Solar energy:
the harvest of 50 years development & challenges towards global impact

Wim Sinke

Prof. em. Photovoltaic Energy Conversion

University of Amsterdam

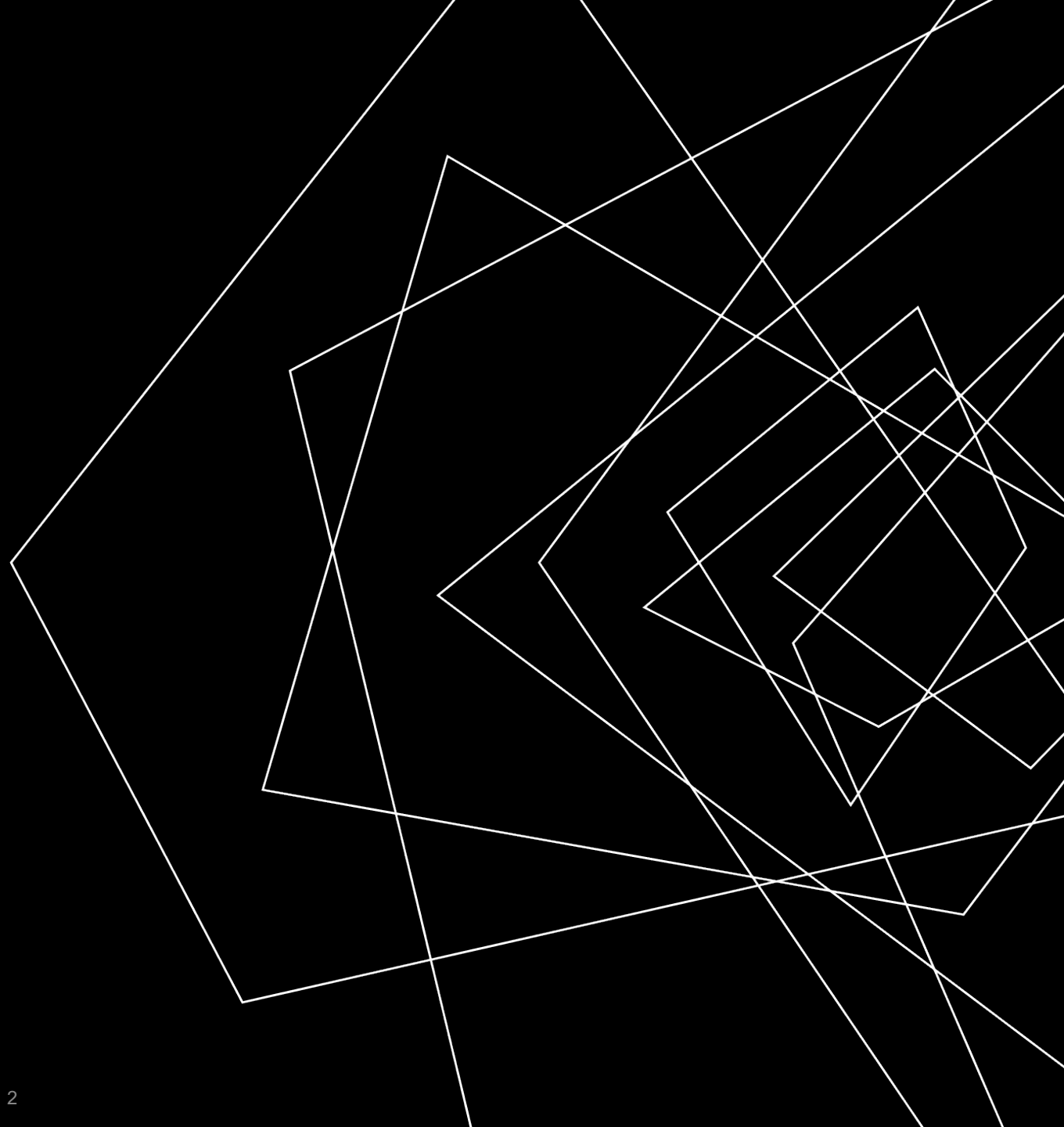
Lecture Meet the Energy Leader – TU Delft – 22 02 2023

Content

A few personal notes

State of the art in solar photovoltaics
The harvest of 50 years development

Challenges towards global impact
- *From niche to corner stone*
- *From electricity to energy*
- *From renewable to sustainable*
- *From addition to integration*
- *From dependency to ‘fair share’*



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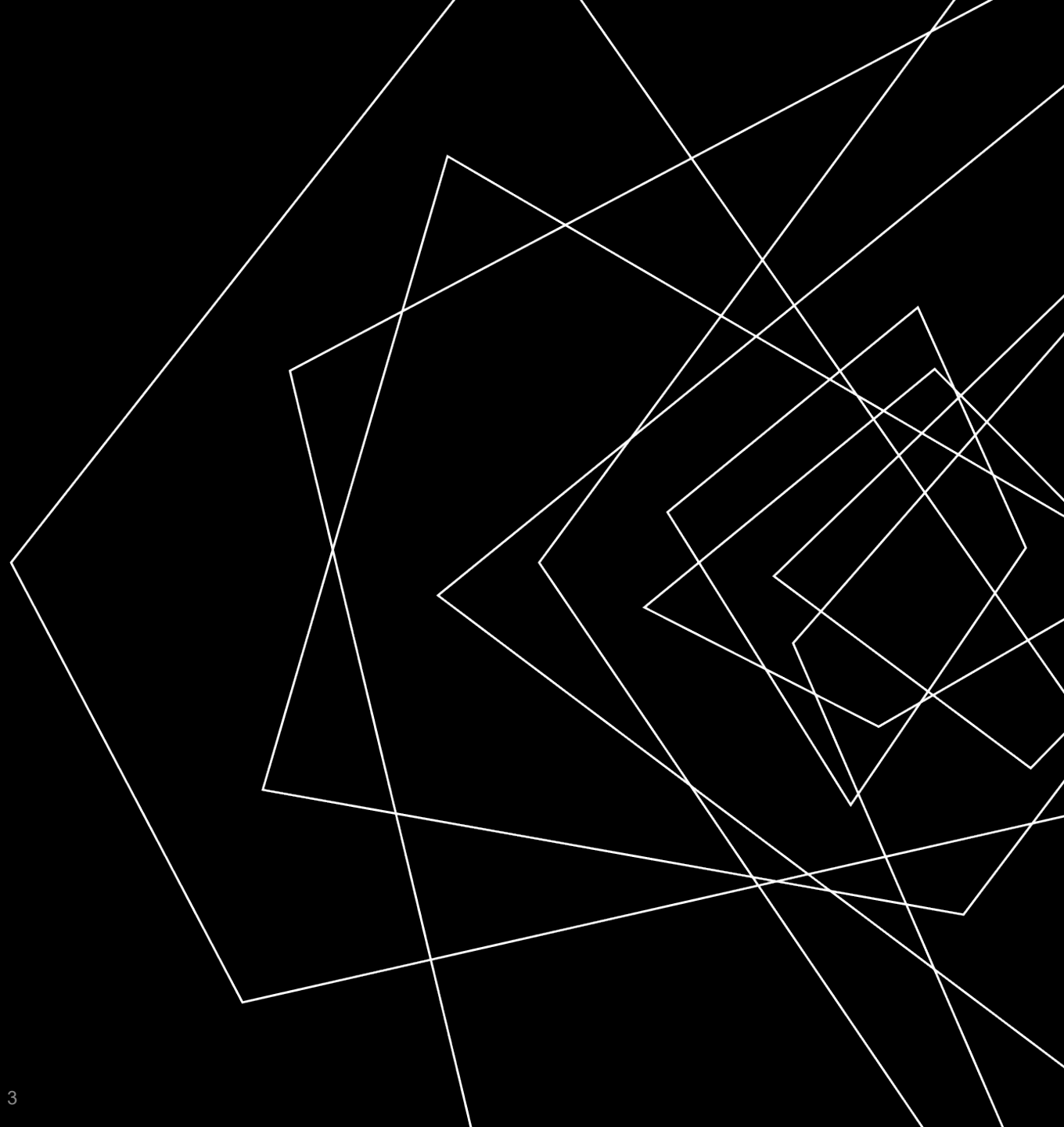
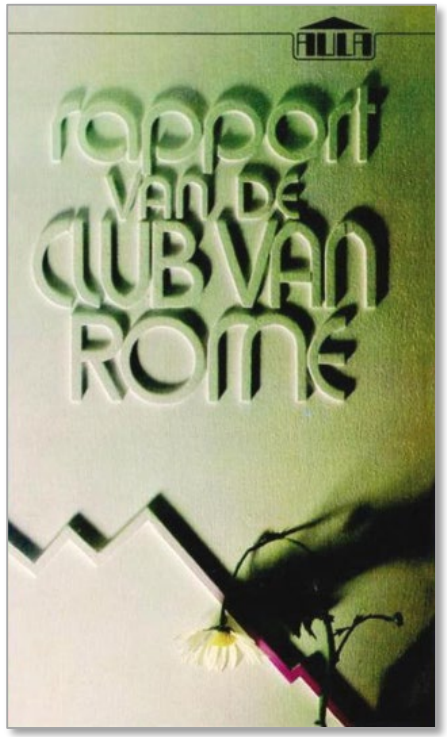


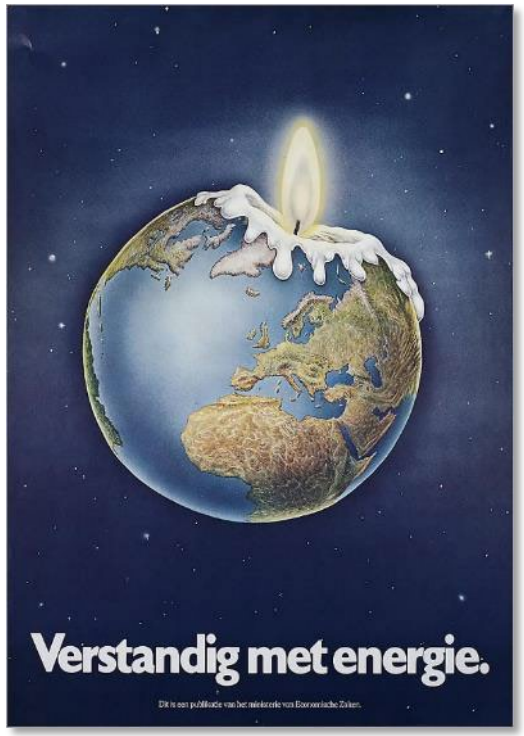
The world in my student time

1973

1979



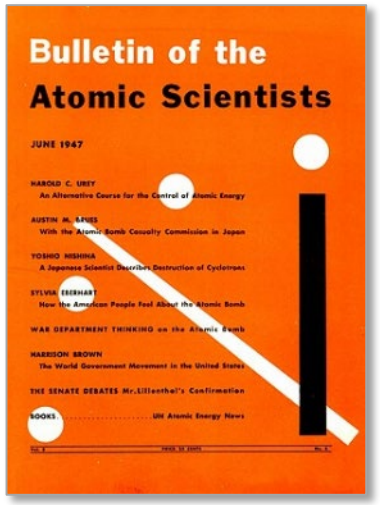
1972: Club of Rome
Limits to growth



1974

1984: nuclear threat

The world today



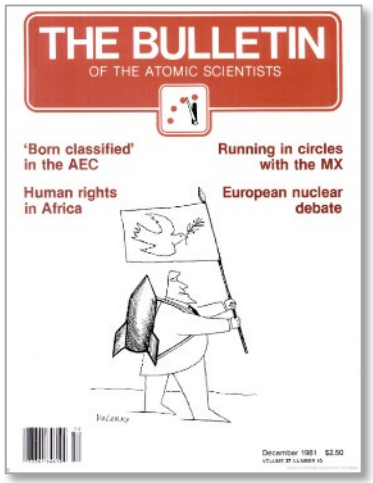
1947

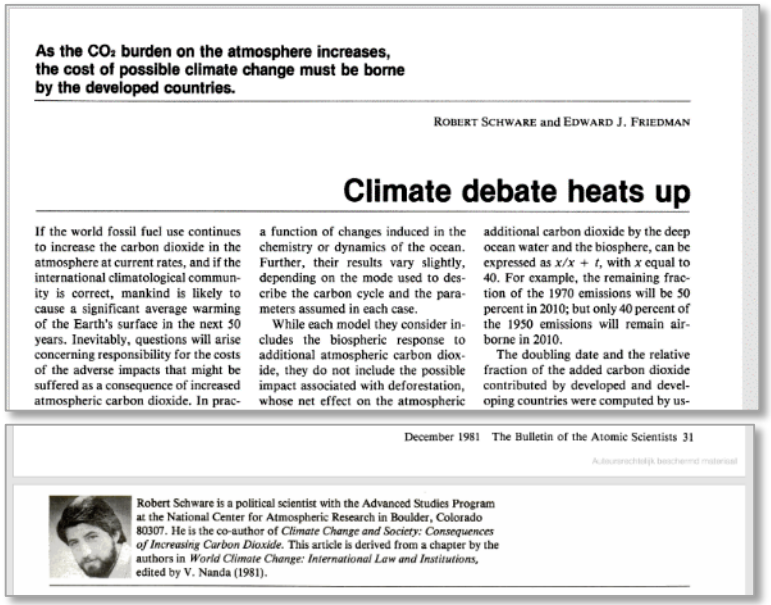
ENGLISH • РУССКИЙ • УКРАЇНСЬКА

"Unprecedented Danger": Russia-Ukraine War Pushes Iconic Doomsday Clock Closest to Midnight Ever in its History.

Bulletin of the Atomic Scientists Also Cite Bio-Threats, Nuclear Proliferation, Climate Crisis, State-Sponsored Disinformation and Disruptive Technology.

2023





As the CO_2 burden on the atmosphere increases, the cost of possible climate change must be borne by the developed countries.

ROBERT SCHWARE and EDWARD J. FRIEDMAN

Climate debate heats up

If the world fossil fuel use continues to increase the carbon dioxide in the atmosphere at current rates, and if the international climatological community is correct, mankind is likely to cause a significant average warming of the Earth's surface in the next 50 years. Inevitably, questions will arise concerning responsibility for the costs of the adverse impacts that might be suffered as a consequence of increased atmospheric carbon dioxide. In practice a function of changes induced in the chemistry or dynamics of the ocean. Further, their results vary slightly, depending on the mode used to describe the carbon cycle and the parameters assumed in each case.

