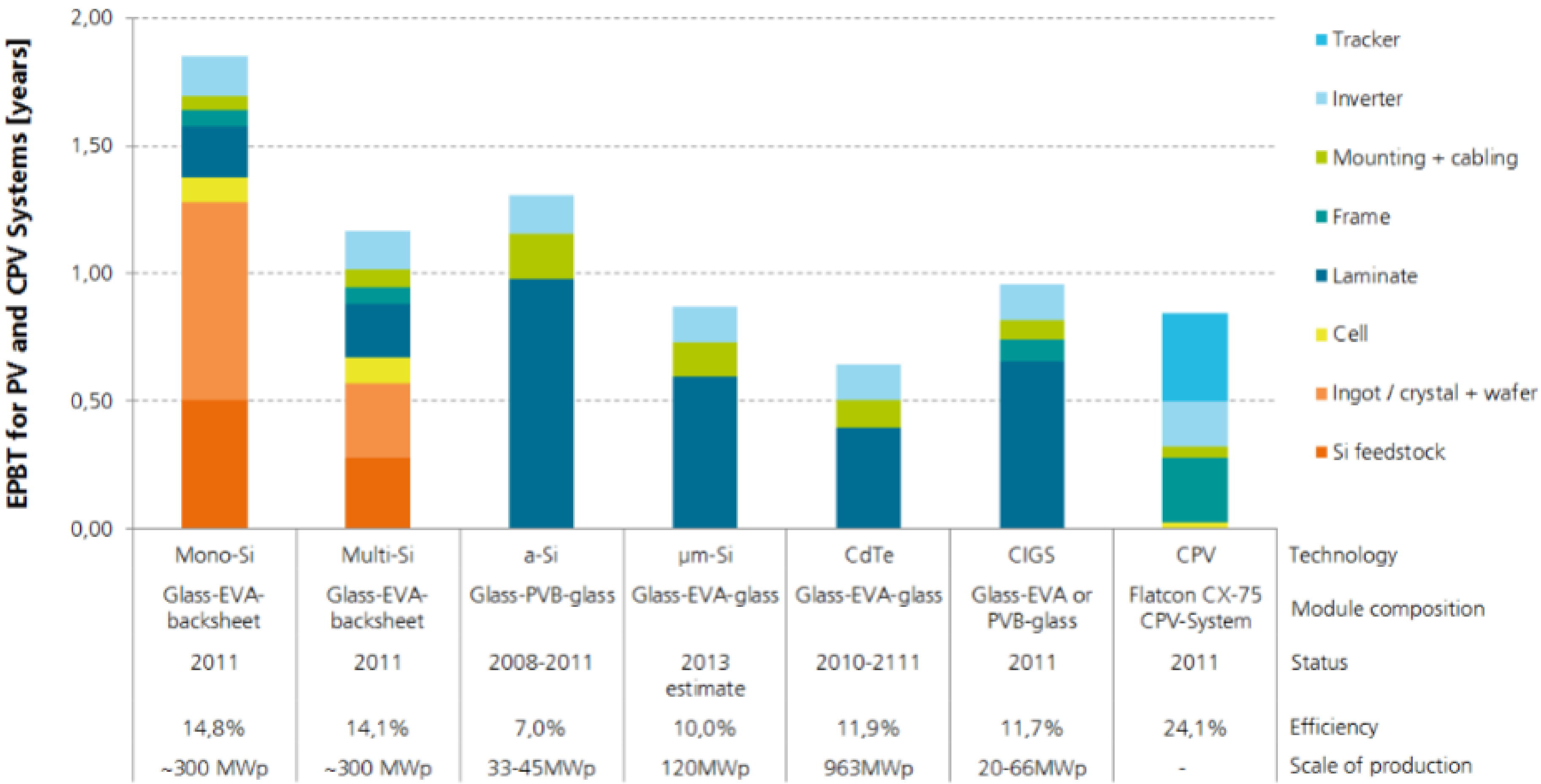
Energy payback time of rooftop systems from different PV technologies in Germany (Global Irradiation 1000 kWh/m²/a)



Source: http://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf

Energy Payback Time

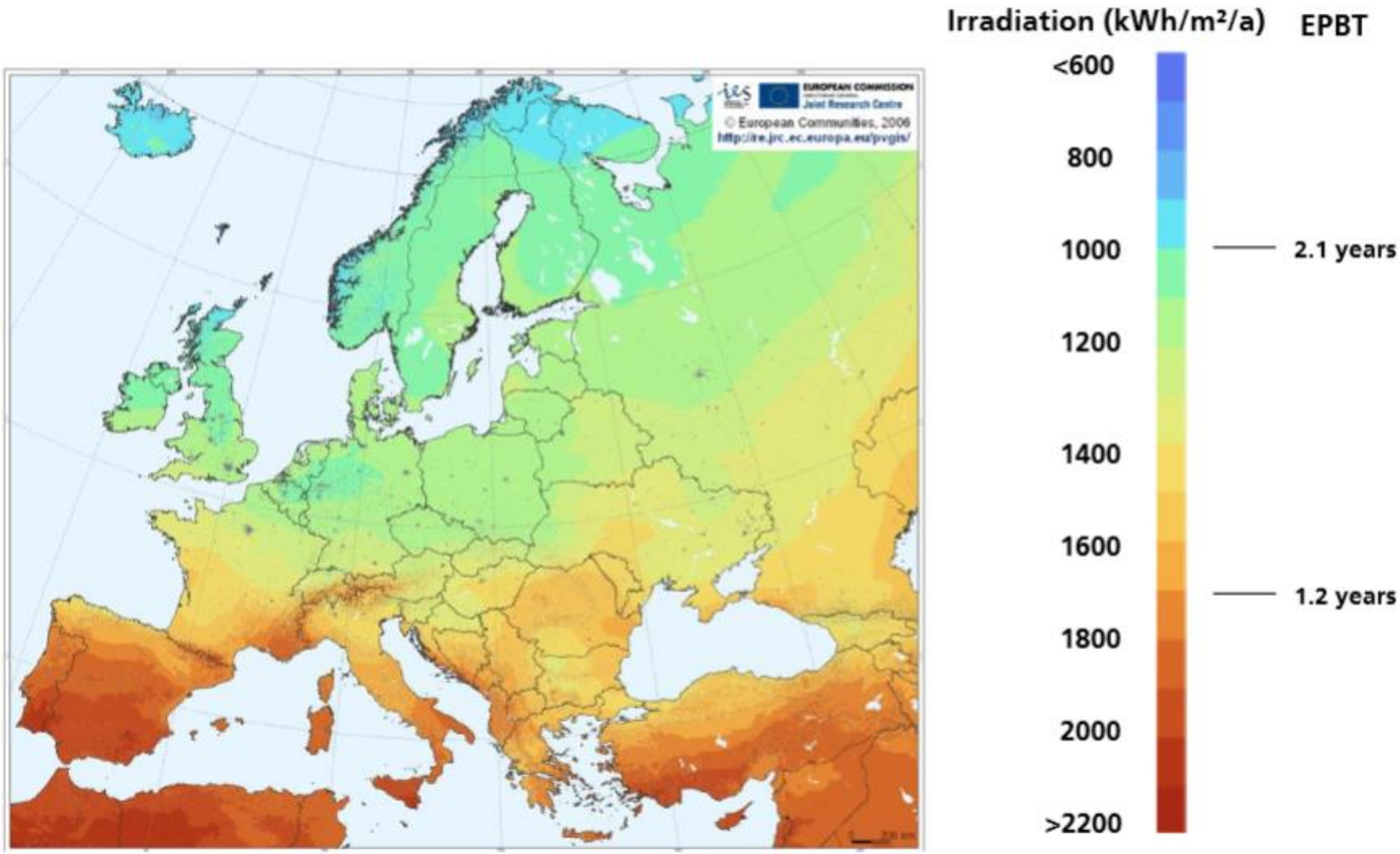
Energy payback time of rooftop systems from different PV technologies in Germany (Global Irradiation 1794 kWh/m²/a)



Source: http://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf

Energy Payback Time

Energy payback time of rooftop systems of multicrystalline PV modules



Source: http://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf

Compensation schemes:

There exist a wide range of schemes to compensate owners of PV systems for electricity they deliver into the grid.

<u>Key categories:</u>

- Subsidies
- Feed in tariff
- Net metering

The sustainable growth of the PV sector between 2000-2015 has benefitted strongly from sustainable and smart feed in tariffs in different nations (e.g. Germany).

RES LEGAL Europe (www.res-legal.eu/home/) Overview of legislation on the support schemes, grid issues and policies for renewable energy for all the EU 27 Member States and the EFTA Countries.

Source: textbook

Compensation schemes:

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<u>**Net metering**</u> is the very basic electricity billing mechanism that allows consumers who generate some or all of their own electricity to use that electricity anytime, instead of when it is generated.

Old-fashioned analogue electricity meters can operate in both directions. If electricity is consumed from the electricity grid, the electricity counter increases. However, when the PV system produces more than is actually consumed in the house, electricity is delivered to the grid. In this case, the electricity counter decreases.

Modern smart digital electricity distinguish between electricity consumed from the grid and electricity delivered to the grid. Not only the amount of electricity delivered to the grid can be monitored, but also adaptations according to tariff system. For example, the electricity price often contains a certain fee for using the electricity grid.

Source: textbook

Compensation schemes:

Feed in tariffs: With the system of feed-in tariffs, electricity generated by the PV system can be sold to the grid utility for a fixed price.

For such a system, either two analogue electricity meters (one measuring the power consumed from the grid, the other measuring energy delivered to the grid) or one smart meter are required.

We distinguish between two kinds of feed-in tariffs:

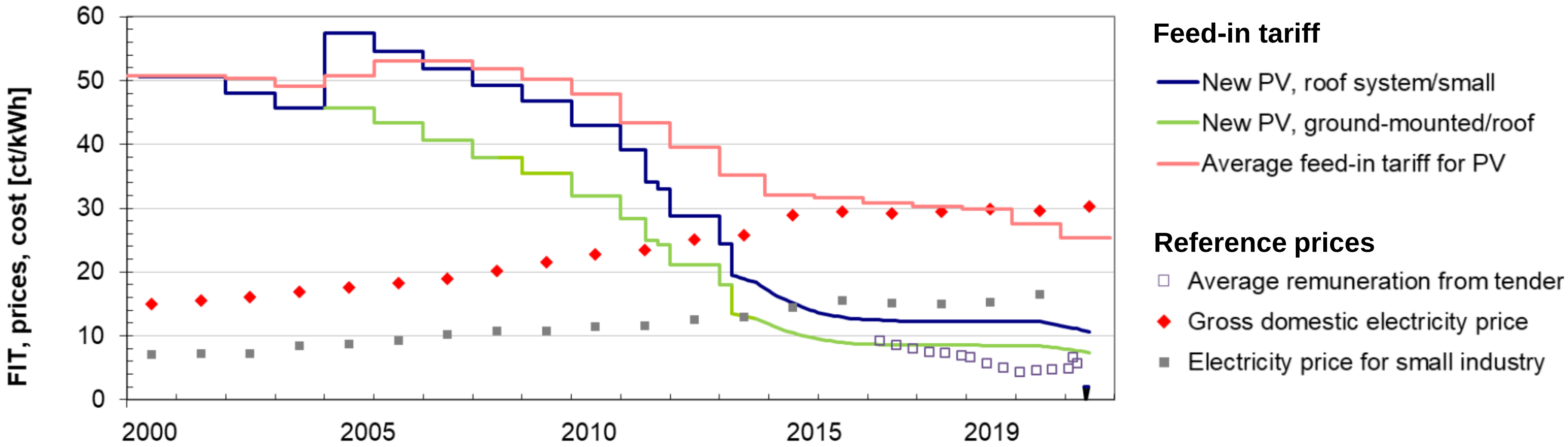
> In the system of gross feed-in tariffs, all the electricity produced by the system is sold to the grid utility and all the electricity consumed by the household is bought from the grid.
>
> In contrast, for *net feed-in tariffs* the actual power consumption is subtracted from the PV power generation and only the surplus electricity is sold to the grid.

