Drivers for progress in PV based on LCOE simulations – past, present & future

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Objective

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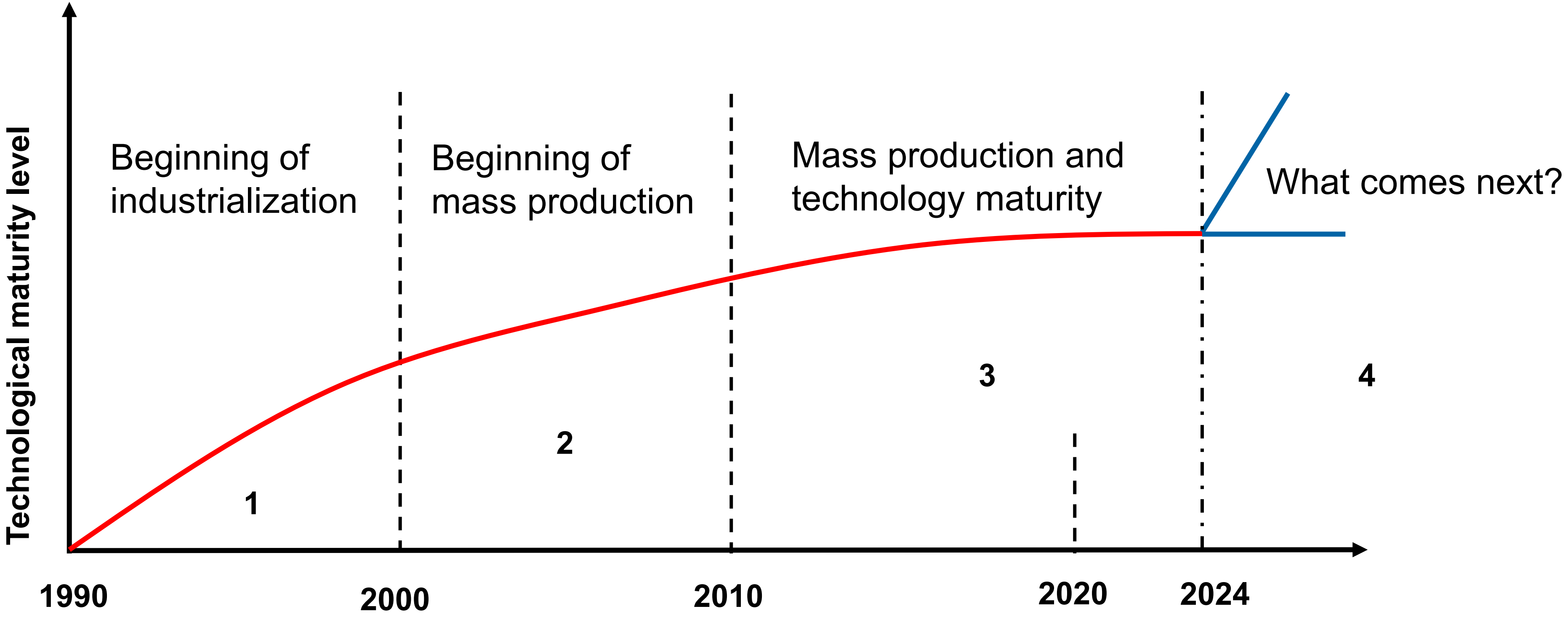
The aim of this work was to analyse whether it is possible to predict future developments in photovoltaics based on the analysis of LCOE. Starting from a retrospective view, a look into the future is taken.

Outline
Stages of the PV industry



Phase 1: Beginning of industrialization
LCOE calculation

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^t}}$$

LCOE	Levelized Cost of Electricity in USD/kWh
I_0	Investment expenditure in USD
A_t	Annual total cost inUSD per year t
$M_{t,el}$	Produced amount of electricity in kWh per year
i	Real interest rate in %
n	Economic lifetime in years
t	Year of lifetime (1, 2, ...n)

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RENEWABLE ENERGY TECHNOLOGIESJUNE 2021

The intention of analysing the LCOE in this presentation is to predict trends over longer periods.

Assumptions:
Reference system size 1kWp
Location central Europe (Switzerland)
Yearly in-plane irradiation (optimized tilt angle and azimuth): 1346 kWh/m^2
Specific energy yield (first year): ~1091 kWh/kWp (no shading)

Differentiation between area- and non-area related cost:

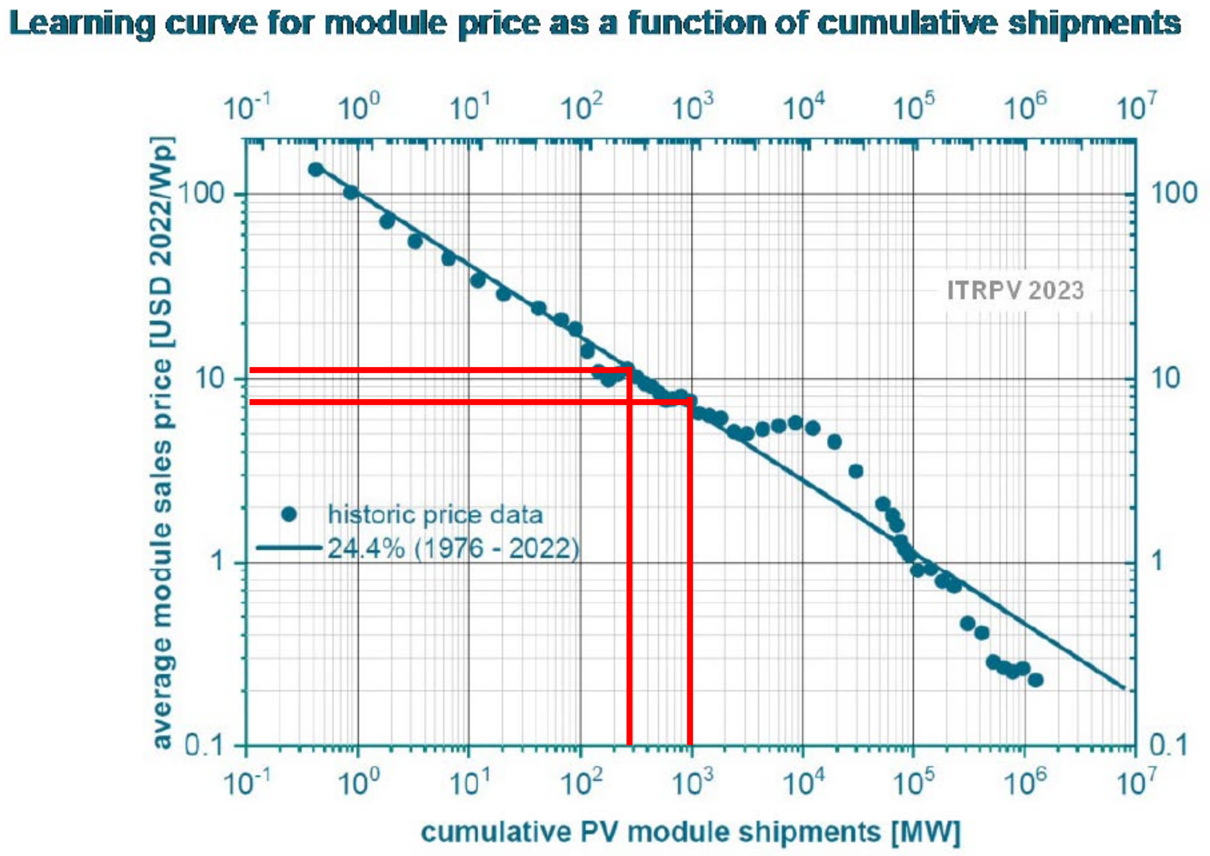
$$I_o(\eta) = I_o(\eta_0) - \left(1 - \frac{\eta_0}{\eta}\right) I_{0\_area}$$

=>Reduction of area related investment cost with increasing efficiency

Example: η_0=16%
Increasing η to 32% would lower the area related cost 50%
Investment for area is included in the calculation

A linear degradation was assumed

Phase 1: Beginning of industrialization
The 90s



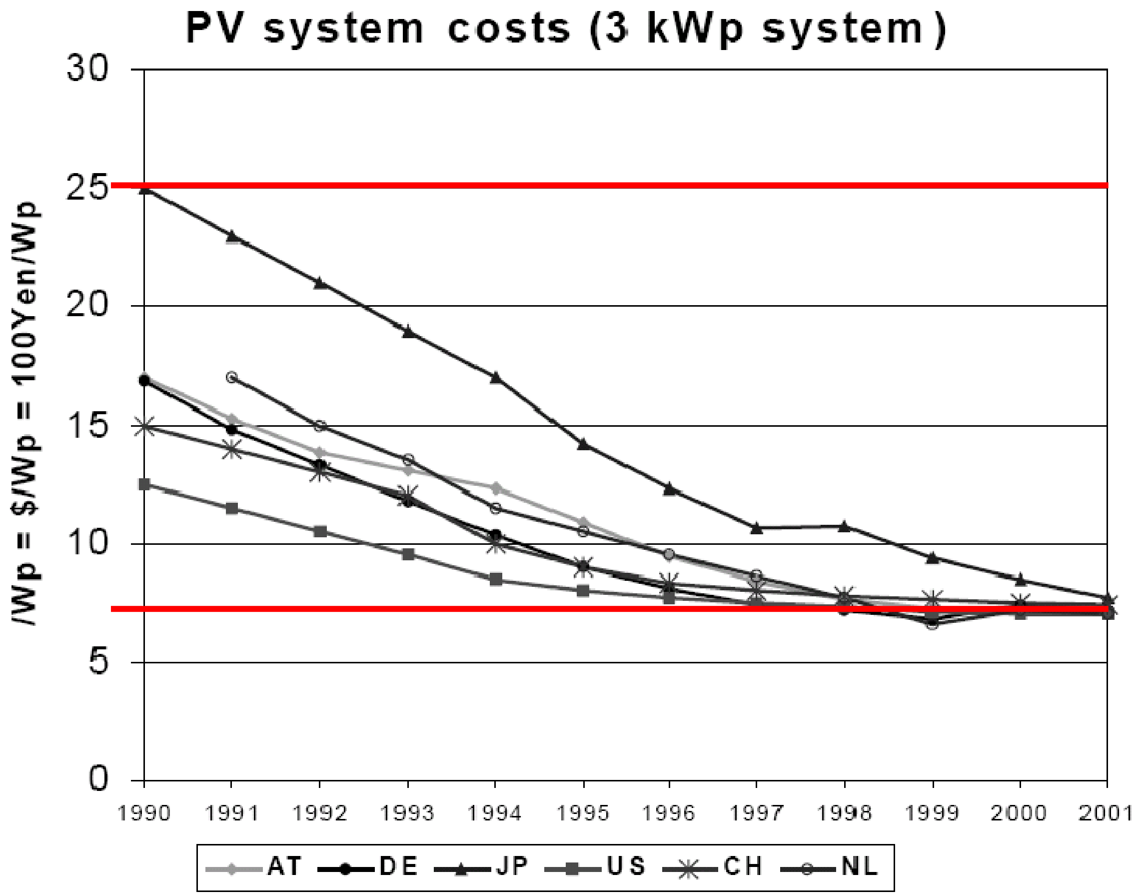
Module price~10 USD/Wp

Total annual production capacity below 225 MWp c-Si (>70% of the market)