While each model they consider includes the biospheric response to additional atmospheric carbon dioxide, they do not include the possible impact associated with deforestation, whose net effect on the atmospheric additional carbon dioxide by the deep ocean water and the biosphere, can be expressed as $x/x + t$, with x equal to 40. For example, the remaining fraction of the 1970 emissions will be 50 percent in 2010; but only 40 percent of the 1950 emissions will remain airborne in 2010.

The doubling date and the relative fraction of the added carbon dioxide contributed by developed and developing countries were computed by us-

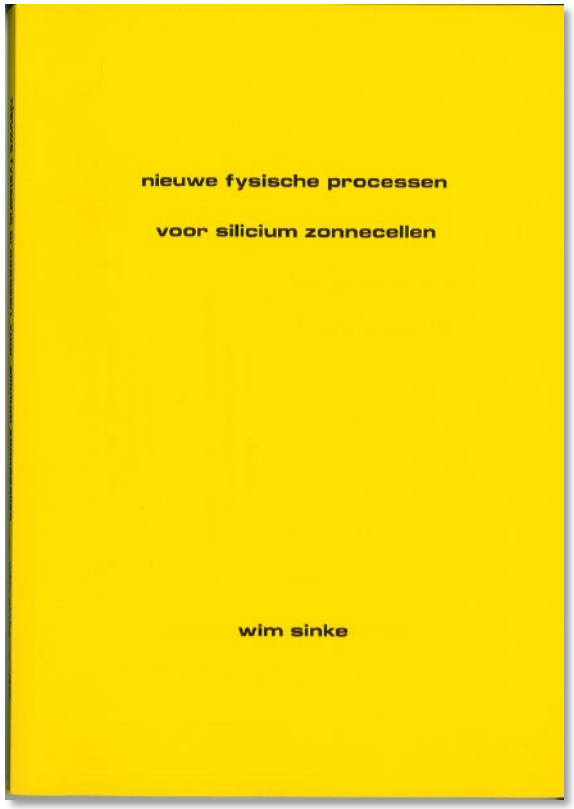
December 1981 The Bulletin of the Atomic Scientists 31

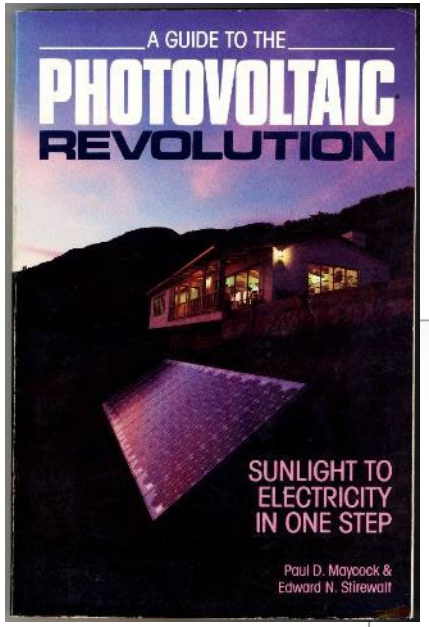
Robert Schware is a political scientist with the Advanced Studies Program at the National Center for Atmospheric Research in Boulder, Colorado 80307. He is the co-author of *Climate Change and Society: Consequences of Increasing Carbon Dioxide*. This article is derived from a chapter by the authors in *World Climate Change: International Law and Institutions*, edited by V. Nanda (1981).

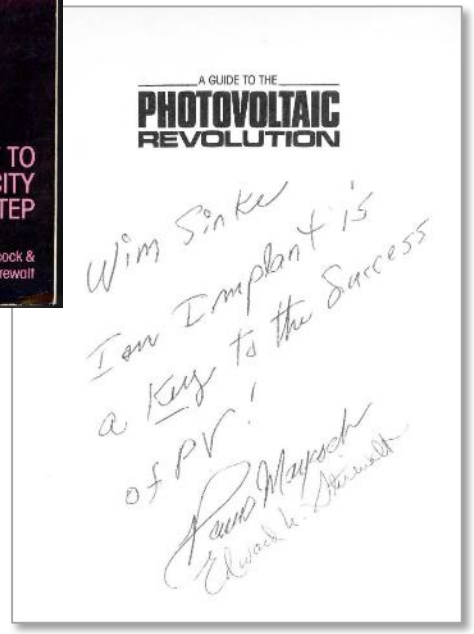
1981

PhD research @ AMOLF Amsterdam

1981-1985







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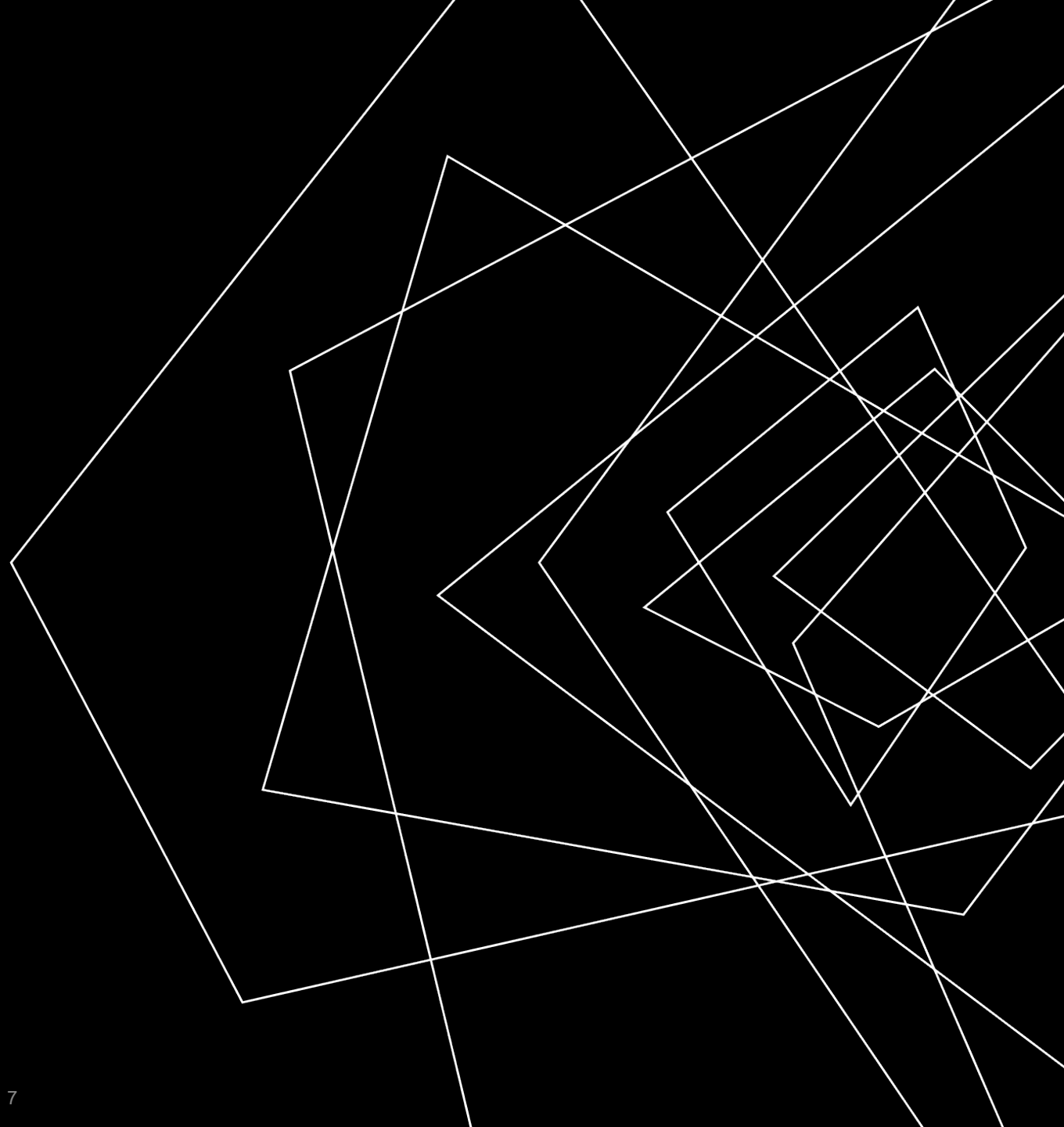
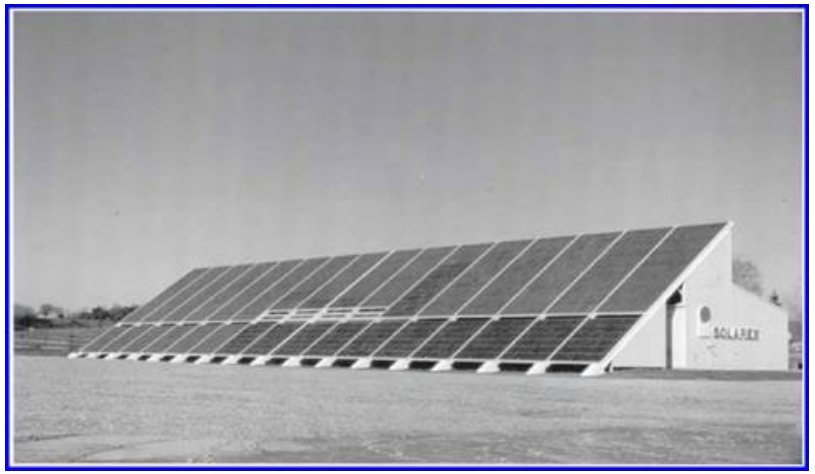


History in big steps

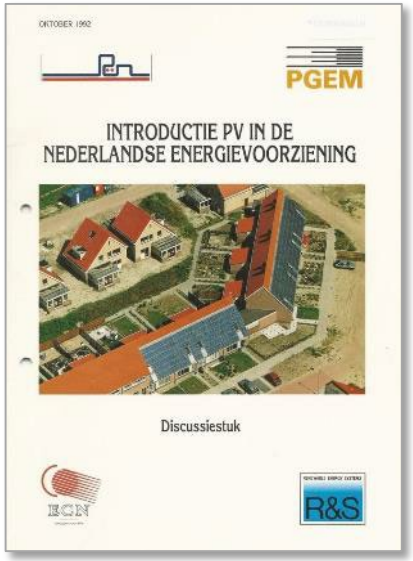
The discovery (1839):
Edmond Becquerel

The technology breakthrough (1954):
Pearson, Chapin & Fuller @ Bell Labs



Industrial production (1982):
Solarex factory, USA - 200 kWp/jr

The policy breakthrough (≈1990):
Hermann Scheer, DE († 2010)



