Status and Innovation Potential of Photovoltaics, Key Enabler for the Energy and Material Transition

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Chair European Technology and Innovation Platform PV

June 19, 2023, Bad Honnef

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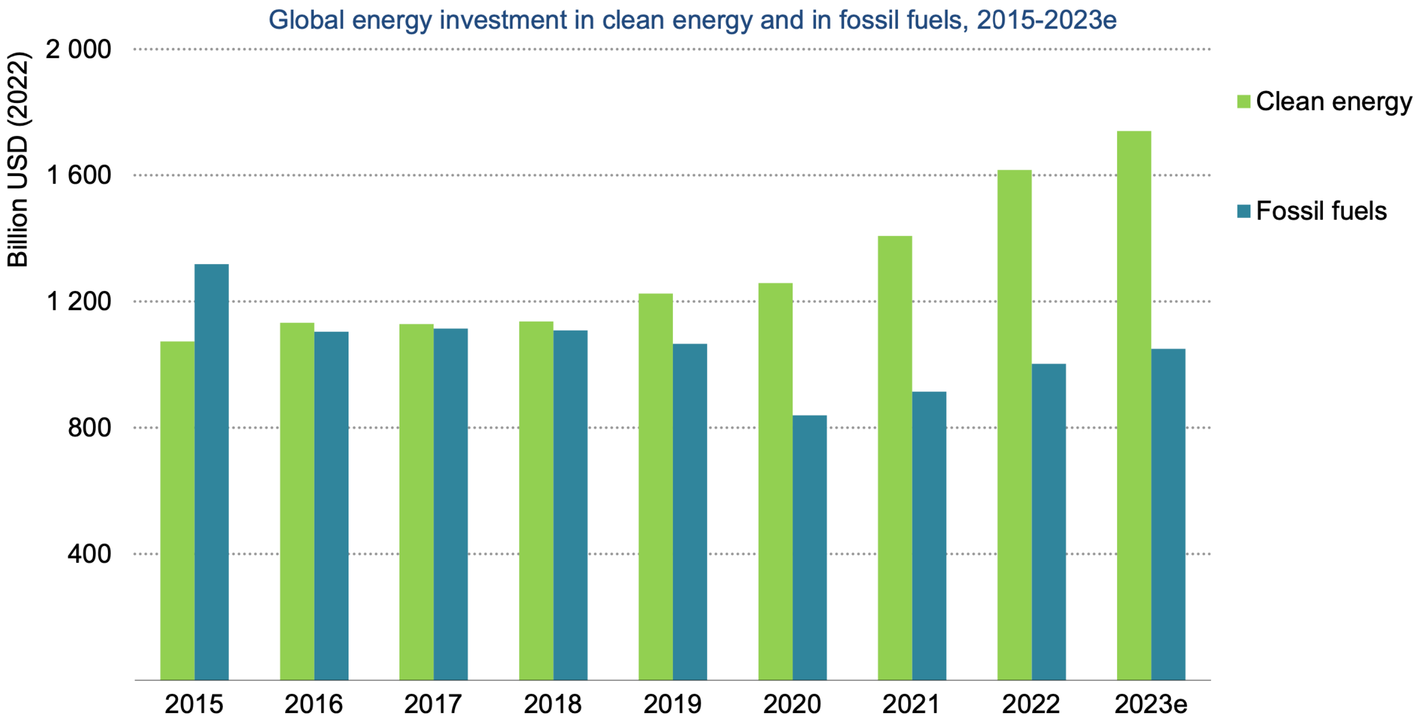
RESEARCH FOR GRAND CHALLENGES

Overview

- Global and European context
- Importance of conversion efficiency
- Tandem cells
- Stability
- Industrializing tandem technology
- Sustainability aspects
- Conclusions

Investments in renewables, led by solar PV



Note: 2023e = estimated values for 2023.

IEA, World Energy Investment 2023

PV can be installed in solar power plants and on homes

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But PV is modular and can be integrated for dual benefit area use!

Bilderquellen Avancis, Manz/Nice, Lightyear, Baywa.re, Oceans of energy, ISE

Potential of Integrated PV

Building-integrated PV

Solar facade at HZB

1.000 GW_p

Agri-PV

Kressbronn, Germany

1.700 GW_p

Road-integrated PV

Neuötting, Germany

300 GW_p

Vehicle-integrated PV

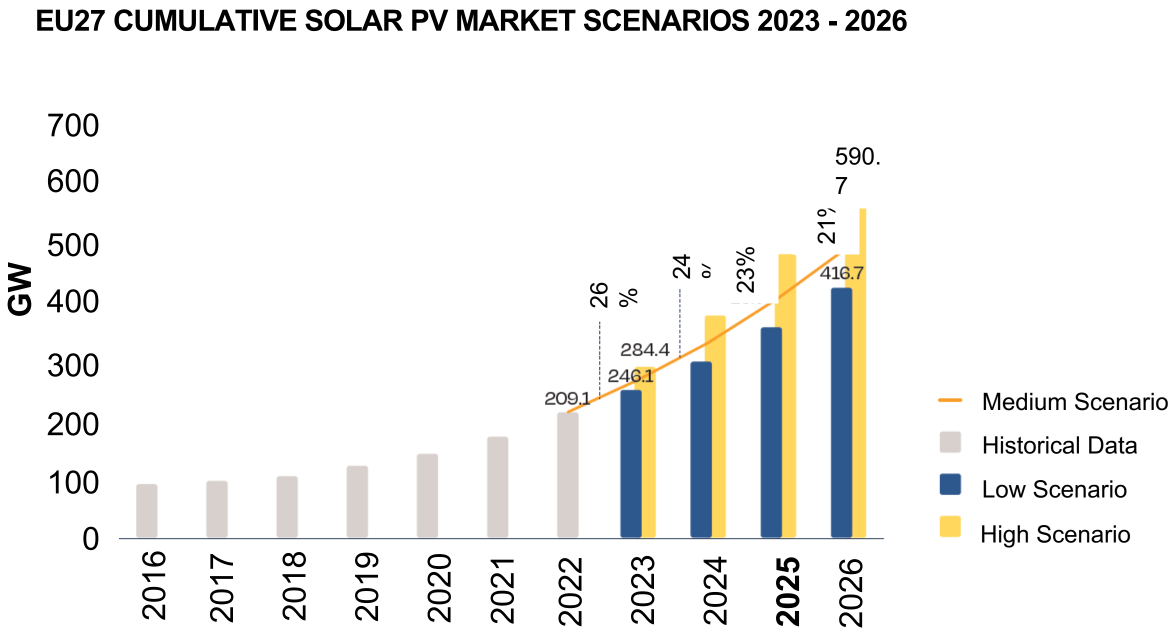
Min. 55 GW_p

Approximated technical potentials in Germany per PV-integrated type

Building-integrated PV: https://www.helmholtz-berlin.de/projects/pvcomb/analytik/living-lab-bipv/index_en.html
Agri-PV: https://www.ise.fraunhofer.de/en/key-topics/integrated-photovoltaics/agrivoltaics.html
Road-integrated PV: https://www.ise.fraunhofer.de/en/key-topics/integrated-photovoltaics/road-integrated-photovoltaics-ripv.html
Vehicle-integrated PV: https://www.ise.fraunhofer.de/en/key-topics/integrated-photovoltaics/vehicle-integrated-photovoltaics-vipv.html

Europe’s present PV objectives: climate, resilience, business/jobs

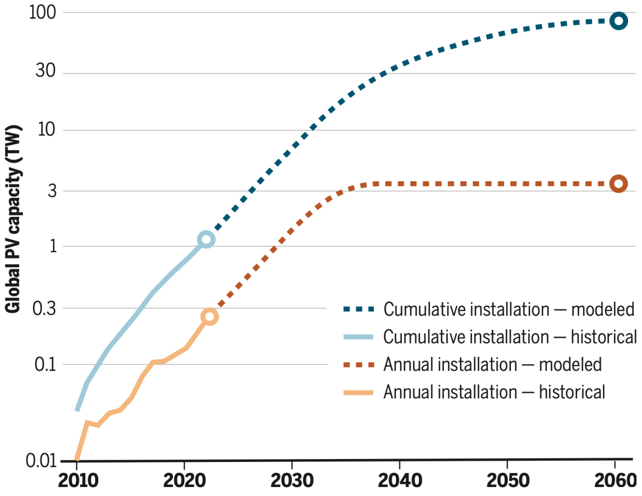
- Deployment of 320 GW of PV capacity by 2025 and 600 GW_p of PV installed by 2030
- 30GW_p/a production capacity across the whole value chain by 2025



PV developments on the global level

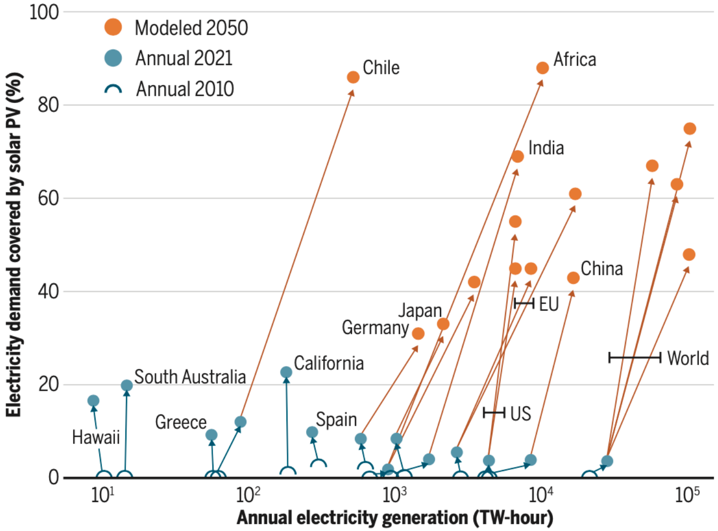
PV installations and growth toward 75 TW by 2050

Modeled cumulative capacity going forward is based on sustaining 25% production rate growth over the next 7 years and then reducing slowly to steady state. Replacement needs are included by simple subtraction of installations 25 years before the modeled date.



Regional electricity demand supplied by solar PV

The data reflect annual percentages of historical regional demand (2010 and 2021) and modeled demand projections (2050). See supplementary materials for details.