Feed-in tariffs stimulate the installation of renewable electricity technologies such as PV, if the feed-in tariffs are above the electricity price. On the other hand, if they are set (slightly) below the electricity price, self consumption can be stimulated.

Source: textbook

Compensation schemes:

<u>Feed in tariff in Germany</u> for PV power as a function of commissioning date, average remuneration of the bidding rounds of the Federal Network Agency, electricity prices and average compensation for PV power.

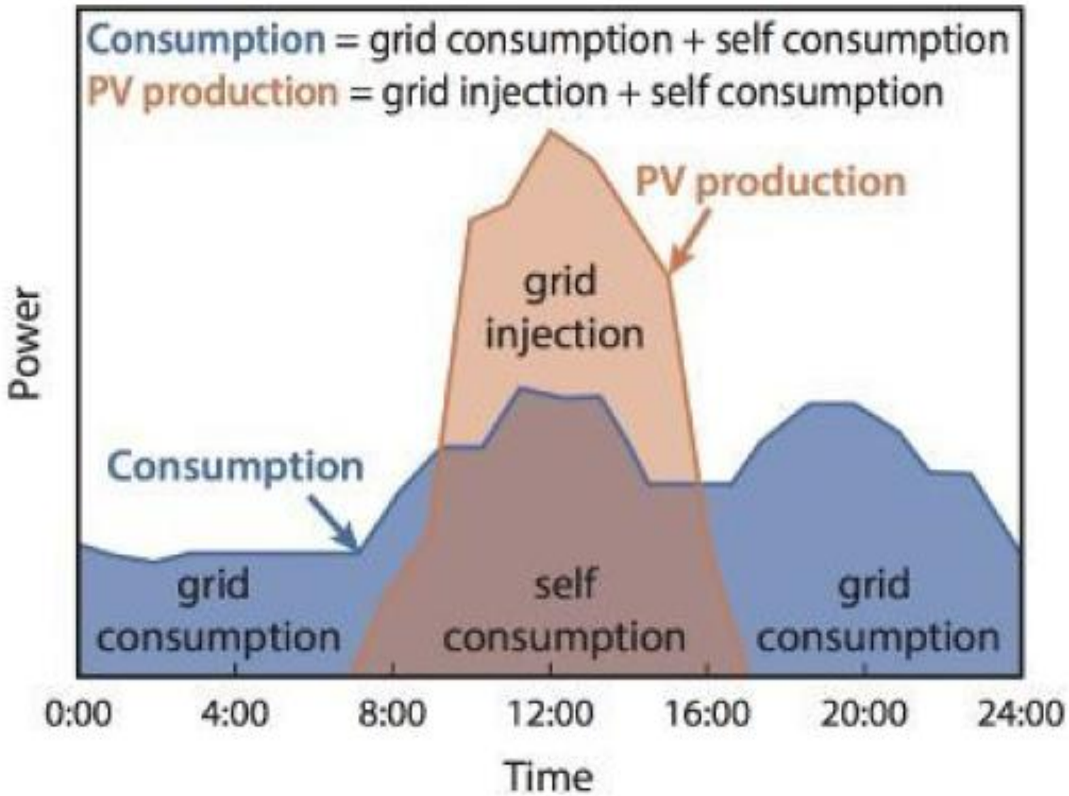


- The first feed-in tariff in 2000 and the subsequent changes have shaped the growth of PV instalments in Germany.
- Feed-in tariff for small roof systems until **October 2019** was up to **10€-cts/kWh** and is guaranteed over the next twenty years.
- Feed-in tariff for medium-size systems (0.75-10 MW) is set by the licensing agreement. The last licensing on the bid date February 1, 2018 set the lowest value of **4€-cts/kWh** ever.

Source: “Recent Facts about Photovoltaics in Germany” Frauenhofer ISE, Freiburg, Okt 2019

PV System Economics

Self consumption: *Self consumption* is an important aspect of PV systems. It defines the possibility for electricity consumers to connect a PV system, with a capacity corresponding to their consumption, to their system for on-site consumption, while injecting non-consumed electricity.



Source: textbook

PV System Economics

Self consumption: *Self consumption* is an important aspect of PV systems. It defines the possibility for electricity consumers to connect a PV system, with a capacity corresponding to their consumption, to their system for on-site consumption, while injecting non-consumed electricity.

$\Rightarrow$ Consumer installs PV system without being charged for grid connection.

$\Rightarrow$ PV systems are penetrating the electricity grid power more and more, issues start to arise: *The peaks in electricity generation are demanding for utility companies that manage the electricity grids. The grid injection levels may even exceed the current demand of a grid well before the PV penetration reaches 100%.*

$\Rightarrow$ This means that there are reasons to encourage prosumers to directly consume the energy they produce in order to avoid grid instability issues. Utilizing the generated PV electricity on site, rather than injecting it into the grid is known as *direct consumption*.

Source: textbook

Levelized cost of electricity

Levelized Cost of Electricity (LCoE) is defined as the cost per kWh of electricity produced by a power generation facility. It is usually used to compare the lifetime costs of different electricity generation technologies.

To be able to estimate the effective price per kWh, the concept of LCoE allocates the costs of an energy plant across its full lifecycle. It is somehow similar to averaging the upfront costs of production over a long period.

$$LCoE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

- n: lifetime of the system n
- I_t : investment expenditures in the year t,
- M_t: operational and maintenance expenditures in the year t,
- F_t: fuel expenditures in the year t.
- E_t: electricity yield in the year t.
- r : discount rate which is a factor used to discount future costs and translate them into the present value.

Source: textbook

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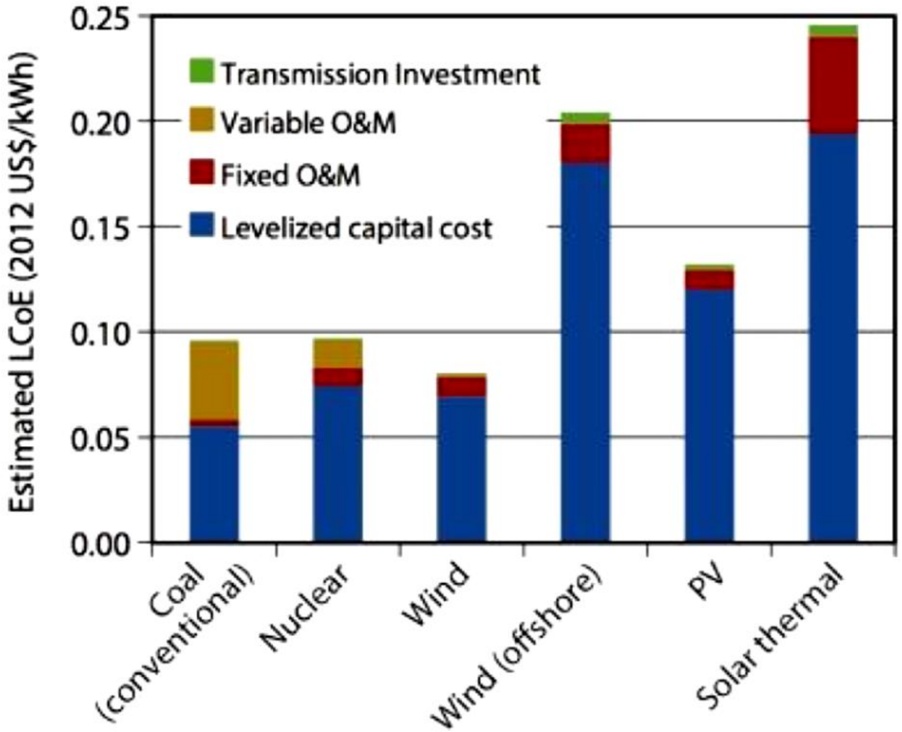
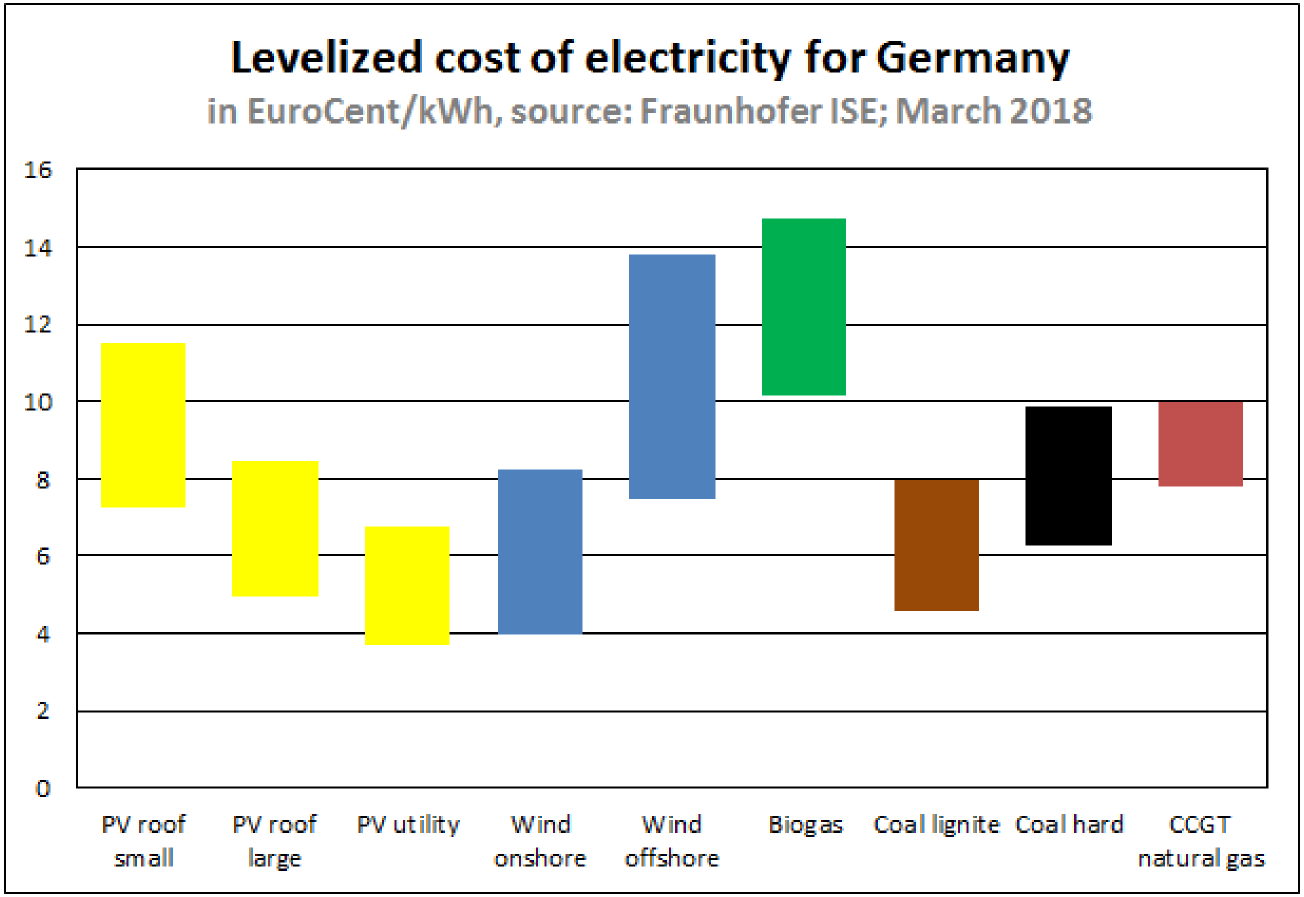


The estimated levelized cost of electricity for different electricity generation technologies that enter service in 2019.