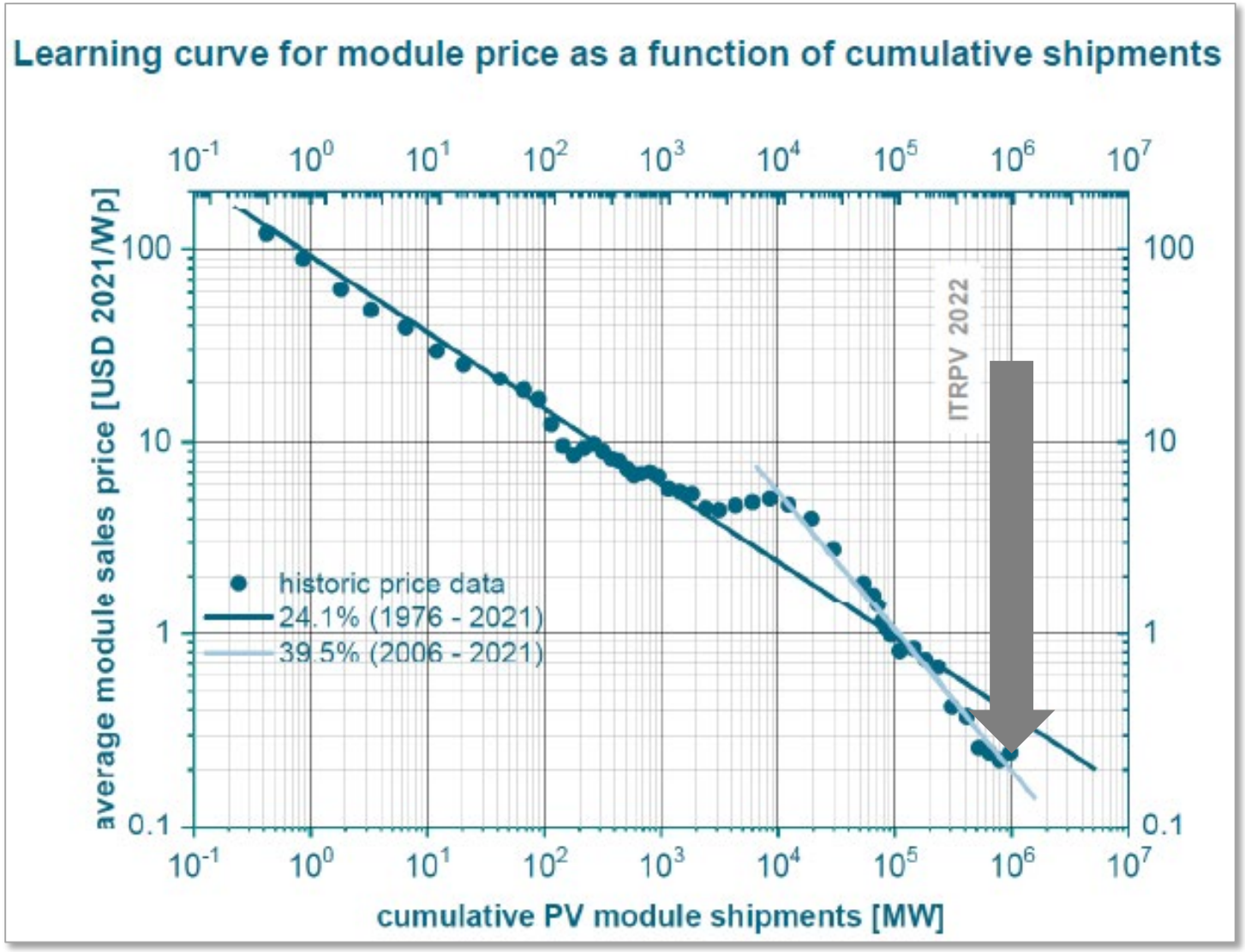
NL: 1992

2023

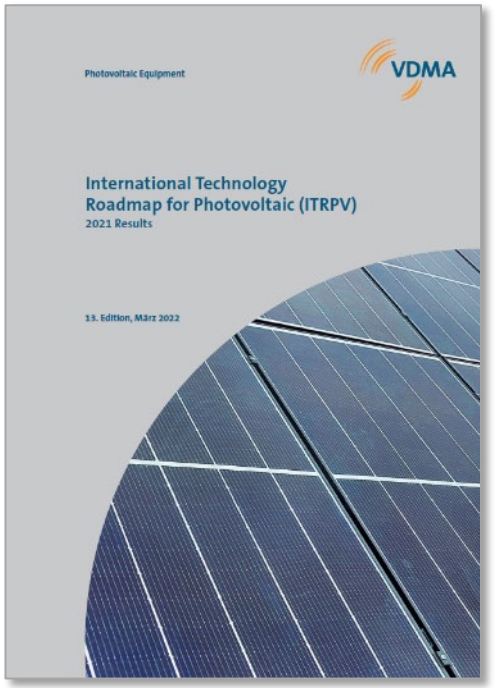
2020

Prices of solar modules

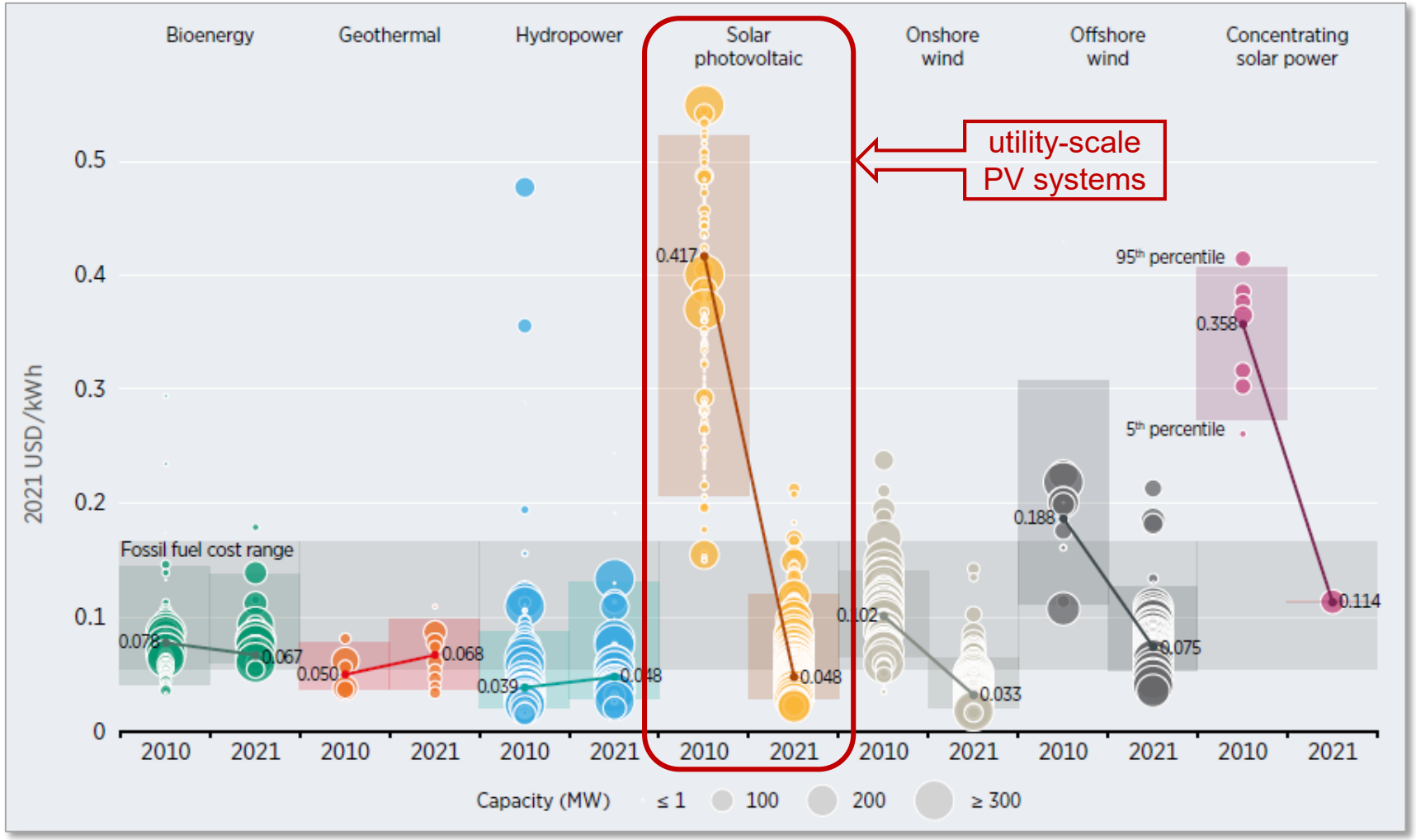
100x lower in 40 yrs

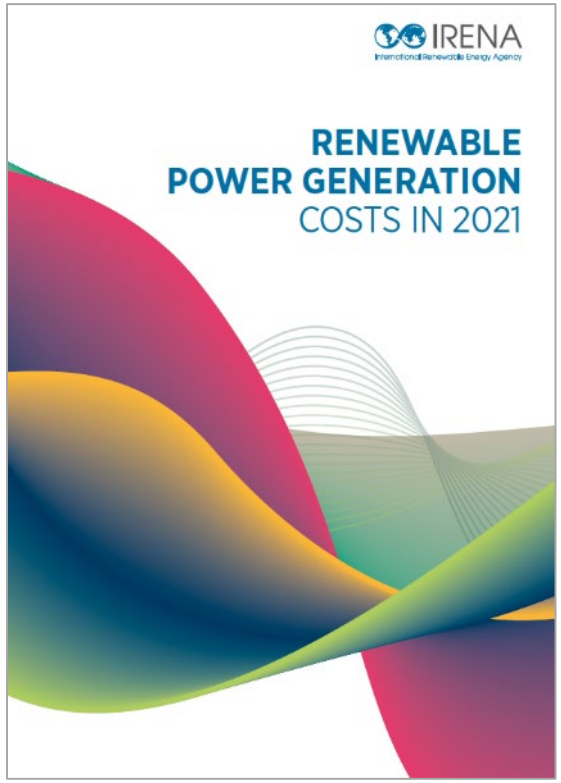


ITRPV 2022



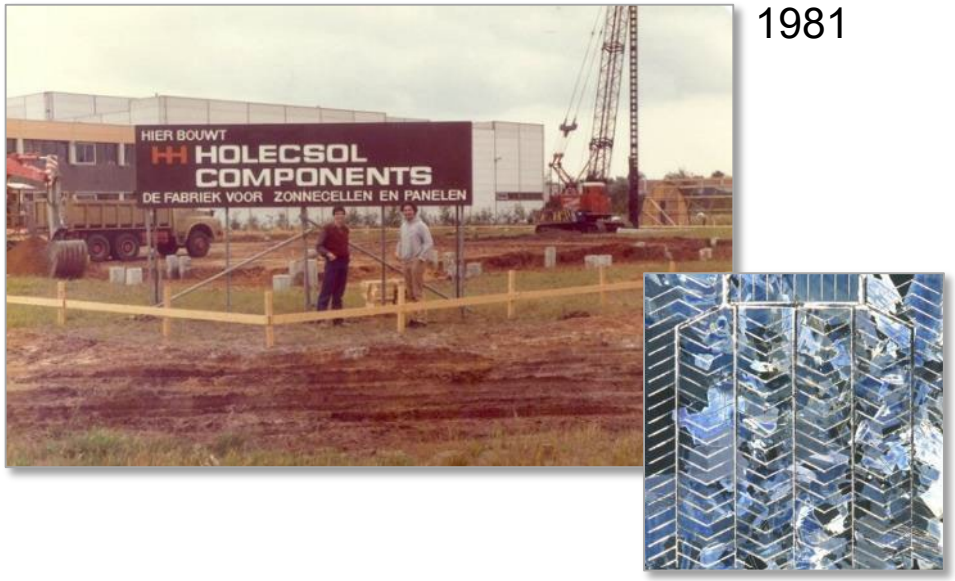
Generation cost (LCoE)



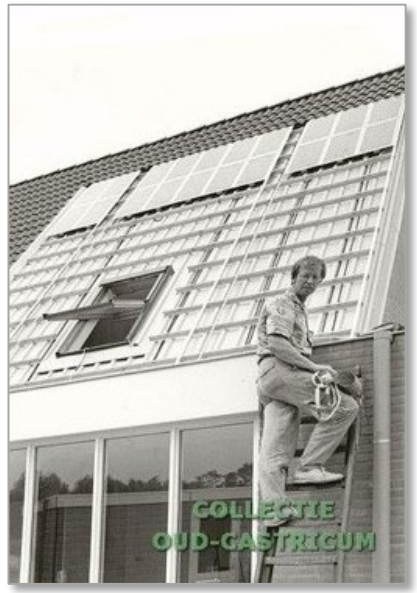


Energy yield of cells, modules and systems

doubled in 40 yrs



1981



1989

Efficiency 10%

Solinso/ BIPV Nederland

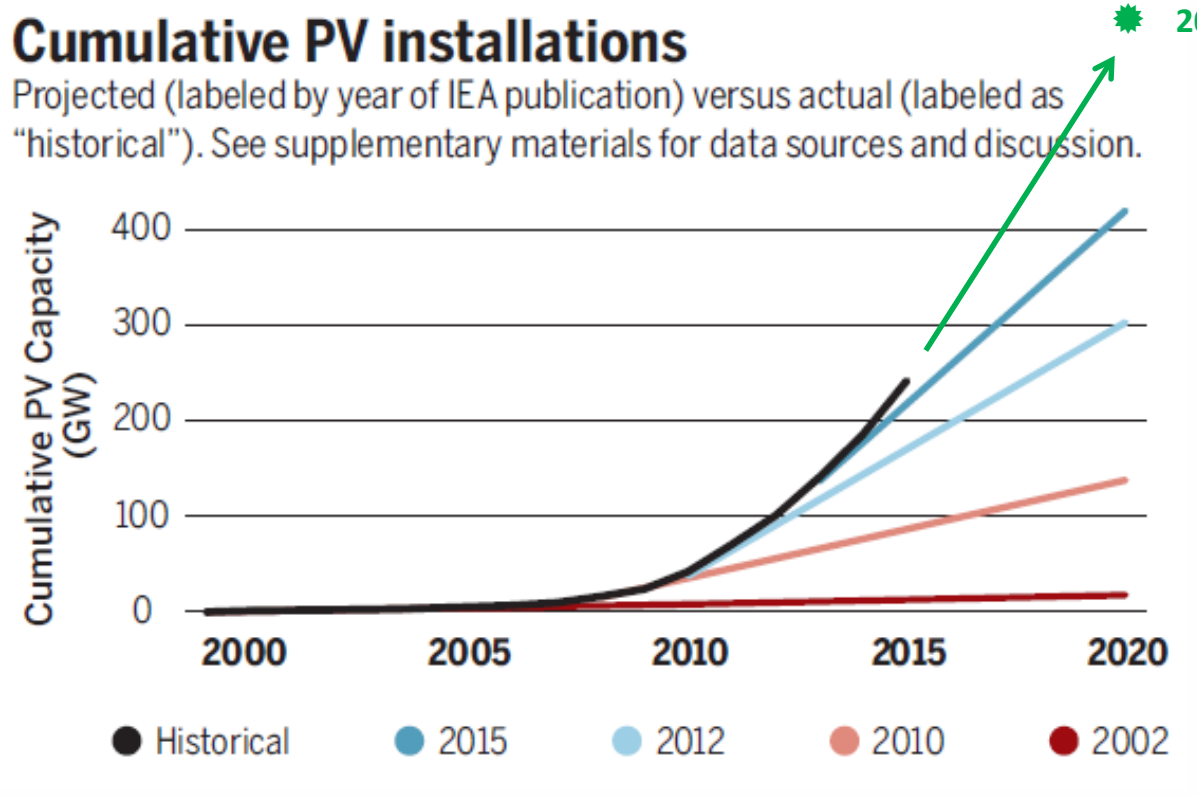
Lightyear

Efficiency ≥20%

Systematically underestimated growth

2022 1.2 TWp

2020



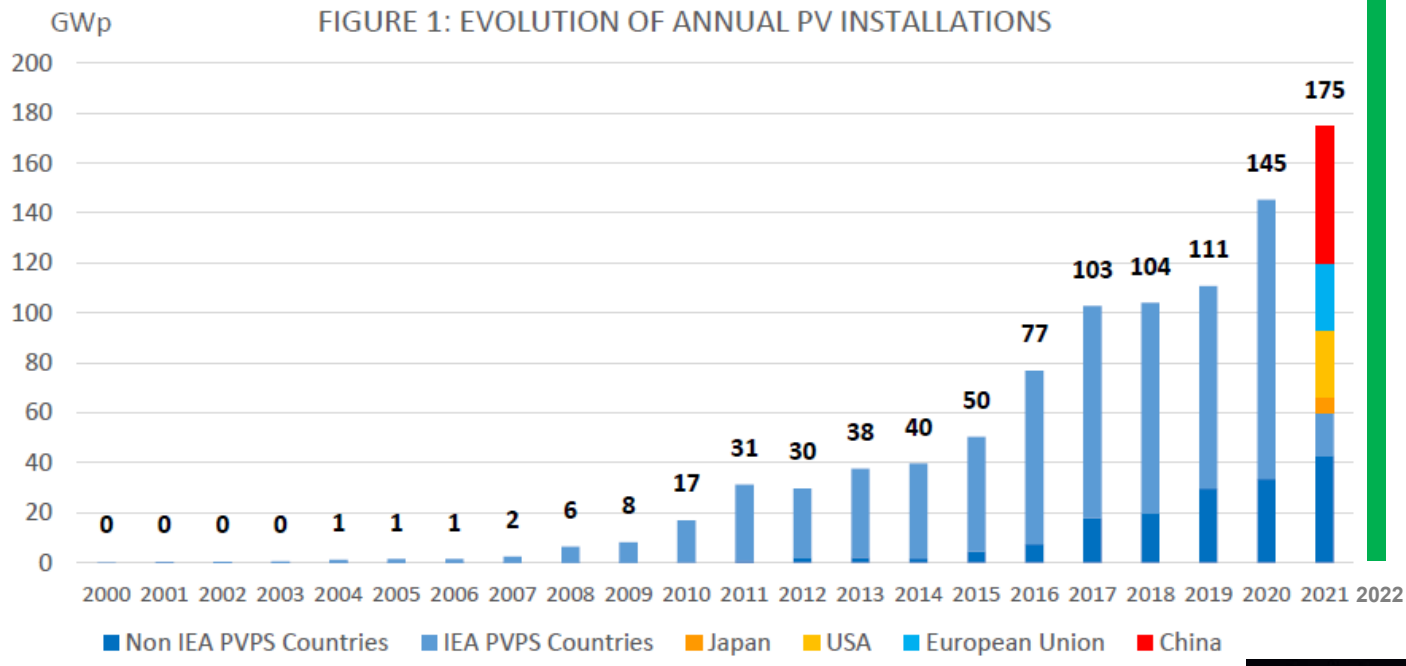
Terawatt-scale photovoltaics: Trajectories and challenges