POLICY FORUM

RENEWABLE ENERGY

Photovoltaics at multi-terawatt scale: Waiting is not an option

25% annual PV growth is possible over the next decade

By Nancy M. Haegel, Pierre Verlinden, Marta Victoria, Pietro Altermatt, Harry Atwater, Teresa Barnes, Christian Breyer, Chris Case, Stefaan De Wolf, Chris Deline, Marwan Dharmrin, Bernhard Dimmler, Markus Gloeckler, Jan Christoph Goldschmidt, Brett Hallam, Sophia Haussener, Burkhard Holder, Ulrich Jaeger, Arnulf Jaeger-Waldau, Izumi Kaizuka, Hiroshi Kikusato, Benjamin Kroposki, Sarah Kurtz, Koji Matsubara, Stefan Nowak, Kazuhiko Ogimoto, Christian Peter, Ian Marius Peters, Simon Philipps, Michael Powalla, Uwe Rau, Thomas Reindl, Maria Roumpani, Keiichiro Sakurai, Christian Schorn, Peter Schossig, Rutger Schlatmann, Ron Sinton, Abdelilah Slaoui, Brittany L. Smith, Peter Schneidewind, BJ Stanbery, Marko Topic, William Tumas, Juzer Vasi, Matthias Vetter, Eicke Weber, A. W. Weeber, Anke Weidlich, Dirk Weiss, Andreas W. Bett

Science 2023 (10.1126/science.adf6957)

Key unit to compare options: Levelized Cost of Electricity (LCOE)

$$\text{LCOE [€/kWh]} = \frac{\text{sum of costs over lifetime}}{\text{sum of (electrical) energy produced over lifetime}}$$

It is the trend that counts

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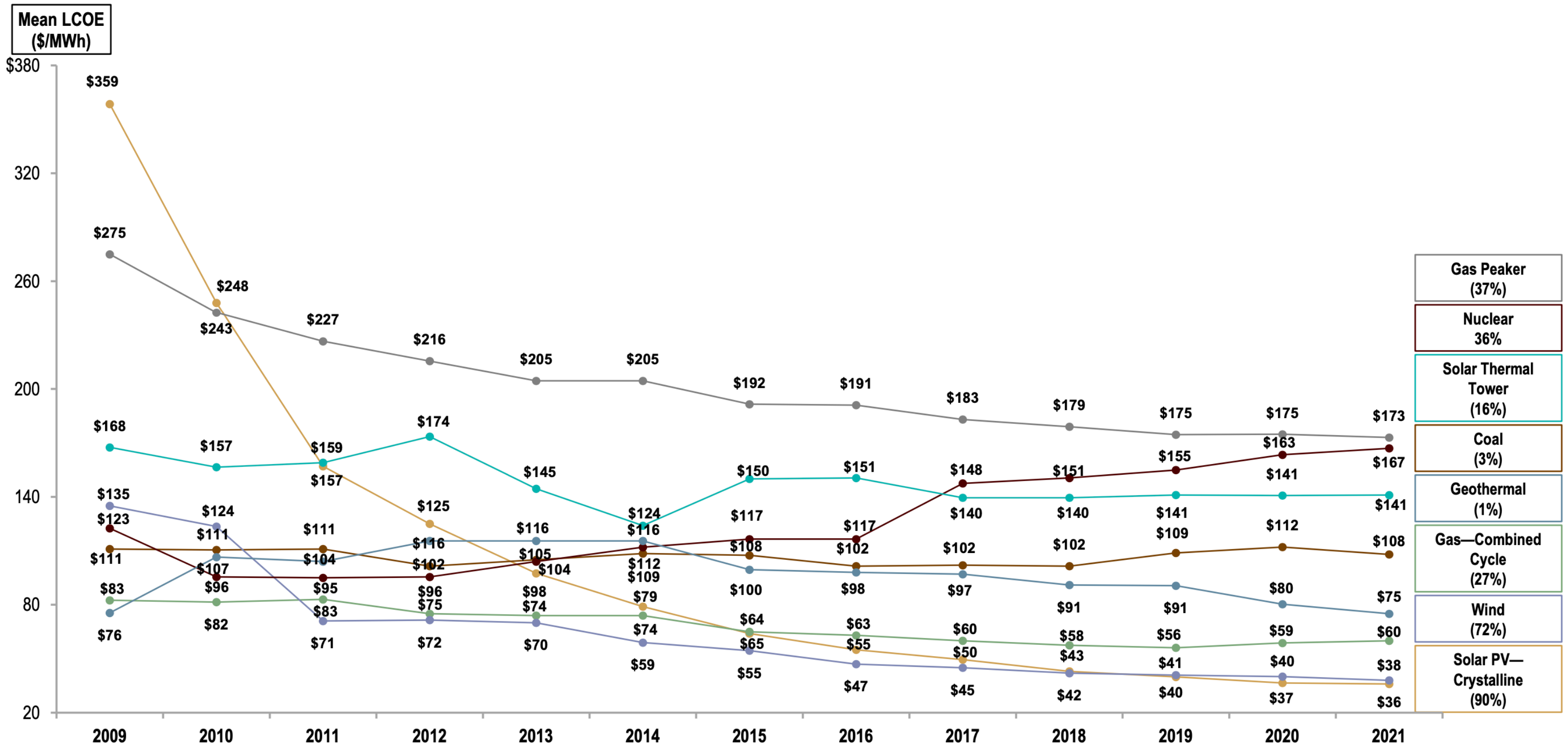
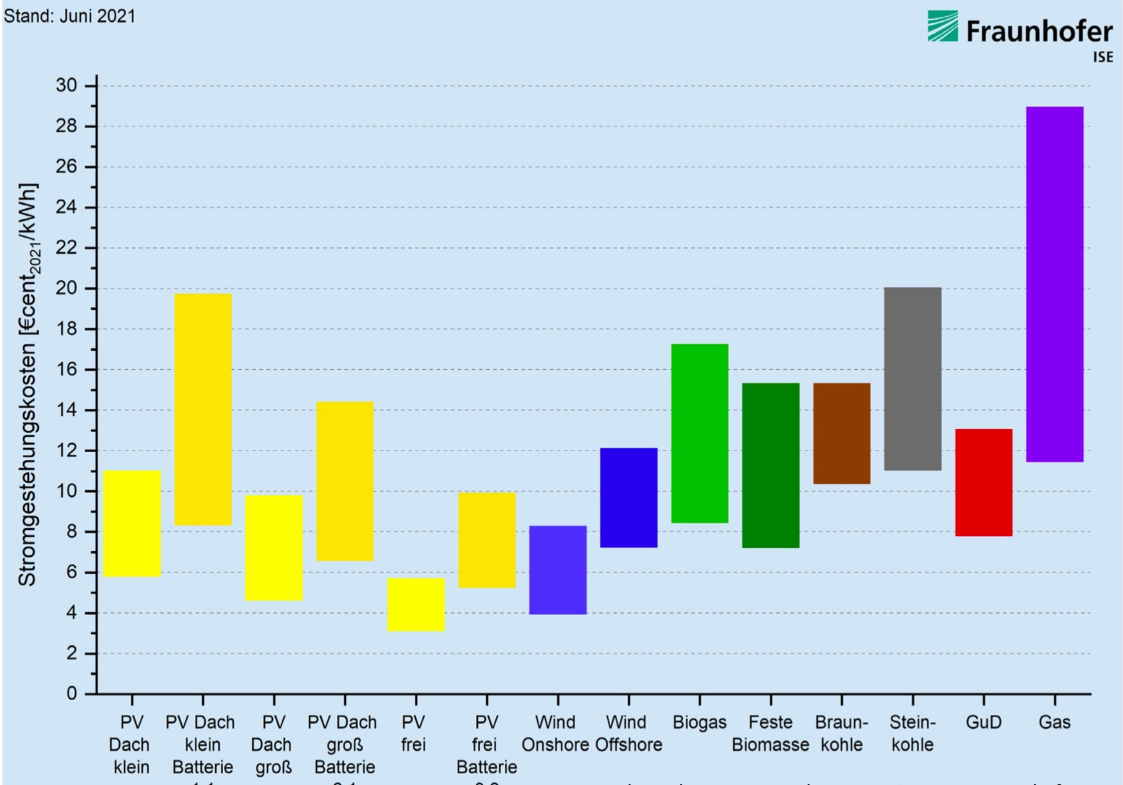
Selected Historical Mean Unsubsidized LCOE Values[1]



Source: Lazard

LCOE of Energy Technologies (Germany)

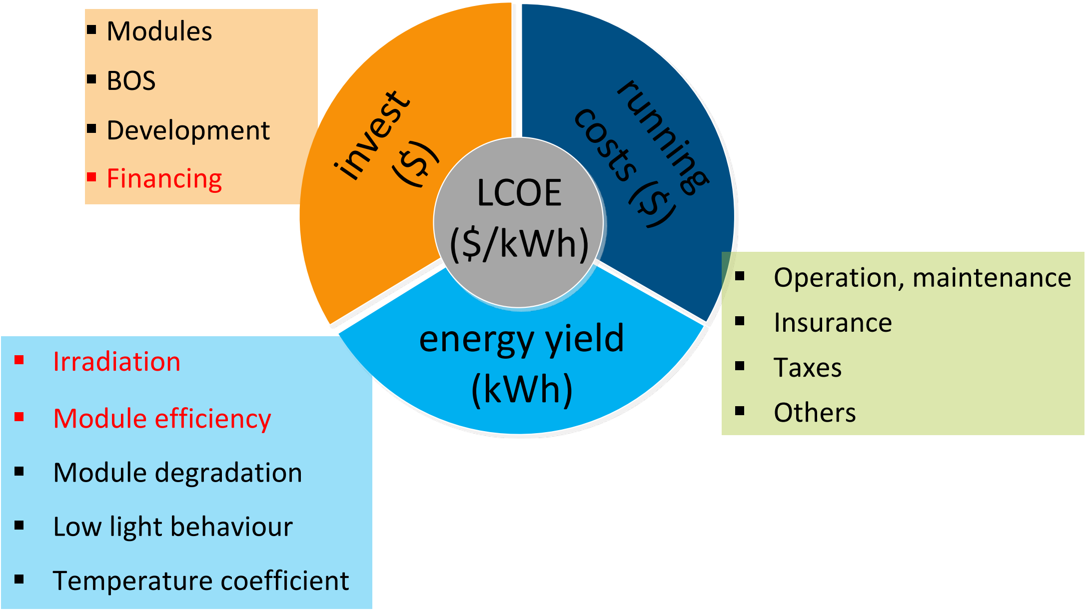
- LCOE of PV systems around 4 – 11 €cents/kW *in Germany* (even much lower in sunbelt, cheapest large power plants)
- Energy conversion efficiency at minimal cost needed



Stromgestehungskosten Erneuerbare Energien, **2021**, Fraunhofer ISE

Levelized Cost of Electricity (LCOE)

$$\text{LCOE [€/kWh]} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}}$$



Cost of Silicon Modules: the learning curve

- Learning Curve: "more production -> more experience -> cheaper"
- Module price drops by a quarter (23-39%) each time cumulative PV module shipments doubles