Source: textbook

Levelized cost of electricity

Latest Numbers from March 2018:



- PV start to surpass coal and biogas as in terms of LCOE.

Source: Studie: Stromgestehungskosten erneuerbare Energien - März 2018". Fraunhofer ISE. 2018.

Levelized cost of electricity

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German LCOE in €/MWh

		ISE (2013)		ISE (2018)	
Technology		Low cost	High cost	Low cost	High cost
Coal-fired power plants	brown coal	38	53	46	80
	hard coal	63	80	63	99
CCGT power plants		75	98	78	100
Wind power	Onshore wind farms	45	107	40	82
	Offshore wind farms	119	194	75	138
Solar	PV systems	78	142	37	115
Biogas power plant		135	250	101	147

Source: Fraunhofer ISE (2013) – Levelized cost of electricity renewable energy technologies[50]

Source: Fraunhofer ISE (2018) – Stromgestehungskosten erneuerbare Energien[49]

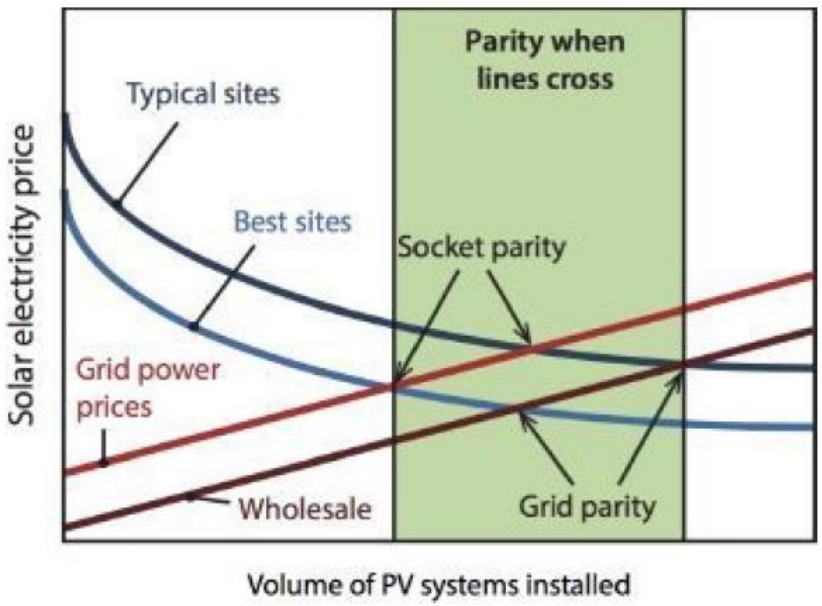
- The levelized cost of electricity evolves with time. In particular the costs for renewable energies decrease due to technological advance.

Source: Studie: Stromgestehungskosten erneuerbare Energien - März 2018". Fraunhofer ISE. 2018.

Grid and socket parity

It is key to investigate whether electricity generated with PV is competitive when compared to electricity generated by other means. For this purpose, the concepts of grid parity and socket parity are used.

Warning: Often falsely used interchangeably.



Grid Parity: The owners of large-scale PV power plants have to compare the LCoE of their system to the cost of electricity production of other sources, ignoring subsidies and other incentives. The point at which the cost of PV electricity is equal to the cost of other electricity generation technologies is called *grid parity*.

Source: textbook

Grid and socket parity

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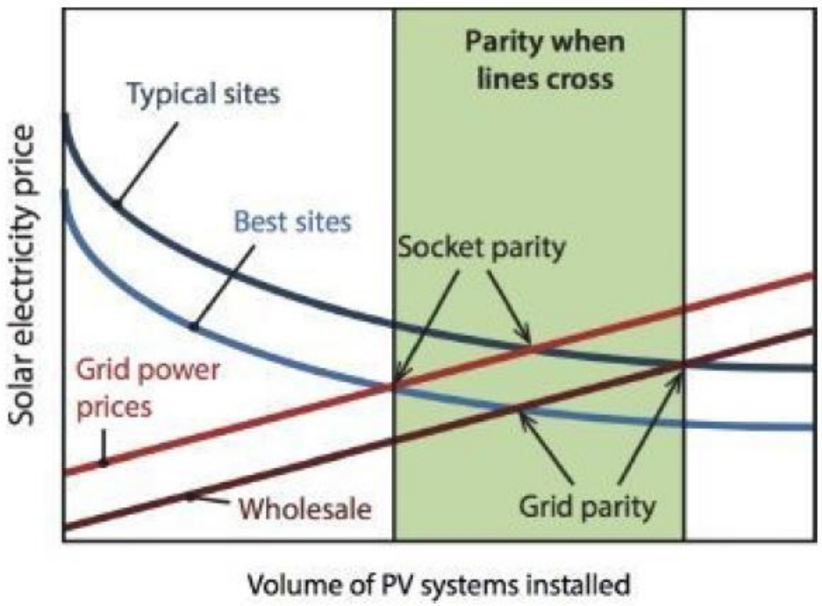

Socket Parity: In contrast, PV can be scaled down to the level of a single module, such that a house owner can become an electricity producer with his small scalable PV installation on his roof. The residential electricity price often also includes grid maintenance fees as well as taxes. The point at which the LCoE of a PV system is equal to the price the consumer pays for electricity from the grid is called socket parity.

Source: textbook

Evaluation

Part II: Environmental Aspects

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- **Carbon Footprint**
- **Scarcity of Materials**
- **Pollution**

Carbon Footprint

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The concept of the *carbon footprint* estimates the CO_2 emissions caused by manufacturing PV modules and compares them with the reduction of CO_2 emissions due to the electricity generated with PV instead of combusting fossile fuels.

A more analytical approach is to look at the total energy required to produce either the PV modules or all the components of a PV system. As production processes vary considerably for the different PV technologies, the energy consumption for producing 1 kW*p* also varies considerably.

If a complete *lifecycle assessment* (LCA) is performed, the energy and carbon footprints of the PV panels are traced where possible, throughout their lifetime. Therefore LCA is also known as *cradle-to-grave analysis*.

Carbon Footprint

- Global warming potential considers not only CO_2 emissions, but also any anthropogenic greenhouse gas emission.

Table 3: Global warming potentials of greenhouse gases
Potentials are expressed as a multiple of the global warming potential of carbon dioxide.

Gas	Global warming potential over 100 years
Carbon dioxide	1
Methane	24
Nitrous oxide	360
Chlorofluorocarbon-11	4 600
Chlorofluorocarbon-12	10 600
Hydrofluorocarbons	10–14 800
Sulfur hexafluoride	22 200
Other perfluorocarbons	5 700–11 400

Source: Granier and Shine (1999).

- 1kg of CFC-12 (former refrigerant and aerosol spray propellant) caused damage to ozone layer and very powerful GHG – if released today will cause 10600x as much warming as 1kg of CO_2

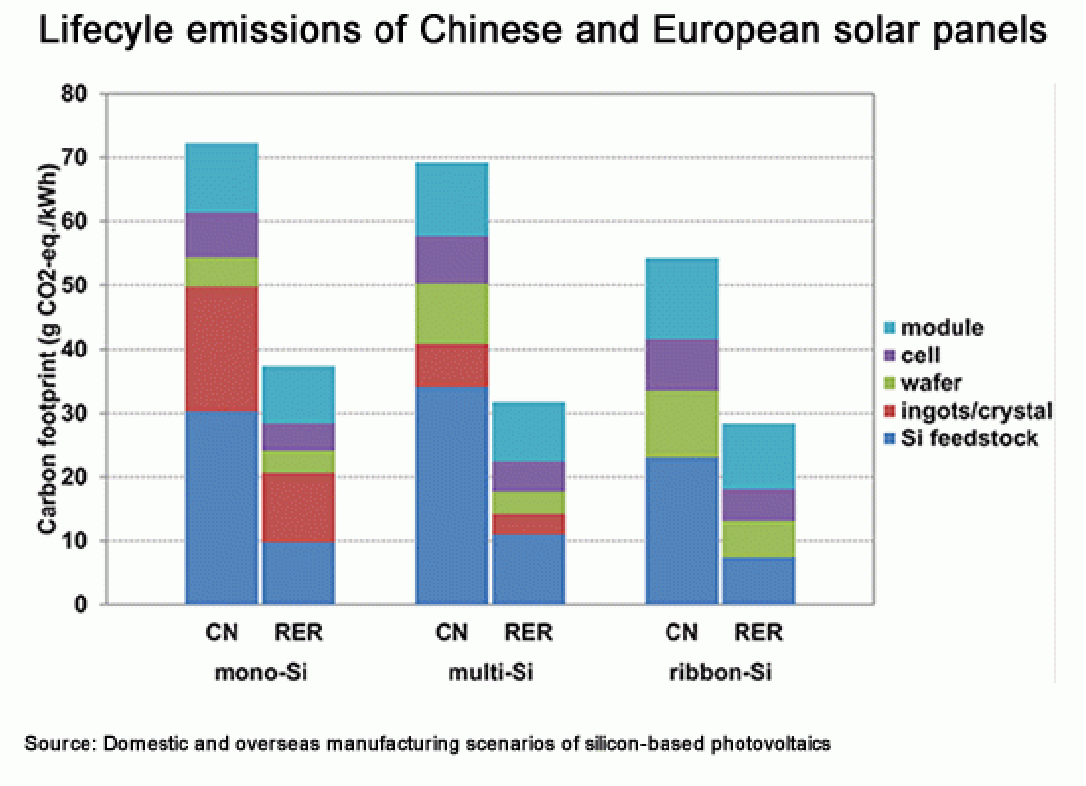
Source: textbook

Carbon Footprint

- The **carbon footprint of a solar** photovoltaic (**PV**) **panel** – the average level of greenhouse gas **emissions** it is responsible for over its lifetime – is about 25-72 grams of **carbon** dioxide-equivalent per kilowatt-hour of electricity generated (gCO2e/kWh)

For comparison:

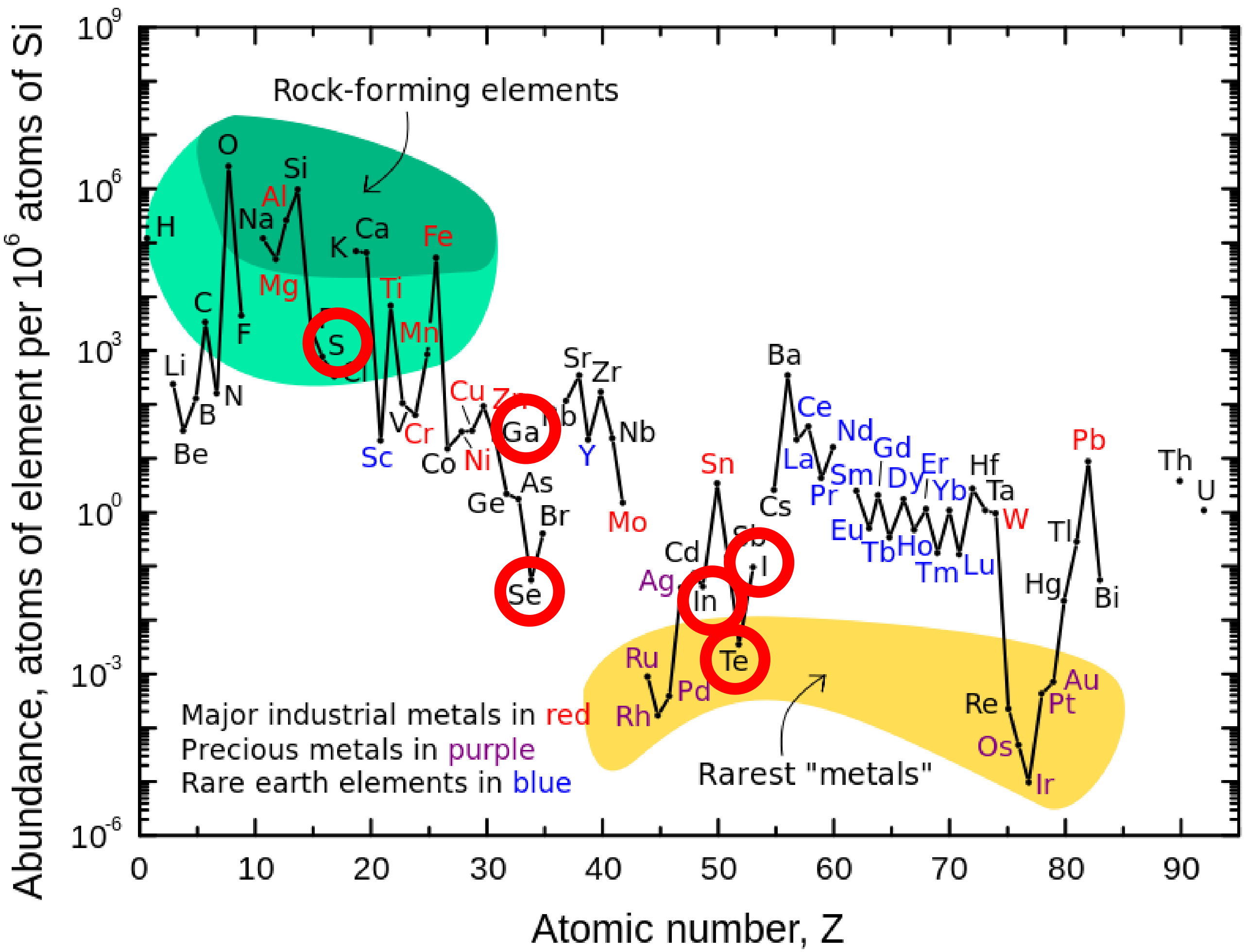
- coal (750-1700 gCO2e/kWh)
- oil (500-1200 gCO2e/kWh)
- gas (250-800 gCO2e/kWh)



Source: D. Yue et al. Solar Energy 105, p. 669-678 2014.

Scarcity of Materials

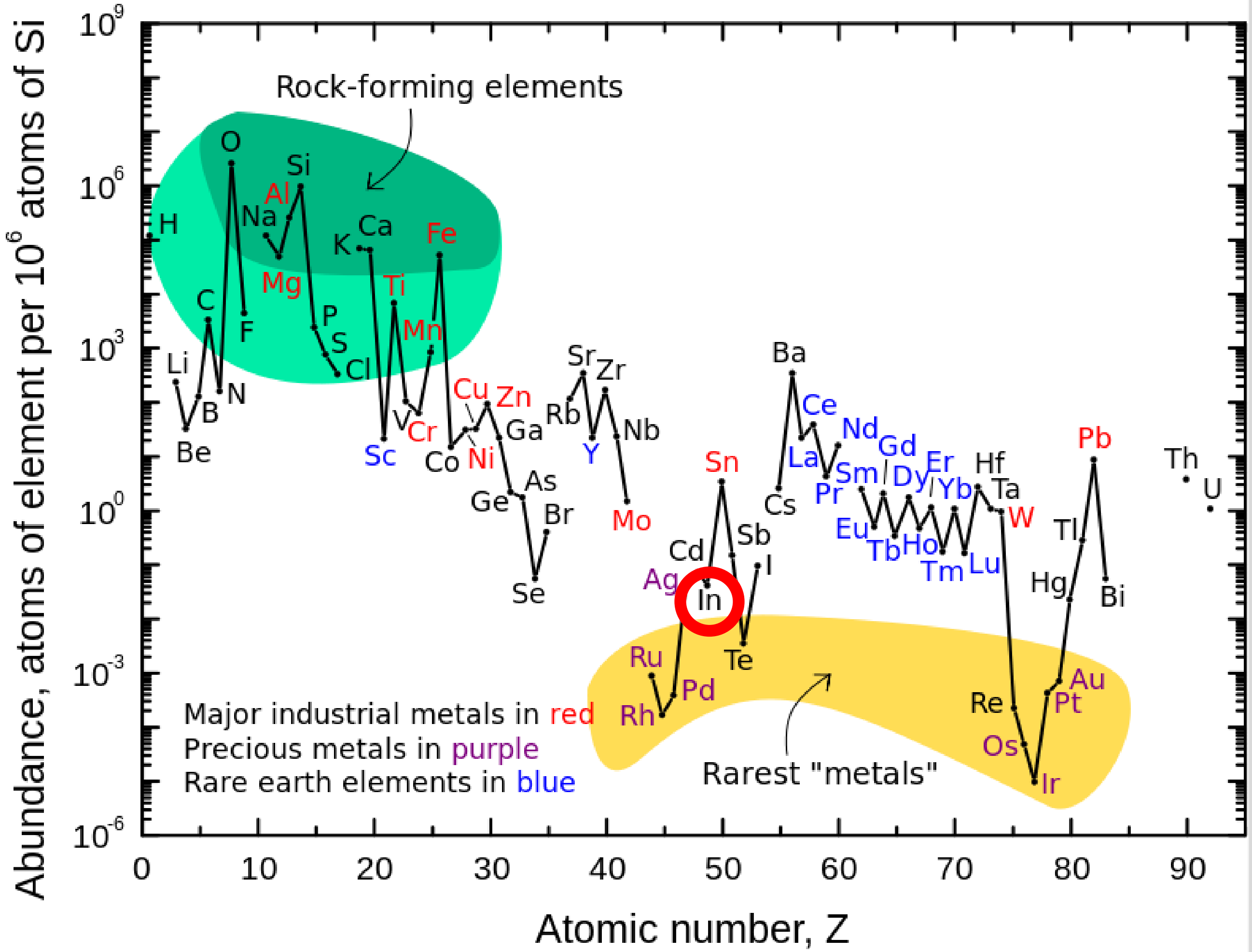
The various PV Technologies introduced in this course partly rely on scarce materials:



Source: Wikipedia // https://en.wikipedia.org/wiki/Abundance_of_elements_in_Earth%27s_crust

Example: Scarcity of Materials

- Indium – soft metal, not so toxic ⇒ does not occur alone as an element, but together with zinc, iron, lead, and copper ores
- Worldwide reserves estimated at ~6,000 tonnes of economically viable In
- Other elements used for CIGS/Se PV: not so much Se in the world, but S and Ga better



Source: textbook

Example: Pollution

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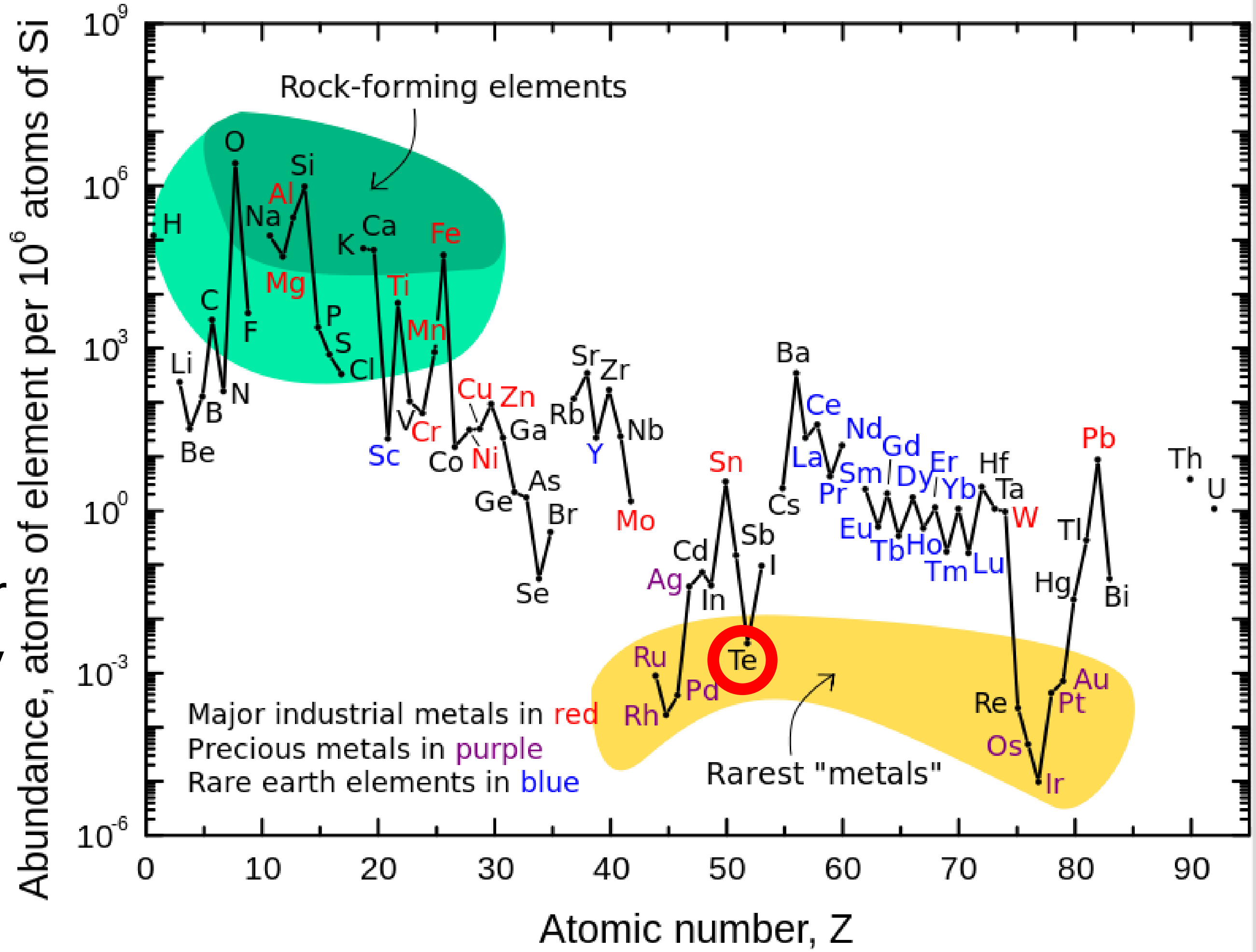
- Tellurium - metal mostly obtained as by-product from copper refining
- According to USGS, global production in 2007 was 135 metric tons ⇒ 1 GW of CdTe PV modules would require about 93 metric tons (c.f. First Solar production capacity in 2014 ~ 2GW) ⇒ recycling?



Source: textbook

Pollution

The last environmental issue that we want to mention is pollution caused by the production of PV modules. As many (sometimes toxic) chemicals are required for producing PV modules, this can be a serious threat to the environment. Therefore it is very important to have strong legislation in order to prevent pollution of the surroundings of PV factories. This is especially so in countries with weak environmental legislation.