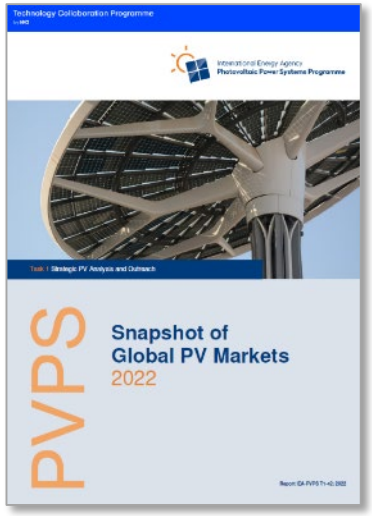
Coordinating technology, policy, and business innovations

By **Nancy M. Haegel, Robert Margolis, Tonio Buonassisi, David Feldman, Armin Froitzheim, Raffi Garabedian, Martin Green, Stefan Glunz, Hans-Martin Henning, Burkhard Holder, Izumi Kaizuka, Benjamin Kroposki, Koji Matsubara, Shigeru Niki, Keiichiro Sakurai, Roland A. Schindler, William Tumas, Eicke R. Weber, Gregory Wilson, Michael Woodhouse, Sarah Kurtz**

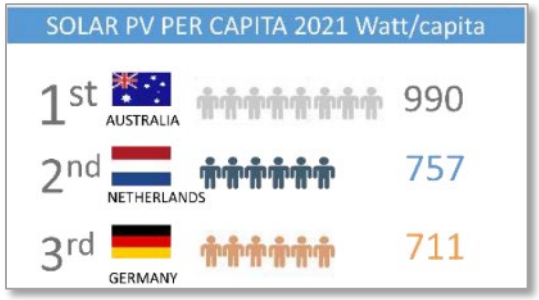
Nancy M. Haegel et al., Science, Vol 356, Issue 6334 (2017) 141

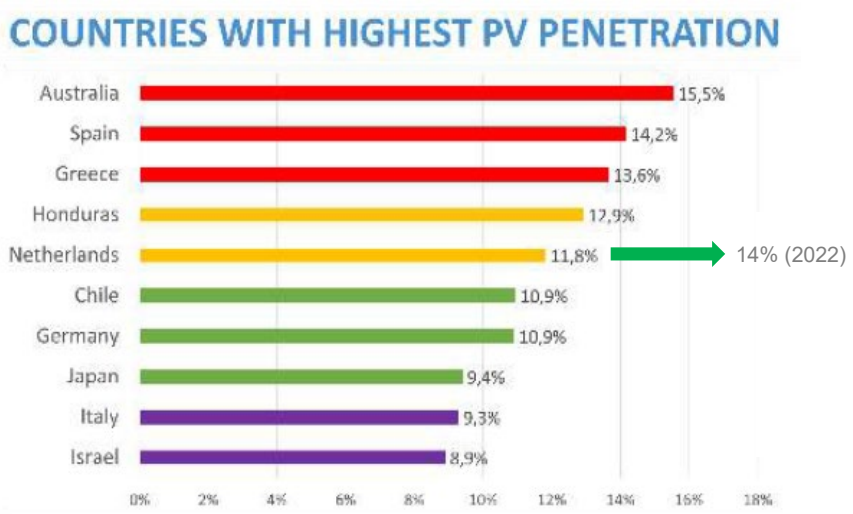
Annual and cumulative market





10.000x bigger in 40 yrs



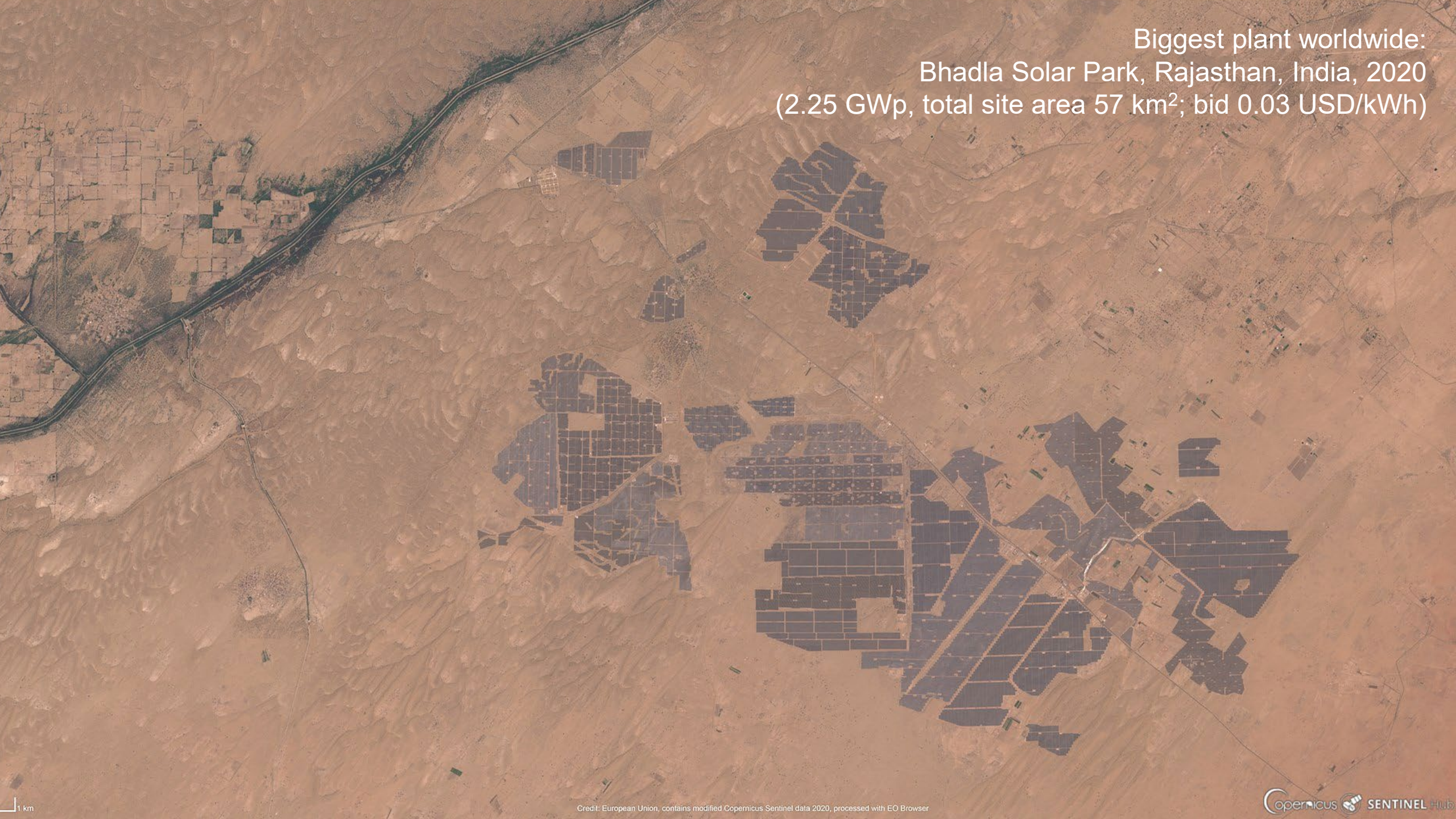


Applications

Grid-connected system, Petten, NL
(1 kWp; ECN, 1989)

Solar park
Dorhout Mees,
Biddinghuizen, NL
(144 MWp;
Solarfields, 2022)

City of the Sun,
Heerhugowaard, NL
(4 MWp; Municipality
Dijk en Waard,
status 2020)


Biggest plant worldwide:
Bhadla Solar Park, Rajasthan, India, 2020
(2.25 GWp, total site area 57 km^2; bid 0.03 USD/kWh)
1 km
Credit: European Union, contains modified Copernicus Sentinel data 2020, processed with EO Browser
Copernicus SENTINEL Hub

Energy pay-back time (EPBT) of systems

10x shorter in 40 yrs

Energy Policy 94 (2016) 336–344

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Energy Return on Energy Invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation

Ferruccio Ferroni [a,*], Robert J. Hopkirk [b]

[a] Energy Consultant, Zurich, Switzerland
[b] Engineering Research & Development, Maennedorf, Switzerland

optimistic choices resulting in low the ERoEI is significantly below 1. supply system based on today's PV t

Zonnecellen leveren echt wel meer energie op dan ze kosten

Energie Er is zware kritiek op onderzoek waaruit zou blijken dat zonnecellen per saldo energie kosten.

NRC, 27 10 2016

Energy Policy 102 (2017) 377–384

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

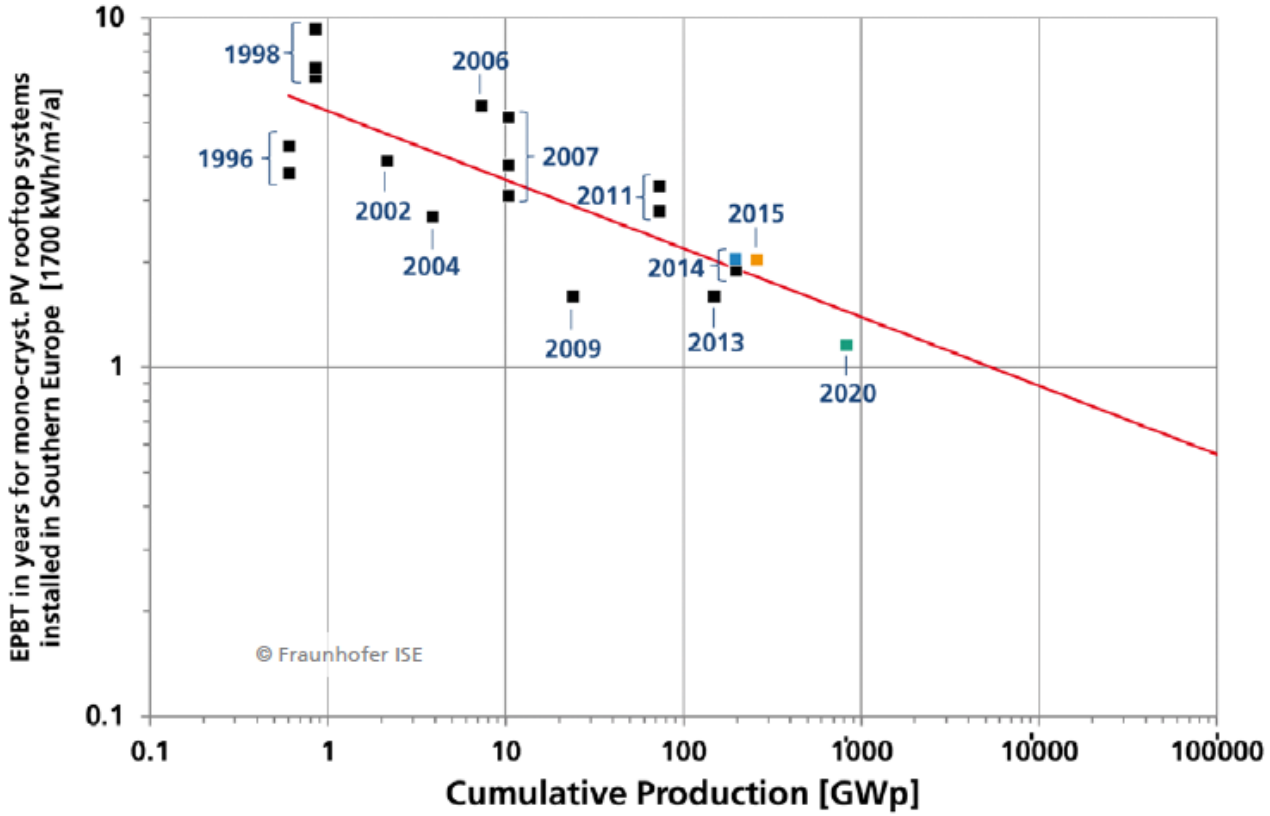
Energy Return on Energy Invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation: A comprehensive response

Marco Raugei[a,b,*], Sgouris Sgouridis[c], David Murphy[d], Vasilis Fthenakis[b,e], Rolf Frischknecht[f], Christian Breyer[g], Ugo Bardi[h], Charles Barnhart[i], Alastair Buckley[j], Michael Carbajales-Dale[k], Denes Csala[l], Mariska de Wild-Scholten[m], Garvin Heath[n,o], Arnulf Jæger-Waldau[p], Christopher Jones[q], Arthur Keller[r], Enrica Leccisi[s], Pierluigi Mancarella[t], Nicola Pearsall[u], Adam Siegel[v], Wim Sinke[w], Philippe Stolz[f]

