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Sustainable Development

Photovoltaics has paid its carbon debt

Trends in environmental footprint

Wilfried van Sark

(met dank aan Atse Louwen, Ruud Schropp, André Faaij)

NNV Energie&Klimaat, Utrecht, 9 June 2017

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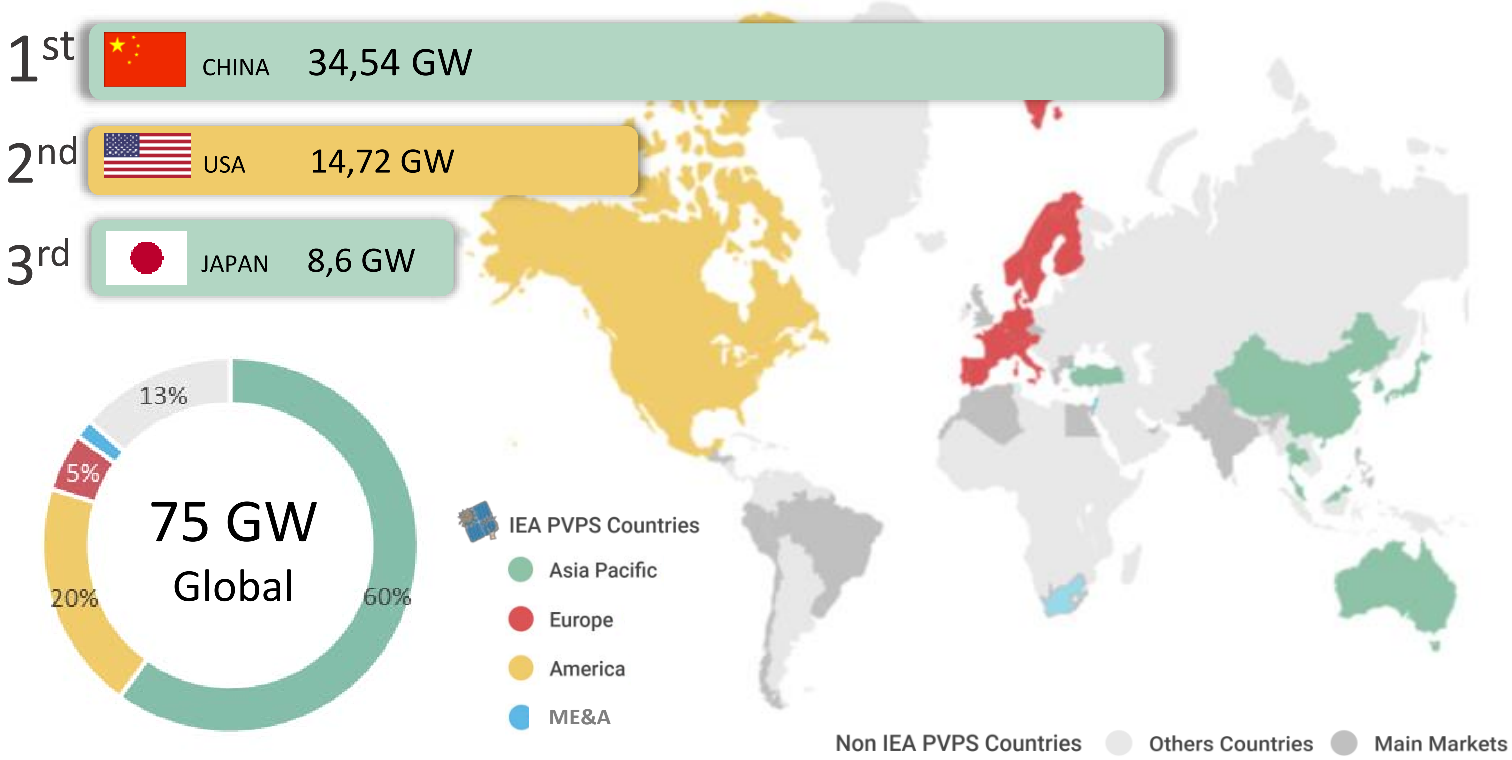
- Context
  - PV growth, consequences
  - Silicon PV process
  - Direct versus indirect GHG emissions
- Approach
  - Experience curve
- Results
- Geographical variation
- Concluding remarks

Status of photovoltaics

Global PV Market 2016

TOP PV MARKETS 2016



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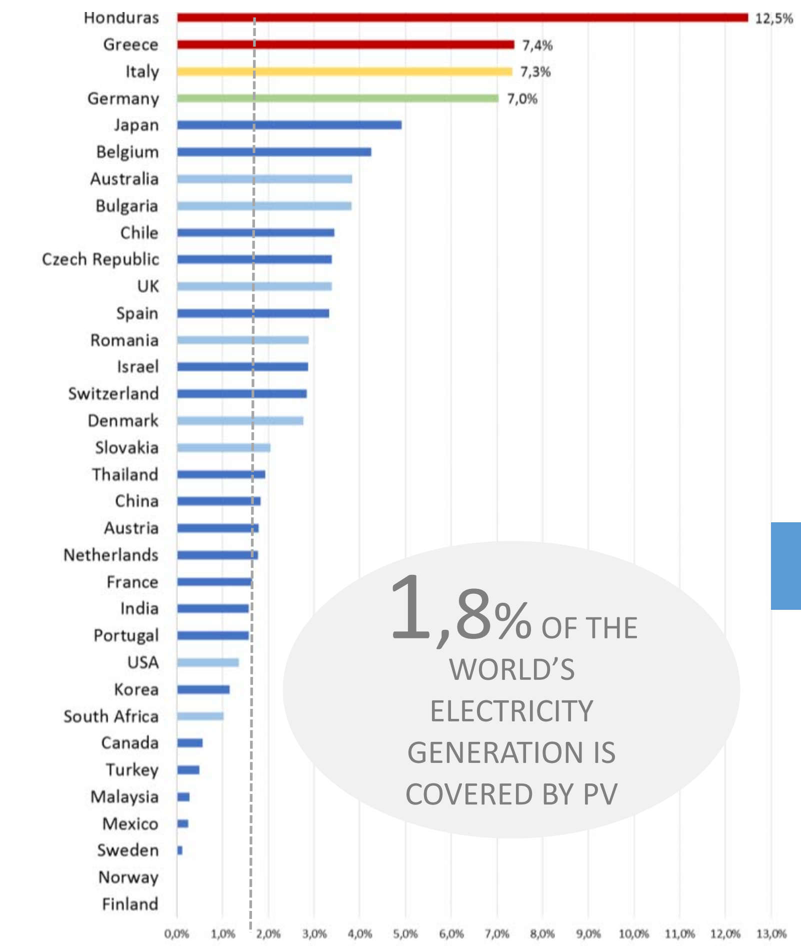
2016 THEORETICAL PV PRODUCTION



1,8% OF THE WORLD'S ELECTRICITY GENERATION IS COVERED BY PV

©Snapshot of Global PV Markets – IEA PVPS

303GW has been installed all over the world by the end of 2016

China is the world's 1st PV market

24 countries had at least 1GW of cumulative PV capacity at the end of 2016

16 countries installed at least 500MW each in 2016

SOLAR PV PER CAPITA 2016 Watt/capita

1st	GERMANY	511
2nd	JAPAN	336
3rd	ITALY	322

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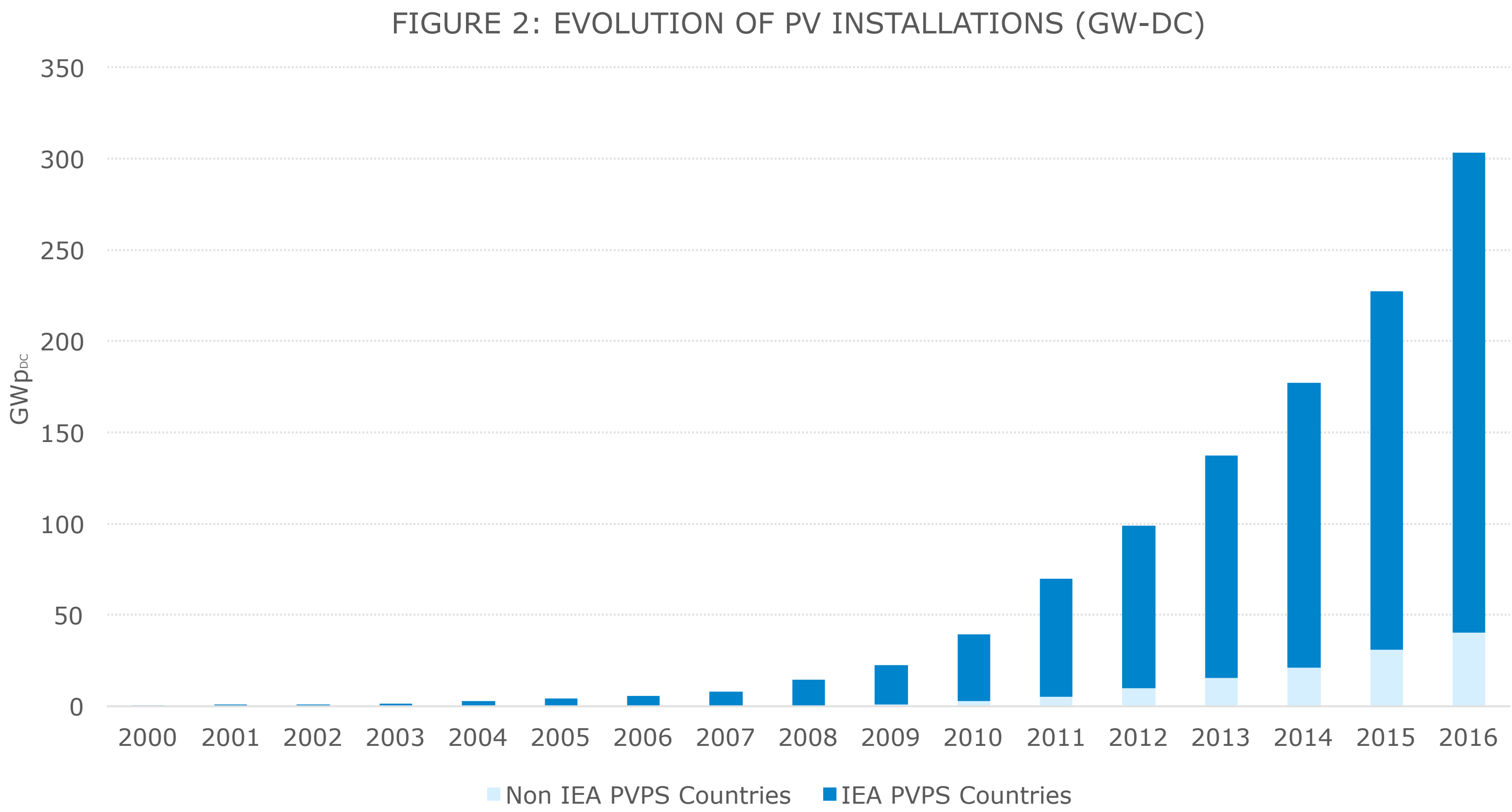
PV capacity growth: 303 GWp (end 2016)