<u>Manufacturing</u>

Toxicity and explosive nature of some gases. Problems with

- Accidental release
- Explosions or inhalations
- Exposures to low levels of toxic materials over long periods

<u>Use/Operation</u>

Leaching of heavy metals (cadmium, selenium)

Accidental fires could release toxic fumes

Source: textbook

Example: Pollution

- Cadmium - a heavy metal classes as a hazardous substance
  $\Rightarrow$ toxic and carcinogenic
- Waste by-product of zinc refining therefore its production does not depend on PV market demand
- cadmium chloride ($CdCl_2$) used to increase the CdTe device overall efficiency $\Rightarrow$ but is both toxic and highly soluble in water
  $\Rightarrow$ possibly replace with harmless magnesium chloride
- N.B. large growth in the CdTe PV sector actually has the potential to reduce global cadmium emissions! How?!
  Well, burning coal releases about 140 g of Cd for every GWh of electricity produced (as well as about 1000 tons of CO_2, 8 tons of SO_2, 3 tons of NO_x, and 0.4 tons particulates)

Source: textbook

Pollution

POST BUSINESS Japan tsunami spares major economic zones

Solar Energy Firms Leave Waste Behind in China

By Ariana Eunjung Cha
Washington Post Foreign Service
Sunday, March 9, 2008

GAOLONG, China -- The first time Li Gengxuan saw the dump trucks from the nearby factory pull into his village, he couldn't believe what happened. Stopping between the cornfields and the primary school playground, the workers dumped buckets of bubbling white liquid onto the ground. Then they turned around and drove right back through the gates of their compound without a word.

This ritual has been going on almost every day for nine months, Li and other villagers said.

PHOTOS

"It's poison air. So to close all the do front of a dumping son's health. (Zha

China quells village solar pollution protests

BY ROYSTON CHAN
HAINING, China | Sun Sep 18, 2011 6:58am EDT

Tweet 18 | in Share | Share this | 8+1 0 | Email | Print

Riot policemen remove protesters outside the entrance of a factory of Zhejiang Jinko Solar Co. Ltd. in Haining, Zhejiang province September 17, 2011.
CREDIT: REUTERS/STRINGER

Pollution

Decommissioning

- Disposal of large quantities of modules to a single landfill presents potential risks for humans, communities and the environment as the leaching of chemicals can contaminate local ground and surface water.
- Fthenakis (2003) indicates that one main concern during this life cycle phase will be associated with the presence of cadmium.

> **At First Solar, we believe that powering the future with renewable solar energy** requires a commitment to responsible product life cycle and end-of-life (EOL) management. As PV solar scales globally, we need to ensure that solutions to clean energy don't pose a waste management burden for future generations. First Solar leads the industry with proven recycling solutions that fulfill solar's promise as a clean and sustainable renewable energy.

- The long life of PV cells and the fact that it is a young industry makes data from landfills not yet available.
- The disposal of e-waste is becoming and escalating environmental and health problem in countries in West Africa, Asia and Latin America. This should be prevented in the case of PV systems!


Hard Rock
ST. THOMAS



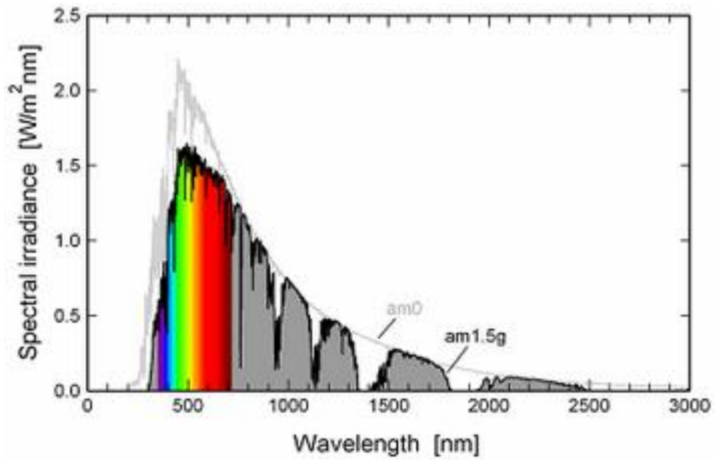
Part III: Energy Yield

- **Why is the Energy Yield so important?**
- **Energy Yield Calculations**
- **Example: Energy Yield of tandem PV modules**
- **Example: Energy Yield of bifacial solar modules**

Why Energy Yield Modelling ?

Standard Test Conditions of solar cells:

- Solar cell temperature of 25°C
- Defined spectrum AM1.5G
  - **irradiance of 1000 W/m2**
  - with an **air mass 1.5 (AM1.5)**
  - specular light



The standard conditions are essential to allow for independent benchmarking of SCs in different laboratories!

***But:** The Standard Conditions have very limited validity to predict the real outdoor system performance -> need for realistic energy yield modelling!*

Source: 1https://www2.pvlighthouse.com.au/resources/courses/altermatt

Energy Yield Calculations

How do we calculate the Energy Yield

$$EY \approx \int_{t_{start}}^{t_{end}} I(t) \times \eta_{\mathrm{mod}}(t) \times \eta_{rel-\mathrm{mod}}(t) \times \eta_{system}(t) \times \eta_{operation}(t)\,dt$$

Irradiation intensity

Module efficiency

Rel. module efficiency
(accounts for pre-module losses)

System efficiency
(wiring, inverter, MPP tracking)

Operation efficiency
(rel. time of operation)

Comments:

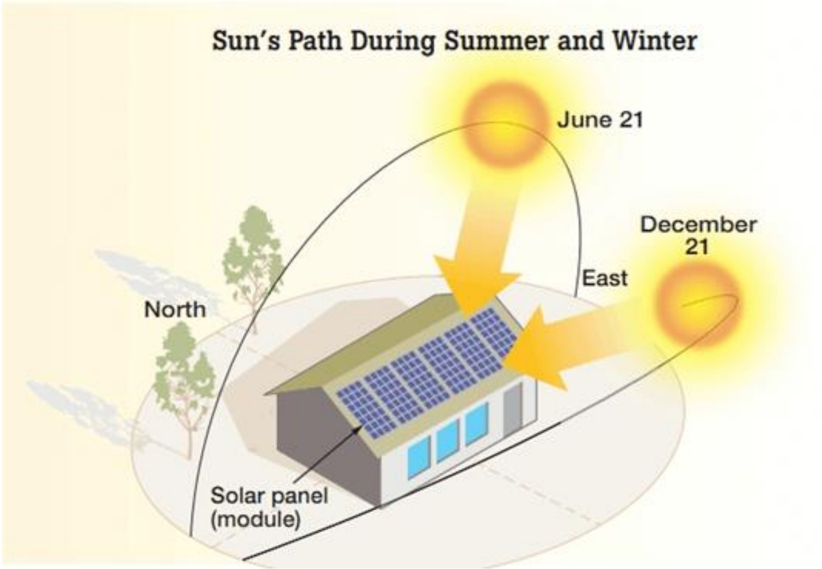
- These efficiencies depend on many aspects (see next slides)
- They partly interdepend (e.g also depends on the irradiation)

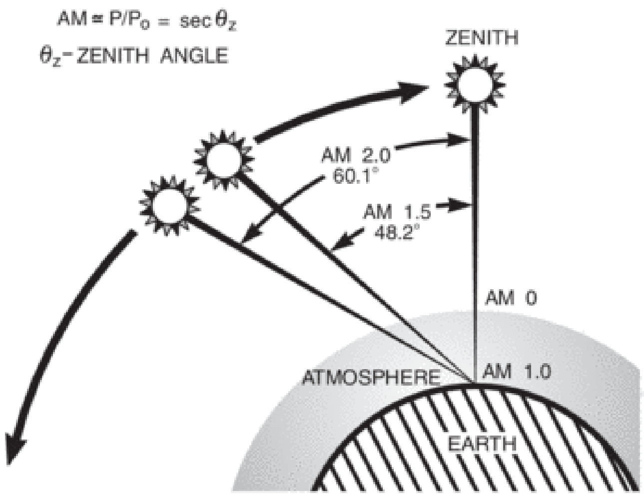
Energy Yield Calculations

There are a large set of parameters influencing the performance of a PV system. Understanding their impact on the energy yield is crucial!

<u>I. Spectrum/Irradiation:</u>

- **Seasonal and intraday variations of the spectrum**
- **Seasonal and intraday variation of the angle of incidence**
- Effect of weather/clouds





Source1: 1http://www.bio.miami.edu/dana/pix/globalseasons.jpg
Source2: https://www.newport.com/t/introduction-to-solar-radiation
Source3: https://www.revolvesolar.com/5-factors-that-affect-solar-panel-efficiency/

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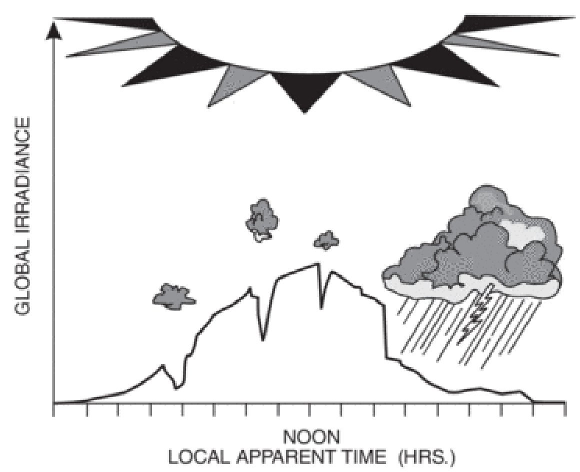
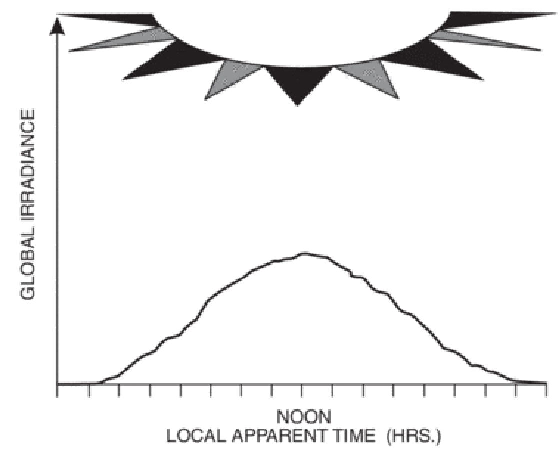




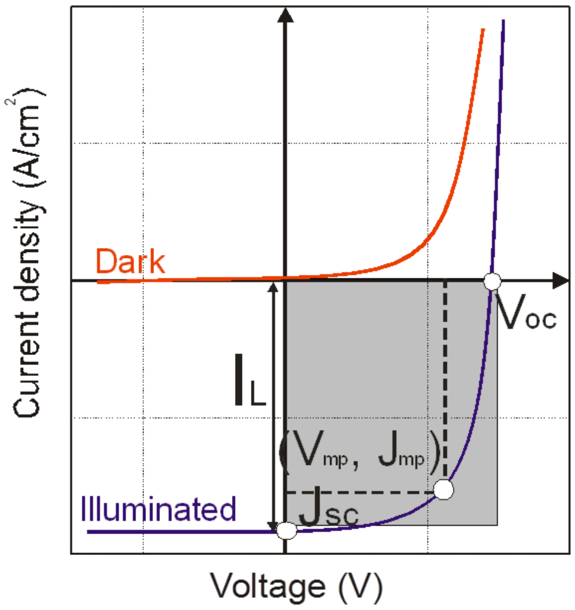
Source: https://www.newport.com/t/introduction-to-solar-radiation

Energy Yield Calculations

There are a large set of parameters influencing the performance of a PV system. Understanding their impact on the energy yield is crucial!