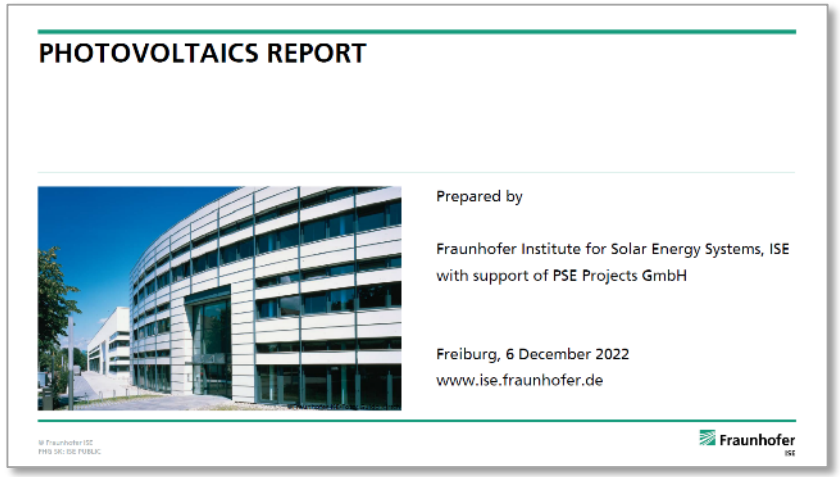
[a] Department of Mechanical Engineering and Mathematical Sciences, Oxford Brookes University, UK
[b] Center for Life Cycle Analysis, Columbia University, New York, NY, USA
[c] Department of Engineering Systems and Management, Masdar Institute, United Arab Emirates
[d] Department of Environmental Studies, St. Lawrence University, NY, USA
[e] National Photovoltaic Environmental Research Center, Brookhaven National Laboratory, Upton, NY, USA
[f] Treeze, Switzerland
[g] School of Energy Systems, Lappeenranta University of Technology, Finland
[h] Department of Chemistry, University of Florence, Italy
[i] Huxley College of the Environment and Institute for Energy Studies, Western Washington University, WA, USA
[j] Department of Physics and Astronomy, University of Sheffield, UK
[k] Environmental Engineering and Earth Sciences, Clemson University, Clemson, SC, USA
[l] Department of Engineering, Lancaster University, UK
[m] SmartGreenScans, Netherlands

equivalent electrical energy investment), but based on the arguments and numbers presented in this paper are, respectively, EROI≈9–10 (when adhering to widely adopted 'conventional' system boundaries as recommended by the IEA (Raugei et al., 2016)) and $EROI_{EXT}$≈7–8 (when instead adopting 'extended' system boundaries that also include the energy investments for service inputs such as 'project management'

Energy pay-back time (EPBT) of systems



Data: Lorenz Friedrich, Fraunhofer ISE. Graph: PSE 2021



Monocrystalline silicon technology

@1700 kWh/(m^2·yr)

Learning rate 13%

EPBT a.o. dependent on irradiation and grid efficiency at point of use

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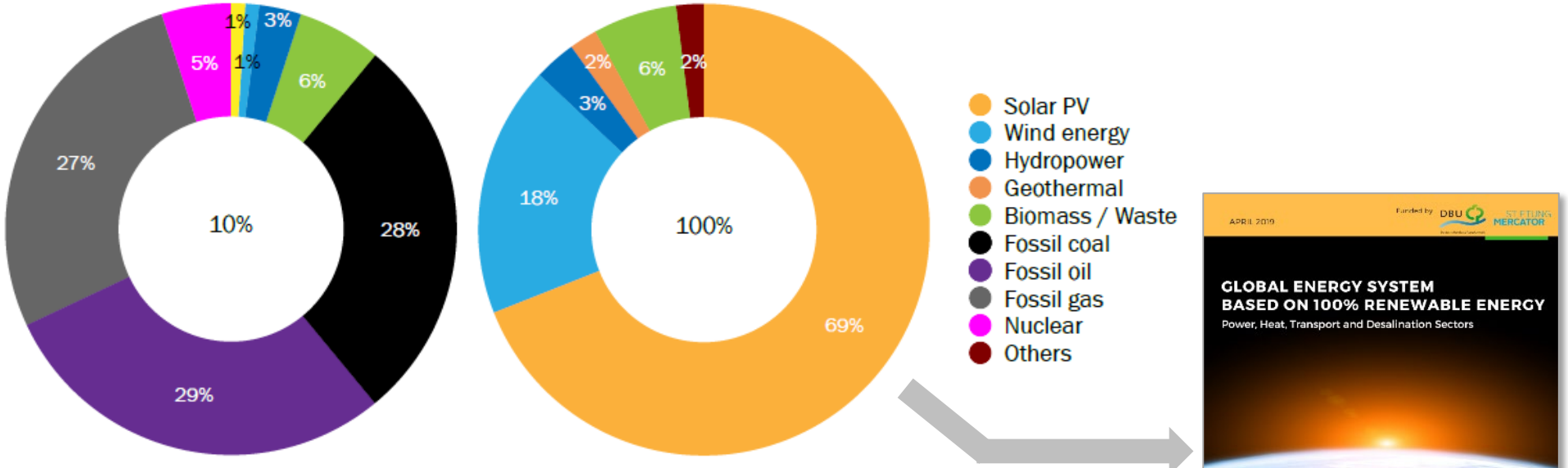
From niche to cornerstone: we need a lot and we need it fast

- **Double digit growth** (this example: ≈15%/yr; historically realized: 25%)

→ **Energy system integration**



100% RE scenario: contributions to global primary energy 2015 and 2050

2050: 60 TWp solar PV

http://energywatchgroup.org/new-study-global-energy-system-based-100-renewable-energy

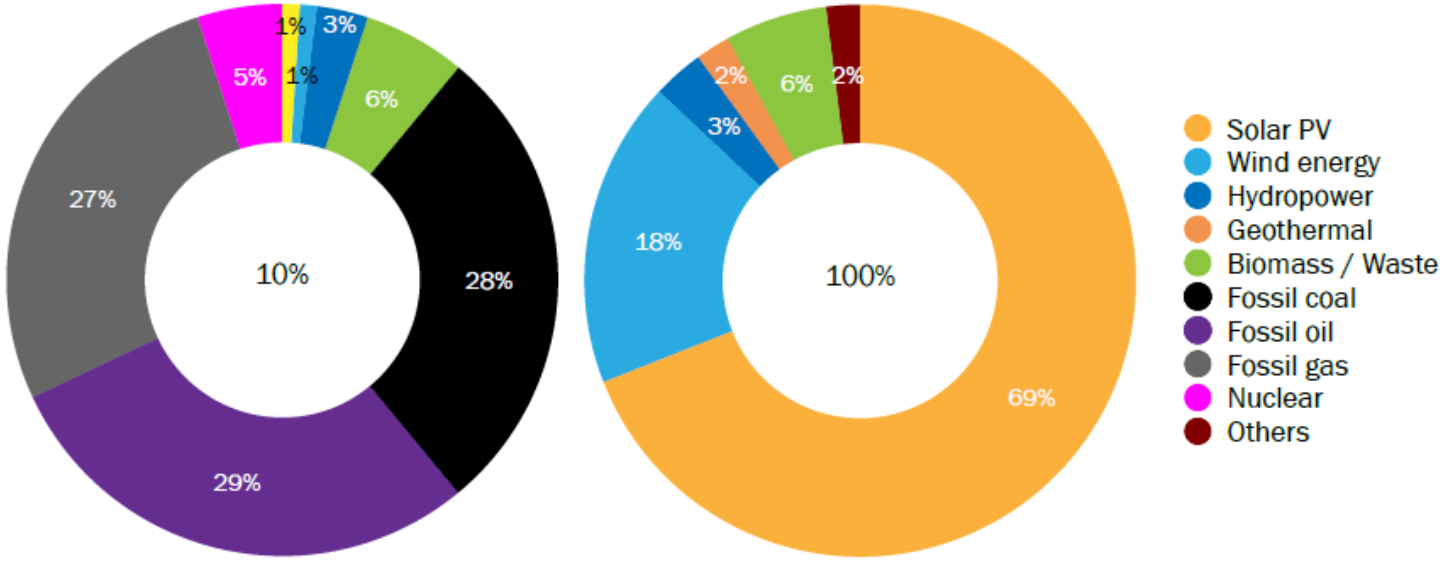
From electricity to energy: from power to all sectors

- **Energy system integration:** flex, storage, conversion & electrification
- **Beyond electricity only:** P2X

Michael Lippert, Saft

From niche to cornerstone: thinking big and bold

- **Energy system integration:** flex, storage, conversion & electrification
- **Beyond electricity only:** P2X



100% RE scenario: contributions to global primary energy 2015 and 2050

2050: 60 TWp solar PV

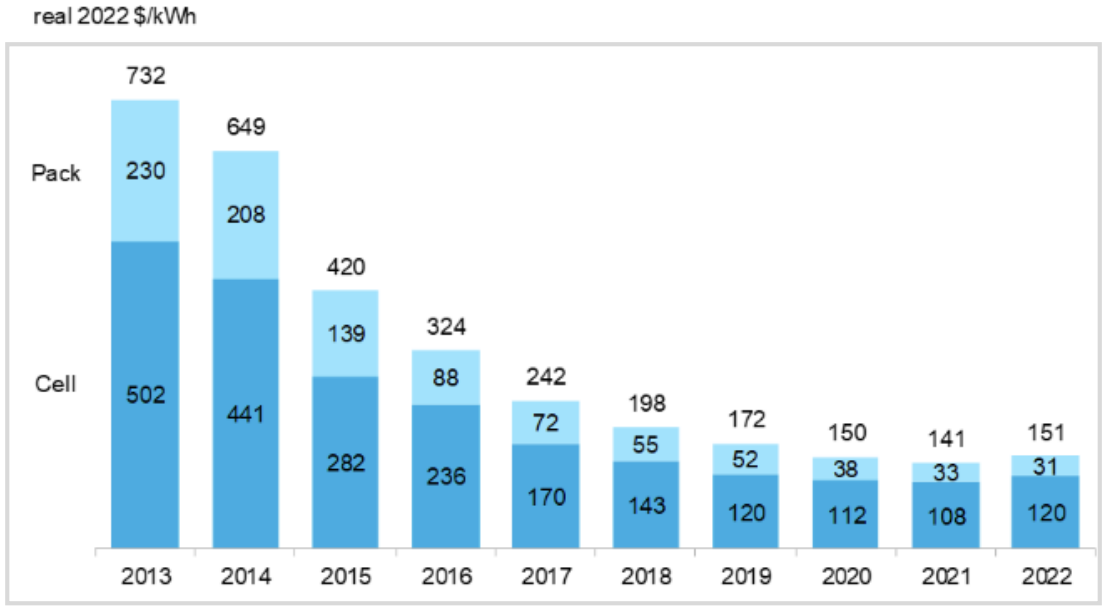
2023 update: 80 TWp to also serve industry → up to 4 TWp/yr

2100: 170 TWp

http://energywatchgroup.org/new-study-global-energy-system-based-100-renewable-energy

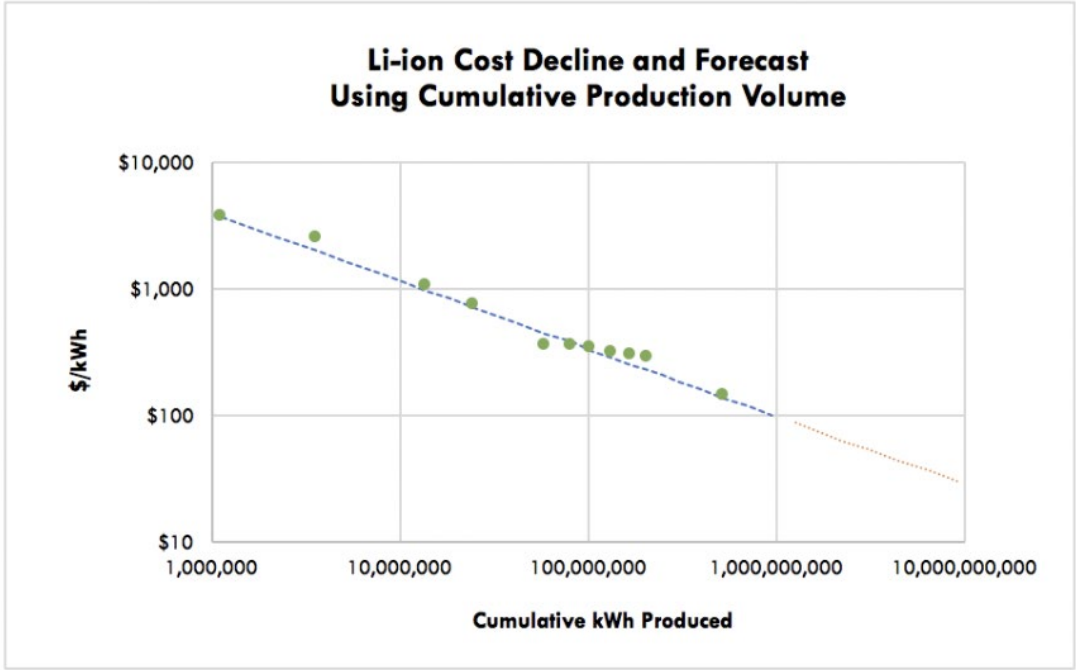
Storage: Li-ion battery cost decline

Figure 1: Volume-weighted average lithium-ion battery pack and cell price split, 2013-2022



Source: BloombergNEF. All values in real 2022 dollars. Weighted average survey value includes 178 data points from passenger cars, buses, commercial vehicles and stationary storage.

https://about.bnef.com/blog/lithium-ion-battery-pack-prices-rise-for-first-time-to-an-average-of-151-kwh/