Source: IEA-PVPS, 2017 - Snapshot of Global PV Markets

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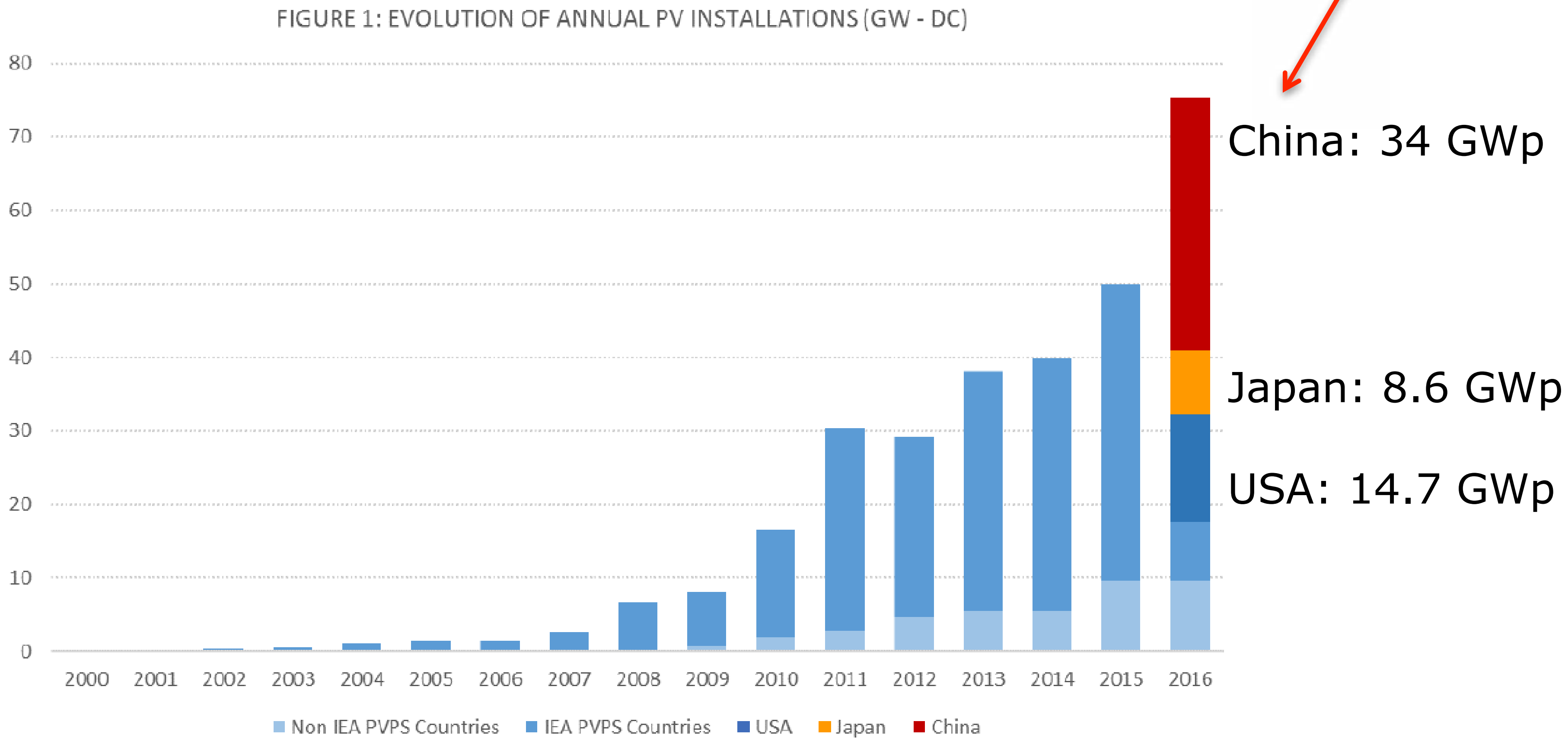
PV annual capacity growth increasing: China



Ger: 1.5 GWp

Source: IEA-PVPS, 2017 - Snapshot of Global PV Markets

Manufacturing of photovoltaics

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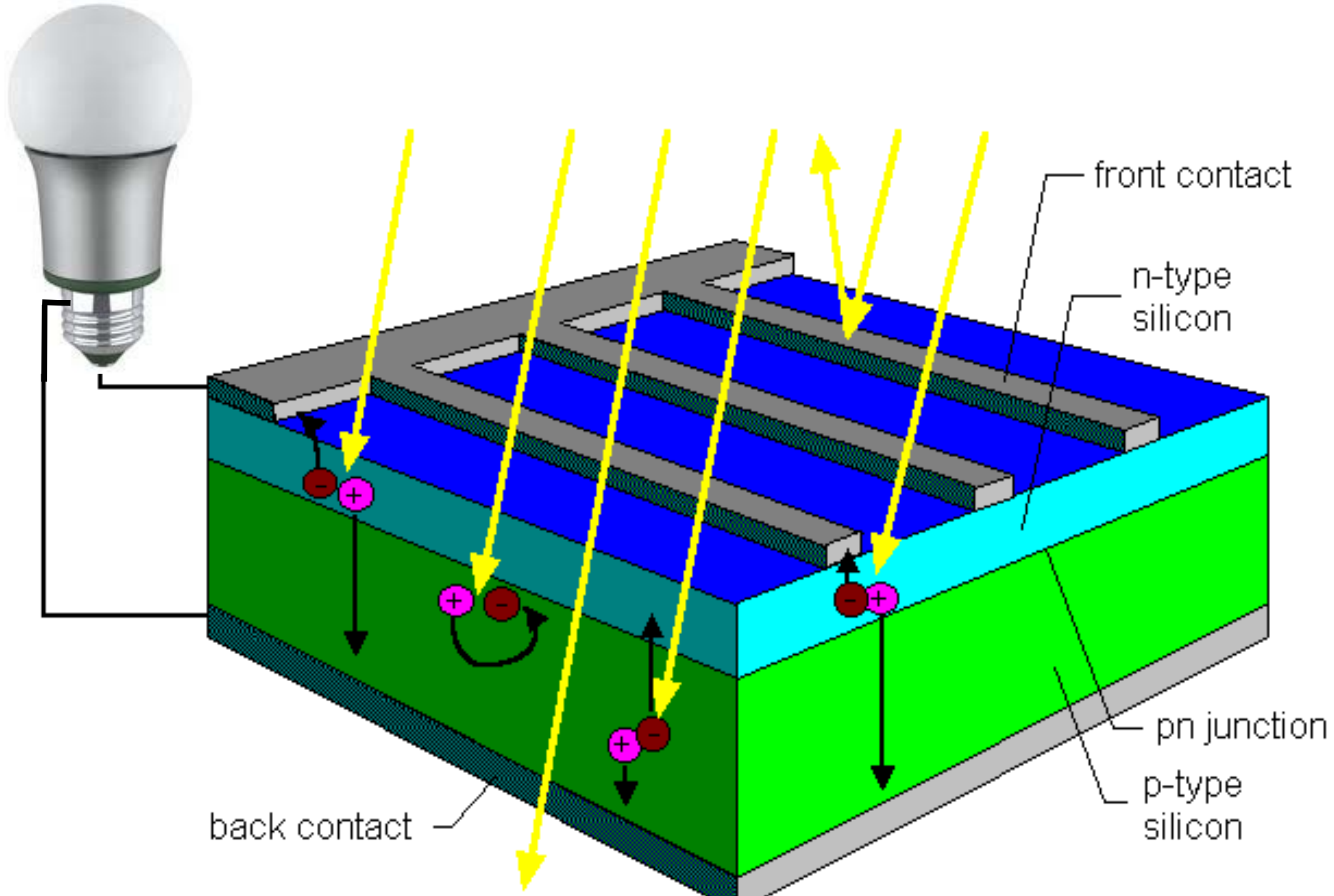
Solar cell design