<u>II. Module efficiency:</u>

- **Losses in efficiency of solar cell/module**
  - Reflection
  - Parasistic absorption
  - Charge carrier extraction
  - Series resistance
  - Shunts
  - ….



Energy Yield Calculations

There are a large set of parameters influencing the performance of a PV system. Understanding their impact on the energy yield is crucial!

II. Module efficiency:

- Losses in efficiency of solar cell/module
- **Temperature (of the solar module)**
  - T dependence of Voc dominant

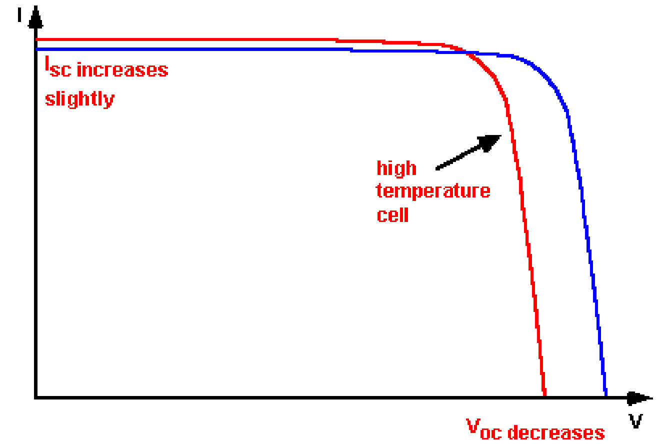
$$V_{OC} = \frac{kT}{q}\ln\left(\frac{I_{SC}}{I_0}\right)$$

Intrinsic charge carrier concentration n_i highly T dependent.

$$I_0 = qA\frac{Dn_i^2}{LN_D} \qquad I_0 = qA\frac{D}{LN_D}BT^3\exp\left(-\frac{E_{G0}}{kT}\right) \approx B'T^{\gamma}\exp\left(-\frac{E_{G0}}{kT}\right)$$

Temperature coefficient:

$$\frac{dV_{OC}}{dT} = -\frac{V_{G0} - V_{OC} + \gamma\frac{kT}{q}}{T} \approx -2.2mV\ per\ {}^{o}C\ for\ Si$$



Energy Yield Calculations

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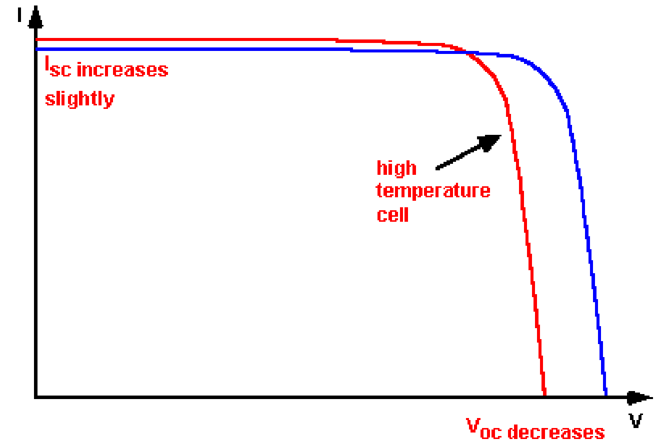
II. Module efficiency:

- Losses in efficiency of solar cell/module
- **Temperature (of the solar module)**
  - T dependence of Voc dominant
  - Isc even increases slightly:

$$\frac{1}{I_{SC}}\frac{dI_{SC}}{dT} \approx 0.0006\, per\ \ ^{o}C\ for\ Si$$



The short-circuit current, I_{sc}, increases slightly with temperature, since the band gap energy, E_G, decreases and more photons have enough energy to create e-h pairs. However, this is a small effect and not valid for all semiconductors.

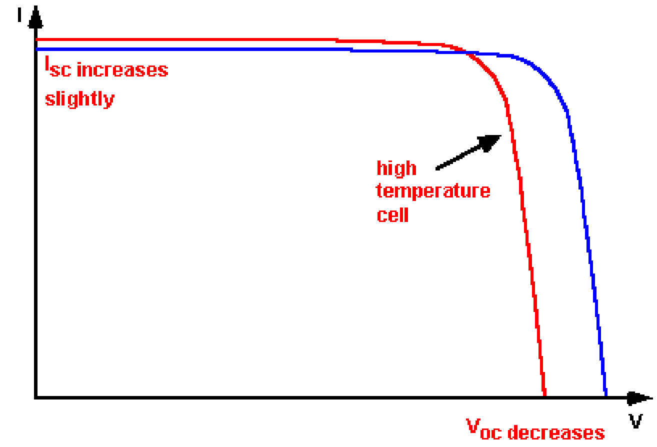
Source1: http://www.pveducation.org/pvcdrom/modules/nominal-operating-cell-temperature

Energy Yield Calculations

There are a large set of parameters influencing the performance of a PV system. Understanding their impact on the energy yield is crucial!

II. Module efficiency:

- Losses in efficiency of solar cell/module
- **Temperature (of the solar module)**
  - T dependence of Voc dominant
  - In Si: Isc even increases slightly:
  - FF slightly T dependent as interrelated to Voc



Fill factor

$$FF \approx \frac{qV_{OC}/k_B T - \ln(0.72 + qV_{OC}/k_B T)}{1 + qV_{OC}/k_B T}$$

$$\frac{1}{FF}\frac{dFF}{dT} \approx \left(\frac{1}{V_{OC}}\frac{dV_{OC}}{dT} - \frac{1}{T}\right) \approx -0.0015\ per\ {}^{o}C\ for\ Si$$

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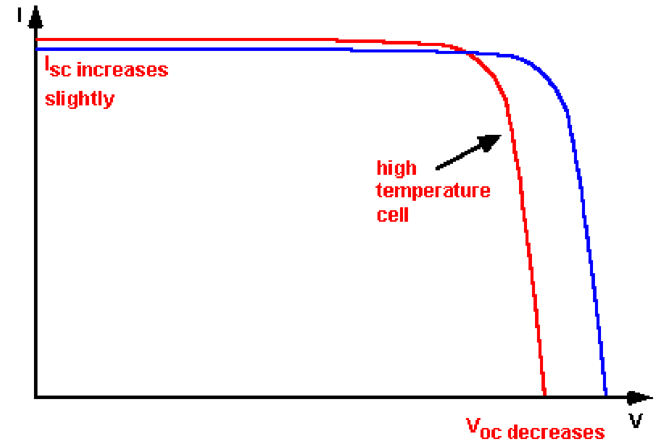

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Energy Yield Calculations

Karlsruher Institut für Technologie

There are a large set of parameters influencing the performance of a PV system. Understanding their impact on the energy yield is crucial!

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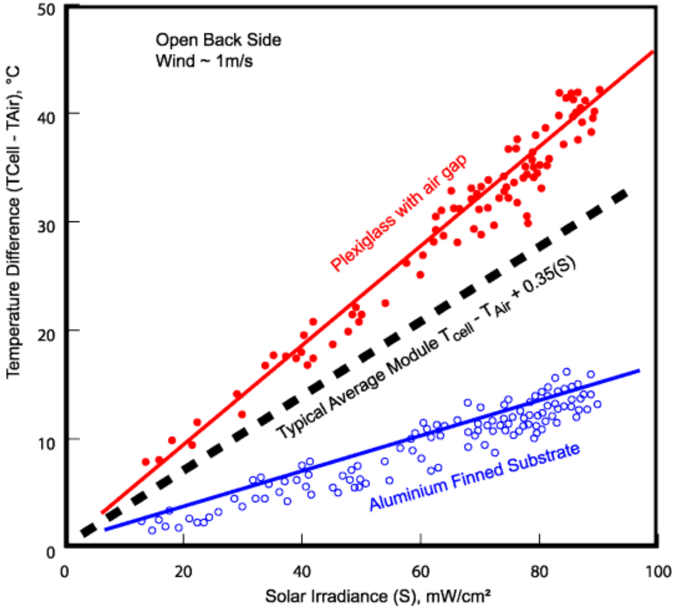

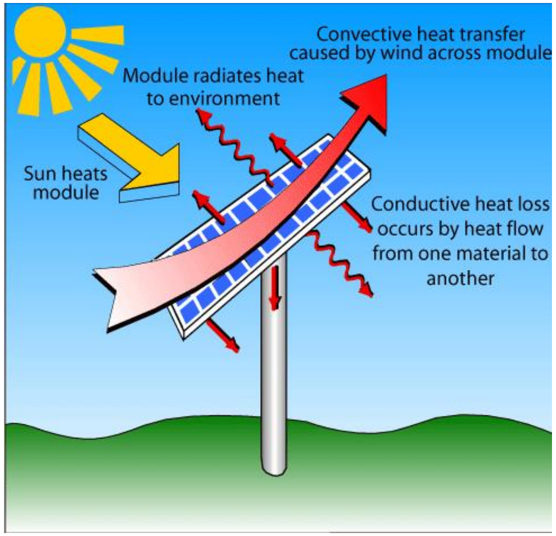

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Energy Yield Calculations

There are a large set of parameters influencing the performance of a PV system. Understanding their impact on the energy yield is crucial!

II. Module efficiency:

- Losses in efficiency of solar cell/module
- Temperature (of the solar module)
- **Irradiance dependence**

Remember last lecture: Current generation as well as the voltage of the photovoltaics device depends on incident irradiation intensity.

Short circuit current density

$$J_{sc} = \int_0^\infty EQE(\lambda) \times P(\lambda) d\lambda$$

Open circuit voltage

$$V_{oc} = \frac{k_B T}{q} \cdot \ln\left(\frac{J_{SC}}{J_0} + 1\right)$$

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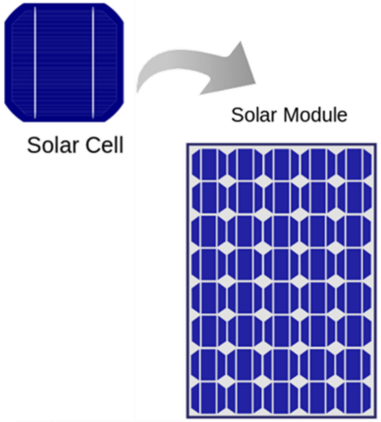
Energy Yield Calculations

There are a large set of parameters influencing the performance of a PV system. Understanding their impact on the energy yield is crucial!

<u>III. Pre-Module losses:</u>

- Shadows



Remember, the cells of cell stripes are connected in series -> If you shadow only partly one cell the efficiency of the entire module is heavily affected.

Source1: http://www.greenbeltsolar.com/solar_shading_article.html

Energy Yield Calculations

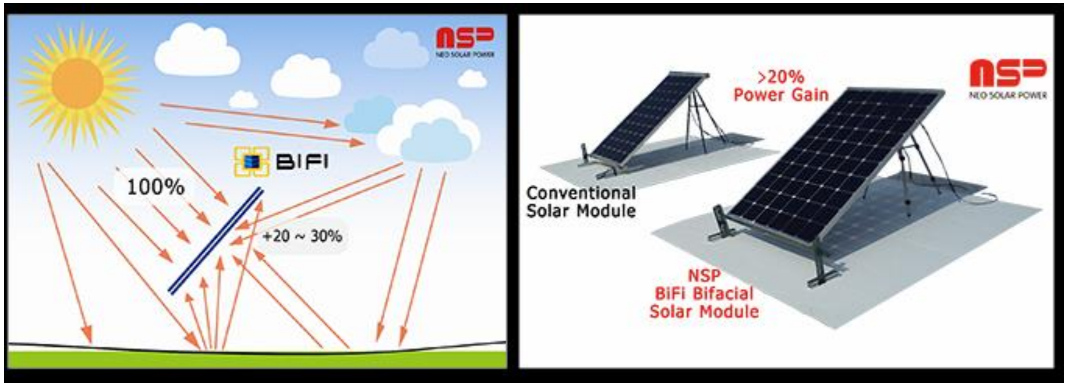
There are a large set of parameters influencing the performance of a PV system. Understanding their impact on the energy yield is crucial!