Biggest producers Siemens, Kyocera, BP Solarex

Source: ITRPV Roadmap
https://www.vdma.org/international-technology-roadmap-photovoltaic

Phase 1: Beginning of industrialization
The 90s



System price ~15 USD/Wp

Module price ~10 USD/Wp

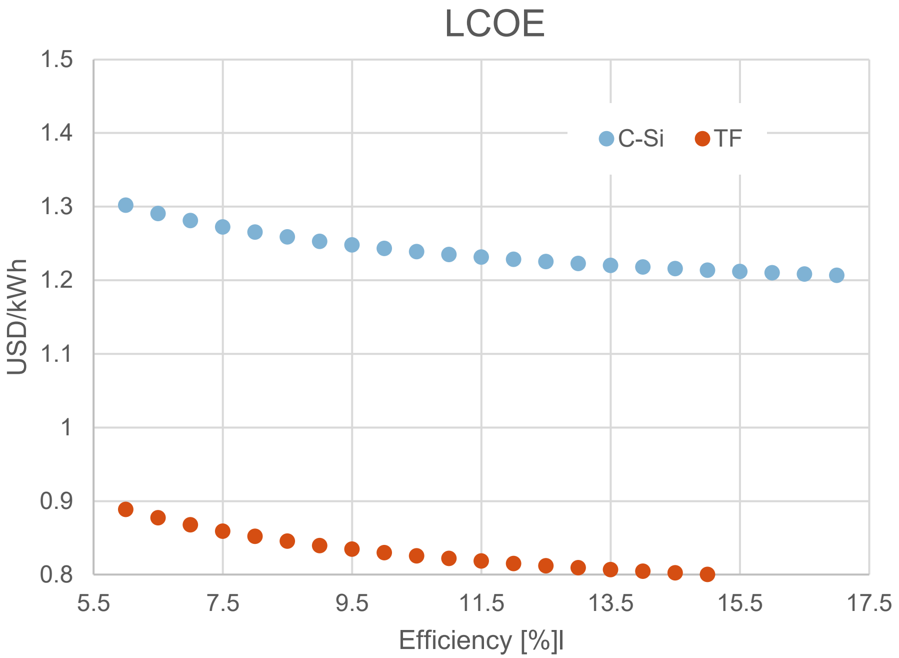
=> 75% cost for module

=> 25% BOS

Source:
TY - BOOK
AU - Anderson, Jason
AU - Bassi, Samuela
AU - Stantcheva, Emilia
PY - 2006/10/04
SP -
T1 - INNOVATION CASE STUDY: PHOTOVOLTAICS

Phase 1: Beginning of industrialization
The 90s -LCOE

20 years lifetime,1% linear degradation, module price
TF = 0.5 x C-Si, I_0 = 15000 USD, A_t = 1.3% of I_0 , i = 4%



Conclusion

A reduction of USD/Wp of the module was the driver for lowering the LCOE

Area related components of the system (sub-construction,…) represent a small proportion of the total costs

A thin film or ribbon-based technology saving 50% of module cost would be winner, “no matter” at which efficiency level

Module lifetime and degradation were not the focus of customers

Phase 1: Beginning of industrialization
The 90s

<u>c-Si</u>
Cell size 10 x 10 cm^2
Industrial solar cell efficiencys 13 -18%
Si technology: Ag backside metallization => Al backside, Al-BSF
TiO_2 ARC => SiN ARC and front side passivation (end 90s)

<u>a-Si</u>
Efficiencies <10%

Phase 1: Beginning of industrialization
The 90s

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Two main drivers for **reducing USD/Wp** of the module

a) Cost reduction of the module or

b) Enhancement of Wp

Phase 1: Beginning of industrialization
The 90s- major research topics

a) Lowering the cost of the module (USD/Wp)

Ribbon technologies (huge research effort):

Wafer process/year started	1990		2000	2001
	Status	Level		
EFG/1971	Pilot	1.5MW	Production 12MW	Production 20MW
Dendritic Web/1967	R&D	<0.1MW	R&D <0.2MW	Pilot 0–1MW
String Ribbon/1980	R&D	–	Pilot <0.5MW	Production <5MW
Silicon Film/1983	R&D	–	Pilot 1–2MW	Production ~5MW
RGS/1983	R&D	–	R&D	Pilot 0–1MW

J.P. Kalejs / Solar Energy Materials & Solar Cells 72 (2002) 139–153

Target: Reducing cost for the solar cell by saving the cost for wafer dicing & kerf loss

Challenges: material quality, yield

None of these technologies survived

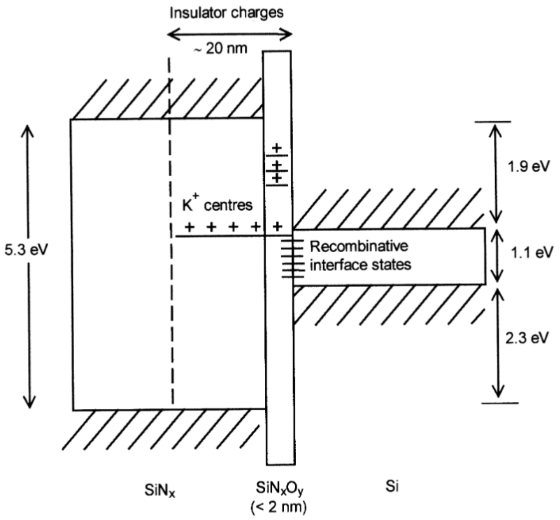
Last approach 1366 technologies

Phase 1: Beginning of industrialization
The 90s- major research topics

b) Enhancement of Wp

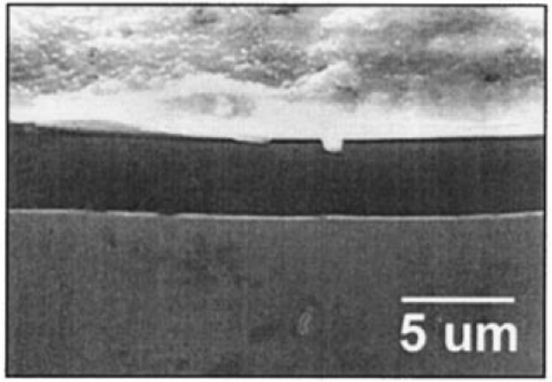
Technical improvements c-Si technology:

SiN-ARC, (H-pass)



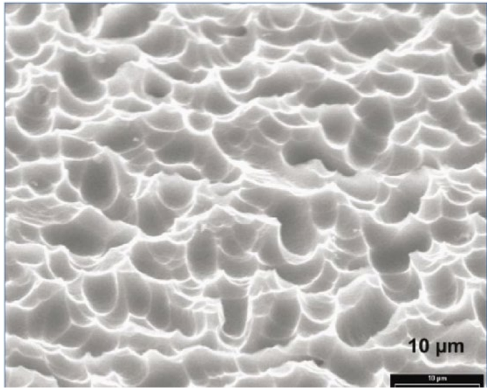
A.G. Aberle / Solar Energy Materials & Solar Cells 65 (2001) 239}248

Al-BSF



Shreesh Narasimha, Ajeet Rohatgi, Fellow, IEEE, and A. W. Weeber, IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 46, NO. 7, JULY 1999

mc-Si texturing

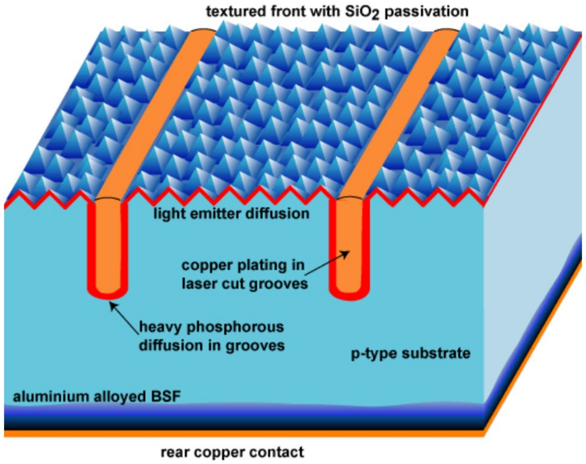


AU - Beaucarne, Guy, P.Choulat, Chan, (BT) Boon, Dekkers, Hendrik, John, Joachim, Poortmans, J.
PY - 2008/01/01, SP - 66, EP - 71, «Etching, texturing and surface decoupling for the next generation of Si solar cells»
VL - 1
JO - Photovoltaics International magazine

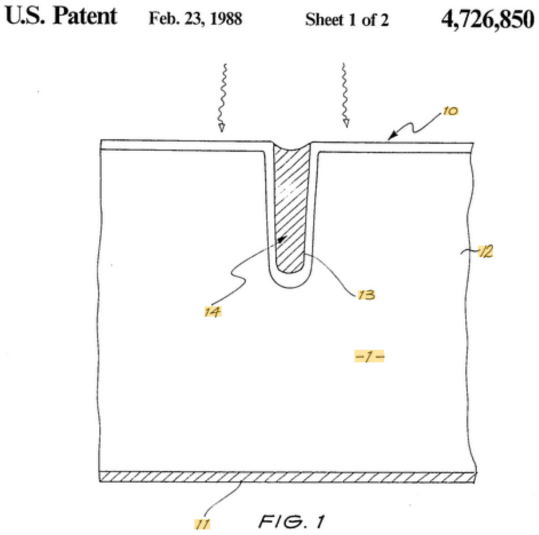
Phase 1: Beginning of industrialization
The 90s- major research topics

b) Enhancement of Wp

- Buried contact solar cells (UNSW) - BP Solar
- Copper contacts, heavy diffusion in the contact area, LPCVD nitride ARC



Source: https://www.pveducation.org



Source: Stuart R. Wenham and Martin A. Green 1988

Parameter		
Jsc	(mA/cm^2)	36.28
Voc	(mV)	625.1
FF		.806
Eff.	(%)	18.3
Area	(cm^2)	147.5

TM, Bruton & Mason, Natdanai & Roberts, S. & Hartley, O.N. & Gledhill, S. & Fernandez, J. & Russell, Ronald & Warta, Wilhelm & Glunz, Stefan & Schultz-Wittmann, Oliver & Hermle, Martin & Willeke, Gerhard. (2003). Towards 20% efficient silicon solar cells manufactured at 60 MWp per annum. Proceedings of the 3rd World Conference on Photovoltaic Energy Conversion. 1. 899 - 902 Vol.1.