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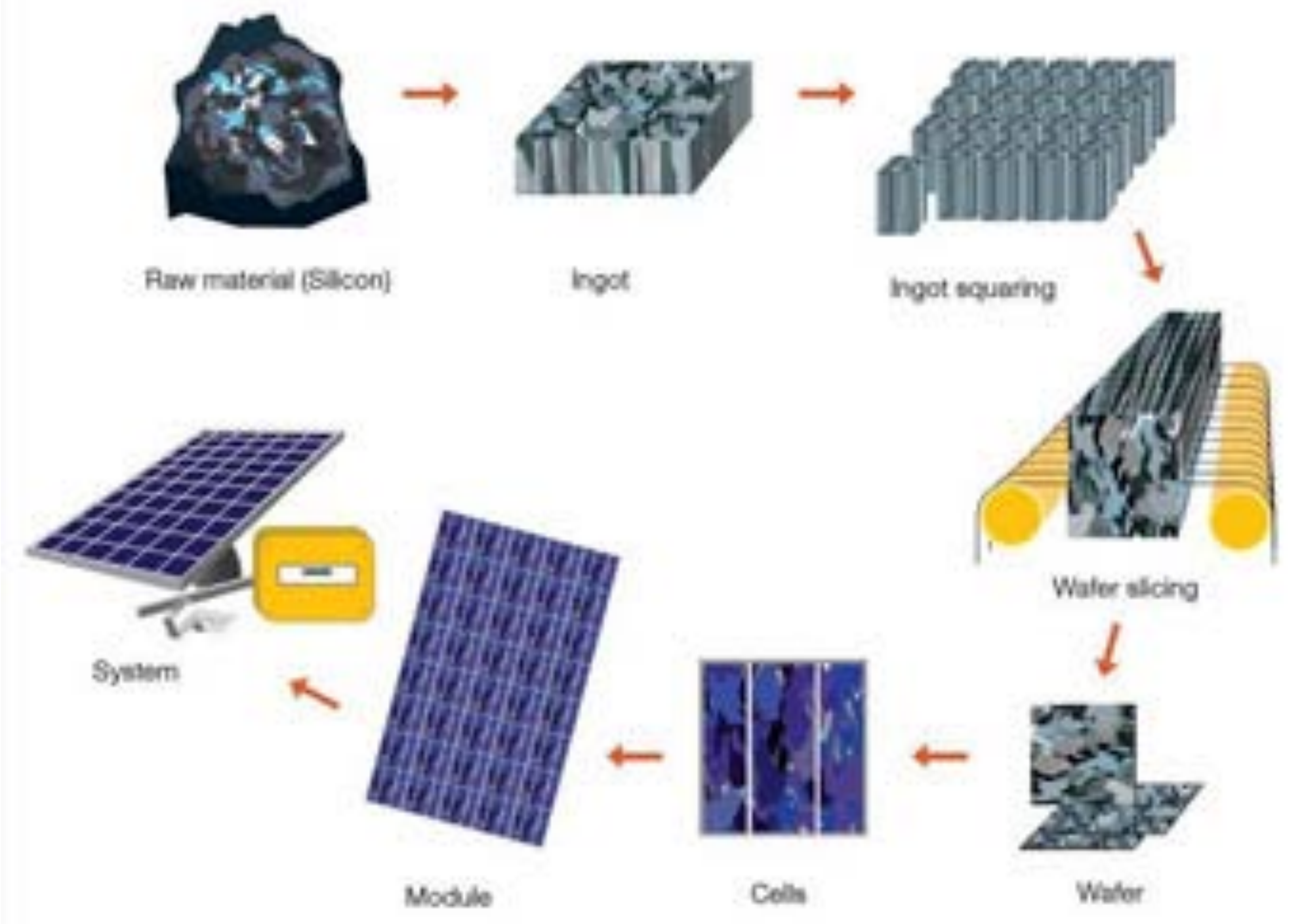
From silicon to panel



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Wafer to cell

Ref-cSi

- 180µm p-type mono wafer
- Saw damage & texturing
- Emitter diffusion
- Edge Isolation
- PSG etch
- AR coating
- Al Print rear
- Ag Print front
- Firing
- IV & Sort

16.7% cell

Silicon PV technology steps

Louwen, 2015

Build your own cell

https://factory.pvlighthouse.com.au/

GHG emissions: direct versus indirect

- Large fraction of emissions are **indirect**
  - Use of energy, which is generated in a non-renewable way: coal, gas
- **Direct** emissions (CO_2, CO_2-eq):
  - Production of silicon feedstock
    - $SiO_2 + C \rightarrow Si + CO_2$
  - Release of fluorinated process gases: HF_3, CF_4
  - Incineration of plastics during module recycling
    - EVA: $4(CH_2\text{-}CH_2\text{-}CH_2\text{-}CH\text{-}O\text{-}C\text{-}O\text{-}CH_2) + 29O_2 \rightarrow 24CO_2 + 18H_2O$

(Reich et al., PIP 2011)

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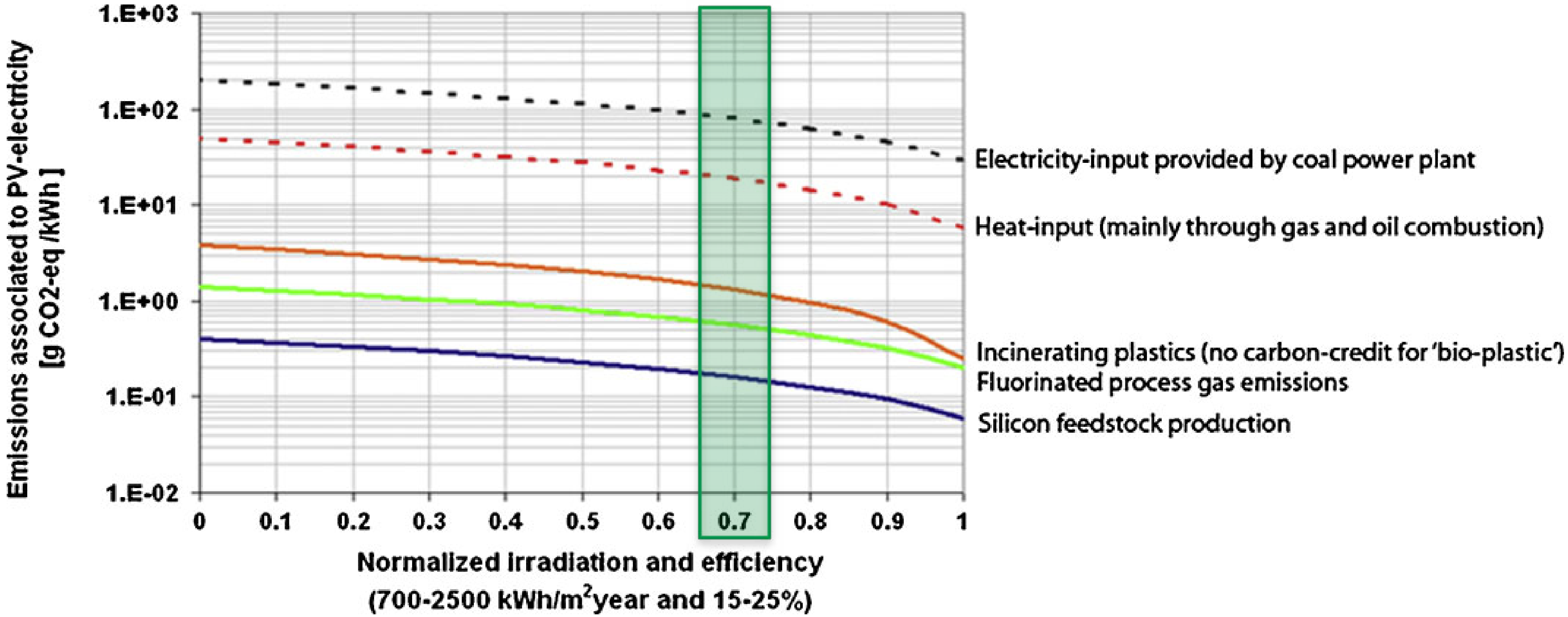
Direct versus indirect emissions



→Direct emissions ~1-2 gCO2-eq/kWh
factor ~20-40 lower than indirect emissions

(Reich et al., PIP 2011)

Concerns from fast growth

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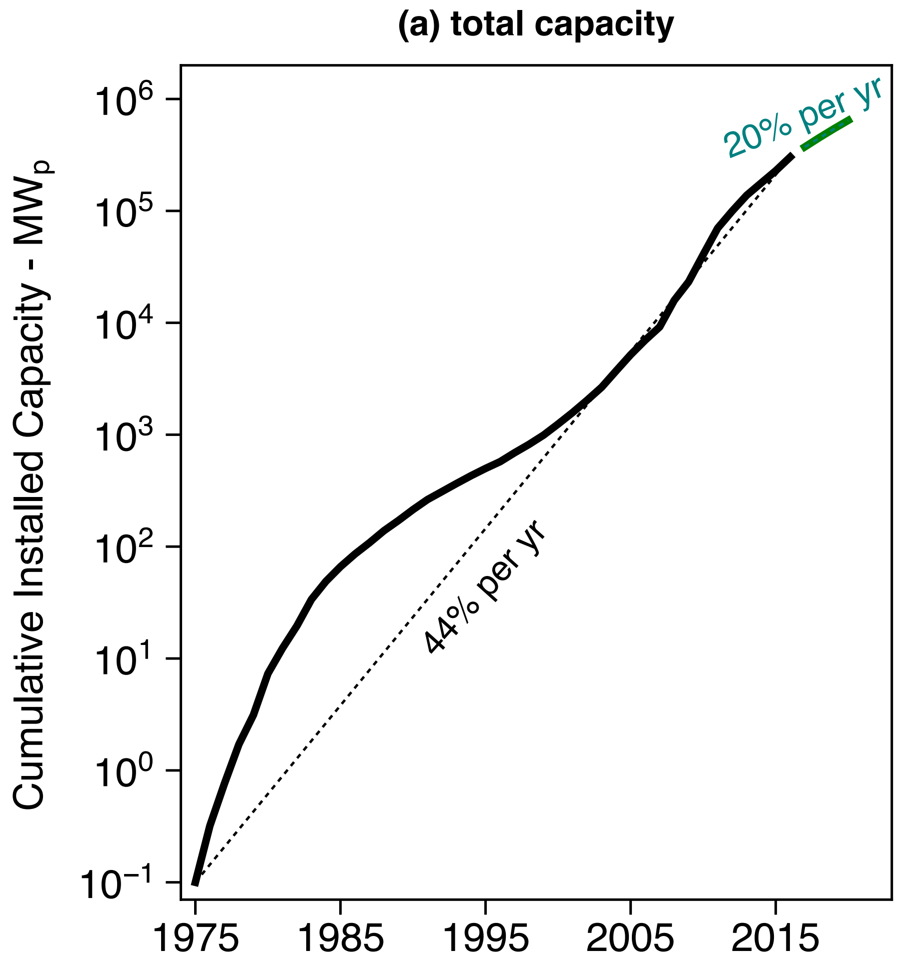
Context: strong growth of PV



(Louwen et al. 2016, updated)