- Module efficiency
- Productivity
- Material usage and costs

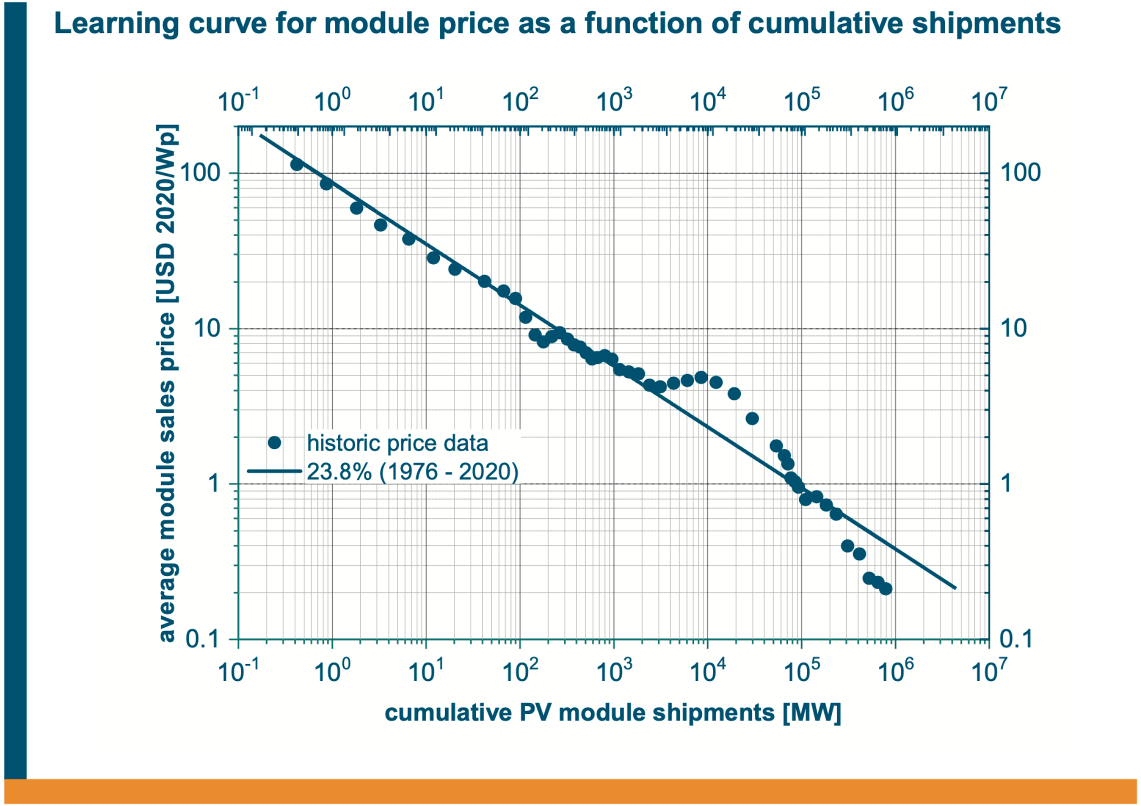
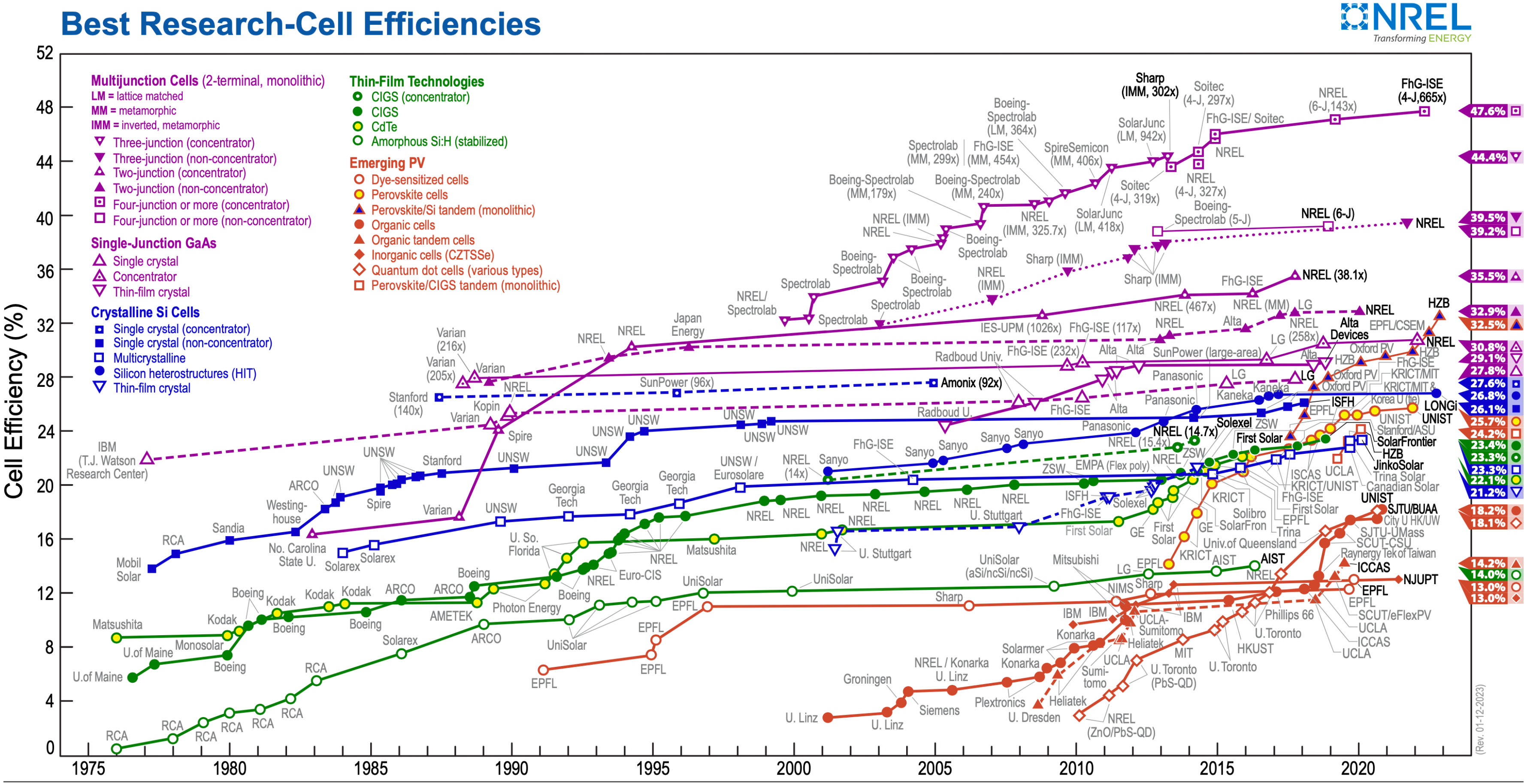


Fig. 1: Learning curve for module spot market price as a function of cumulative PV module shipments.

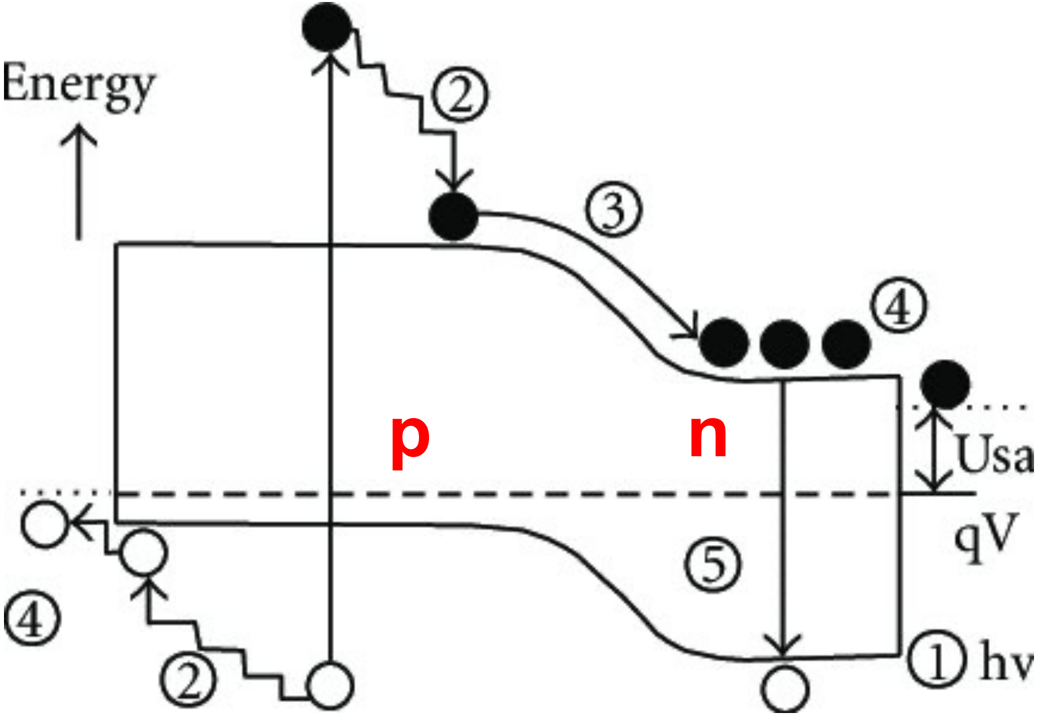
ITRPV, edition 2021

Conversion efficiency

Best Research-Cell Efficiencies



Basic solar cell (p-n junction) energy diagram



Loss mechanisms:

(1) nonabsorption of below-bandgap photons

(2) lattice thermalisation loss

(3) junction loss

(4) contact voltage loss

(5) recombination loss.