Phase 2: Beginning of mass production 2000 – 2010 LCOE

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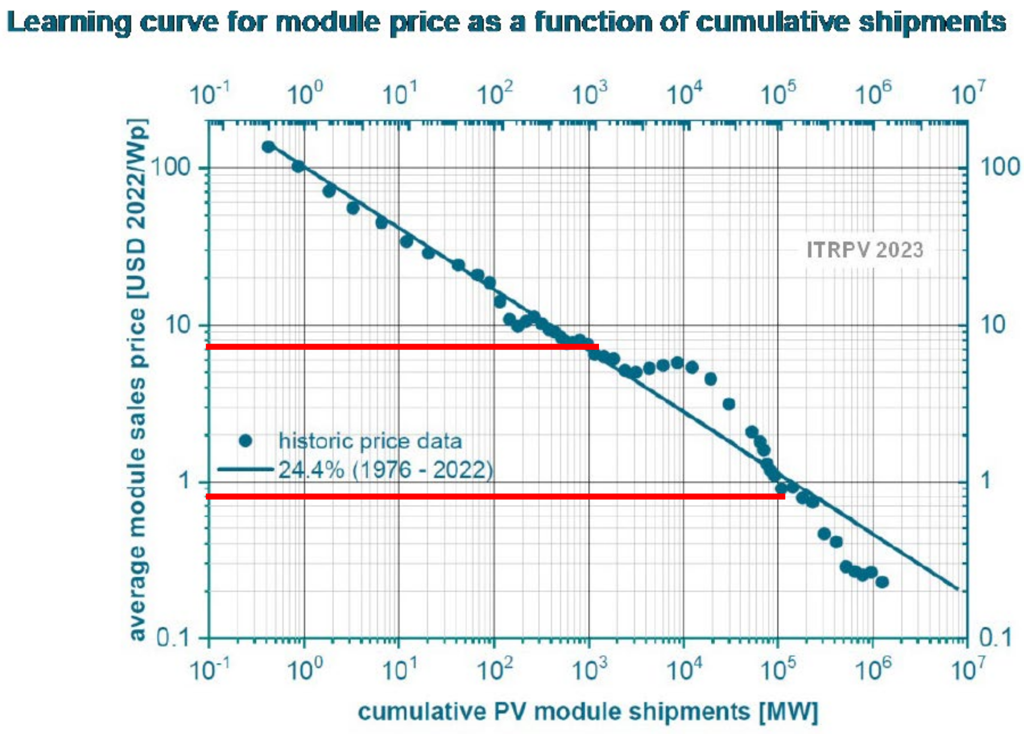

Module price 7 USD/Wp => 0.8 USD/Wp

For the LCOE calculations:
C-Si: I_0 ~ 4000 -5000 USD
TF: I_0 ~ 3000 USD

A_t = 1% of I_0
i = 4%
Yearly degradation 1%

Phase 2: Beginning of mass production 2000 – 2010 LCOE

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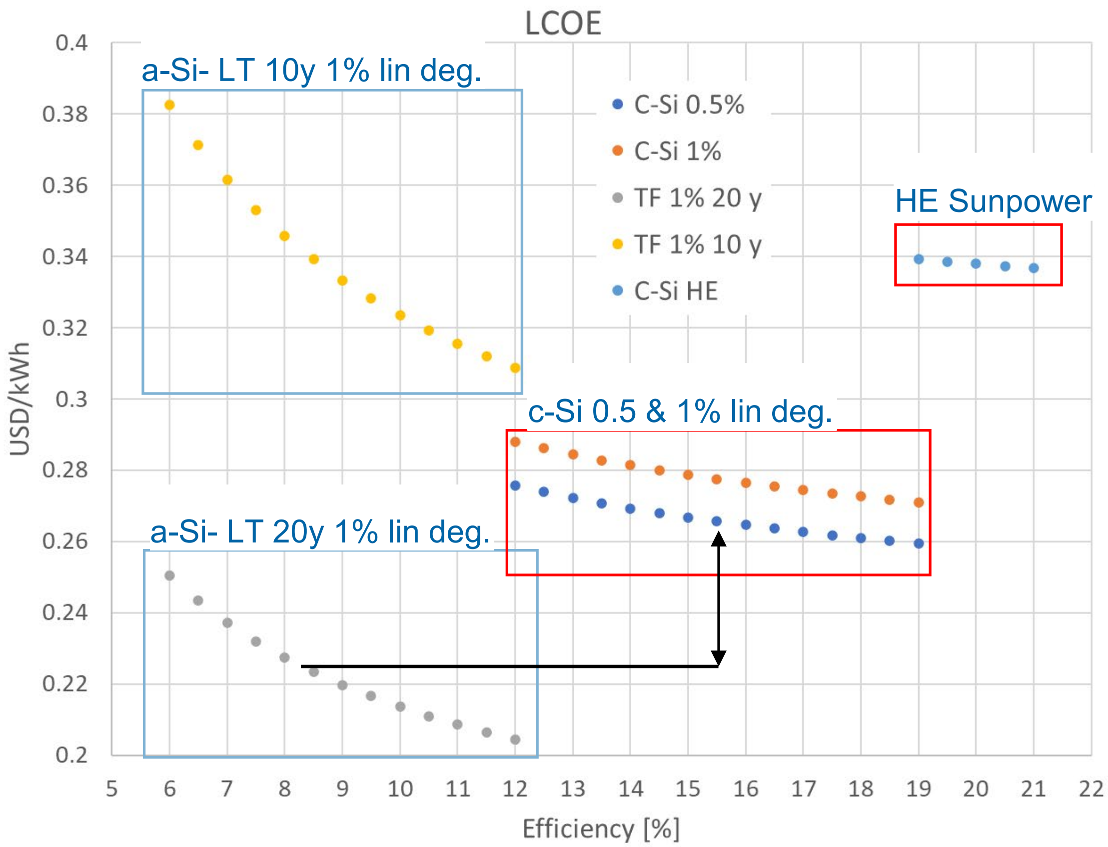

- **Thin film modules are of interest**, because of the lower USD/Wp potential, however only with similar lifetimes and degradation! => a-Si hype, CdTe
- A change in the perspective from USD/Wp to USD/kWh started, however still module counted for around 50% of the system cost and therefore **reduction of USD/Wp remained the biggest driver** for lowering LCOE
- High efficiency modules were restricted to high quality residential & niche markets

Phase 2: Beginning of mass production 2000 - 2010

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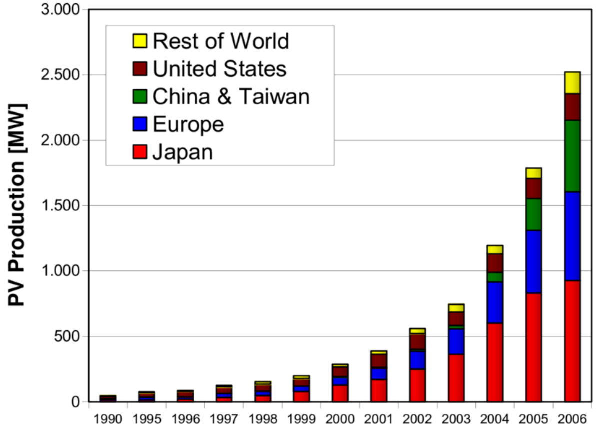
2000: Renewable Energy Sources Act or EEG in Germany (Favourable loans & fixed feed in tariffs for 20 years) => strong market push, module lifetime
Q-Cells, Solarworld,… in Europe

Cell sizes 12.5 x 12.5 cm^2 and 15.6 x 15.6 cm^2
Industrial solar cell efficiencies 16-22.4% (SunPower, IBC)

~2004 Beginning production in China
(technology transfer centrotherm, Roth&Rau, Meyer Burger, Schmid)

Thin film technologies:
First Solar CdTe, a-Si hype with Oerlikon and Amat



Jäger-Waldau, Arnulf. (2007). PV Status Report 2007. 10.2788/48825.

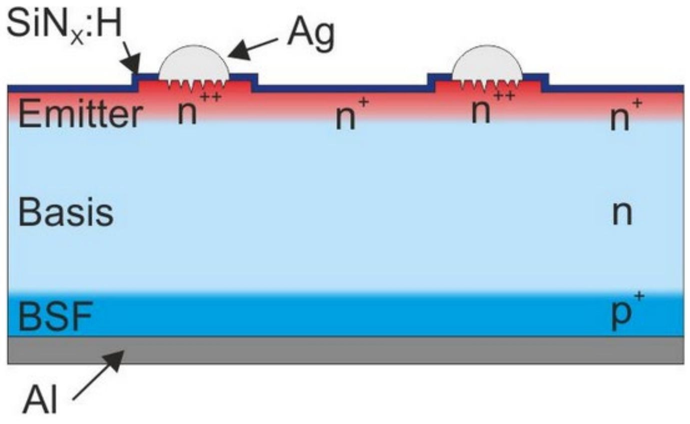
Phase 2: Beginning of mass production 2000 - 2010

C-Si
Reduction of USD/Wp due to increased wafer size for higher productivity 156 x 156 mm^2 (M0)

Al-BSF c-Si solar cell

Approaches to increase efficiency
-Selective emitter
-**Fine line screen printing & paste improvement**
-Laser opening ARC and plating
--…

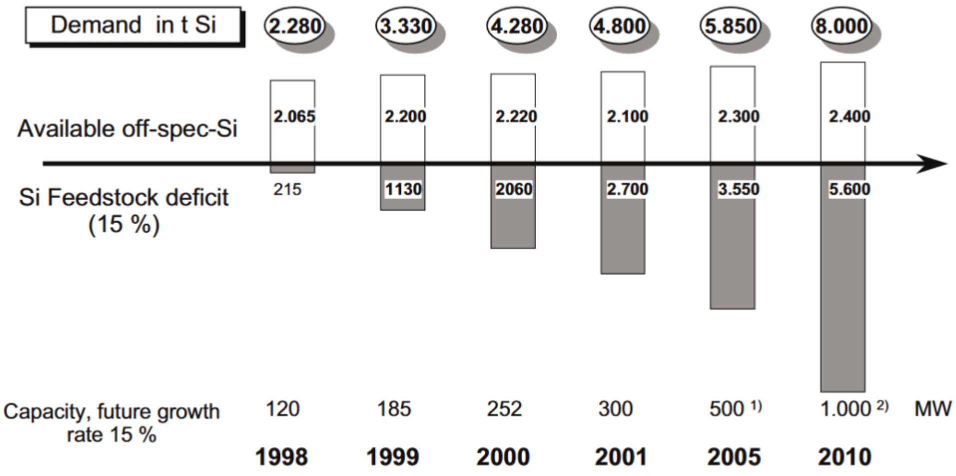
Universität Konstanz



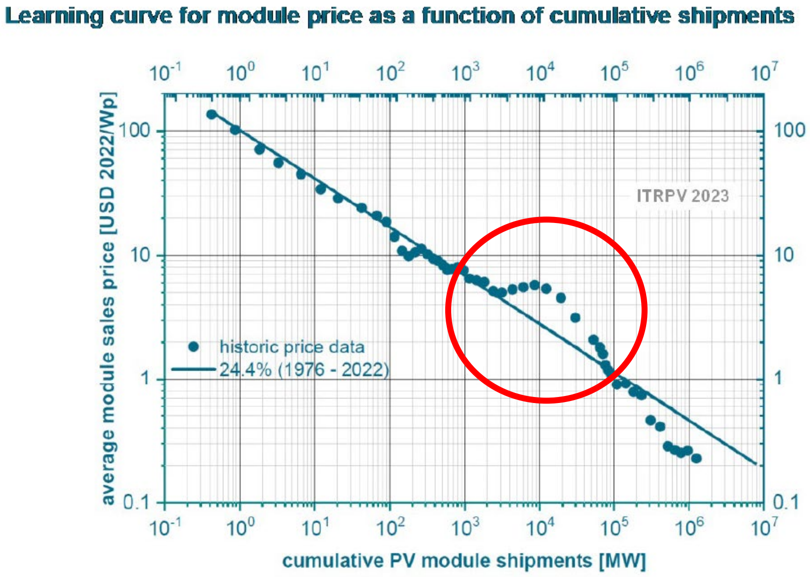
https://www.hahn.uni-konstanz.de/en/research/research-groups/process-technology/