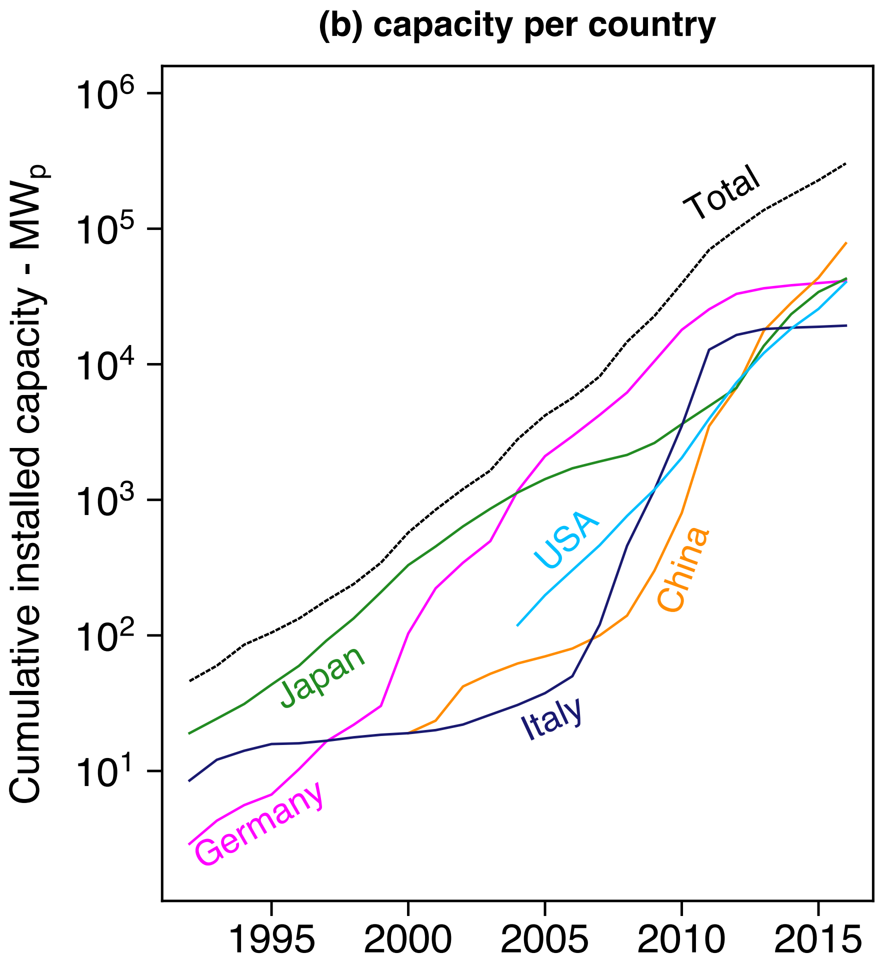
6 orders of magnitude in 40 years

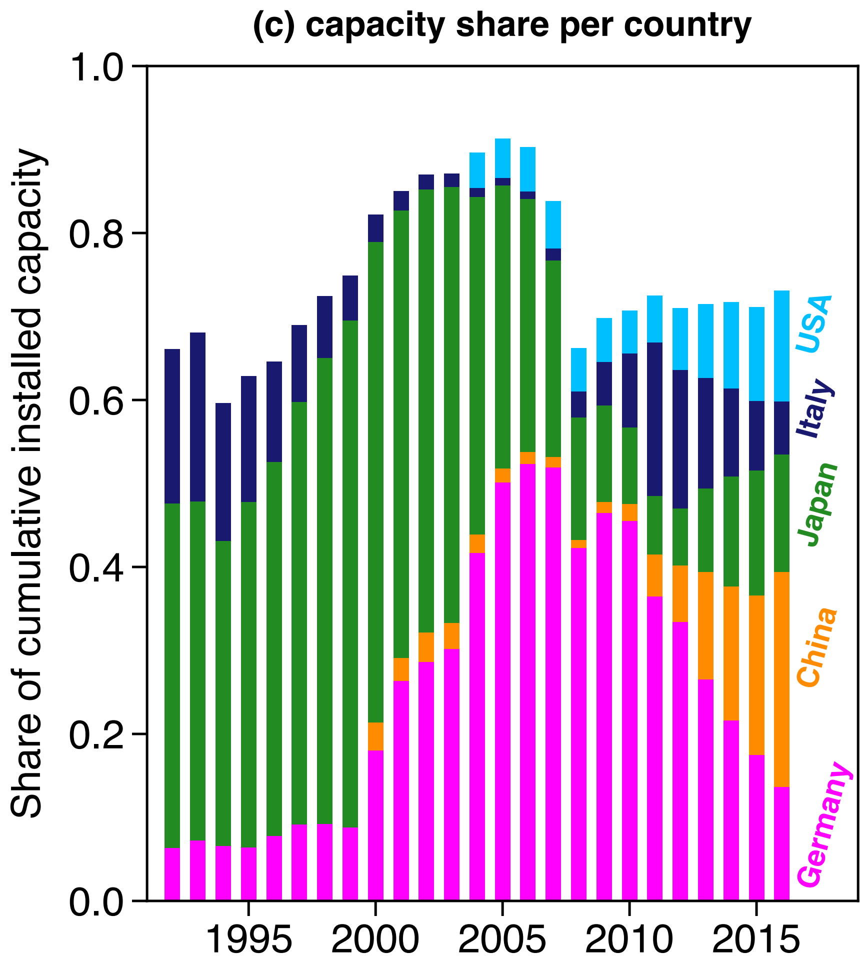
5 TWp in 2030, with 20% growth per year

(Haegel et al., Science, 2017

~30% global electricity

Context: sub-optimal location of PV





(Louwen et al. 2016, updated)

Context: concerns from fast growth

- As of 2013: for every Wp of PV capacity
  - 8-32 MJ of energy used*
  - 0.6-3 kgCO_2-eq released* → 20~80 gCO_2-eq/kWh
  - In the past this was (much) higher

- These external "costs" are paid back by generating "green" electricity
- This takes time: (energy) payback time (PBT)

- When "***PV growth" > 1/PBT***
  - PV industry is net energy user
  - PV industry is net GHG emitter

*M.J. de Wild-Scholten - doi:10.1016/j.solmat.2013.08.037

Aim

- Show historical development of environmental impact of PV production
- Analyse learning rates and compare to cost
- Determine **net contribution of PV** in terms of
  - Energy
  - GHG emission reduction

Approach

- Combine historical development of PV for
  - Installed capacity (e.g., IEA-PVPS, EPIA)
  - Energy demand and GHG from production (LCA studies)
- Establish **experience curve** $C_{cap} = C_0 \times cap^{\log_2(1-L)}$
- Every doubling of *cap*, cost *C* drops with factor *L*
- Normally done for cost
  - Here: energy and GHG
  - Least-squares fit to data

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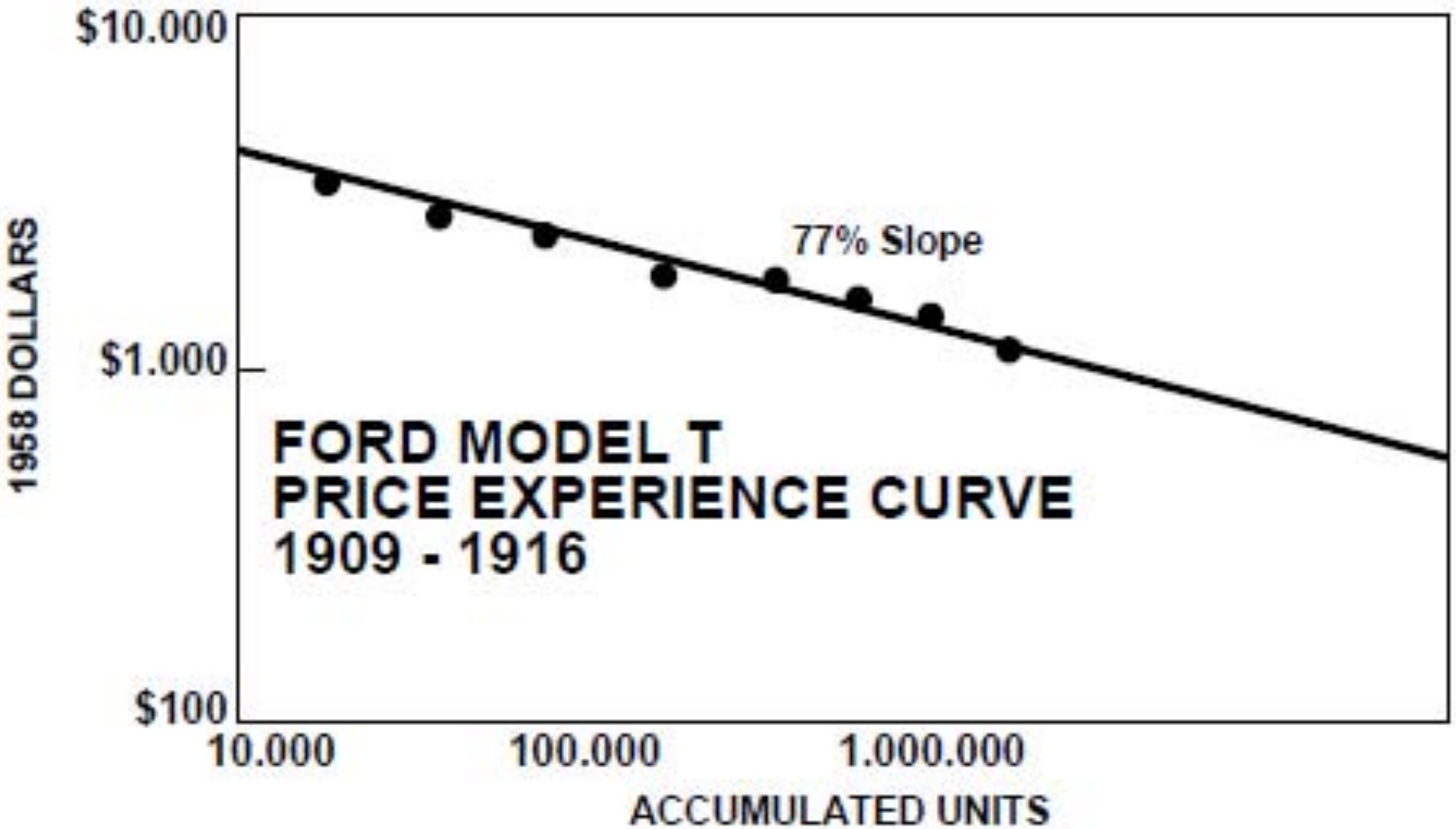
Wright (1936): aircraft production doubled, labour time decreased by 10-15 %