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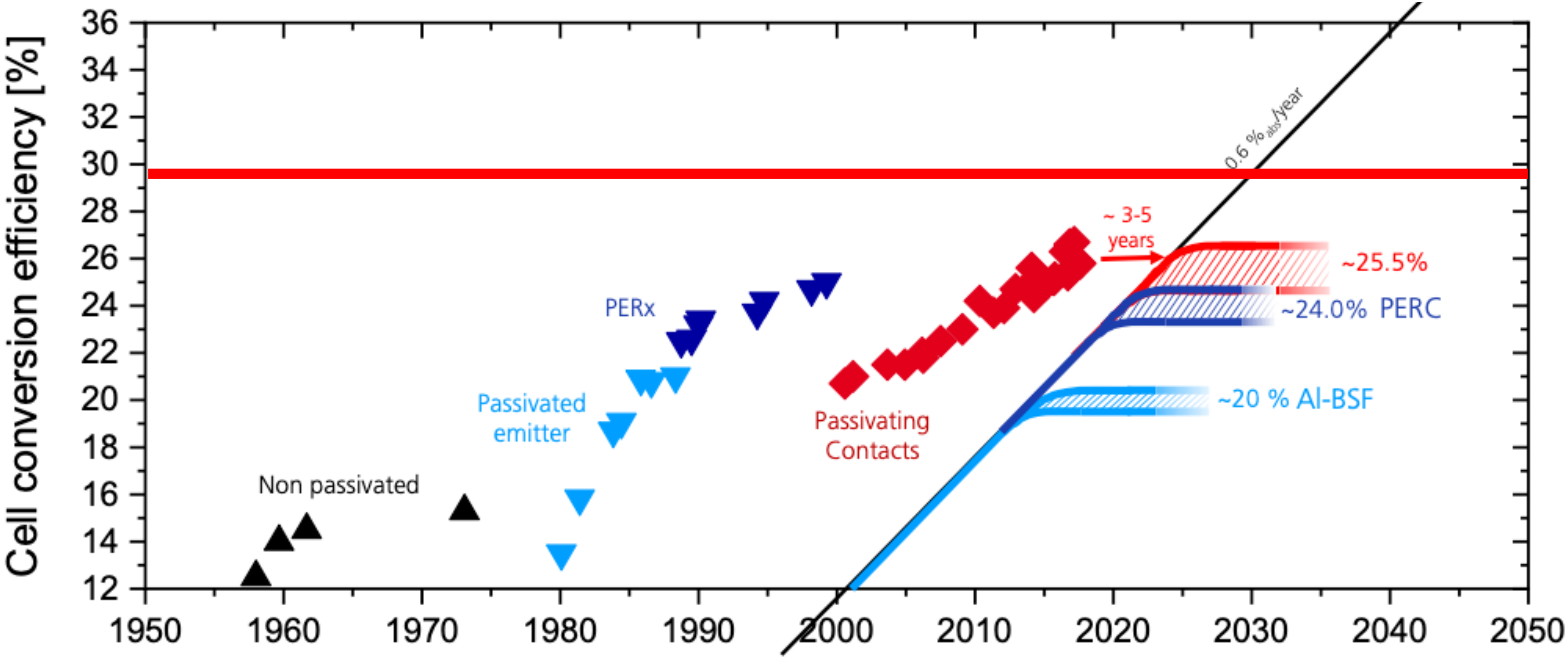
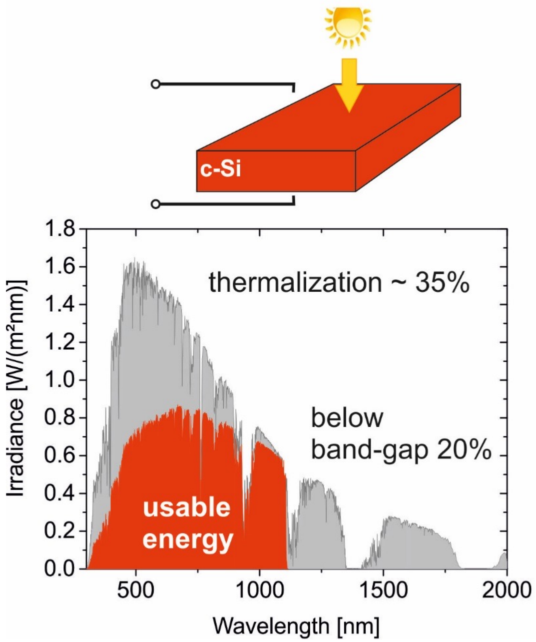
Importance of efficiency

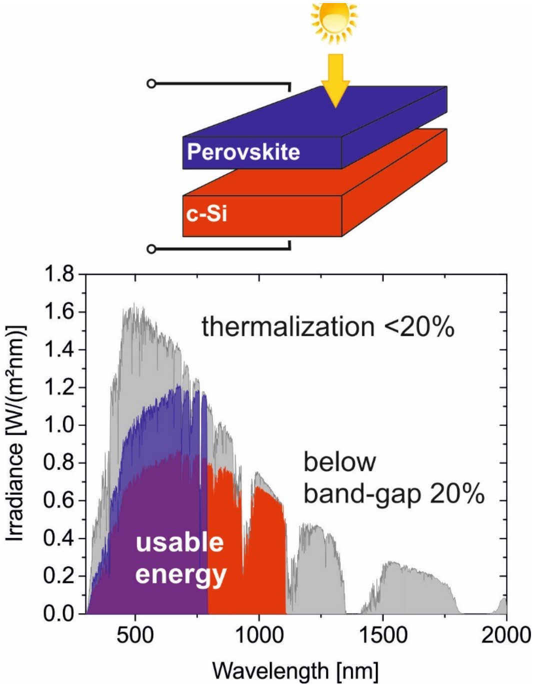


Graph: Fraunhofer ISE 2021

Motivation for tandems

- high loss from thermalization

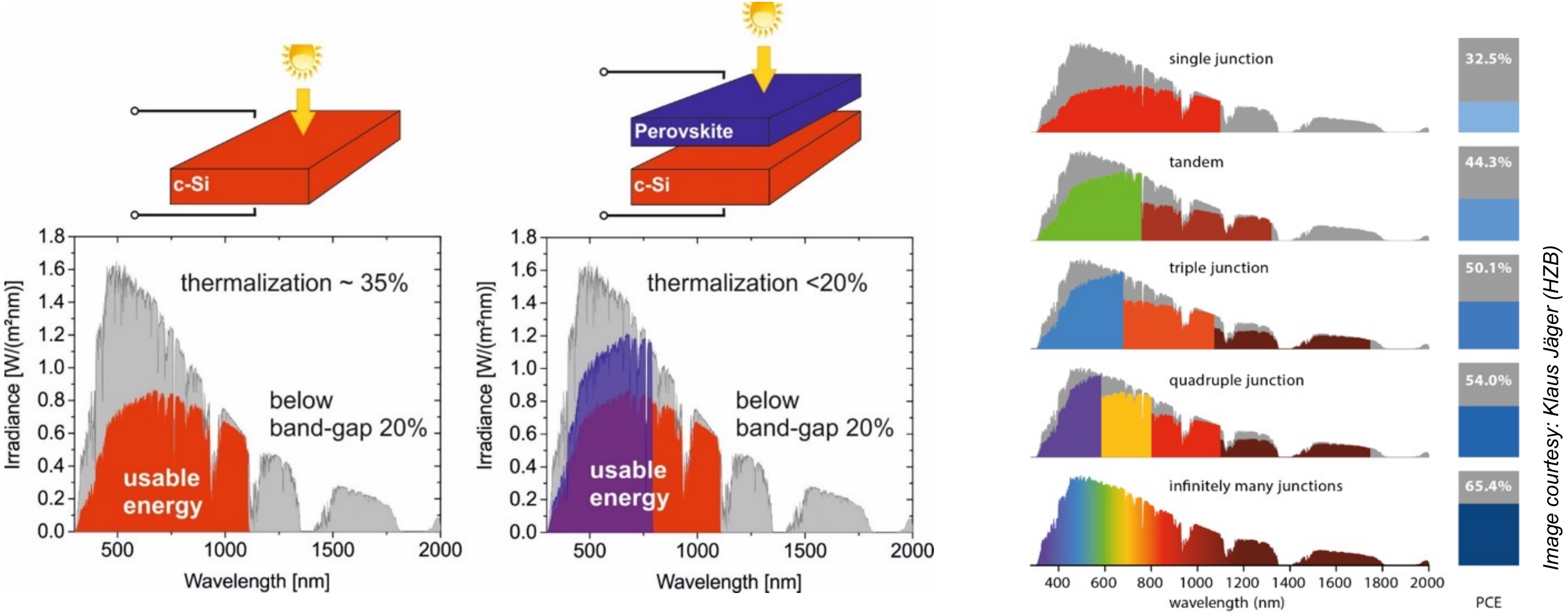




- high energy photons are absorbed by perovskite
  - converted at a high voltage
  - reduced losses from thermalization
- infrared photons are transmitted into c-Si

cover a wide spectral range of absorption

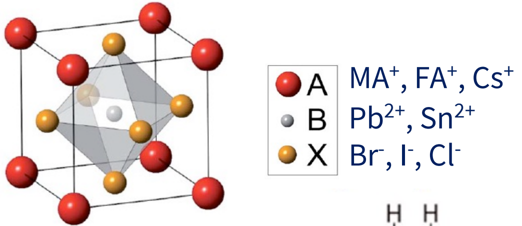
Tandem Cell Concept

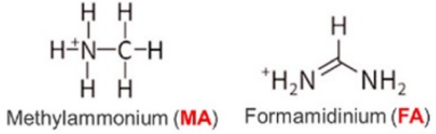


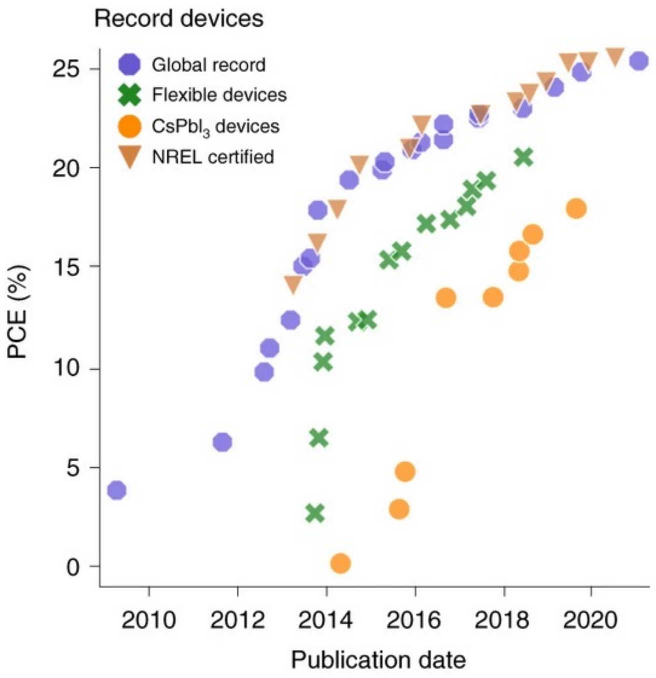
- High loss from thermalization

- High-energy photons are absorbed by perovskite
  converted at a high voltage & reduced thermalization loss
- Infrared photons are transmitted into c-Si
  cover a wide spectral range of absorption