Phase 2: Beginning of mass production 2000 - 2010

Silicon feedstock shortage, foreseen end of 90s



Source: Solar grade silicon feedstock supply for PV industry
Peter Woditsch a, *, Wolfgang Koch
Solar Energy Materials & Solar Cells 72 (2002) 11–26



Source: ITRPV Roadmap
https://www.vdma.org/international-technology-roadmap-photovoltaic

Phase 2: Beginning of mass production 2000 - 2010

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- Disruptive technology changes were not the strong driver
- Continuous improvements and economy of scale resulted in significant reduction of USD/Wp on the module level
- The silicon shortage resulted in a module price increase and slowed down the market development

Phase 3: Mass production and technology maturity 2010-now

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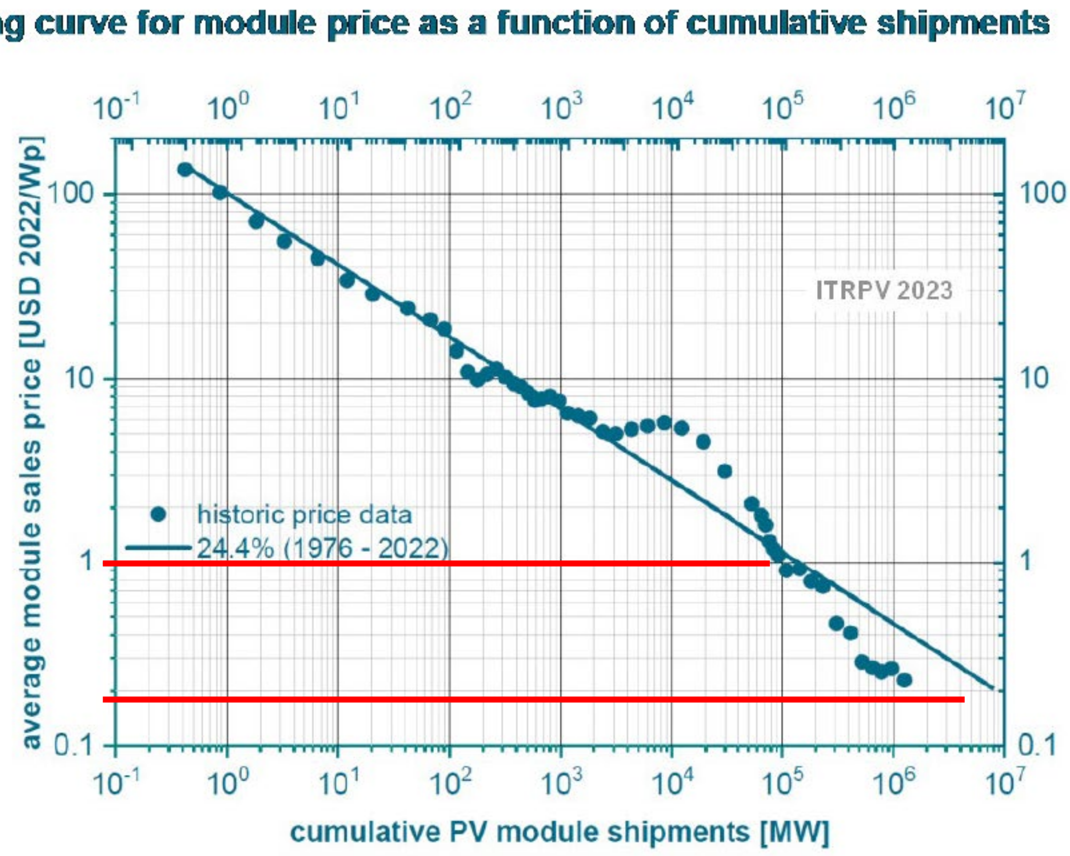
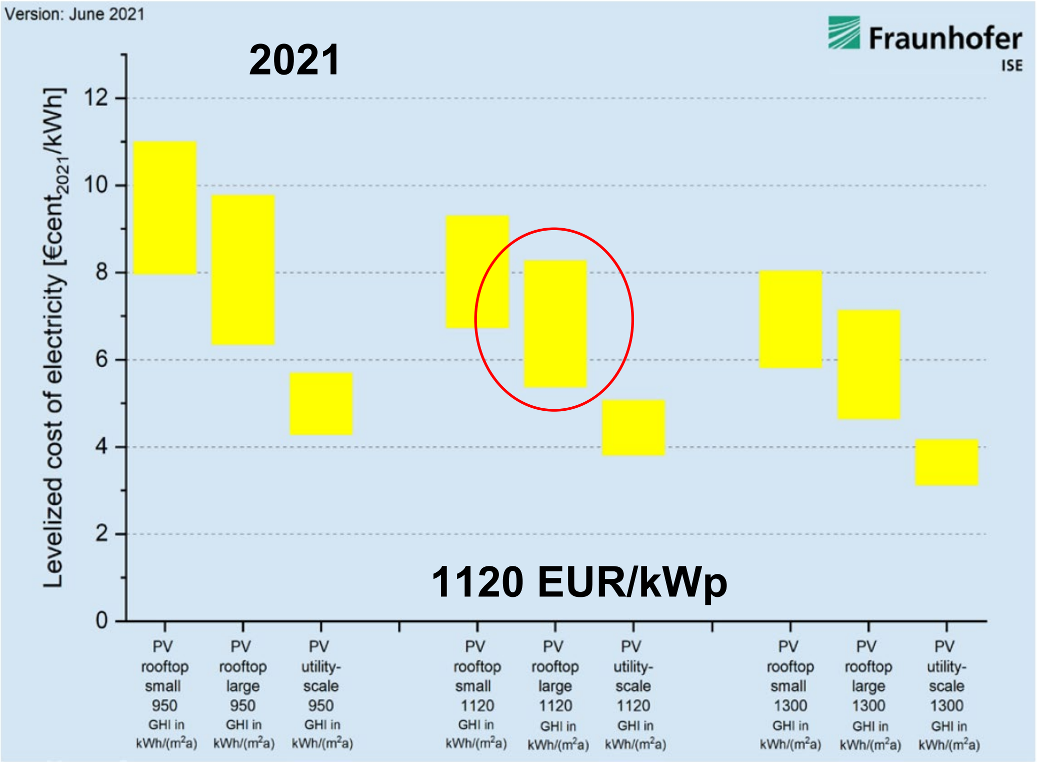


Module prices below 1 USD/Wp

Current market prices 0.11 USD/Wp (depending on technology, wholesaler prices)

Source: ITRPV Roadmap
https://www.vdma.org/international-technology-roadmap-photovoltaic

Phase 3: Mass production and technology maturity 2010-now



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CAPEX	PV rooftop small (≤ 30 kWp)	PV rooftop large (> 30 kWp)	PV utility-scale (> 1 MWp)
Unit	[EUR/kWp]	[EUR/kWp]	[EUR/kWp]
2021 low	1000	**750 EUR/kWp**	530
2021 high	1600	**1400 Eur/kWp**	800

LCOE calculation
2024: module USD/kWp
I_0 = 750 USD/kWp
A_t = 1% of I_0
i = 1%

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Phase 3: Mass production and technology maturity 2010-now