III. Pre-Module Losses:

- Shadows
- Dirt / Dust

Bifacial solar cells.
But do they pay of?

Cleaning needed.
But how often?



Source1: http://www.greenbeltsolar.com/solar_shading_article.html

Energy Yield Calculations

There are a large set of parameters influencing the performance of a PV system. Understanding their impact on the energy yield is crucial!

III. Pre-Module Losses:

- Shadows
- Dirt
- Snow

Source1: http://www.greenbeltsolar.com/solar_shading_article.html

Energy Yield Calculations

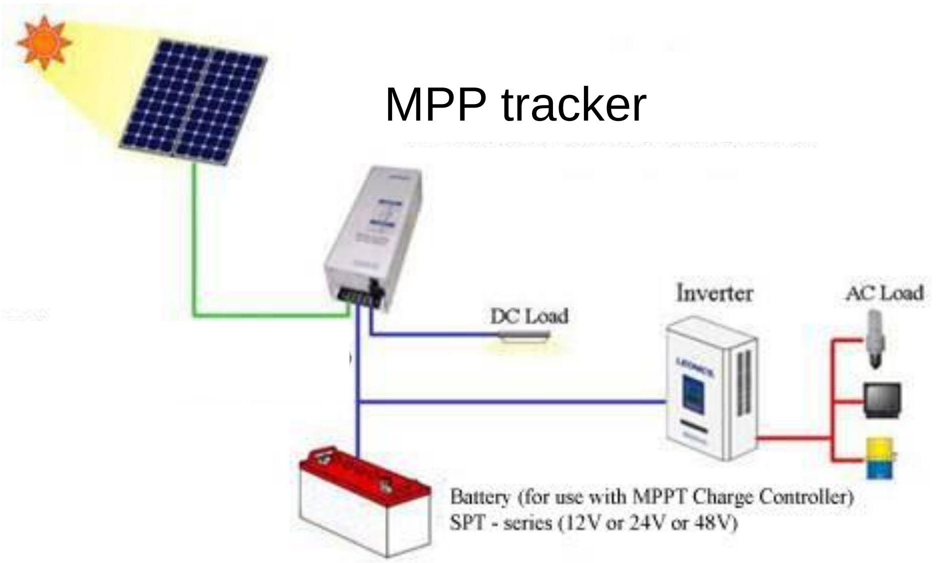
There are a large set of parameters influencing the performance of a PV system. Understanding their impact on the energy yield is crucial!

<ins>IV. System Losses:</ins>

- Wiring
- MPP – tracking
- Transformer

<ins>V. Operation and Maintenance</ins>

- Downtime



Source1:from:http://www.leonics.com/support/article2_14j/articles2_14j_en.php

Energy Yield Calculations

There are a large set of parameters influencing the performance of a PV system. Understanding their impact on the energy yield is crucial!

- Depending on the research question, only specific aspects are looked into in detail. Not all aspects can be covered at the same time.

Two examples in the following:

1) Optical energy yield modelling of tandem PV modules

2) Optical energy yield modelling of bifacial PV modules

Optical Energy Yield Modelling

meteo data

$I_{spec}(\lambda,t)$, $I_{diff}(\lambda,t)$, $\alpha_{inc}(t)$

optics

$A_{t/b}(\alpha_{inc},\lambda)$, $T_t(\alpha_{inc},\lambda)$

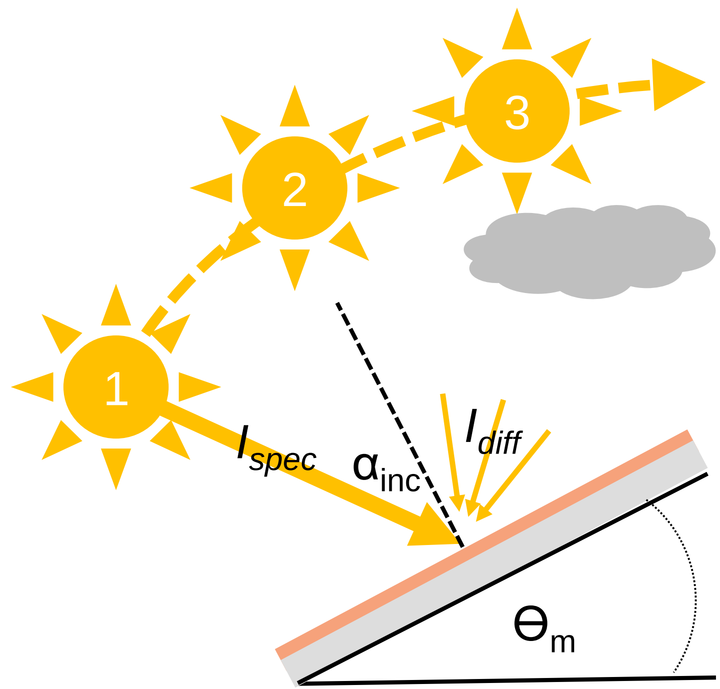
solar cell parameters

$J_{SC}(t)$

$FF(t)$, $V_{oc}(t)$

Energy yield

$$EY = \int J_{SC}(t) \times FF \times V_{OC}\, dt$$



device

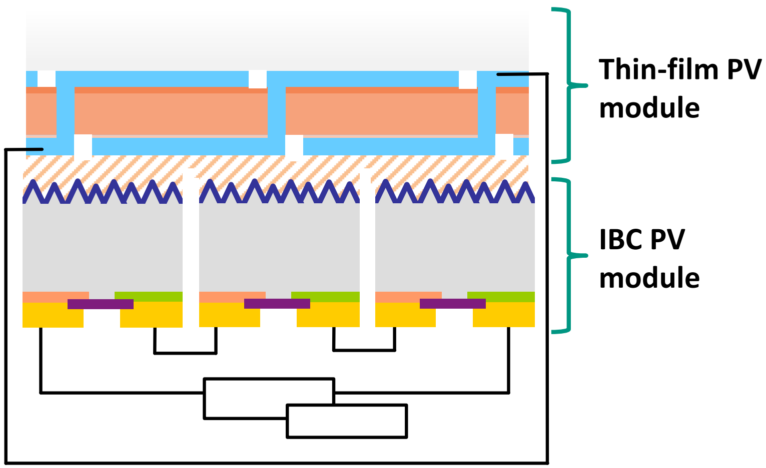
- $A(\alpha_{inc},\lambda)$
- C_{eff}
- FF
- V_{OC}

Source1: Optical Loss Analyses and Energy Yield Modelling of Perovskite/silicon Multijunction Solar Cells
U. W Paetzold, et al. Optics for Solar Energy, SoW2C. 4

Example 1: Perovskite/Si Multijunction PV

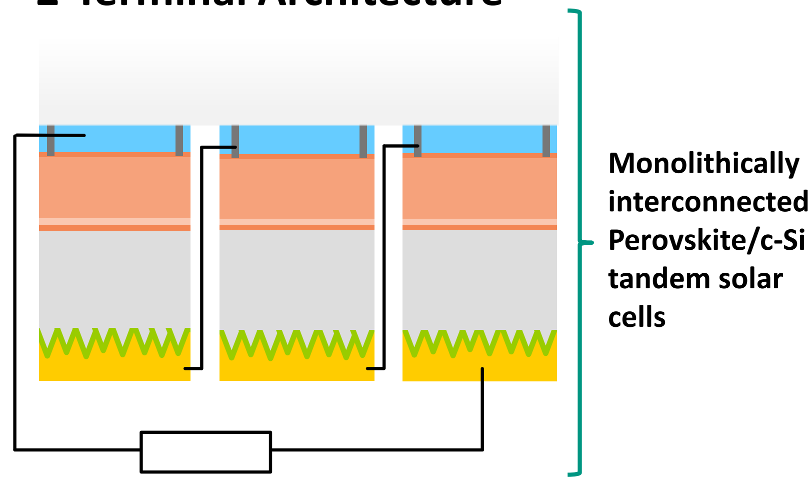
- The perfect marriage -

4-Terminal Architecture



VS.

2-Terminal Architecture



\+ individual control of MPP in each module

\- add layers -> optical losses

\+ low number of add layers and processes

\- current matching of $J_{SC,top}$ and $J_{sc,\,bot}$ required

Which architecture is superior ?

Source1: Optical Loss Analyses and Energy Yield Modelling of Perovskite/silicon Multijunction Solar Cells U. W Paetzold, et al. Optics for Solar Energy, SoW2C. 4

Example 1: Perovskite/Si Multijunction PV

Reference scenario

EY in in one hour of AM1.5 irradiation

	IBC Si	4T (d_{perov}=350nm)	2T (d_{perov}=350nm)
Energy yield (Wh/m^2)	**228.7**	**228.0**	224.2
Jsc (mA/cm^2) top/bottom	**41.5**	**19.1/12.3**	19.1/16.1

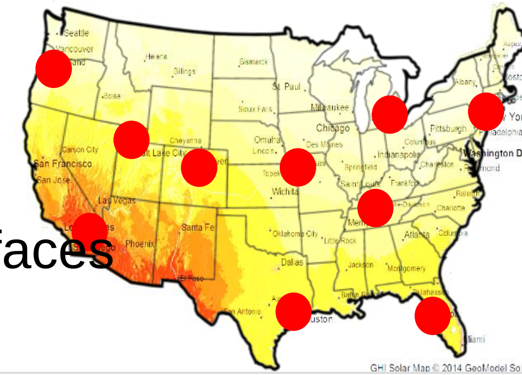
- The energy yield of 2T perovskite/c-Si solar cells is lower than 4T perovskite/c-Si although $PCE_{AM1.5}$ is higher.