The long-missing link: Perovskite solar cells, excellent wide-gap semiconductors







- Solution processing by spin coating (in lab)
- Variable compositions → E_{gap} 1.5 … >1.9 eV
- Perovskite/Silicon tandem requires E_{gap} >1.65 eV, e.g. $Cs_{0.05}(FA_{0.77}MA_{0.23})_{0.95}Pb(I_{0.77}\mathbf{Br}_{0.23})_3$ „Triple Cation/double Halide“

H. Snaith *et al.*, *Energy Environ. Sci.*, **2014**, 7, 982

T. J. Jacobsson, E. Unger *et al.*, *Nature Energy* **2022**, *7, 107-115*

Efficiency race

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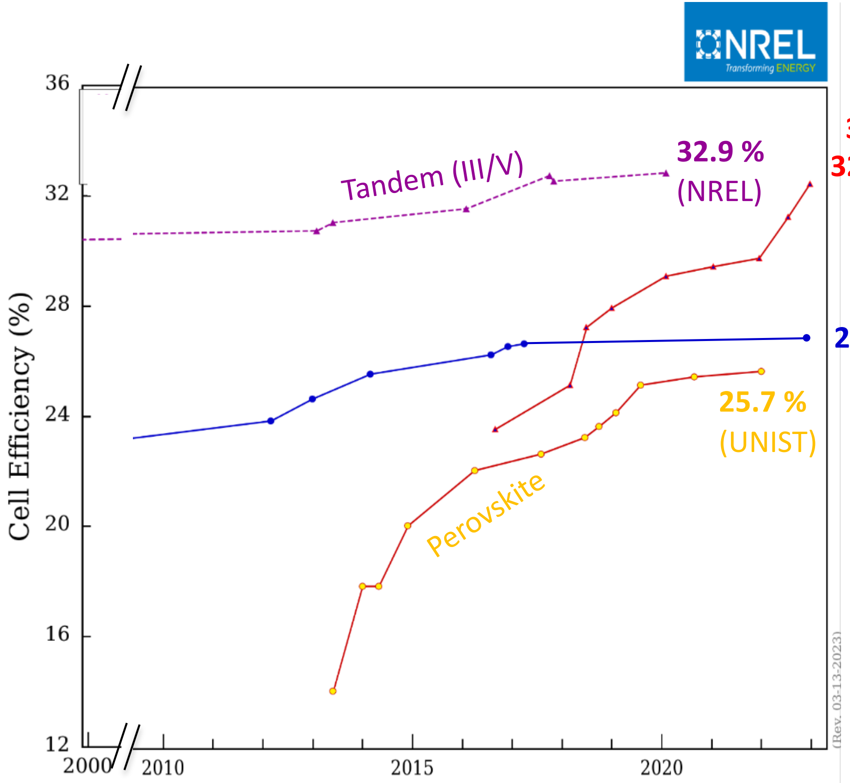


Image: https://www.nrel.gov/pv/interactive-cell-efficiency.html

Detailed-Balance efficiency limit:

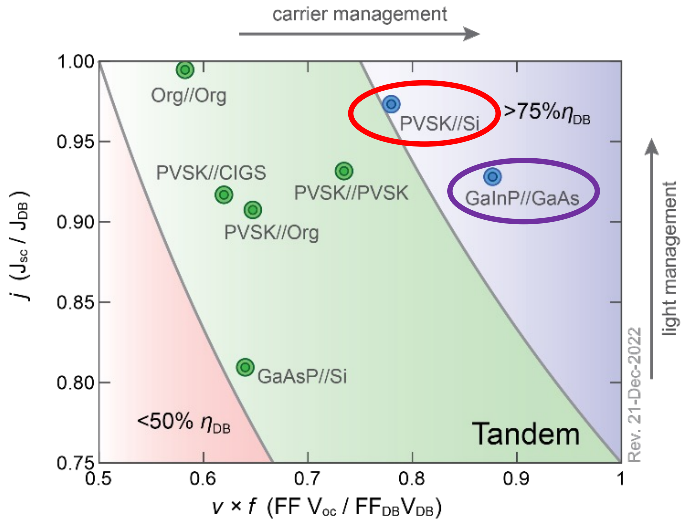
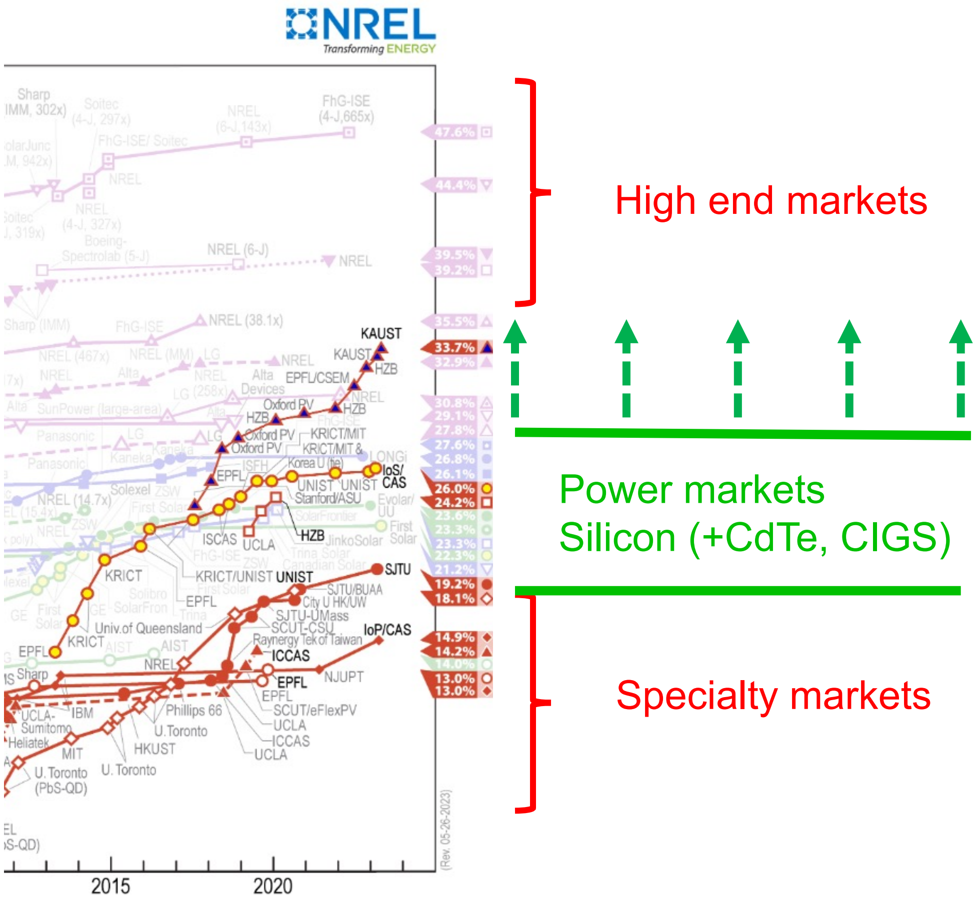


Image: A. Polman et al., *Science* (**2016**) 352, 307

- PVSK/Si Tandem entered the „75% club“
- PVSK/Si Tandem 26% better than Silicon

The efficiency cost balance

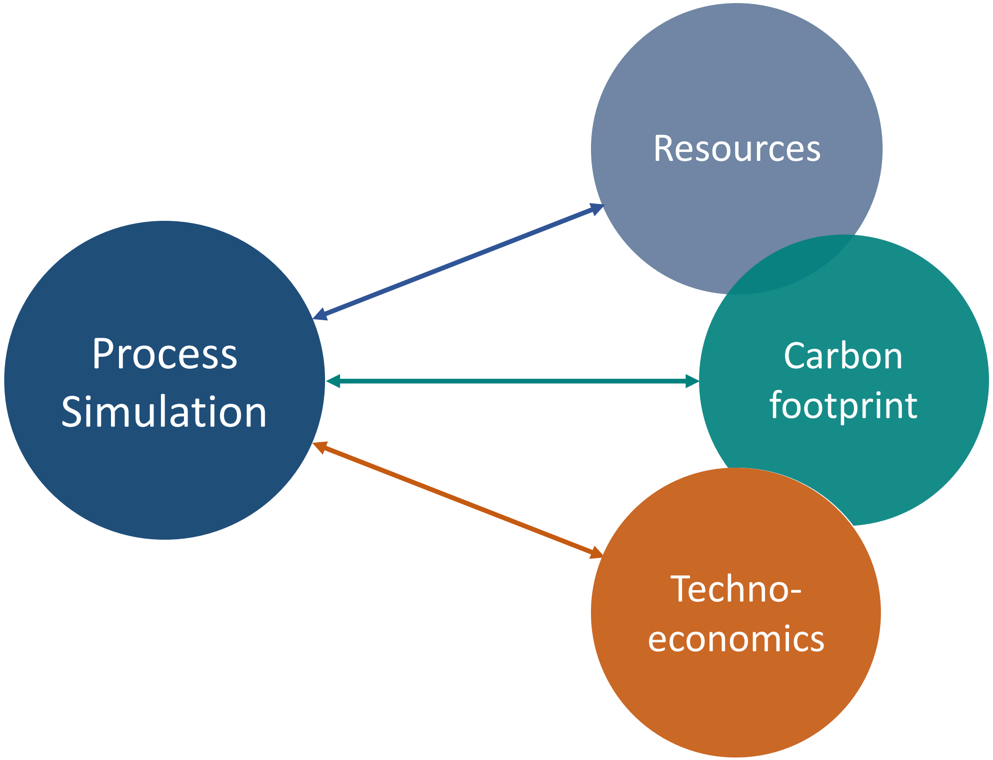


Novel materials like perovskites offer the potential to significantly surpass the 25% module efficiency level for commercial modules in the power market

Sustainability aspects

Ressources : balance cost AND environment

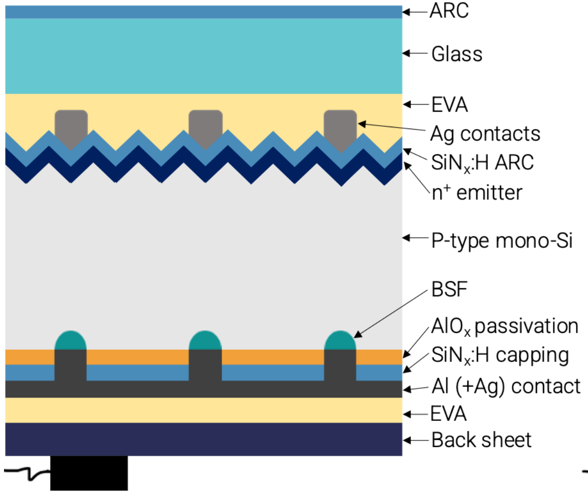
- Full life cycle simulation – closed loop wherever possible
- Thermodynamics based process simulation wherever possible
- Bottom-up cost model updated with process simulation outputs