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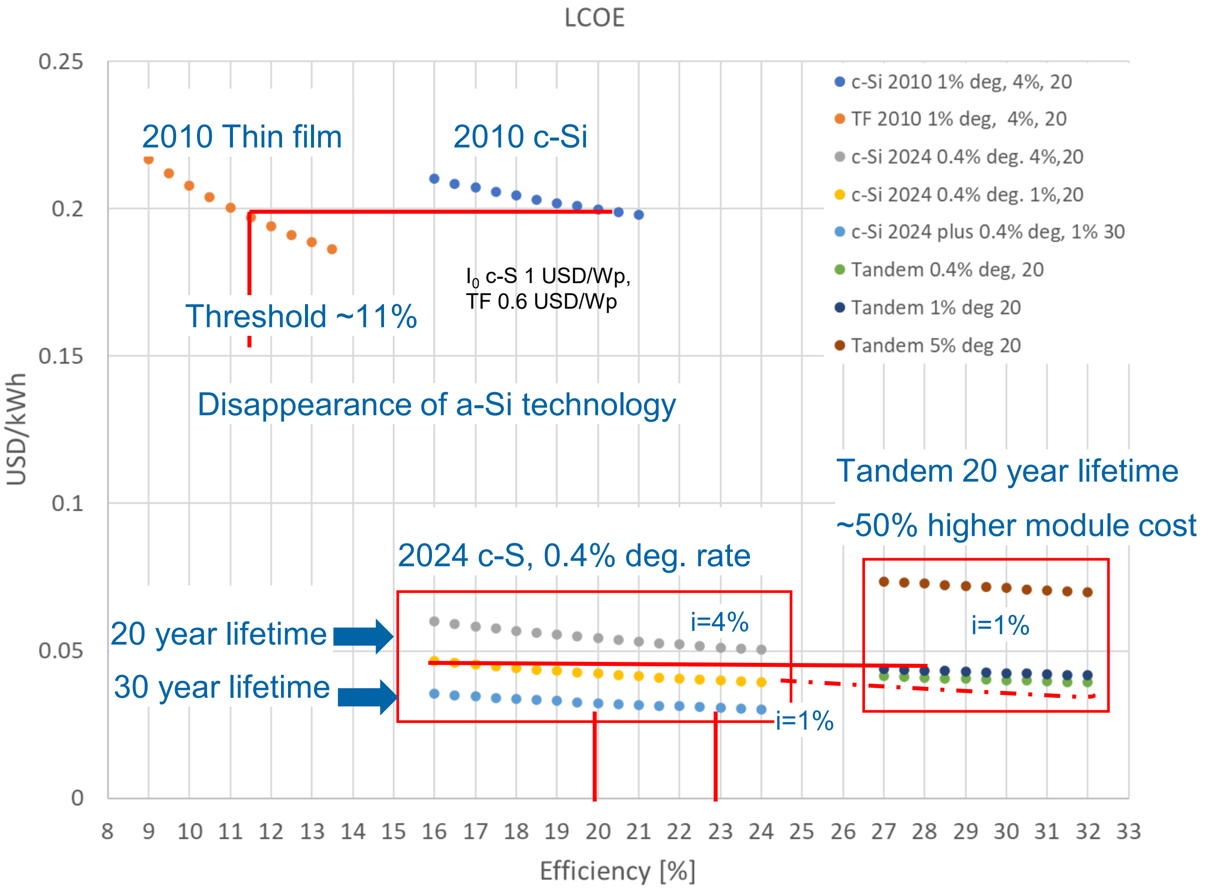
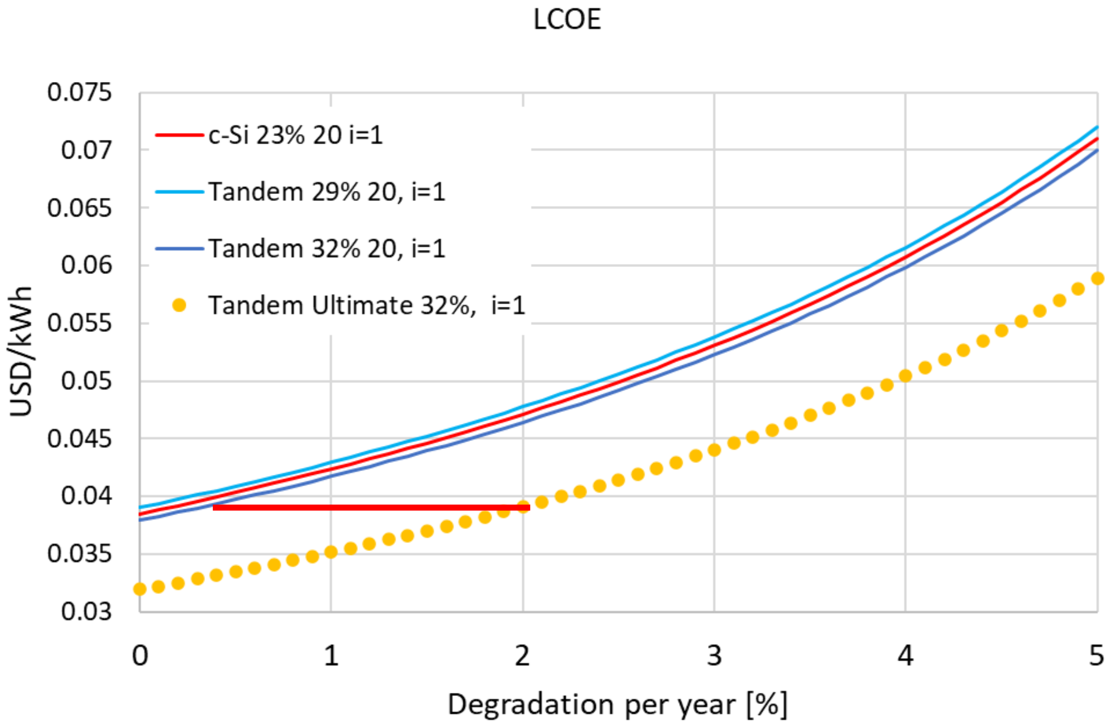


The economy of scale in production of silicon solar modules and the resulting cost reduction led to the disappearance of a-Si modules on the market

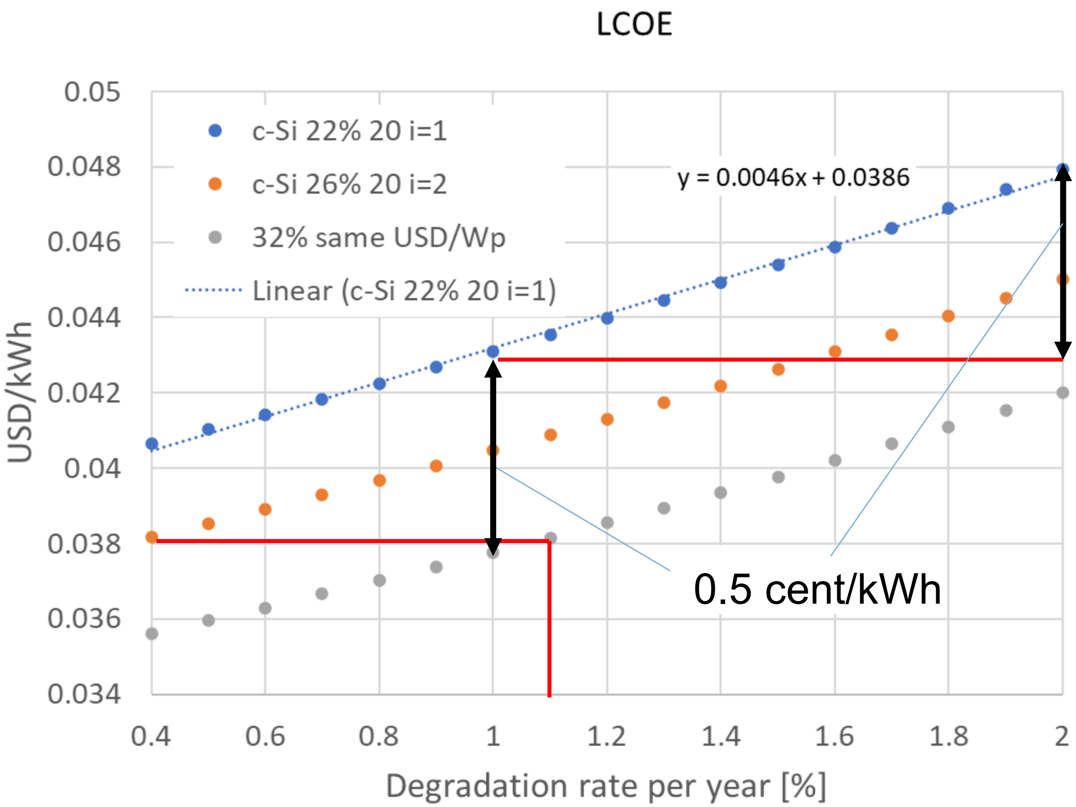
Higher efficiency modules can further reduce the LCOE but on an already low level (only if degradation levels and lifetimes can be kept at a similar level).

Phase 3: Mass production and technology maturity 2010-now



Degradation rate has a much higher sensitivity on LCOE compared to efficiency. Even for constant area cost of the tandem module with a 9% absolute higher efficiency the LCOE is not lower if the degradation rate is 2% instead of 0.4%

Phase 3: Mass production and technology maturity 2010-now



Assuming **same cost** of USD/Wp for c-Si and tandem.
~0.5 cent/kWh per ~10% η
~0.5 cent/kWh per 1% deg
=> ~10% η-gain abs. can be lost by a +1% degradation
=> The tandem technology can only be competitive when achieving similar low degradation rates compared to c-Si technologies
=> An η-increase of 6% absolute at same USD/Wp module cost would tolerate a 0.7% higher degradation rate (20 years lifetime)

Phase 3: Mass production and technology maturity 2010-now

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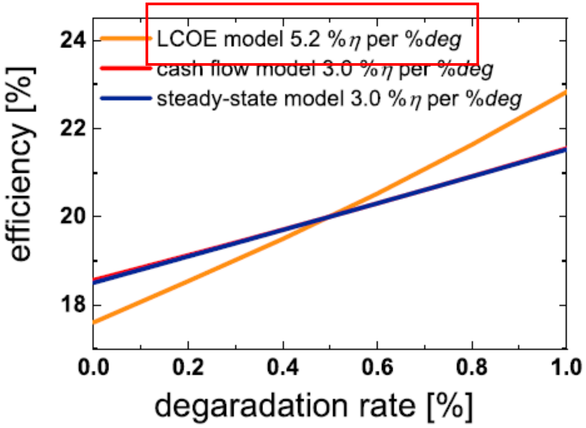
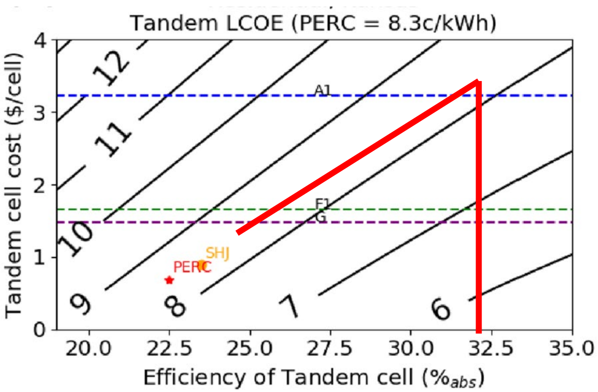


Peters et al., The value of stability in photovoltaics, Joule (2021), https://doi.org/10.1016/j.joule.2021.10.019

5.2% η per 1% deg. at no additional cost for higher efficiency, cost of 2021

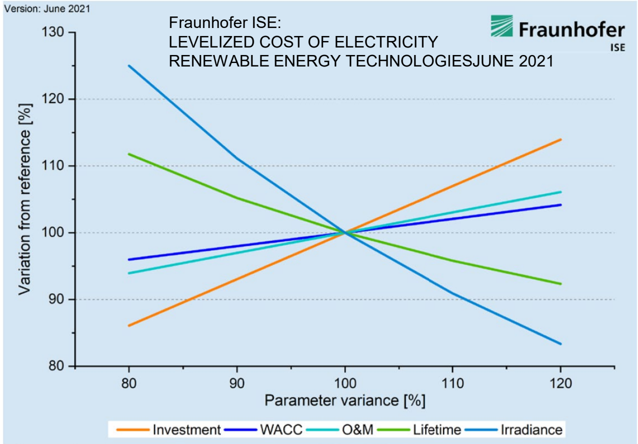
=> we are much more sensitive to degradation now



Chang NL, Zheng J, Wu Y, et al. A bottom-up cost analysis of silicon–perovskite tandem photovoltaics. Prog Photovolt Res Appl. 2020;1–13. https://doi.org/10.1002/pip.3354

Allowance of ~2$ per cell additional cost for 32% tandem => LCOE comparable to PERC