Experience curve: Ford model T

double-log plots

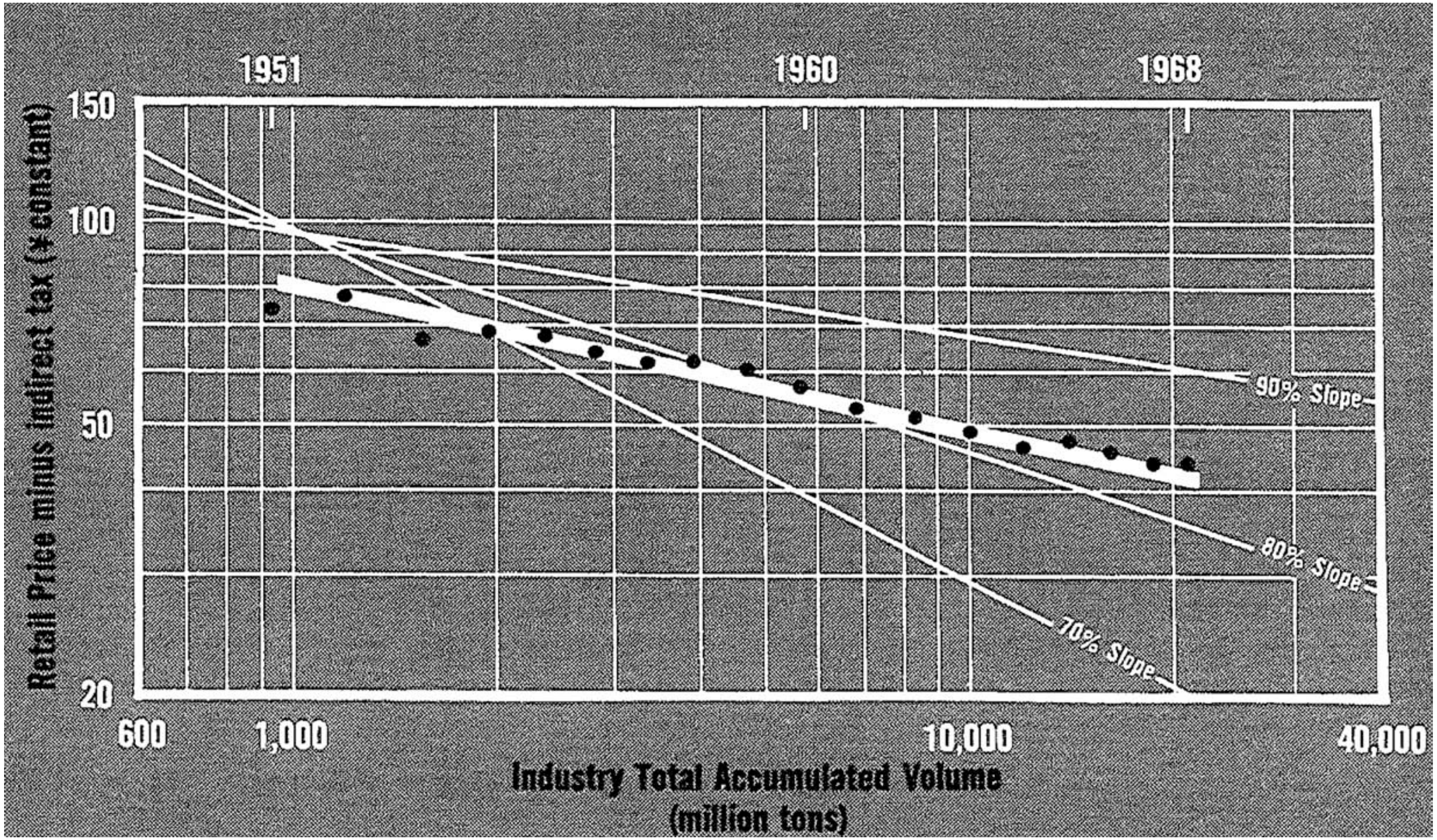


(Boston Consulting Group, 1970)

Wright (1936): aircraft production doubled, labour time decreased by 10-15 %

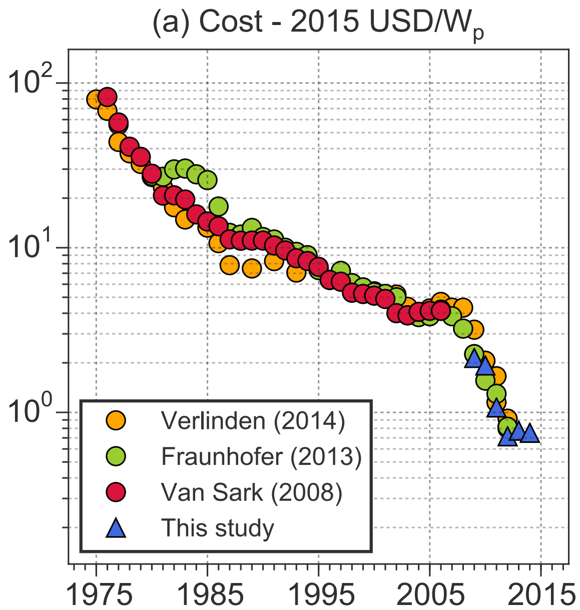
Experience curve: Japanese Beer

double-log plots



(Boston Consulting Group, 1970)

Trends: cost and environmental impact

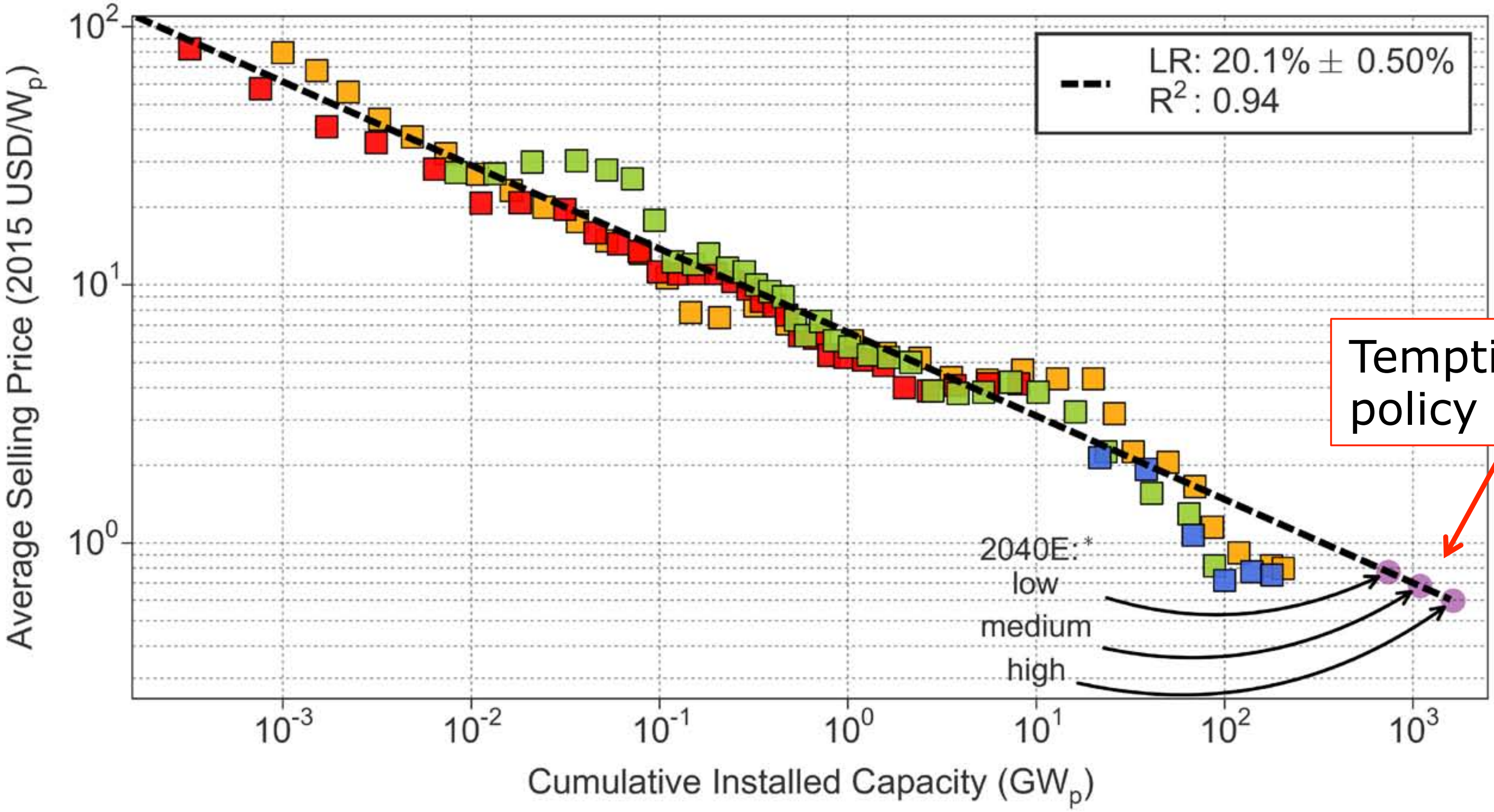


+ cost

+ cost

(Louwen et al. 2016)

Experience curve - cost



With every doubling of installed capacity cost drops with 20%

(Louwen et al. 2016)