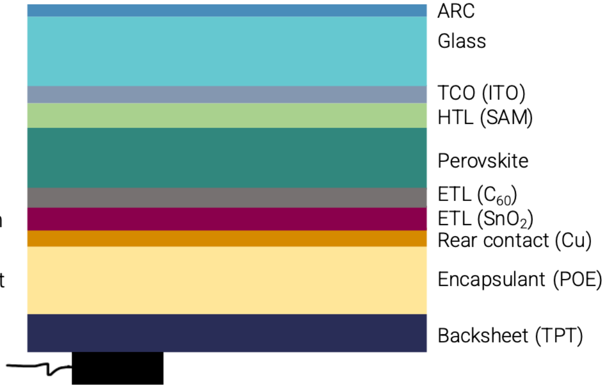
Bartie et al., Mineral Processing and Extractive Metallurgy 2020,
Bartie et al. Resources, Conservation and Recycling, 2021, Bartie et al. IEEE PVSC 2021
Bartie et al. Journal of Industrial Ecology 2023

Comparing three main options

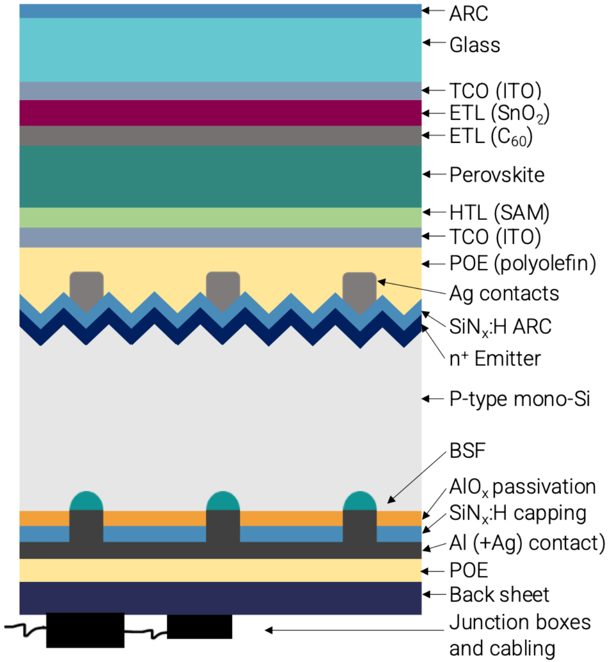
Silicon (PERC)



Perovskite



Tandem (4T)



Bartie et al., J. Ind. Ecol. 2023

Modeling the complete life cycles

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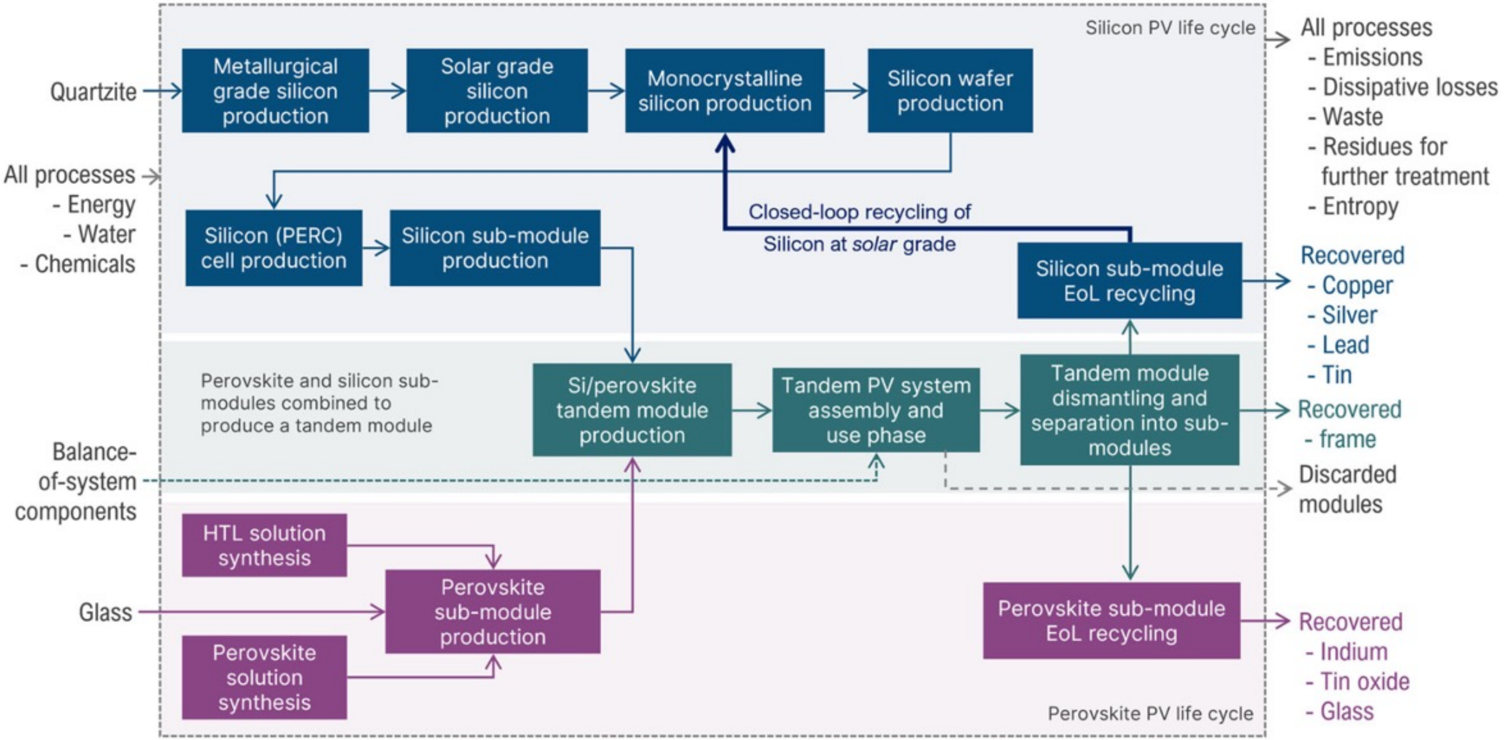

Bartie et al., J. Ind. Ecol. 2023

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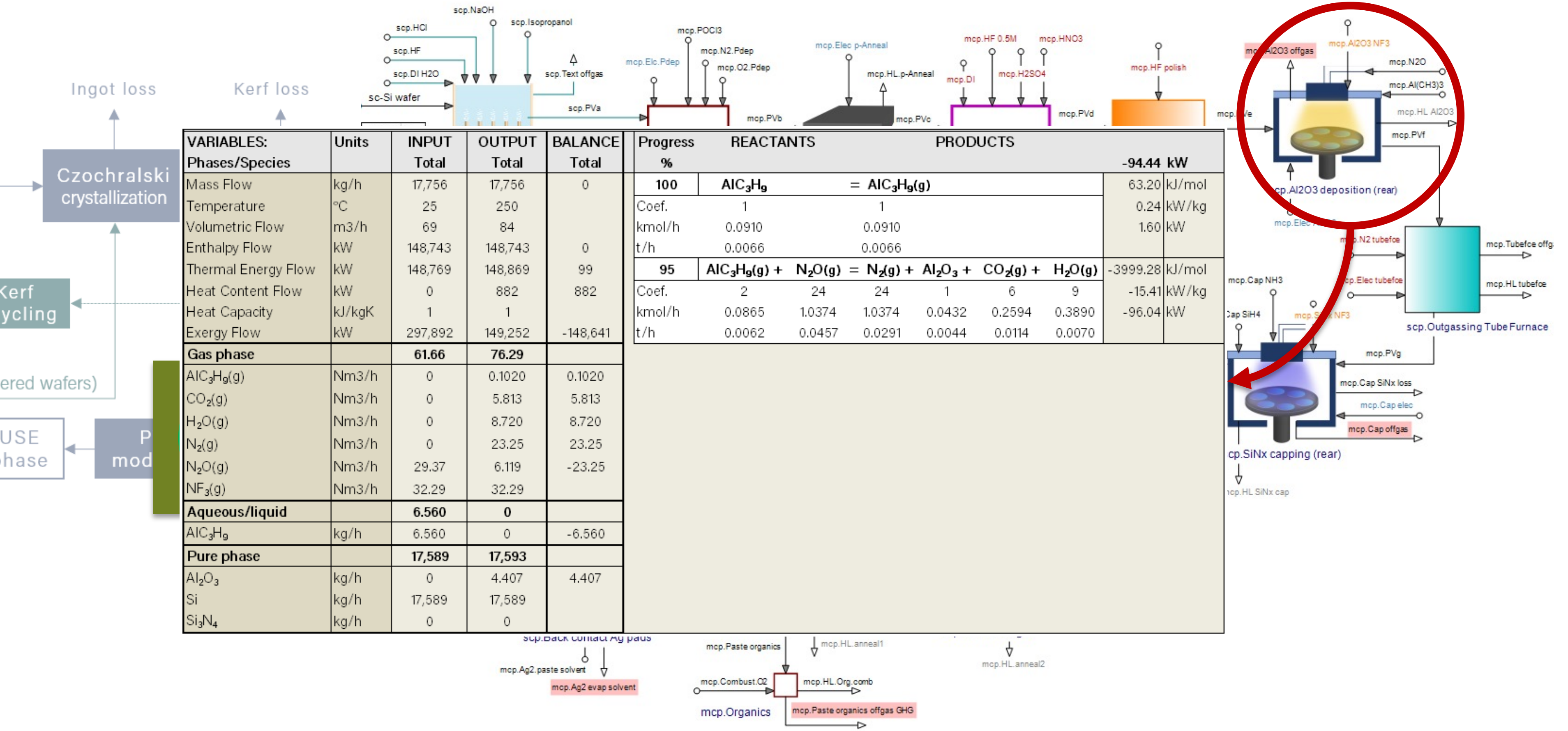
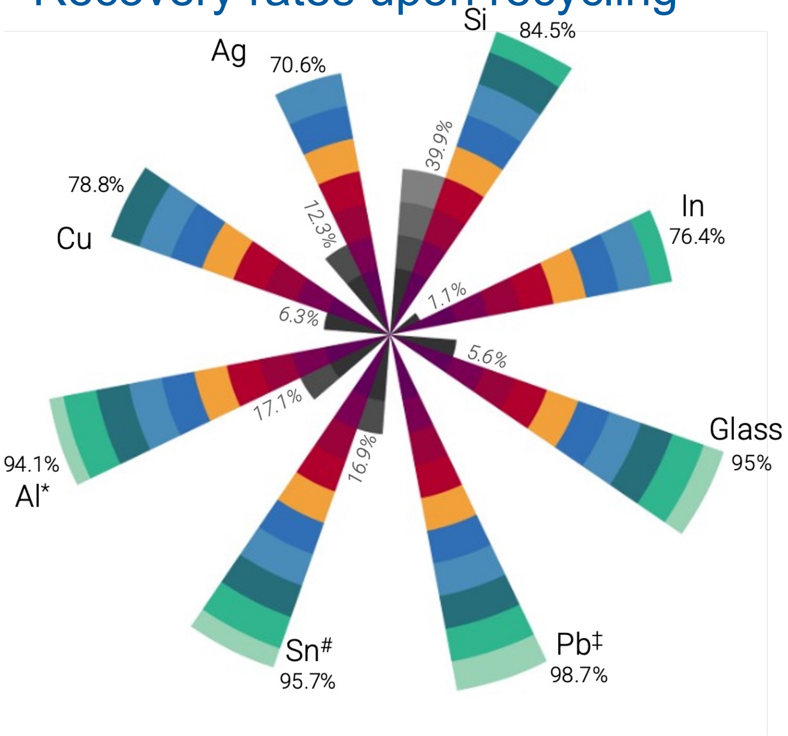