Baseline cell: 244cm^2, 22.5%, 0.26 $/Wp on module level



WACC = weighted average costs of capital

Lifetime second highest sensitivity after irradiance

Phase 3: Mass production and technology maturity 2010-now

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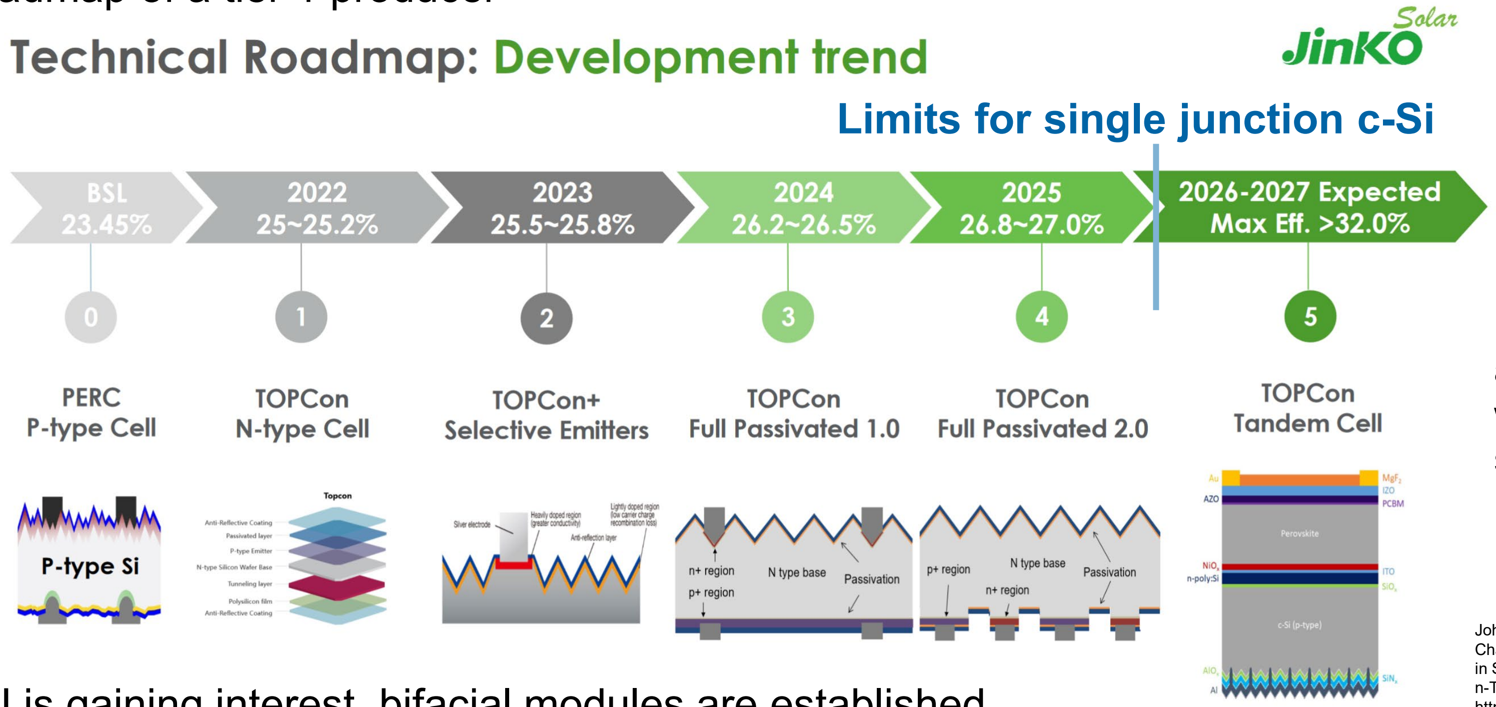
Since the implementation of PERC into mass production technology progressed fast - typical roadmap of a tier 1 producer



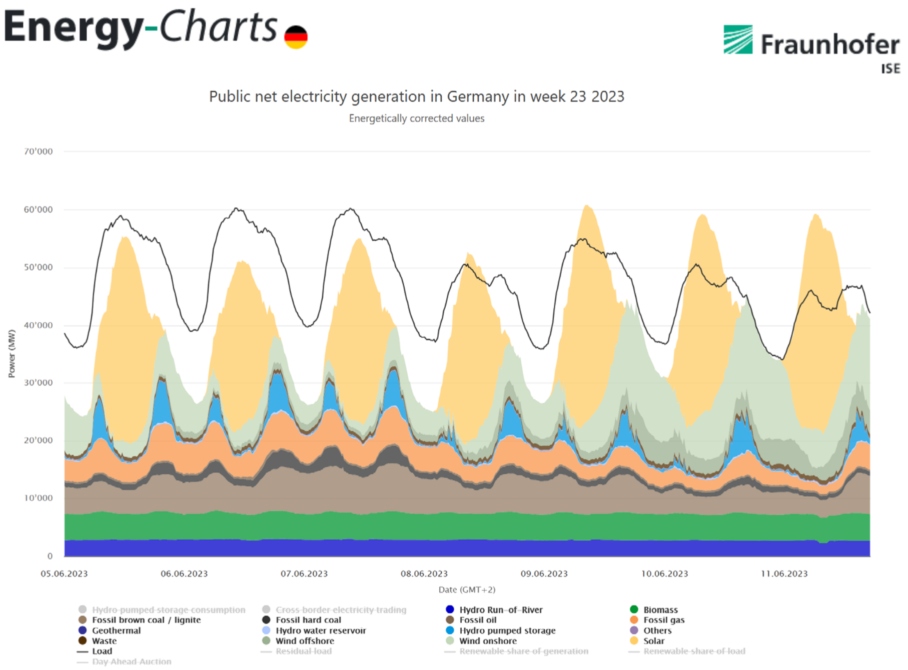
Maybe a roadmap for lowering degradation and enhancing lifetime would make a lot of sense?

HJ is gaining interest, bifacial modules are established

Johanna Bonilla, Challenges & Experiences in Scaling up TOPCon n-Type Manufacturing https://www.pv-magazine.com/wp-content/uploads/2022/01/Session-2_Presentation_Johanna-Bonilla-Jinko-FINAL.pdf

Phase 4: What comes next?
Status quo

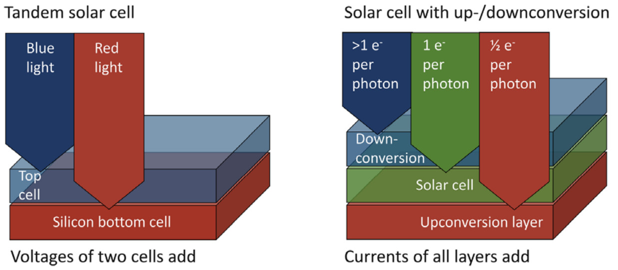
- c-Si single junction technology full potential reached
- In some regions PV cheapest source of electric energy
- Degradation and lifetime of the modules is of high sensitivity for LCOE
- Sub-construction, labour cost for installation and cost for area represent an increasing cost share
- Time dependent value of energy during the day and seasonal dependence



https://energy-charts.info/charts/power/chart.htm?l=en&c=DE&year=2023&week=23

Phase 4: What comes next?

One direction: obvious
Higher efficiencies – tandem, multi-junction solar cells, up- & down conversion
Target: Lowering LCOE by increasing kWh- or even USD/Wp?
Only if long term stability is proven and the technology is bankable (how long will it take?)



Bruno Ehrler et. al. Scalable ways to break the efficiency limit of single-junction solar cells Appl. Phys. Lett. 120, 010402 (2022)

Avoidance of shortages (Ag)

Research on long term stability and degradation mechanisms for the latest products

Increasing the energy yield per ground or roof area ✡

Multiple use of land and building- PV and green roof, Agri PV, BIPV ✡

Producing energy when there is a lack of energy, controlling of the power output over the day (tracking systems) ✡

Phase 4: What comes next?
Increasing the energy per ground or roof area

Zurich University of Applied Sciences
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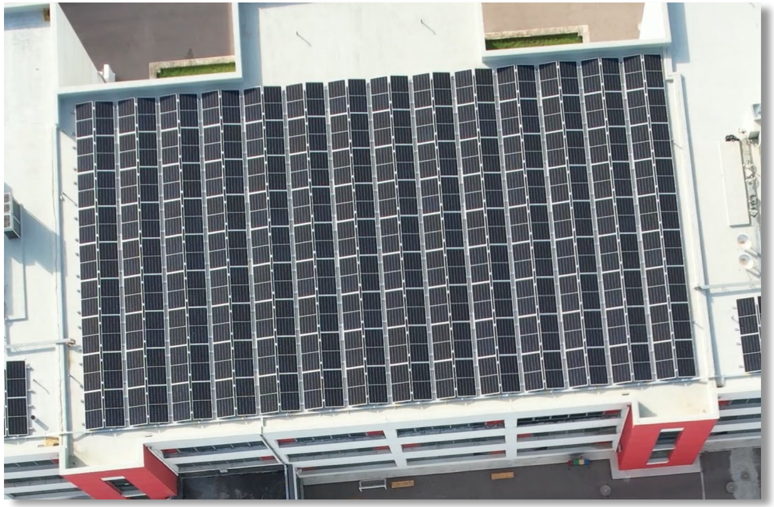
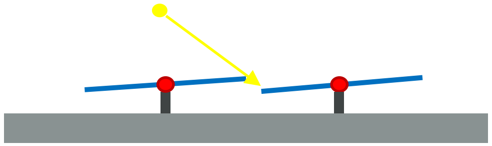
Typical system on a flat roof: Highest GCR

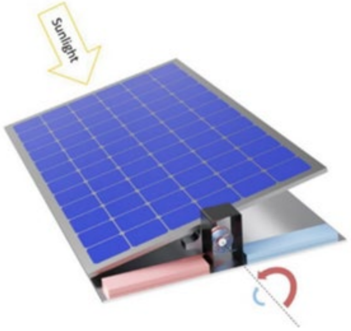


Is there a way to further increase the energy yield, lower LCOE or create higher revenues?

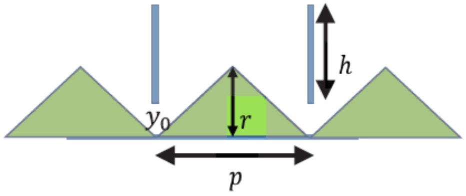
Phase 4: What comes next?
Increasing the energy per ground or roof area

a) Simple HSAT systems

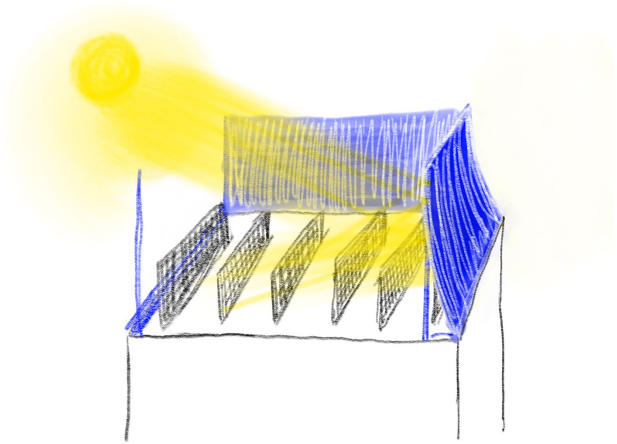




b) Ground Sculptures

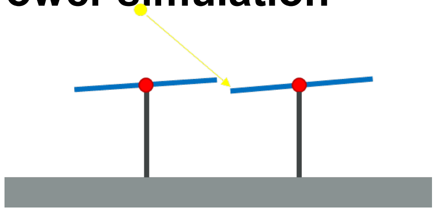


c) Dynamic reflectors



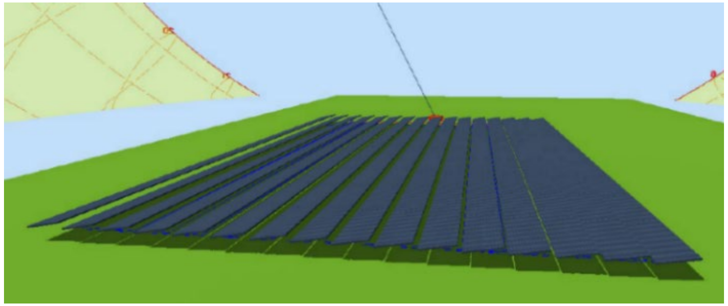
Phase 4: What comes next?
Increasing the energy per ground or roof area
a) HSAT on roofs?