Source: ARK Investment Management LLC, 2018; IEA, Bloomberg New Energy Finance, Avicenne Energy

https://ark-invest.com/articles/analyst-research/wrights-law-2/

Cost of solar electricity incl. storage

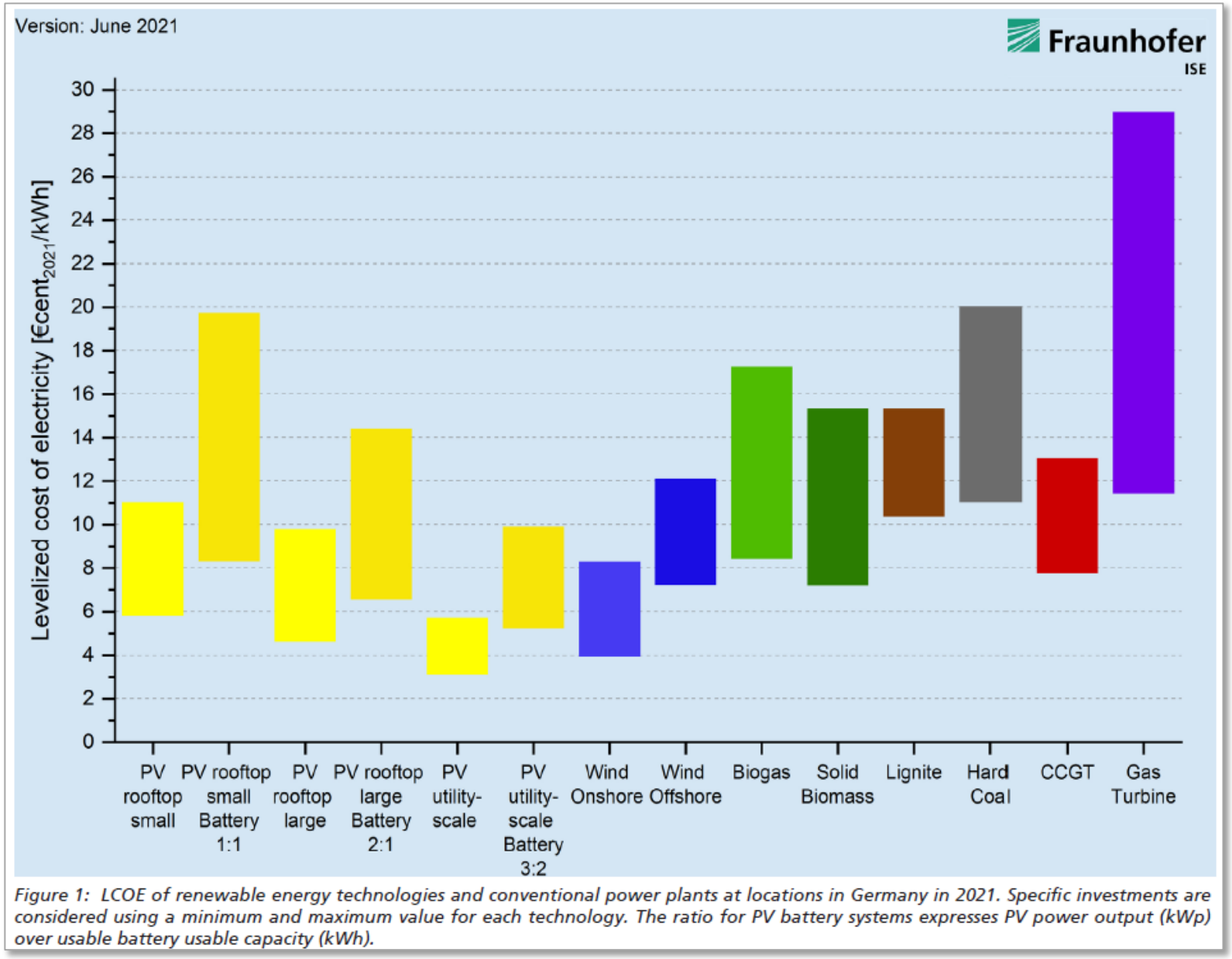
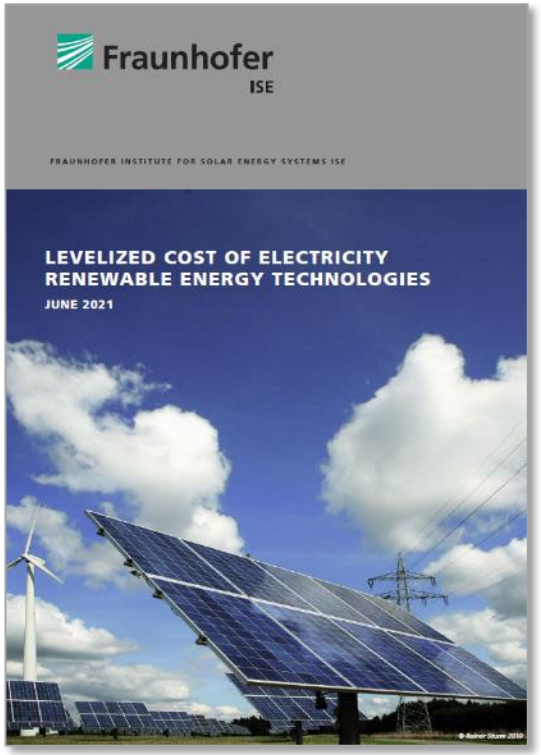
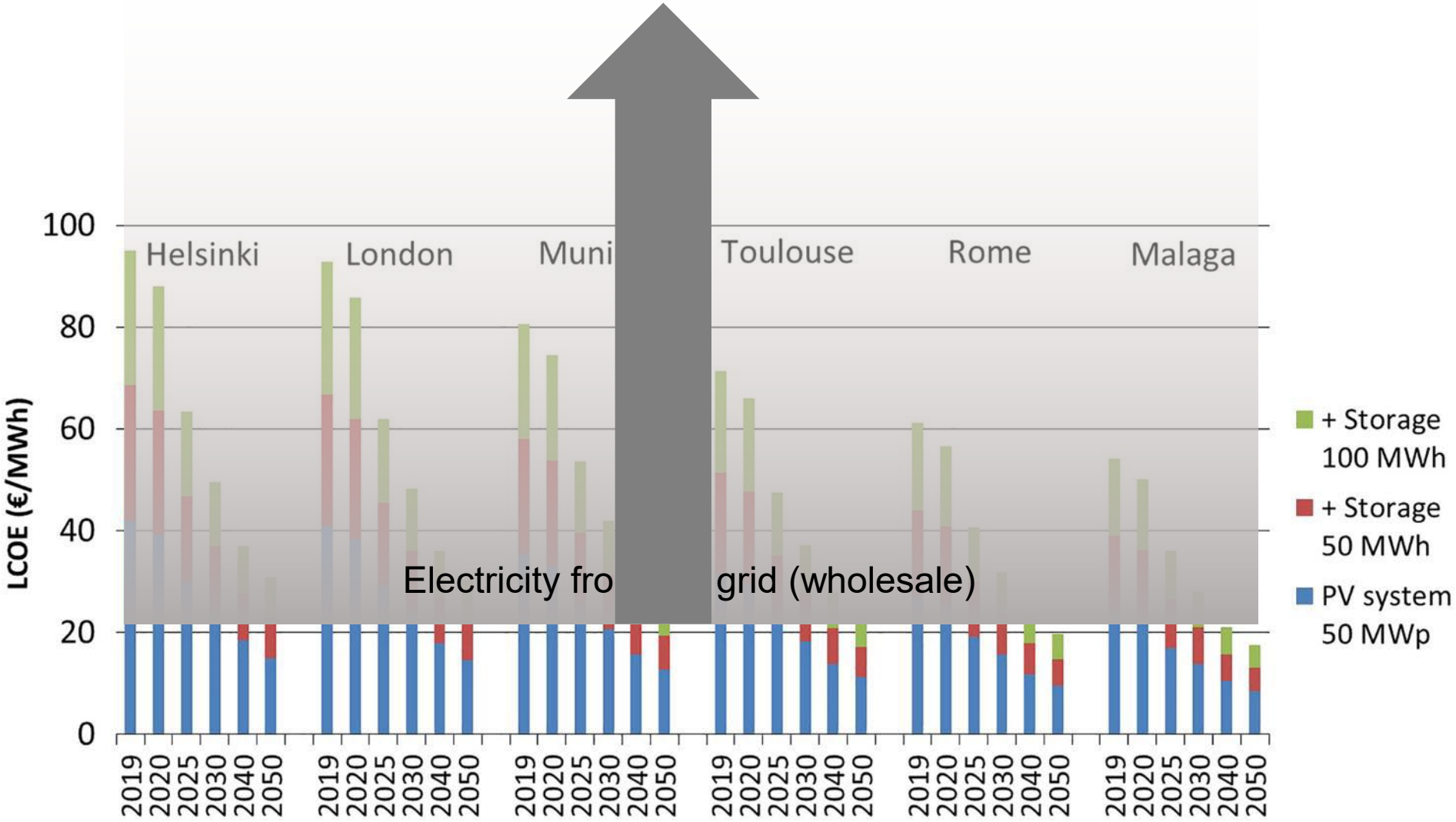


Figure 1: LCOE of renewable energy technologies and conventional power plants at locations in Germany in 2021. Specific investments are considered using a minimum and maximum value for each technology. The ratio for PV battery systems expresses PV power output (kWp) over usable battery usable capacity (kWh).

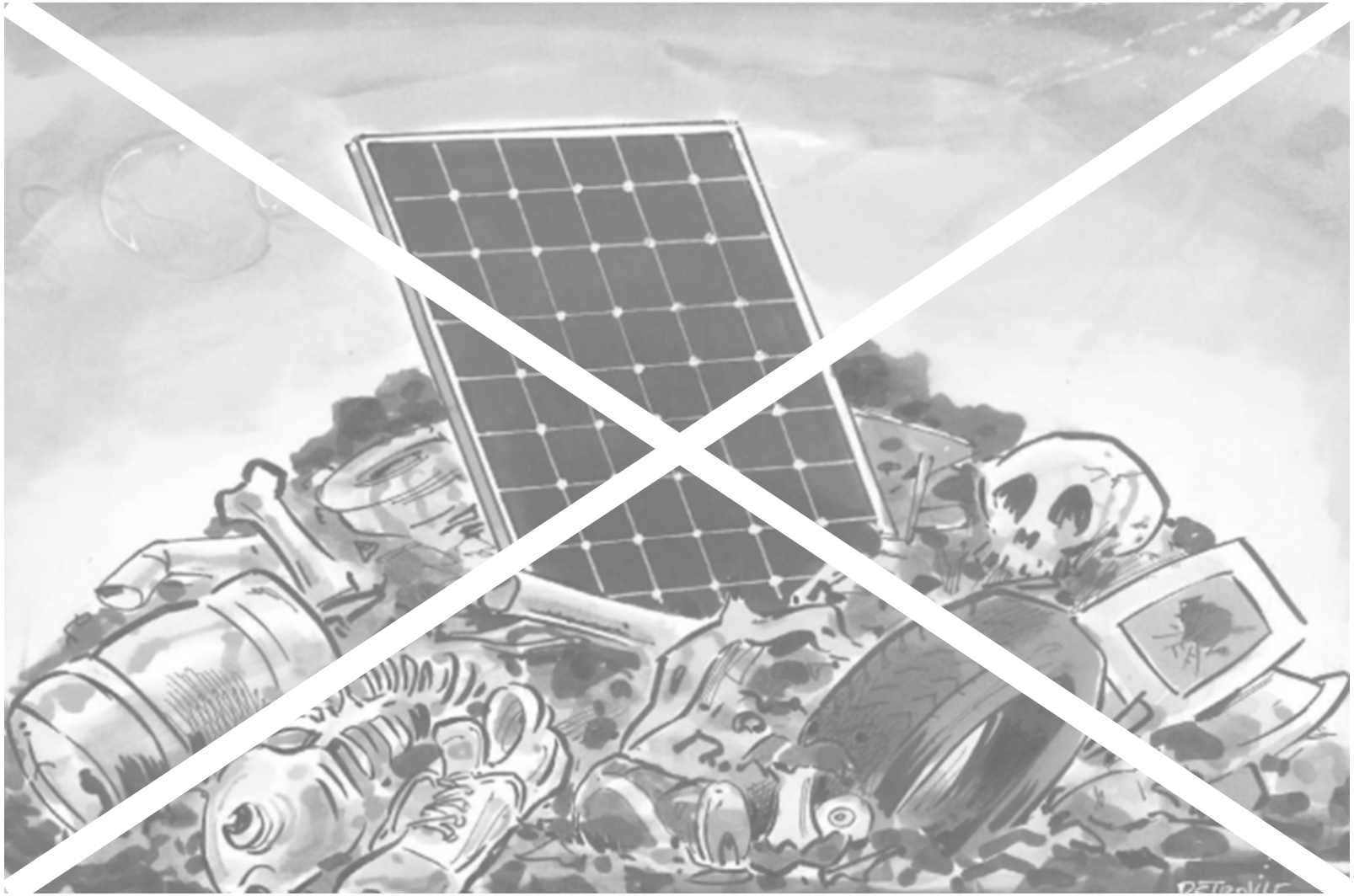


Cost of solar electricity incl. storage



Impact of WACC on PV LCoE, Vartiainen et al, PiP (2020)

From renewable to sustainable: circularity, climate, people, and more



https://electricalconnection.com.au/dont-let-solar-go-to-waste/

From renewable to sustainable: circularity

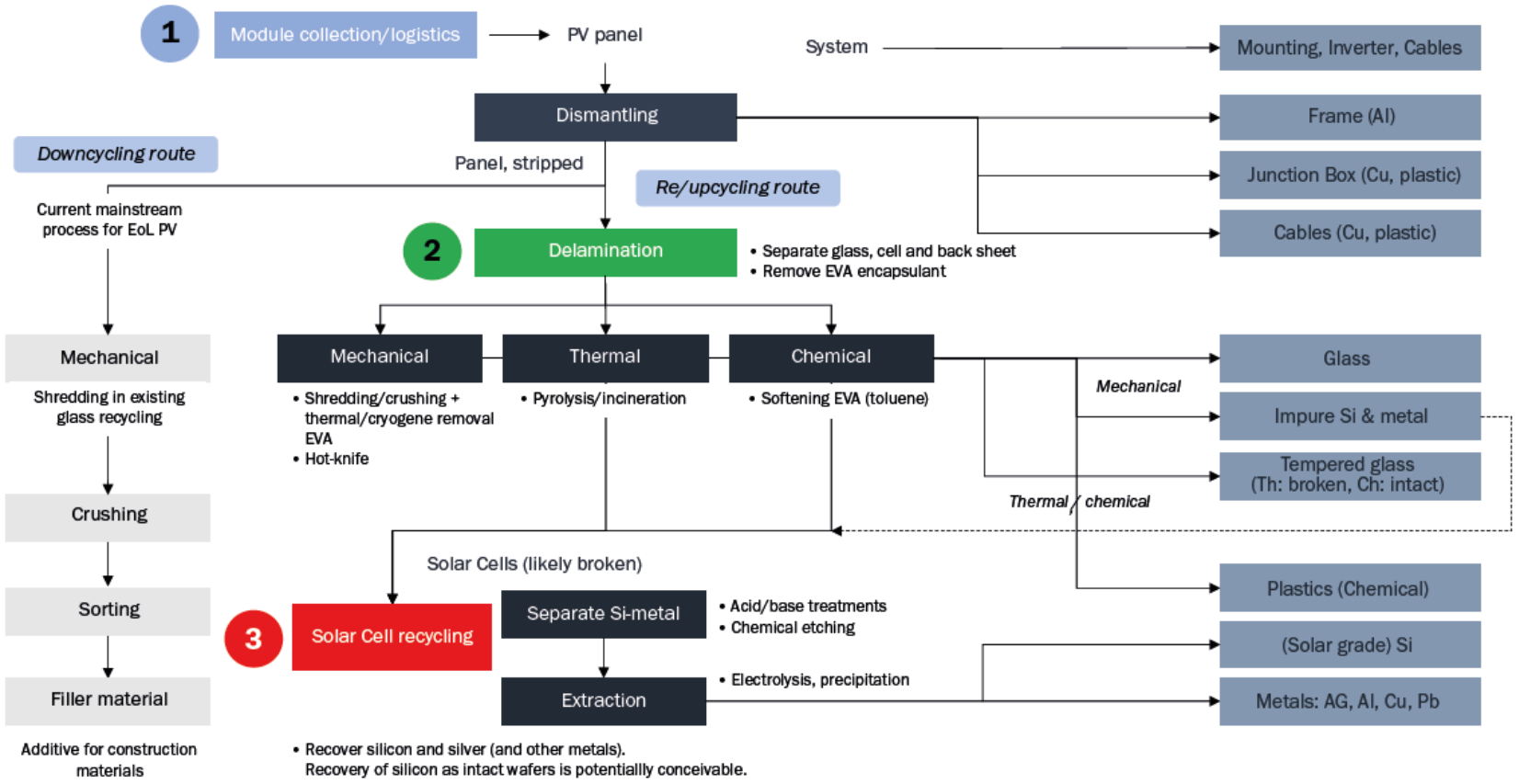


Figure 3. Current and potential future routes for PV recycling.