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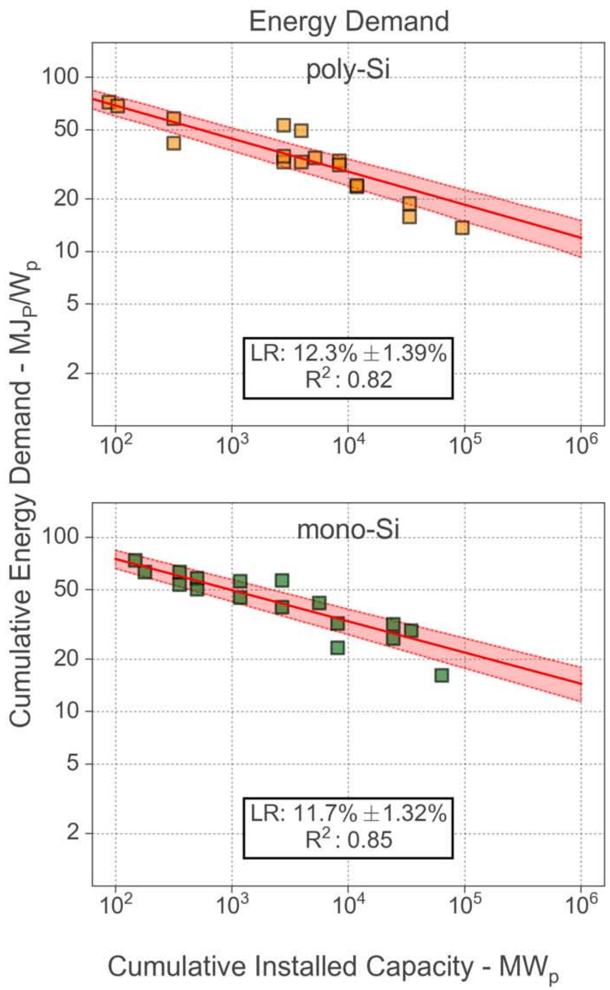
Experience curves – Environmental Impact



Net contributions of PV – Energy

$$E_{net} = \sum_{y=1975}^{n} \left[E_{produced}(y) - E_{consumed}(y) \right]$$

$$E_{produced}(y) = \sum_{L} cap(y,L) \times PR(y) \times insolation(y,L)$$

$$E_{consumed}(y) = \frac{CED(y)}{cap(y)} \times capgrowth(y)$$

from learning curve

Net contributions of PV – GHG emissions

$$GHG_{net} = \sum_{y=1975}^{n} \left[GHG_{avoided}(y) - GHG_{emitted}(y) \right]$$

$$GHG_{avoided}(y) = \sum_{L} cap(y,L) \times PR(y) \times insolation(y,L) \times GHG_{grid}(y)$$

$$GHG_{emitted}(y) = \frac{GHG(y)}{cap(y)} \times capgrowth(y)$$

from learning curve

Performance Ratio

- PR is **the** factor determining yield of PV systems
- Value is uncertain
- We need: accurate statistics of yield and capacity

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Performance ratio definition

$$Y_{final} = \frac{E_{final}}{P_0}$$

Specific yield

$$PR = \frac{Y_{final}}{Y_{ref}}$$

$$Y_{ref} = \frac{H_{final}}{G_{STC}}$$

Reference yield

PR < 100%

good performance PR = 85%

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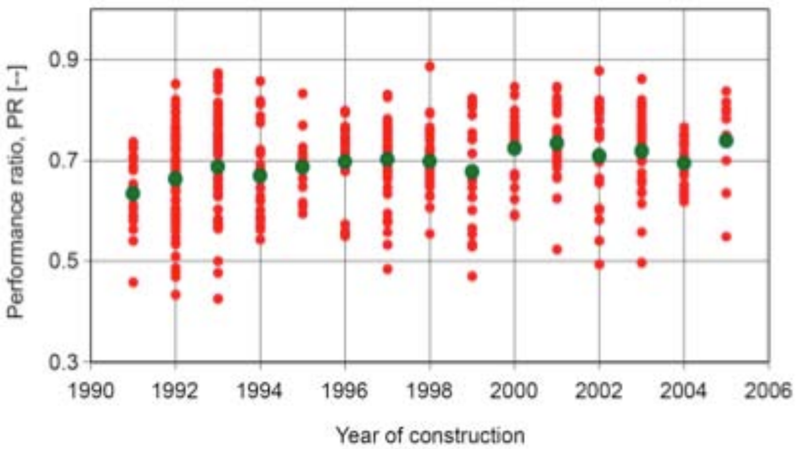
Performance ratio increases

IEA – PVPS Task 2

PR~70%

[Nordmann, 2007]

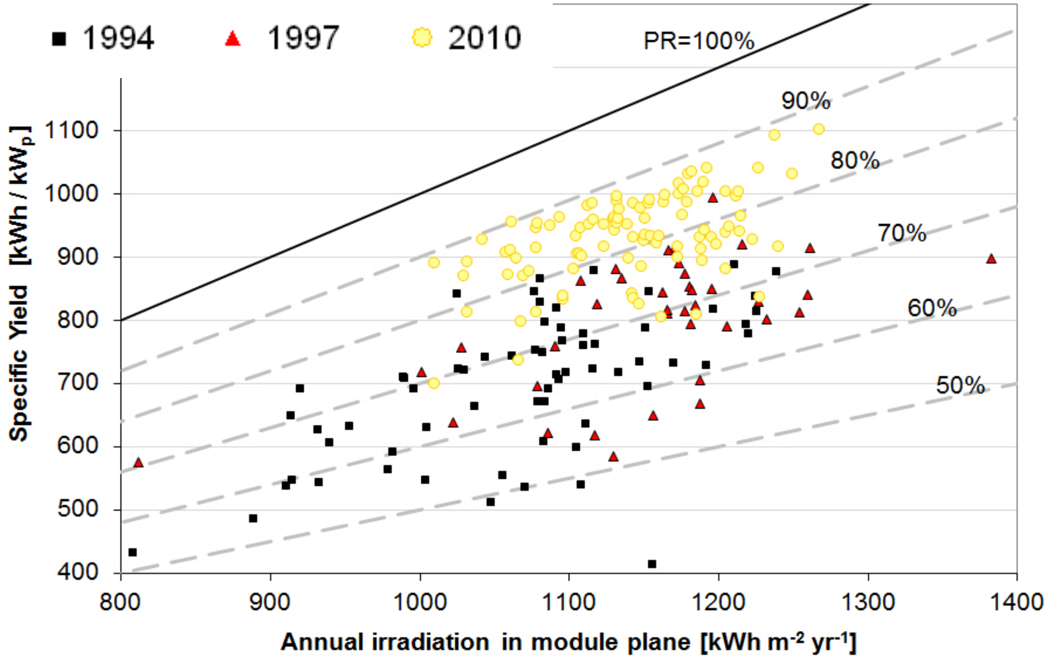


German systems:

PR from ~60% to >80%

[Reich, 2012]

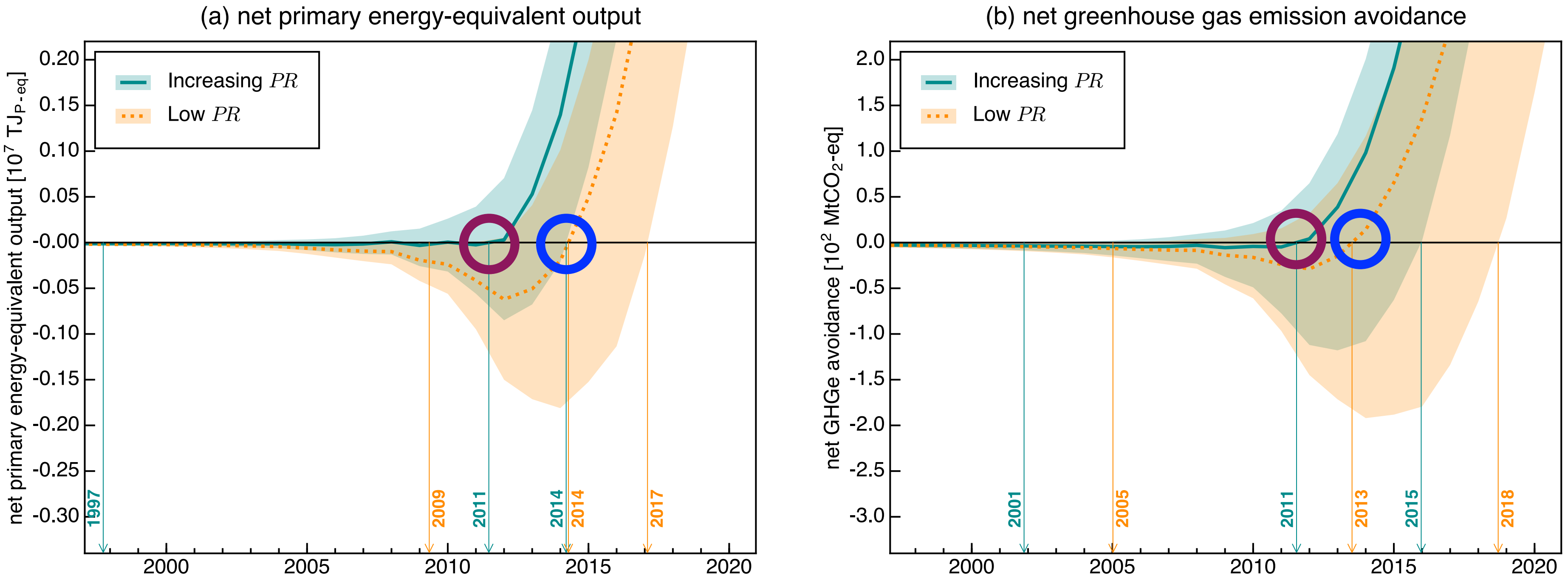
Is 90% the maximum?