VARIABLES: Phases/Species	Units	INPUT Total	OUTPUT Total	BALANCE Total
Mass Flow	kg/h	17,756	17,756	0
Temperature	°C	25	250	
Volumetric Flow	m3/h	69	84	
Enthalpy Flow	kW	148,743	148,743	0
Thermal Energy Flow	kW	148,769	148,869	99
Heat Content Flow	kW	0	882	882
Heat Capacity	kJ/kgK	1	1	
Exergy Flow	kW	297,892	149,252	-148,641
Gas phase		**61.66**	**76.29**	
$AlC_3H_9(g)$	Nm3/h	0	0.1020	0.1020
$CO_2(g)$	Nm3/h	0	5.813	5.813
$H_2O(g)$	Nm3/h	0	8.720	8.720
$N_2(g)$	Nm3/h	0	23.25	23.25
$N_2O(g)$	Nm3/h	29.37	6.119	-23.25
$NF_3(g)$	Nm3/h	32.29	32.29	
Aqueous/liquid		**6.560**	**0**	
AlC_3H_9	kg/h	6.560	0	-6.560
Pure phase		**17,589**	**17,593**	
Al_2O_3	kg/h	0	4.407	4.407
Si	kg/h	17,589	17,589	
Si_3N_4	kg/h	0	0	

Progress %	REACTANTS			PRODUCTS			-94.44	kW
100	AlC_3H_9		= $AlC_3H_9(g)$				63.20	kJ/mol
Coef.	1		1				0.24	kW/kg
kmol/h	0.0910		0.0910				1.60	kW
t/h	0.0066		0.0066					
95	$AlC_3H_9(g)$ +	$N_2O(g)$	= $N_2(g)$ +	Al_2O_3 +	$CO_2(g)$ +	$H_2O(g)$	-3999.28	kJ/mol
Coef.	2	24	24	1	6	9	-15.41	kW/kg
kmol/h	0.0865	1.0374	1.0374	0.0432	0.2594	0.3890	-96.04	kW
t/h	0.0062	0.0457	0.0291	0.0044	0.0114	0.0070		

Bartie et al. Resources, Conservation and Recycling, 2021

Recovery rates upon recycling



*Al from cells recovered as Al_2O_3 (recovered frames sold as scrap Al)

#Sn recovered as SnO_2

‡Pb as PbO_2, PbI_2 and $PbBr_2$

Glass recovery assumed, sold as cullet

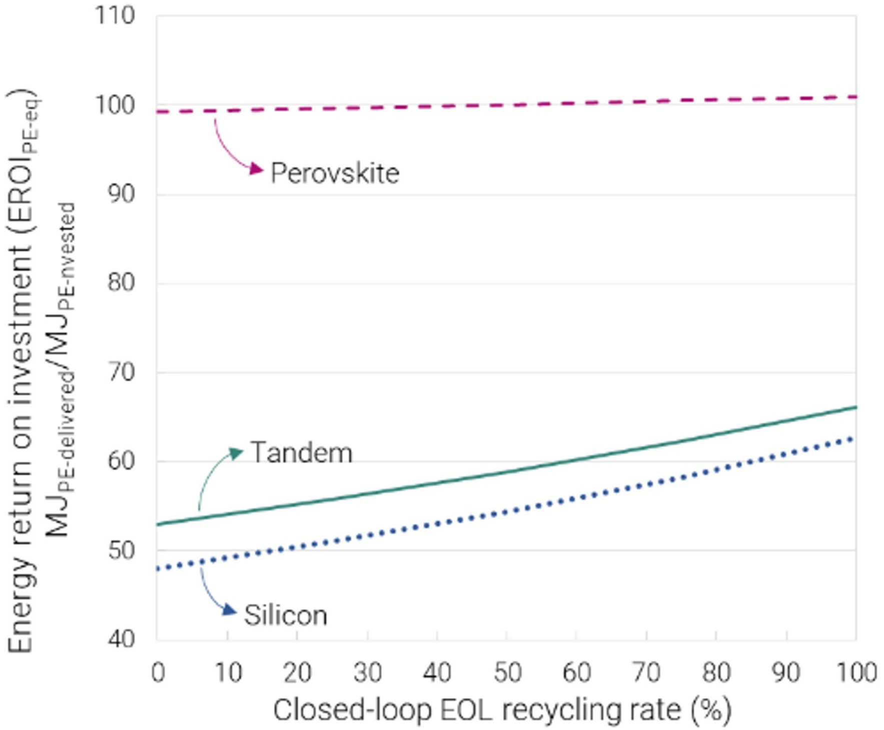
- Indium and Silicon metal are both EU critical raw materials, meaning:
  - they are economically important, and
  - supply risks have been identified.

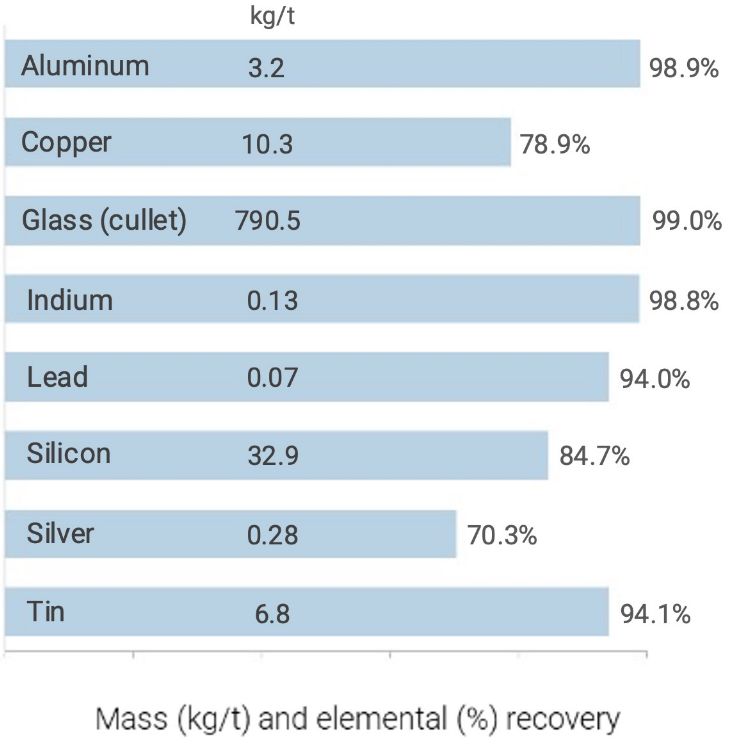
- Pb recovered as PbI_2 can be reused for perovskite PV (proven at laboratory scale).

- All Pb recovery contributes to avoiding its human and aquatic toxicity potential.