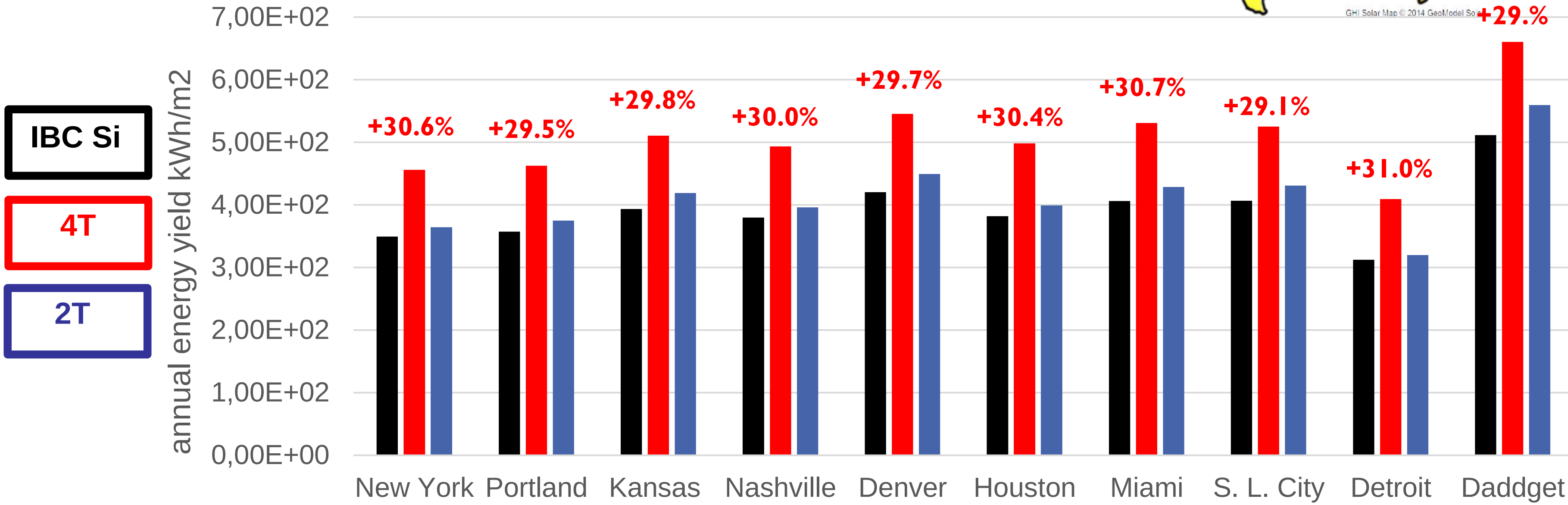
Source1: Optical Loss Analyses and Energy Yield Modelling of Perovskite/silicon Multijunction Solar Cells
U. W Paetzold, et al. Optics for Solar Energy, SoW2C. 4

Example 1: Perovskite/Si Multijunction PV

Optimized Scenario

- No parasitic absorption losses
- No parasitic reflection losses at the front interfaces



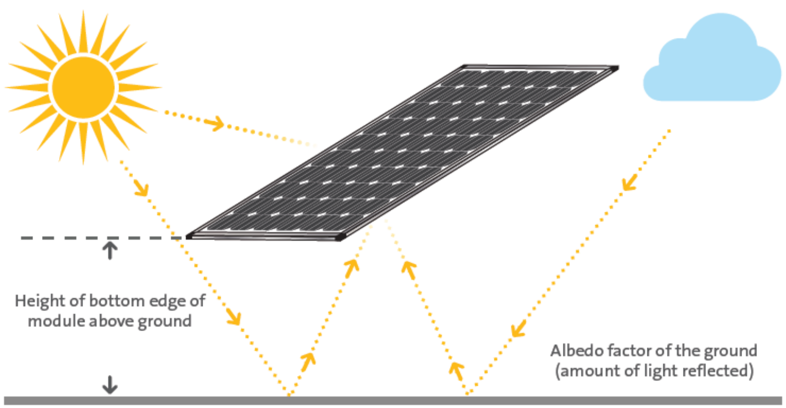


If we would only look at efficiency measurements we would misjudge the potential of the 2T architecture.

Source1: Optical Loss Analyses and Energy Yield Modelling of Perovskite/silicon Multijunction Solar Cells
U. W Paetzold, et al. Optics for Solar Energy, SoW2C. 4

Example 2: Relevance of bifacial PV

Performance increase for bifacial Si solar cells



SURFACE TYPE	ALBEDO
Green field (Grass)	23%
Concrete	16%
White painted concrete	60-80%
White gravel	27%
White roofing metal	56%
Light grey roofing foil	62%
White roofing foil (for solar applications)	> 80%

Source1: SolarWorld. Highlights Special insert.

Example 2: Relevance of bifacial PV

Performance increase for bifacial Si solar cells

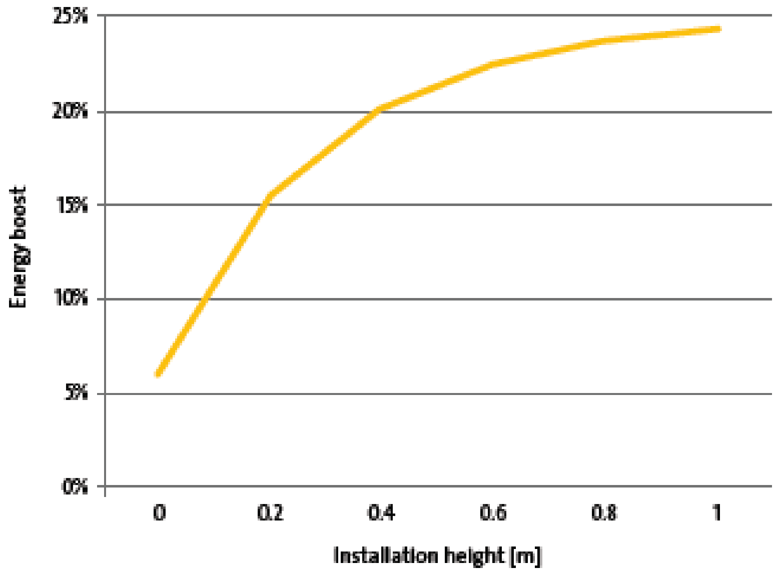


FIGURE 6: *Energy boost of a bifacial PV system with landscape mounted module, south oriented, 30 degree pitch and a row pitch of 2.5 meters, 80 percent albedo*

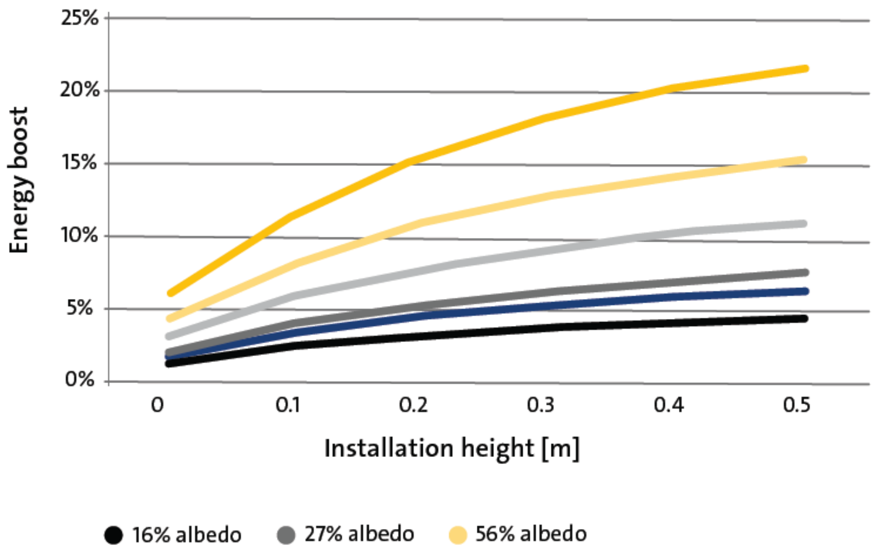


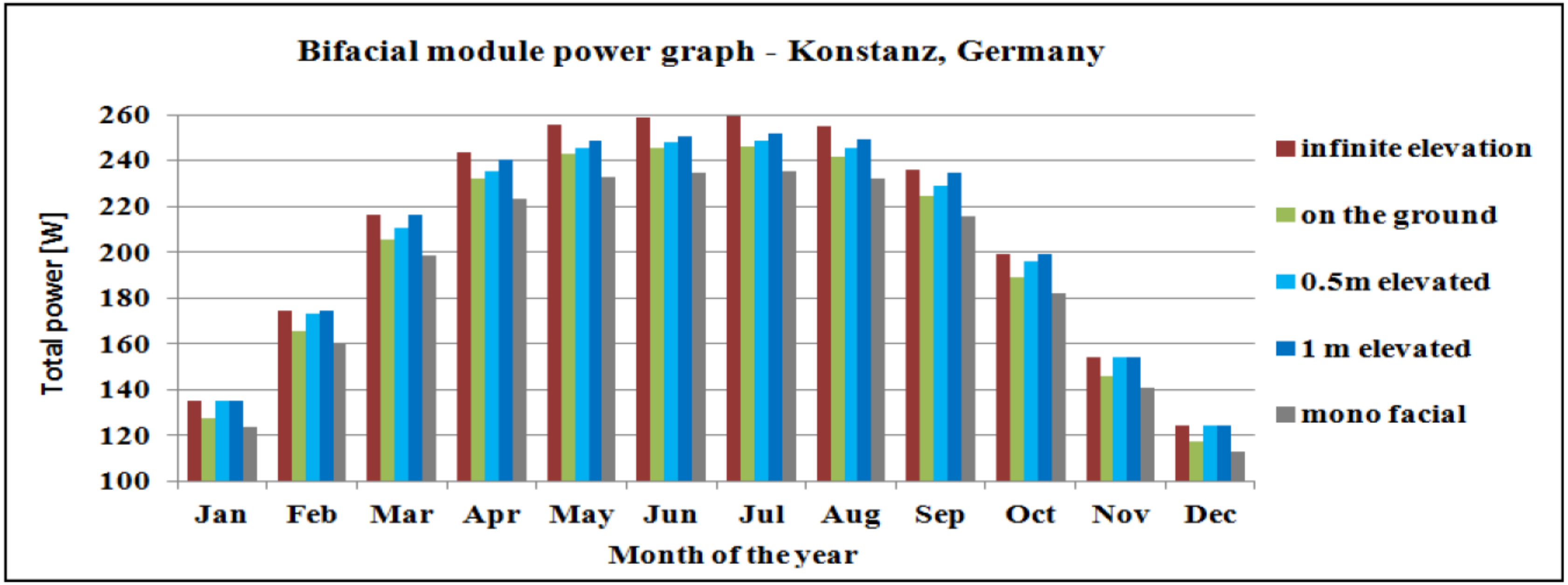
FIGURE 8: *Additional energy yield of a bifacial photovoltaic system with landscape-mounted module, 65 percent bifaciality, south orientation, 30° pitch and a row pitch of 2.5 meters for various albedo values (source: own calculation)*

Up to 25% increase in EY due to bifacial Si solar module design

Source1: SolarWorld. Highlights Special insert.

Example 2: Relevance of bifacial PV

When and where do bifacial Si solar cells make sense ?



- Bifacial PV is a promising route to advance the energy yield based on existing solar module designs
- Depending on the albedo of the underlying ground up to 25% improvement in EY can be achieved

Source1: Stanley Wang et al. Energy Procedia 77 p. 428-433 (2015)

QUESTION ?

Quick Test

- Define Energy Payback Time.
- What is a typical value for the EPT in Germany?
- Make a "back of the envelope" calculation for the EPT of solar cell with E_{in} = 1000kWh/m², η=20%, 5 PSH/day

$$EPT = \frac{E_{in}}{E_{gen}} = \frac{1000\ \text{kWh/m}^2}{0.20 \times 5\ \text{kWh/m}^2 \times \#\text{days}}$$

$$\#\text{years} = \frac{1000}{365\ \text{days/year}} = 2.7$$

- Explain the most important compensation schemes (feed-in tariff, net metering).
- Name advantages of "self-consumption" of PV for the energy system.

Quick Test

Karlsruher Institut für Technologie

- Define the Levelized Cost of Electricity. What are the key factors for a PV system?
- Explain the difference between grid and socket parity.
- Explain the rational behind the Carbon Footprint. What is roughly the Carbon Footprint of electricity generated by PV and coal?
- Name five scarce materials of existing PV technologies.
- Why is the Energy Yield so important?
- Motivate the different contributions to energy yield calculations.
- Give examples for aspects influencing (i) module efficiency, (ii) rel. module efficiency, (iii) system efficiency, (iv) operation efficiency.