Performance Ratio

- PR is **the** factor determining yield of PV systems
- Value is uncertain
- We need: accurate statistics of yield and capacity
- We have: (very) inaccurate estimations
- Therefore: two scenarios:
  - **Low PR** (worst case): 0.5 for all systems
  - **Increasing PR** (realistic): from 0.5 in 1975 to 0.8 from 2015 & onward

Results: breakeven energy and GHG



global

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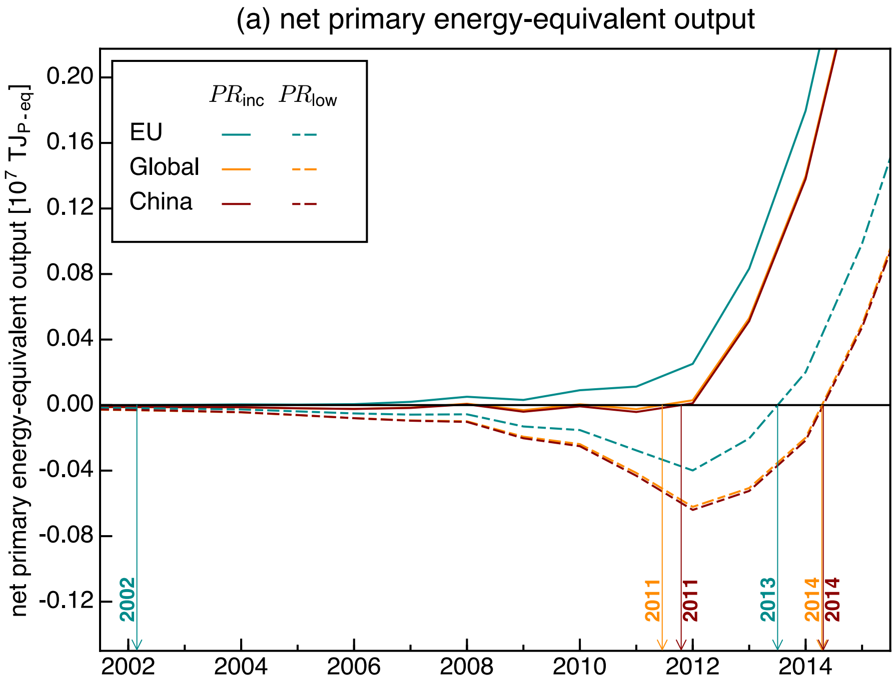
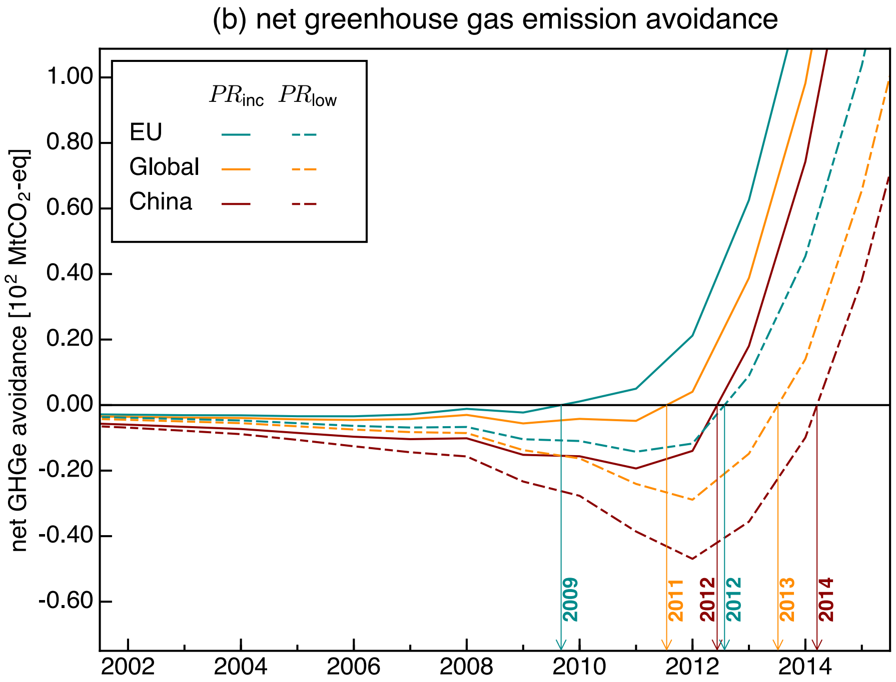
Results: breakeven energy and GHG regional differences in production





regional

Summary

- Clear downward trend of environmental impact of PV from 1975 to now

- Similar to cost, PV shows a learning effect for environmental impact

- We have likely achieved, or will do so soon, break even in terms of
  - Energy
  - GHG emissions

Great news!

nature COMMUNICATIONS

my birthday present

ARTICLE

Received 2 Feb 2016 | Accepted 28 Oct 2016 | Published 6 Dec 2016

DOI: 10.1038/ncomms13728 OPEN

Re-assessment of net energy production and greenhouse gas emissions avoidance after 40 years of photovoltaics development

Atse Louwen[1], Wilfried G.J.H.M. van Sark[1], André P.C. Faaij[2] & Ruud E.I. Schropp[3]

Since the 1970s, installed solar photovoltaic capacity has grown tremendously to 230 gigawatt worldwide in 2015, with a growth rate between 1975 and 2015 of 45%. This rapid growth has led to concerns regarding the energy consumption and greenhouse gas emissions of photovoltaics production. We present a review of 40 years of photovoltaics development, analysing the development of energy demand and greenhouse gas emissions associated with photovoltaics production. Here we show strong downward trends of environmental impact of photovoltaics production, following the experience curve law. For every doubling of installed photovoltaic capacity, energy use decreases by 13 and 12% and greenhouse gas footprints by 17 and 24%, for poly- and monocrystalline based photovoltaic systems, respectively. As a result, we show a break-even between the cumulative disadvantages and benefits of photovoltaics, for both energy use and greenhouse gas emissions, occurs between 1997 and 2018, depending on photovoltaic performance and model uncertainties.

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Utrecht, 06 December 2016

Comprehensive study reveals:

"Solar energy currently cheapest and cleanest alternative to fossil fuels"

The positive effect of solar energy as a sustainable energy source offsets the negative impact of the production of solar panels. This applies to energy consumption as well as greenhouse gas emissions during the production process, according to a comprehensive study by Atse Louwen and Wilfried van Sark from Utrecht University and colleagues from University of Groningen and Eindhoven University of Technology, the Netherlands. Their research results are published 6 December in the leading journal *Nature Communications*.

HOWEVER….

ENERGY

THE DAILY CALLER NEWS FOUNDATION

Solar Power Actually Made Global Warming Worse, Says New Study

ANDREW FOLLETT
Energy and Science Reporter

2:37 PM 12/07/2016

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Solar cells

How clean is solar power?

A new paper may have the answer

Print edition | Science and technology ›

Dec 10th 2016

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Solar panels less green than you think, say experts

THE TIMES

The solar industry has been "a temporary net emitter of greenhouse gas emissions", the study by Utrecht University concluded.

2020 the solar panel on your home may take only six months to pay back its energy debt, the report says
PHILIPPE HUGUEN/GETTY IMAGES

More than a billion solar panels have been installed around the world but they may so far have failed to reduce overall emissions, a study has found.

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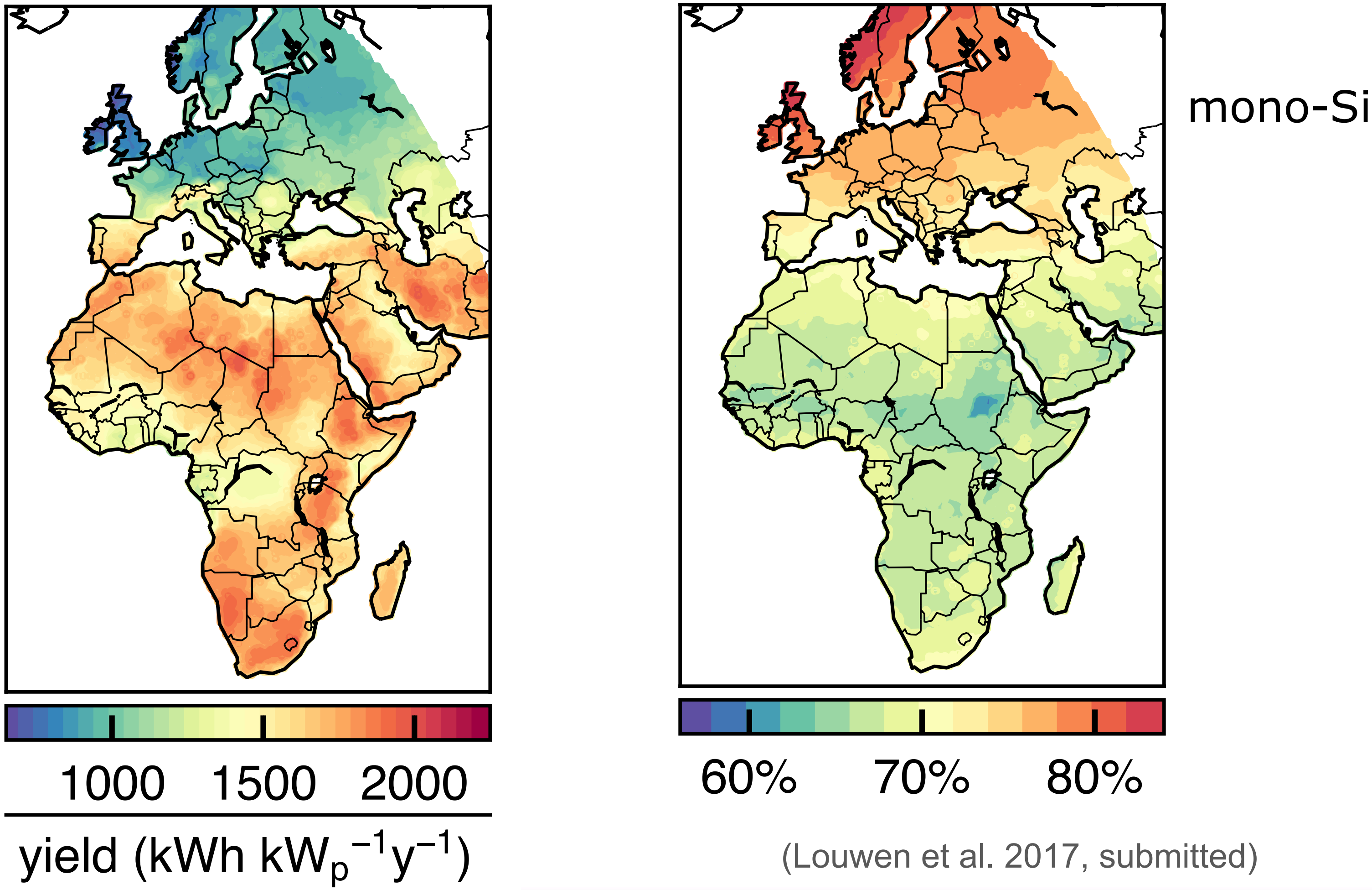
Geographical variation:

specific yield performance ratio



(Louwen et al. 2017, submitted)