Bartie et al., J. Ind. Ecol. 2023

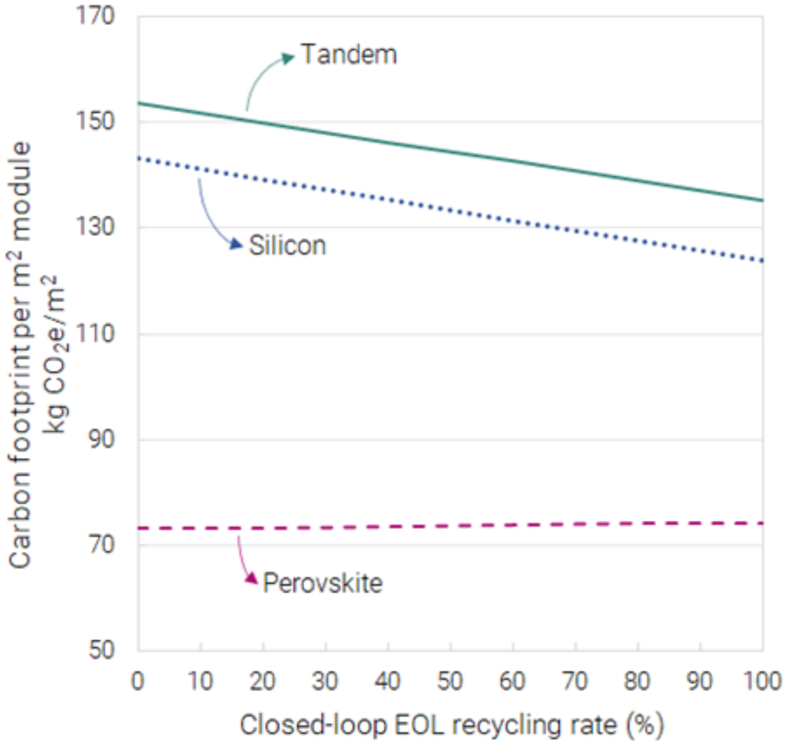
Energy ROI and recycling rates

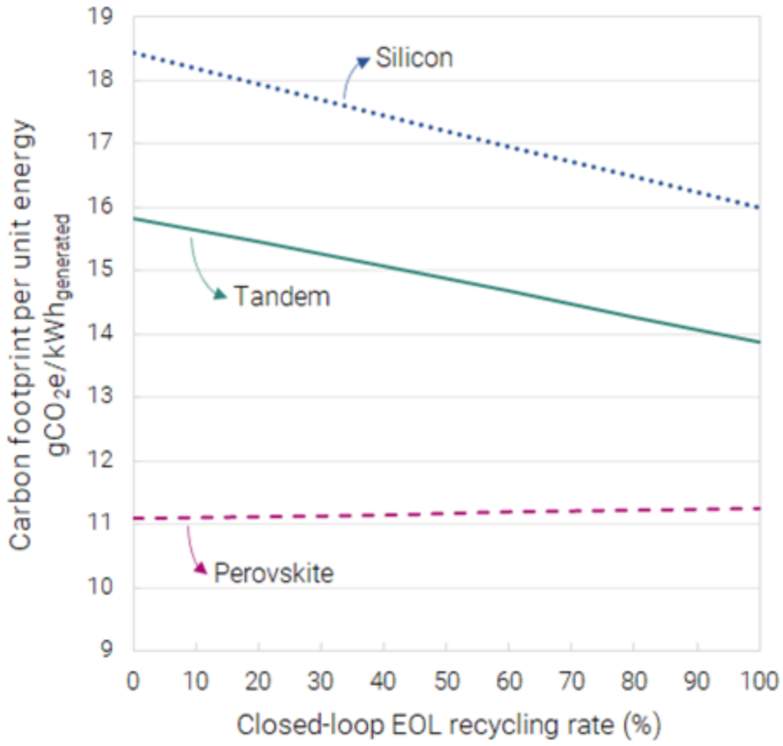




Bartie et al., J. Ind. Ecol. 2023

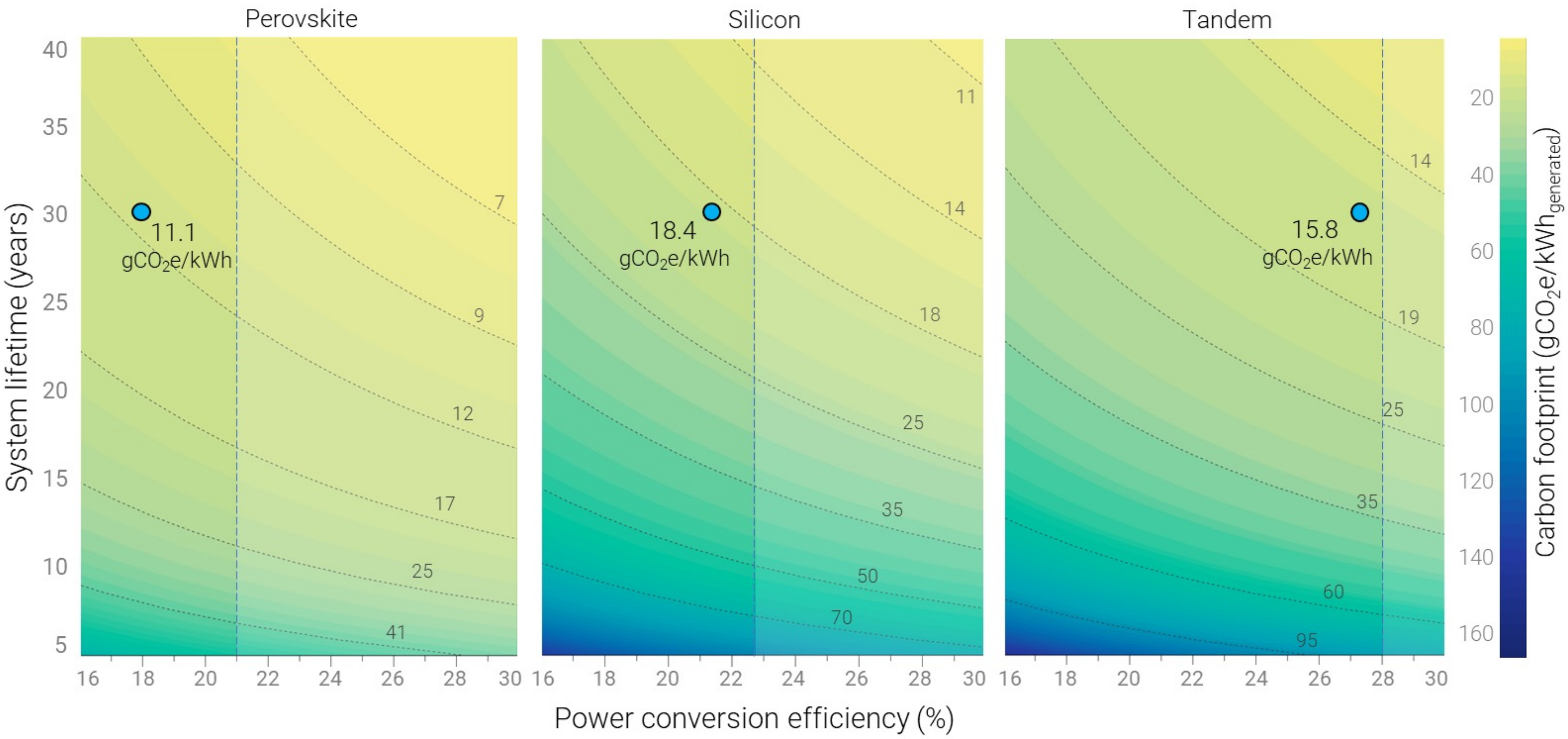
Carbon footprint





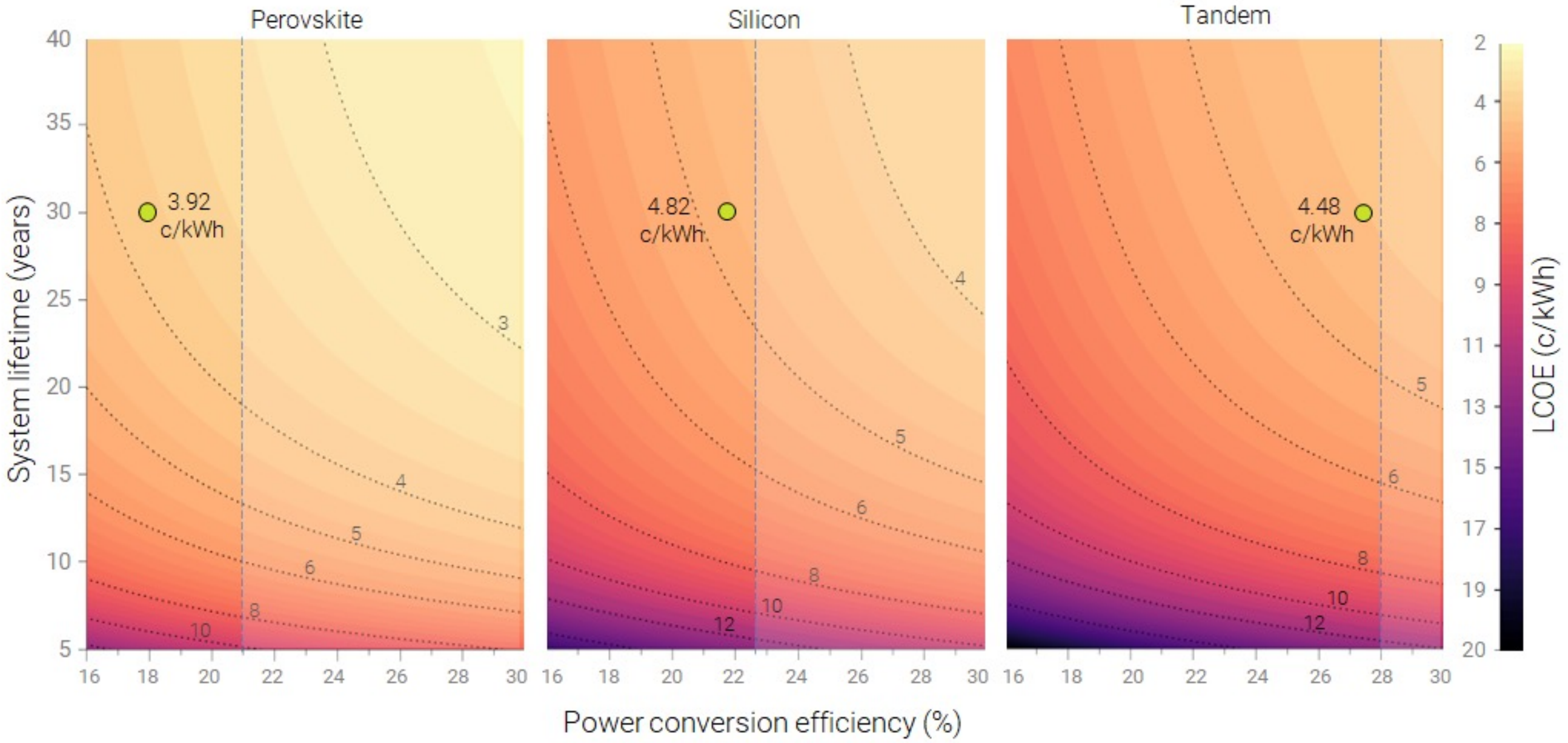
Bartie et al., J. Ind. Ecol. 2023

Carbon footprint, dependence on lifetime and efficiency



Bartie et al., J. Ind. Ecol. 2023

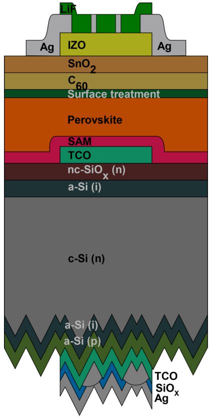
LCOE, Dependence on lifetime and efficiency

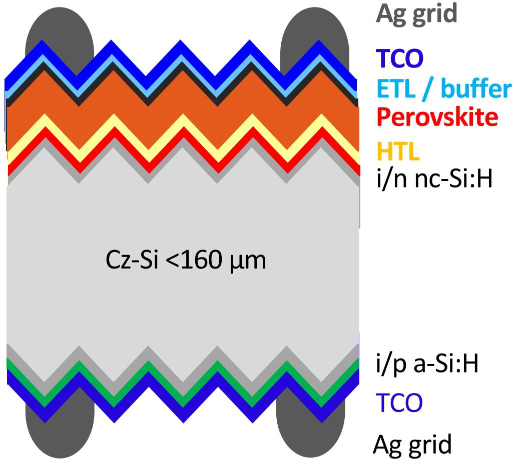


Bartie et al., J. Ind. Ecol. 2023

Conclusions

- Very dynamic developments in politics, market and production
- Innovation must be achieved in the labs AND at scale!
- Tandem technology based on Si wafers most prominent cell development
- Thin film technologies such as perovskites or multijunctions based on them, have very high potential too and have an **even** better sustainability profile than Silicon PV
- Diversifying markets offer enormous potential for further innovations: even the ´niche´ markets can be huge





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Federal Ministry of Education and Research

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