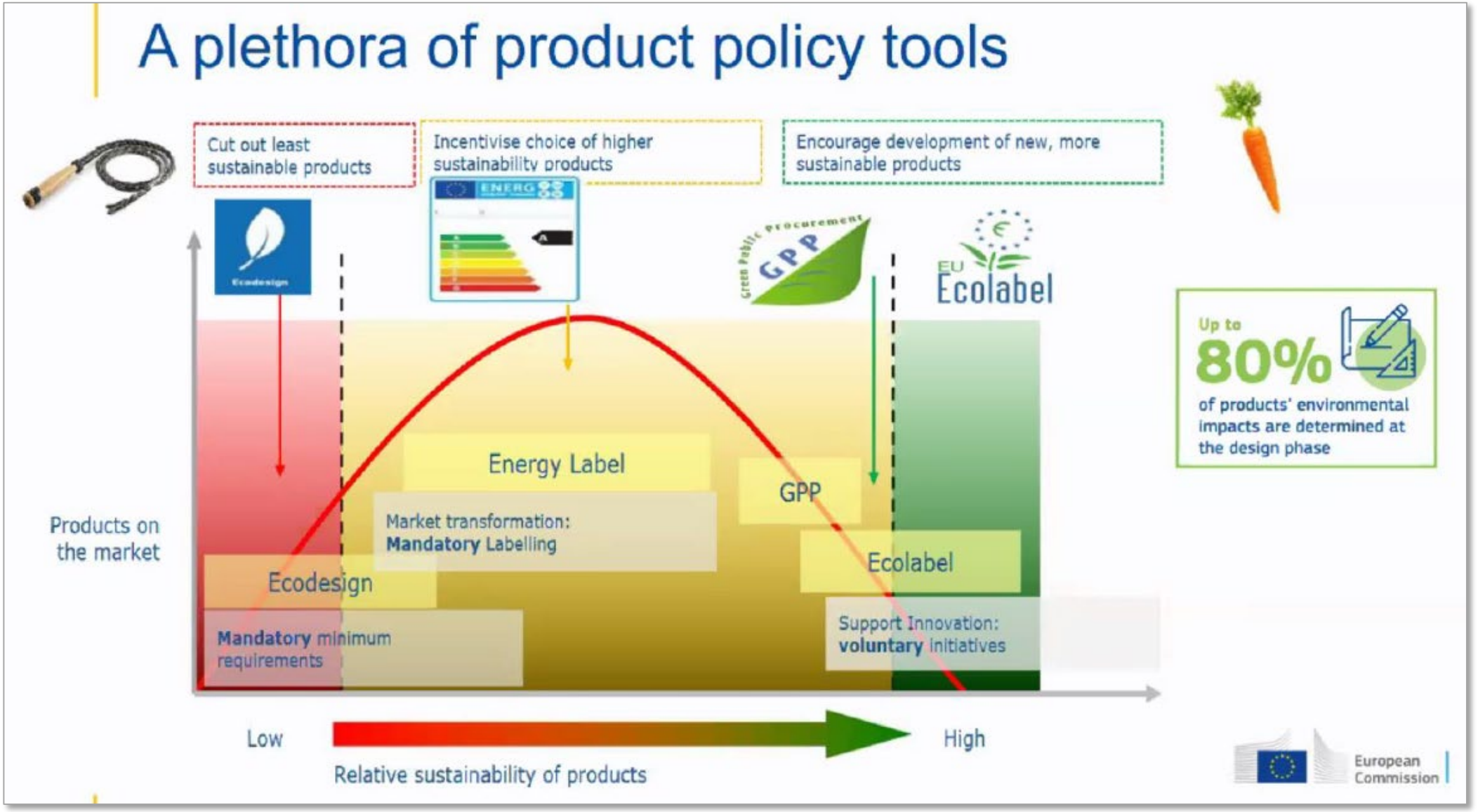
TNO, 2022

From renewable to sustainable: carbon footprint of solar electricity

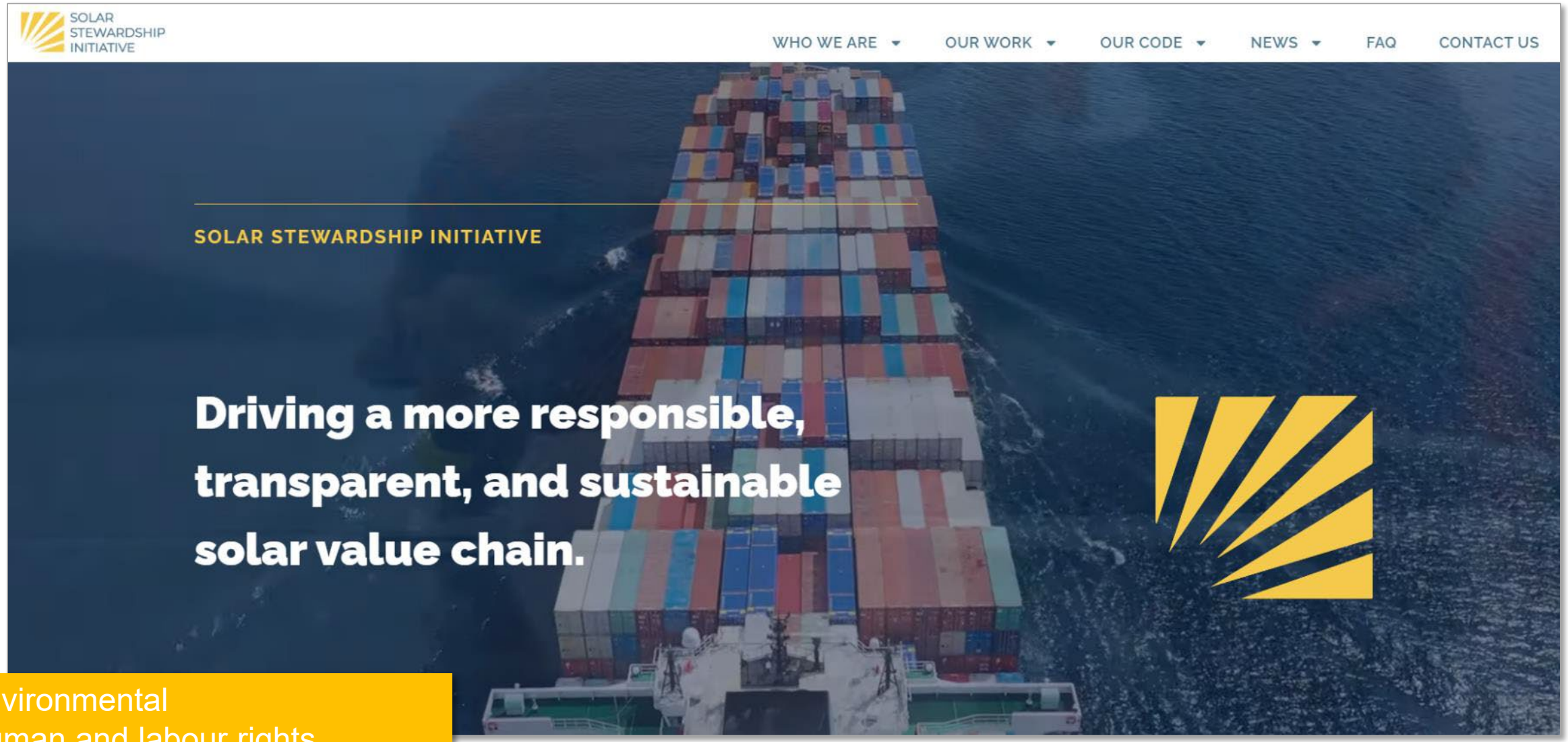
TNO, 2021

CO_2-footprint of solar electricity generated in the Netherlands: importance of energy mix and innovation (indicative values)

From renewable to sustainable: EU approach and policy-in-the-making



From renewable to sustainable: a broad approach



Environmental
Human and labour rights
Governance and business ethics

https://solarstewardshipinitiative.org

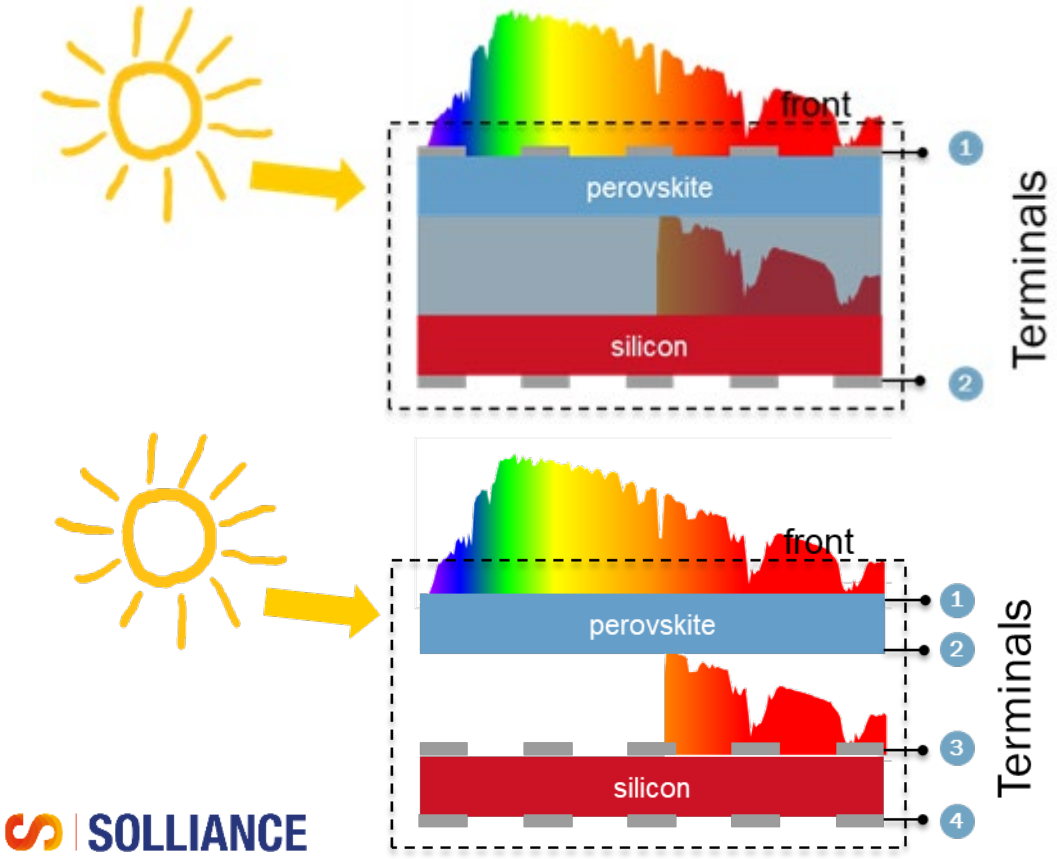
From addition to integration:
efficient use of available areas, jointly with other challenges

- Integration and multiple use of space
- (Aided by) higher energy yield

zon op gebouwen
zon op infra
Nationale Consortia
zon in landschap
zon op water

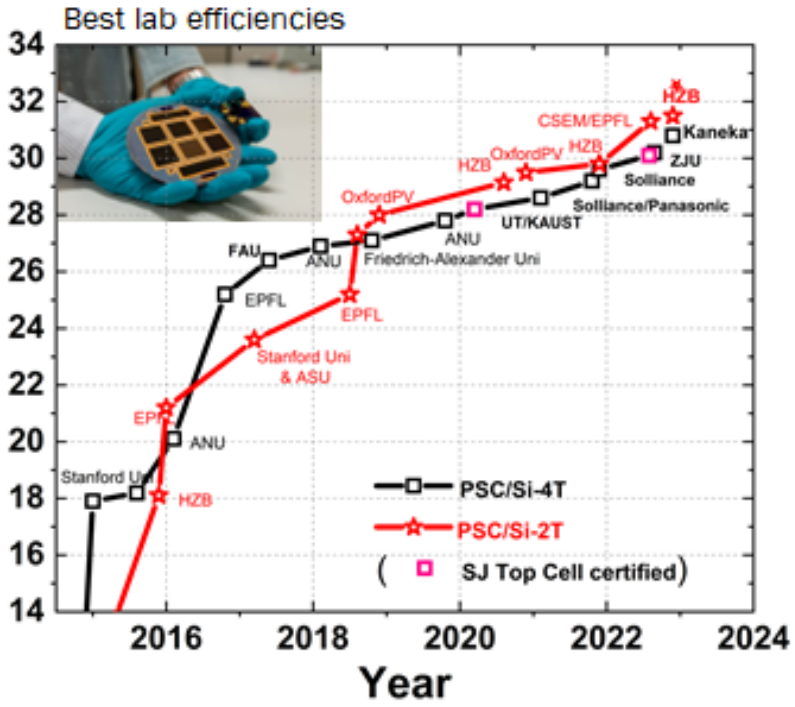
From addition to integration:
efficient use of available areas, jointly with other challenges

- Integration and multiple use of space
- (Aided by) higher energy yield



Courtesy Gianluca Coletti (TNO)