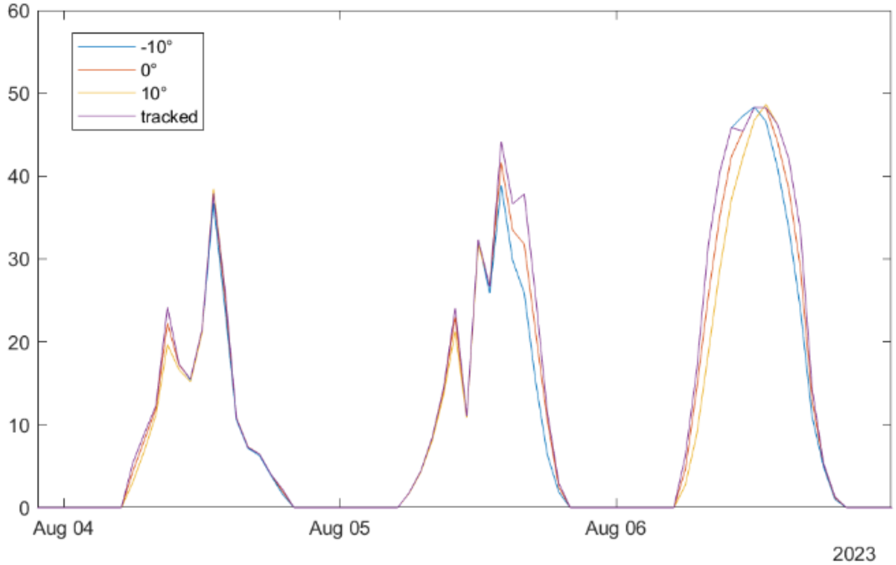
Power simulation



Simple «Flip-Flop»-Tracker?

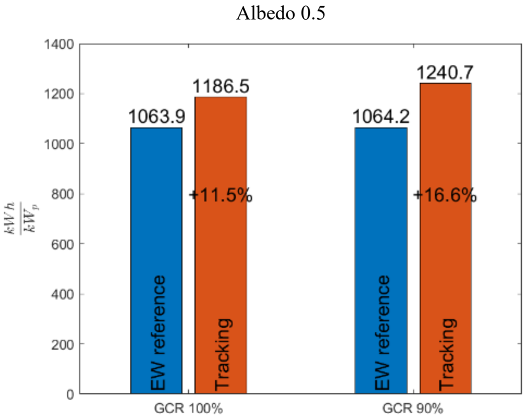
High GCR!

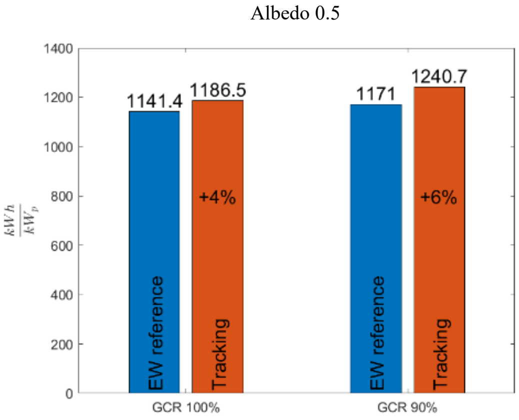


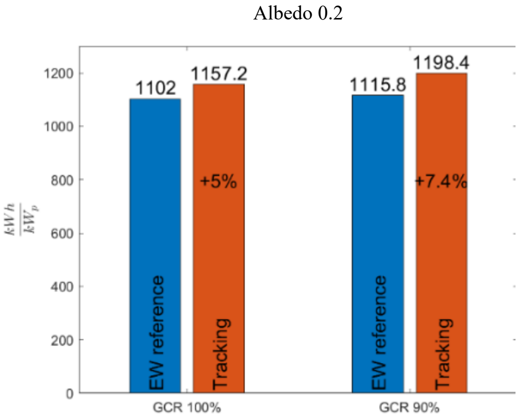


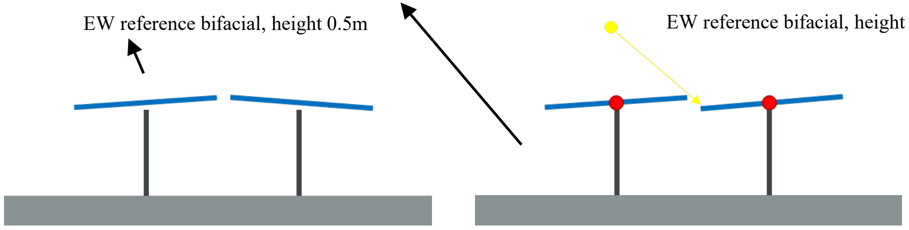
Tracking angles of -10° in the morning until 10 am
0° from 10am to 2pm
+10° starting from 2pm

Phase 4: What comes next?
Increasing the energy per ground or roof area
a) HSAT on roofs?
Yearly specific energy yield simulation using for Winterthur, Switzerland









More information: see upcoming EUPVSEC 2024

For same GCR simple tracking systems can achieve higher energy yields

Phase 4: What comes next?
Increasing the energy per ground or roof area
b) Ground Sculptures?

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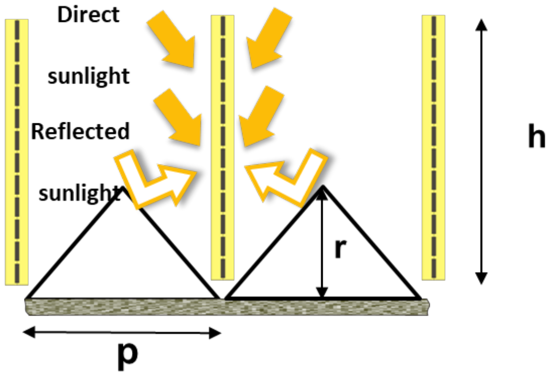
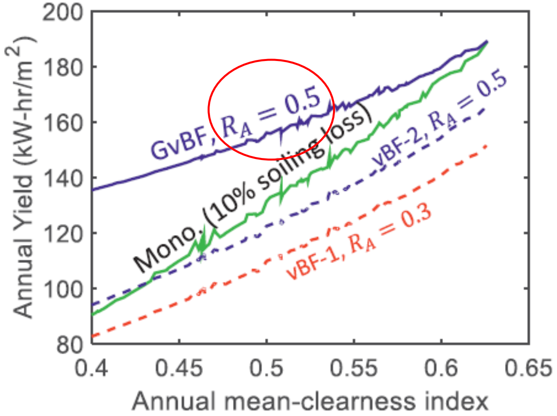
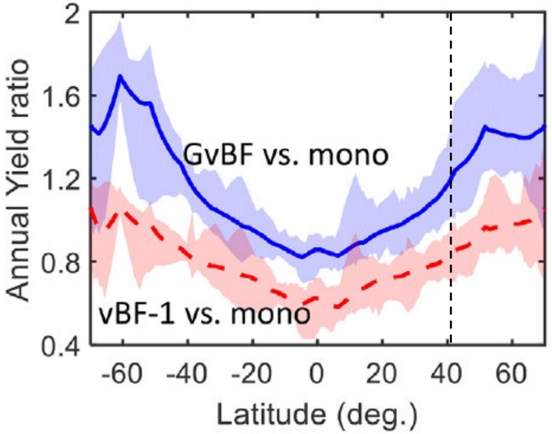
GvBF



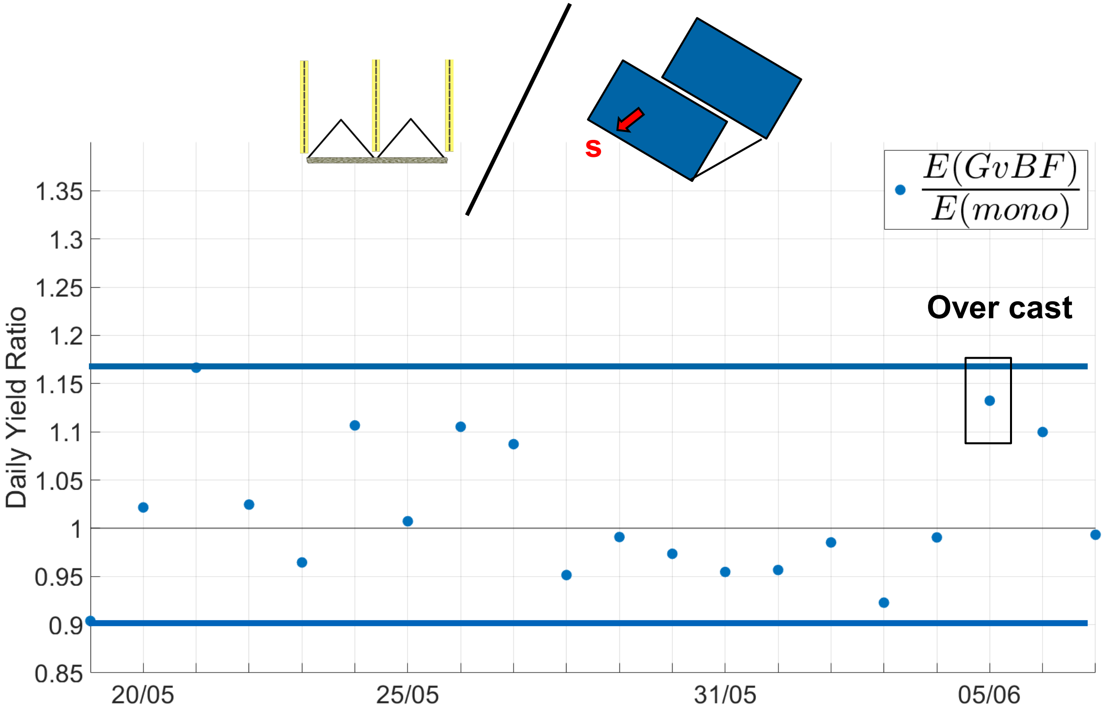




Source: Khan et al. "Ground sculpting to enhance energy yield of vertical bifacial solar" Applied Energy, Volume 241, 1 May 2019, Pages 592-598", https://www.sciencedirect.com/science/article/pii/S0306261919301278

Results of Khan et. al.
For regions with low annual mean-clearness index and high latitudes GvBF design is resulting in superior annual yield per area compared to a south orientated monofacial system

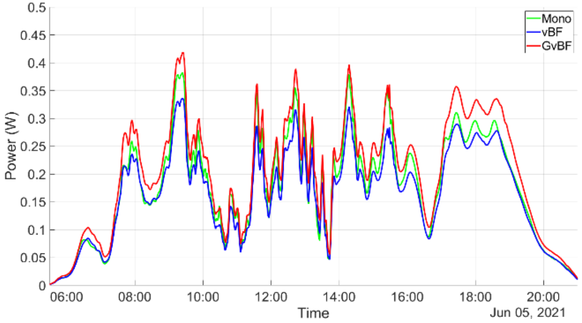
Phase 4: What comes next?
Increasing the energy per ground or roof area
b) Ground Sculptures?