Higher efficiency (>30%) and energy yield:
tandem modules + (option) bifaciality



From addition to integration: new technologies and applications

- E.g. solar foils, semi-transparent, coloured and 3D elements
- Customized solar: every surface can generate electricity

SOLLIANCE

ECN (now TNO)

Solinso/ BIPV Nederland

Solar Highways, Uden, NL

TNO Solar Lab @ E&HC, Petten (with Solar Visuals)

Click-&-Go™ gevel, Waalwijk (BIPV.world)

Terracotta PV (Exasun)

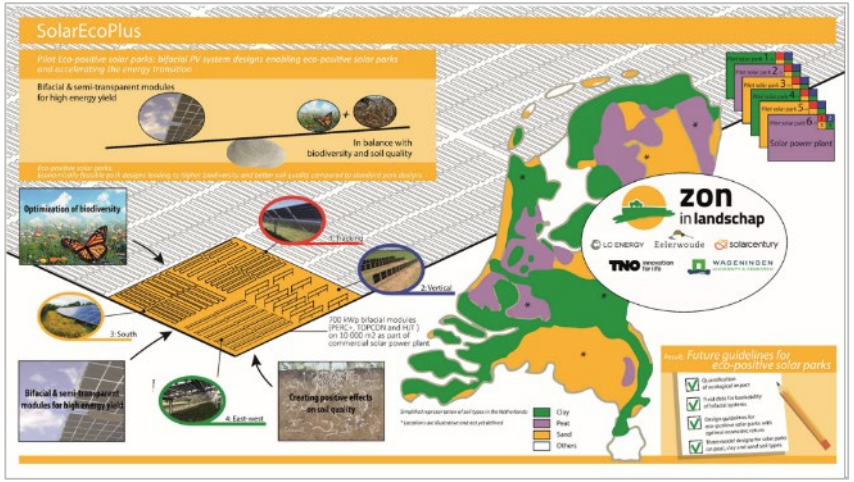
From addition to integration: new technologies and applications

- E.g. solar foils, semi-transparent, coloured and 3D elements
- Customized solar: every surface can generate electricity

Solar foils on floating system (project Solar@Sea, NL)

Project Sunbiose (NL)

Solar carport Lowlands, Biddinghuizen, NL (photo: Solarfields)



Project SolarEcoPlus (NL)

Bifacial agri-PV (Solar park Stal den Heuvel Culemborg, NL)

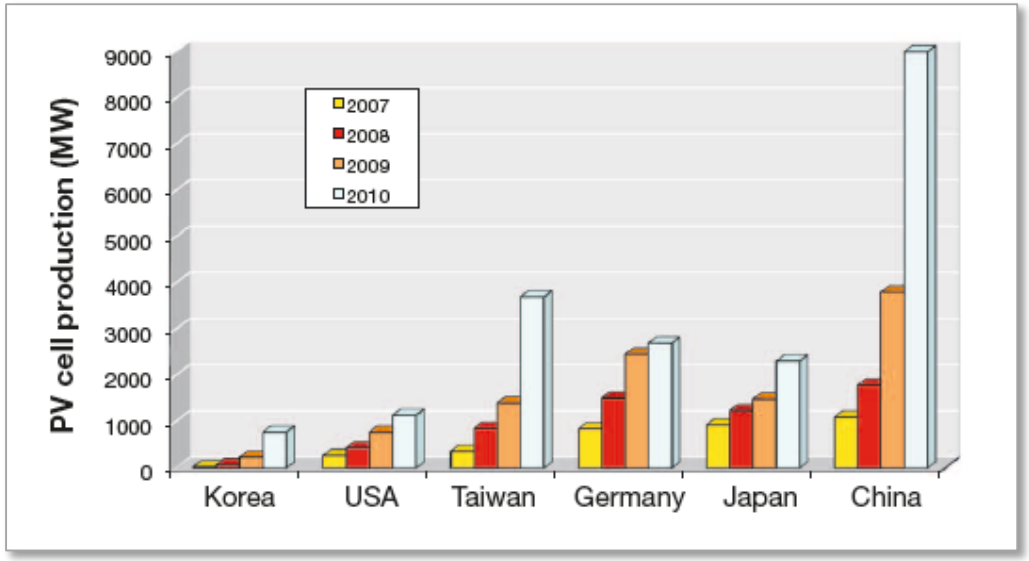
SolaRoad

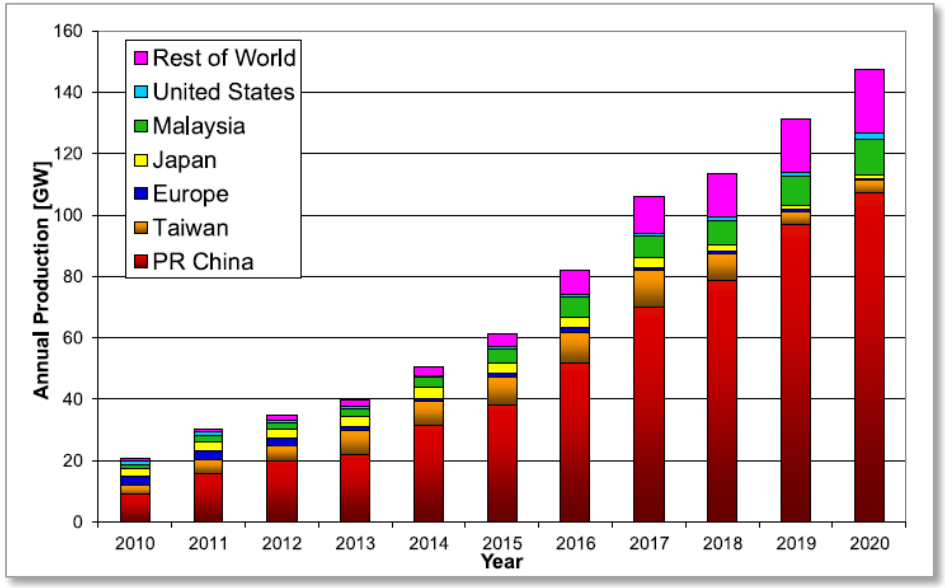
First-ever offshore solar PV system, NL (Oceans of Energy)

Manufacturing: from champion to niche player…

2008

IEA PVPS –Trends in Photovoltaic Applications 1992-2010





Snapshot of photovoltaics – March 2021,
Arnulf Jäger-Waldau,
EPJ Photovoltaics 12, 2 (2021)

Manufacturing: from champion to niche player… and back?

- A ‘fair share’ of global manufacturing: bring solar PV value chain back to Europe

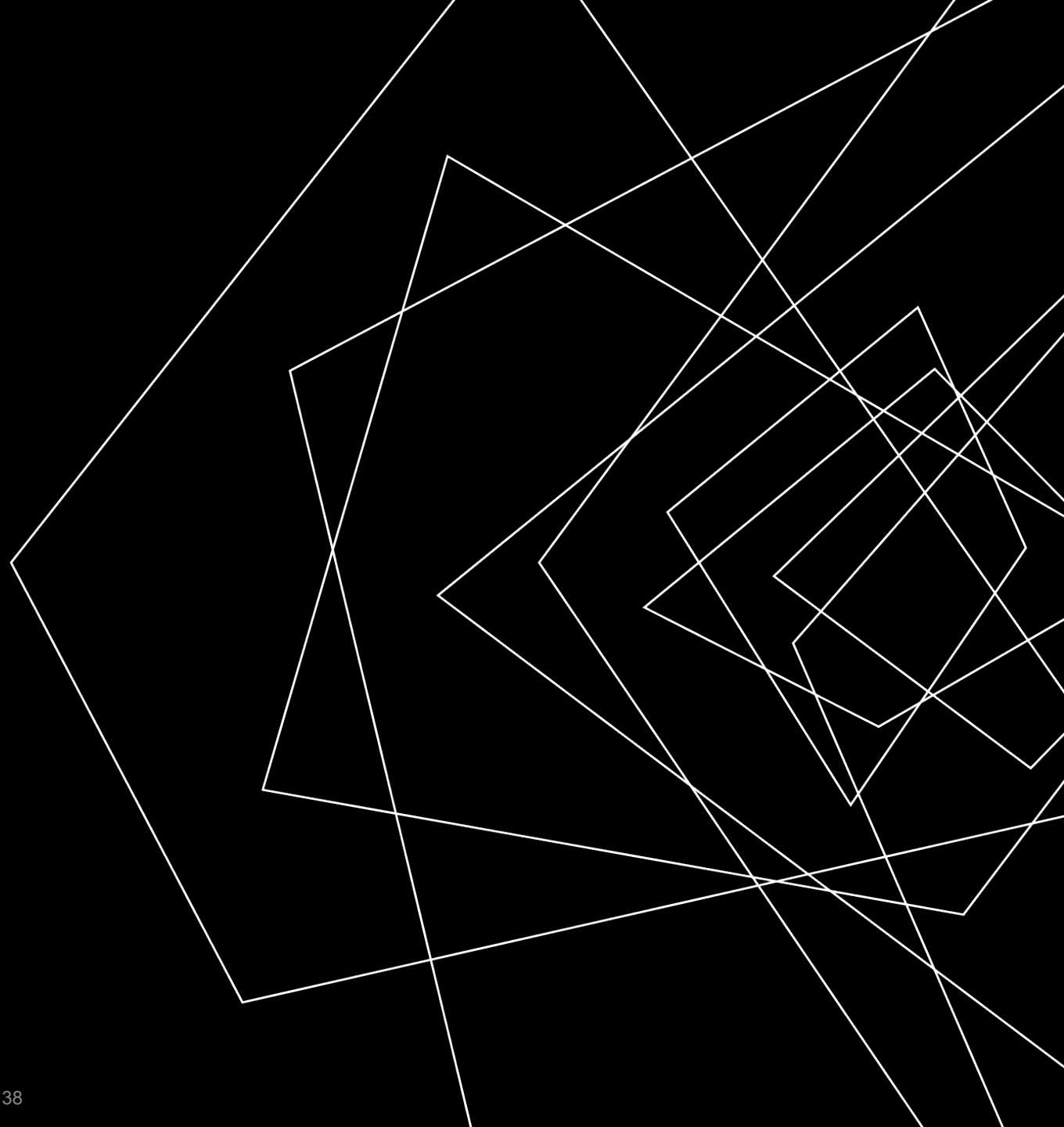
‘Freedom energy’

- A ‘fair share’ of global manufacturing: bring solar PV value chain back to Europe
- Fast and large-scale, but responsible deployment

https://www.politicalcartoons.com (2016!)

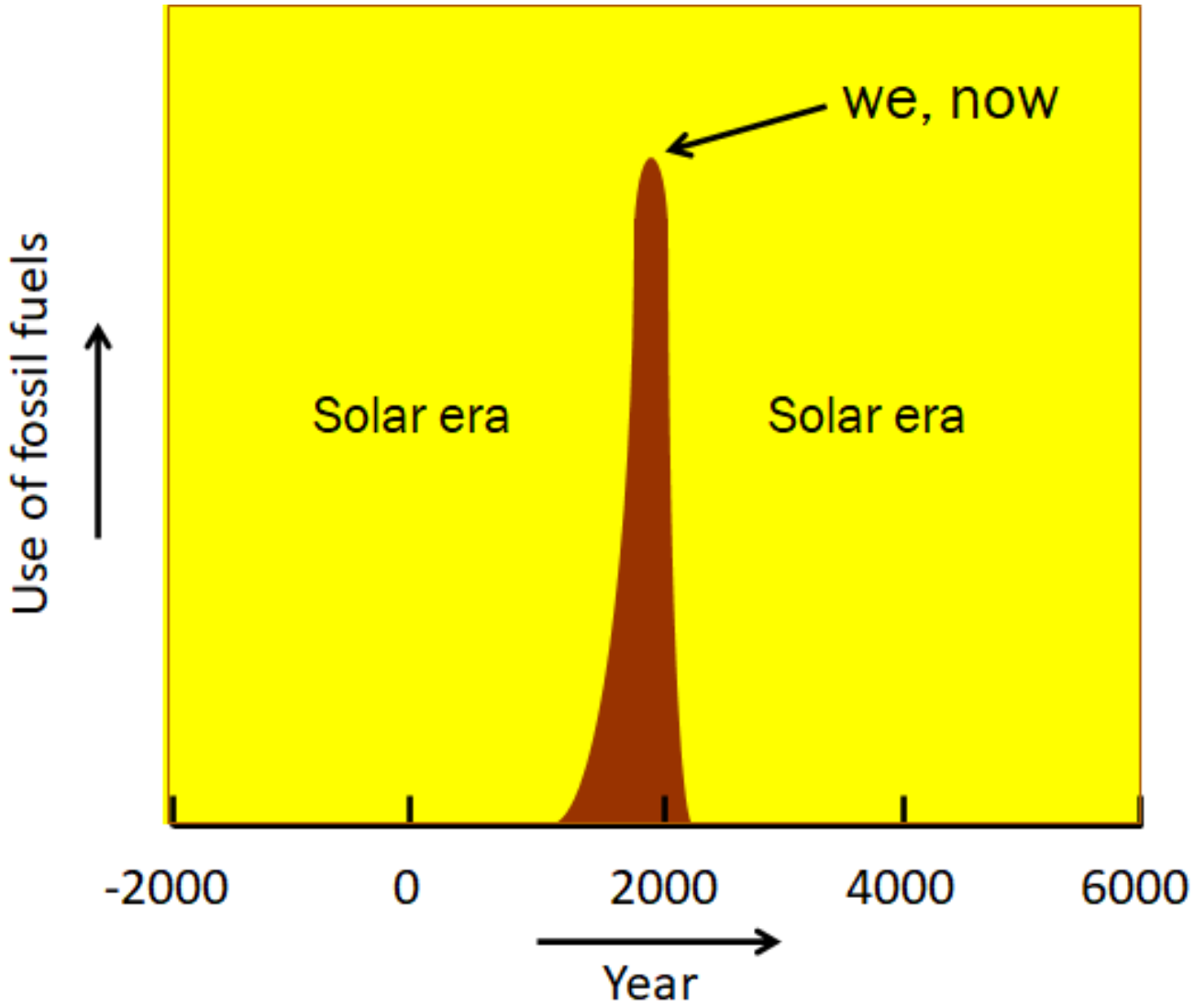
https://pressnetwork.de/erneuerbare-energie-ist-jetzt-freiheitsenergie/

Summary



From solar to solar

in all its (direct & indirect) forms

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