=>There is a higher yield in partly cloudy days, where in future the price for electricity is higher

⇒ GvBF reveals higher yields compared to mono south for overcast days

$$1 \leq \frac{E_{GvBF}(day)}{E_{vBF}(day)} \leq 1.17$$

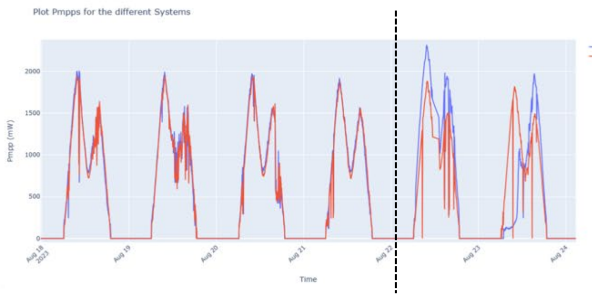


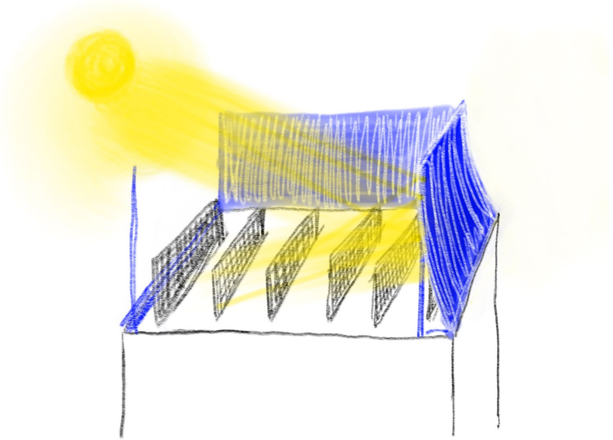
Daily yield ratio GvBF/mono = 1.13

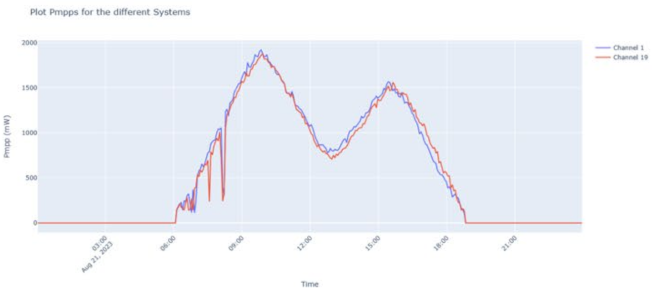
More information available: H. Nussbaumer et al. Comparative energy yield study of vertically installed bifacial PV modules measured by a miniturized test rig, 38th EUPVSEC, 2021

Phase 4: What comes next?
Increasing the energy per ground or roof area
c) Dynamic movable reflectors

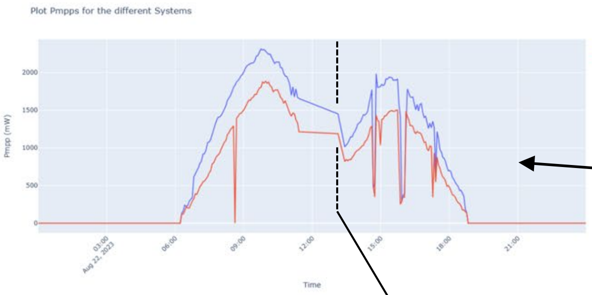
- At up to three sides of a system. Here 3x module height. Center modules.
- E/W reflector-change dependent on time. North fix . Also for non-vertical







Center modules without reflector



With Reflector

Reflector-change E/W

Effect here ~ + 30 % !

Phase 4: What comes next?
Multiple use of land and building

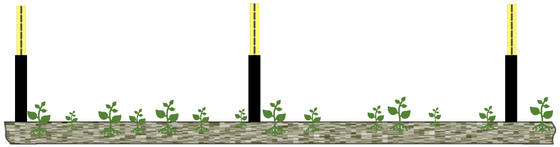
Green roof
- Water retention
- Additional building insulation
- Cooling of the building / urban heating
- Air humidification
- Enhancement of bio diversity

Photovoltaic roof
- Generation of renewable electrical energy

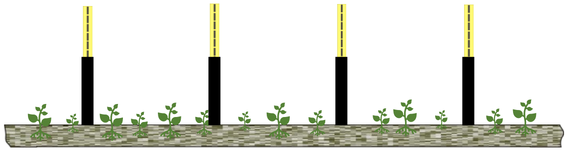
Phase 4: What comes next?
Multiple use of land and building

Vertical bifacial modules

GCR 0.5, Green roof area 100%



GCR 1, Green roof area 100%

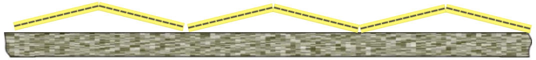


Increased self-shading

Modules under low tilt angles

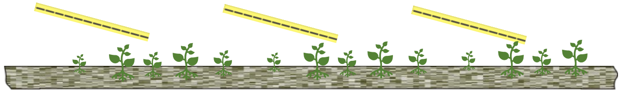
GCR 0.5, Green roof area 50%

GCR 1: No green roof

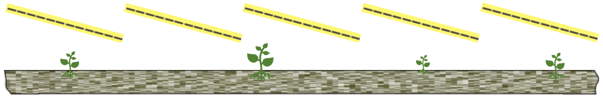


No self-shading

GCR 0.5, Green roof area >50%



GCR 1 Green roof area?



Increased self-shading

Phase 4: What comes next?
Multiple use of land and building

- Dense arrangements of vertically orientated bifacial modules have been analysed in order to optimize the energy generation while maintaining the green roof character (minimizing the area covered by modules)
- The energy yield **per area** can reach comparable values to those of systems with modules under low tilt angles

More information available:

H. Nussbaumer, et al.
Photovoltaic and green roof : energy yield per area of vertically installed bifacial modules in dense arrangements, Proceedings of the 40th European Photovoltaic Solar Energy Conference and Exhibition. pp. 020424-001-020424-007.
https://doi.org/10.4229/EUPVSEC2023/4DO.12.5

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zh aw School of Engineering

Phase 4: What comes next?
Multiple use of land and building- Agrivoltaics

Federal Ministry of Food and Agriculture

https://www.bmel.de/DE/themen/landwirtschaft/klimaschutz/Agri-PV.html

Fraunhofer ISE

https://www.ise.fraunhofer.de/en/key-topics/integrated-photovoltaics/agrivoltaics.html

Phase 4: What comes next?
Multiple use of land and building- Agrivoltaics

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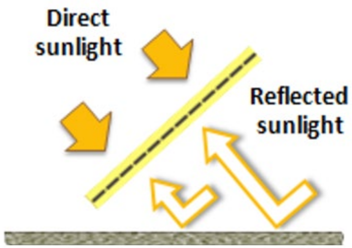
Next 2 Sun

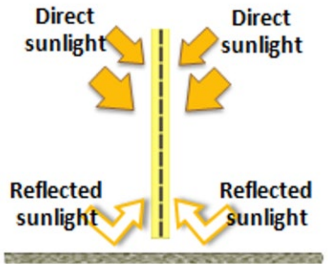
https://next2sun.com/en/agripv/current-agripv-projects/

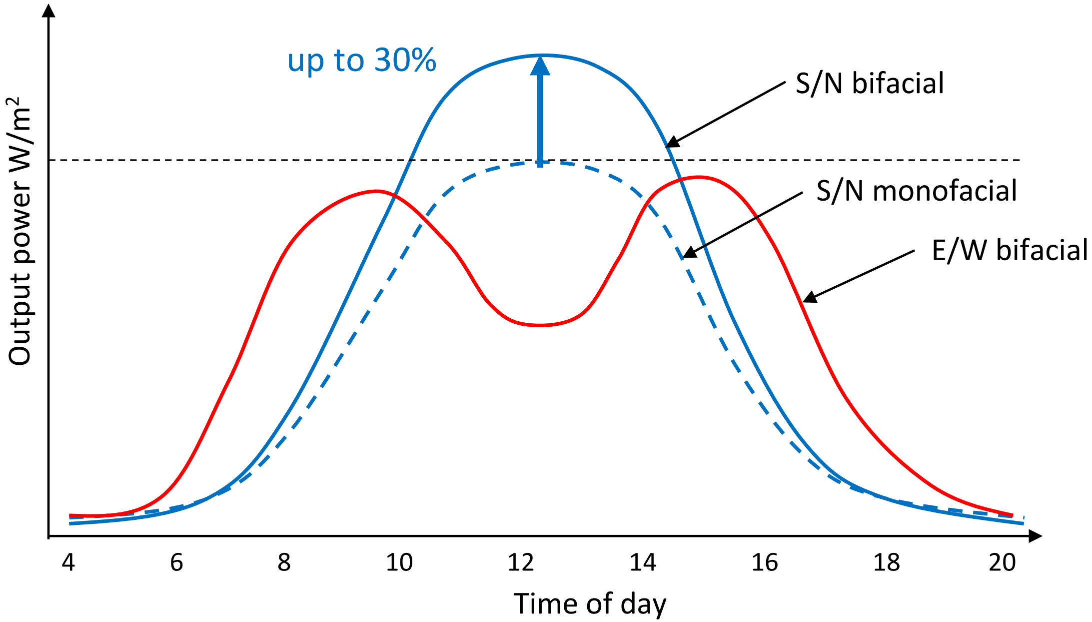
Phase 4: What comes next?
Producing energy when there is a lack of energy

Slanted S/N



Vertical E/W





H. Nussbaumer, Swiss PV conference 2019

Phase 4: What comes next?
Controlling of the power output over the day

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https://www.arctechsolar.us/china/

HSAT systems could be used for controlling the energy output.
Concerning lowest LCOE they compete with systems using higher GCR like 5B

https://5b.co/projects/happy-valley

Summary & conclusion

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LCOE analysis help to predict future developments

However, LCOE analyses alone cannot predict the whole range of developments.
PV in combination with further utilisation of the area will be important in the future.

LCOE is very sensitive on degradation and system lifetime
~10% η-gain absolute can be lost by a +1% degradation
An efficiency increase of 6% absolute at same USD/Wp module cost would tolerate a 0.7% higher degradation rate (20 years lifetime)

Understanding and lowering degradation should be major task in research

Acknowledgement

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IEFE Institute of Energy Systems and Fluid Engineering

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PV systems on flat roofs with highest energy yields per area, SI/502309-01

Development and comparative test of a complete solution for bifacial PV systems on green roofs, SI/502213-01

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Thank you for your attention!