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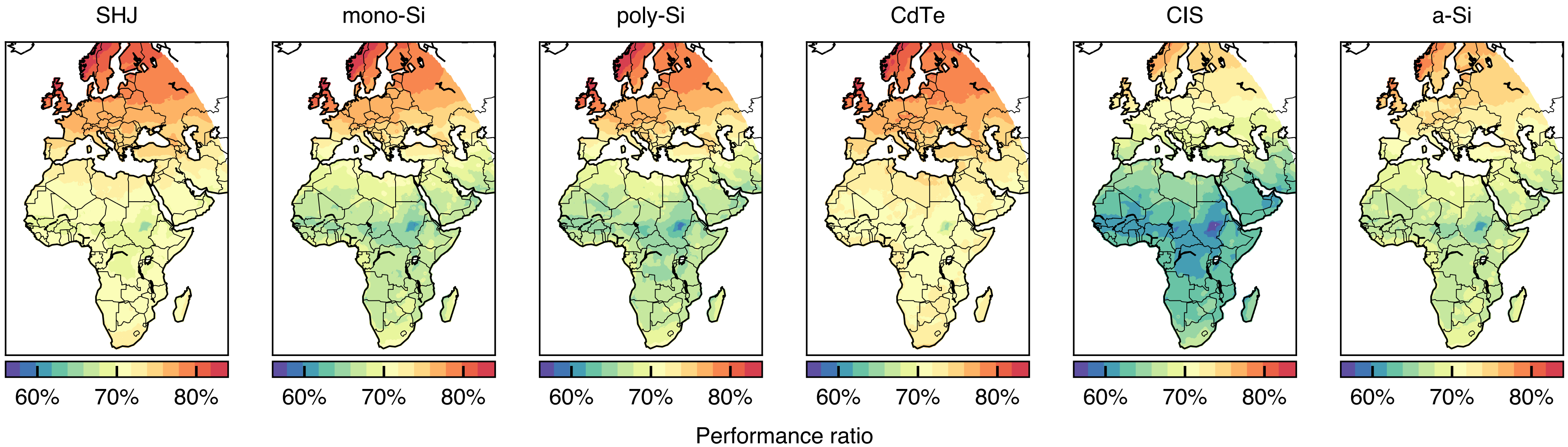
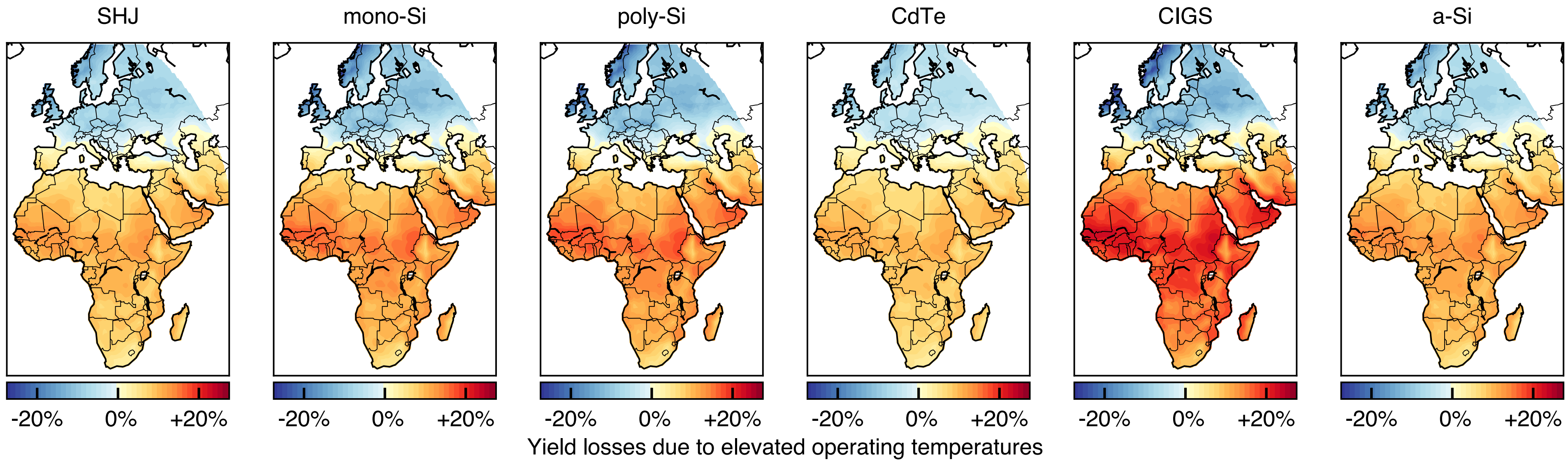
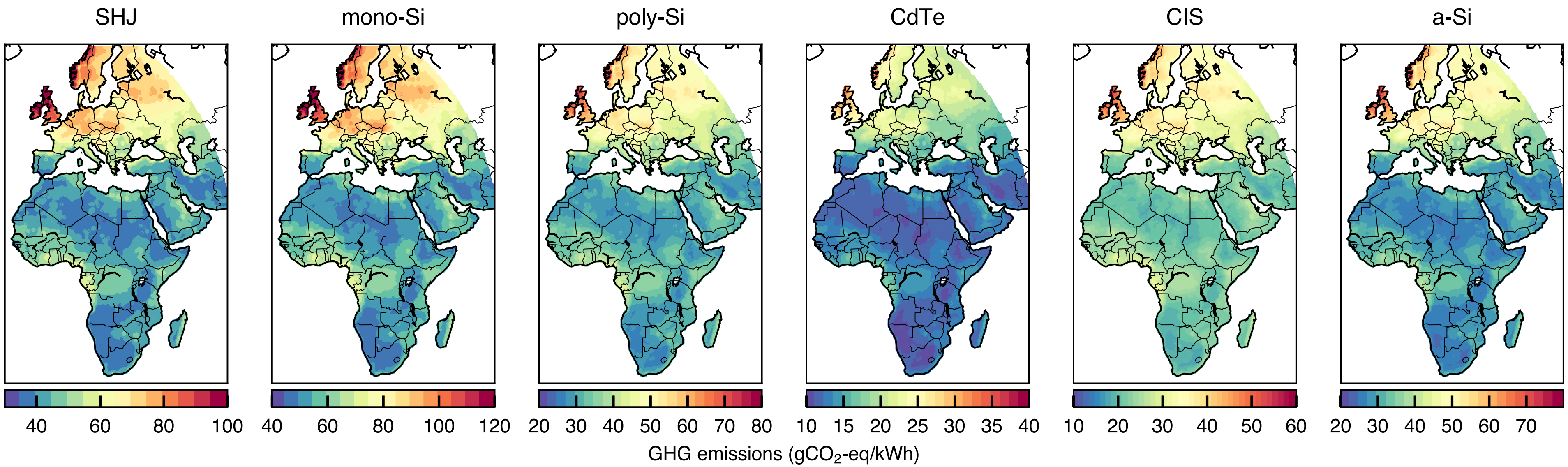
Geographical variation: performance ratio



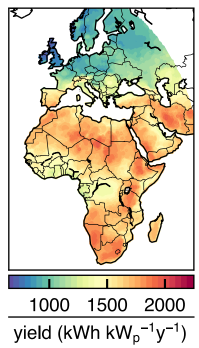
Geographical variation: temperature loss



Geographical variation: GHG emissions



Related to yield



(Louwen et al. 2017, submitted)

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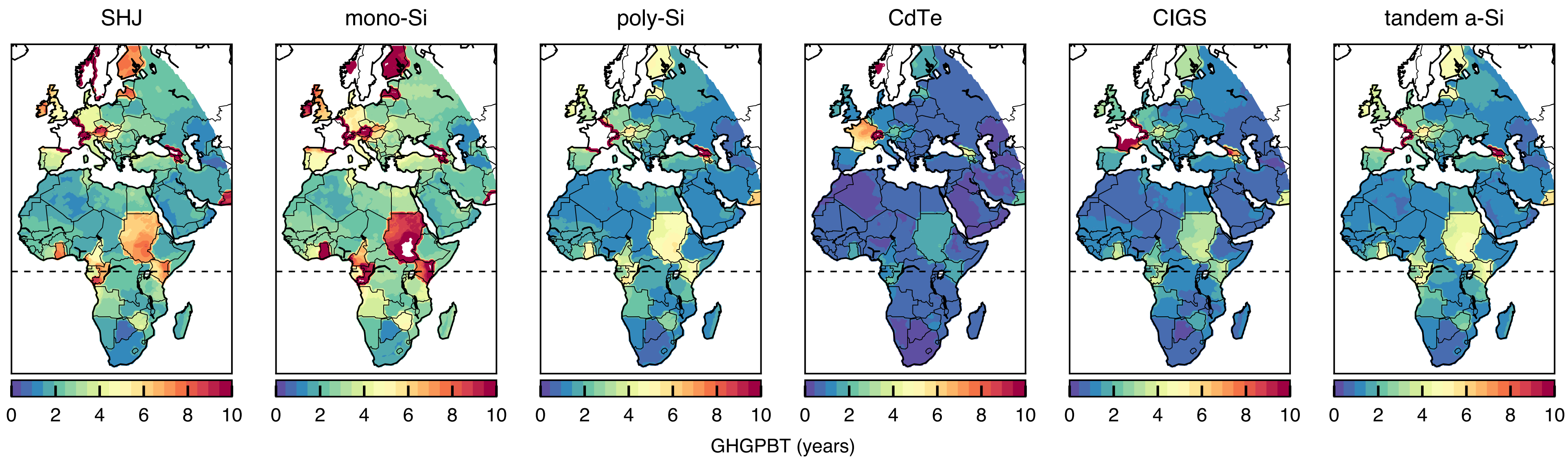
Geographical variation: GHG payback time

GHG payback time:
number of years in which the GHG emissions released during the full PV lifecycle are paid back by replacing electricity produced in the average grid (national GHG emission factor differences)



(Louwen et al. 2017, submitted)

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Concluding remarks

- Environmental impact of PV is stea[illegible]creasing, showing learning effect
- We have likely achieved [illegible]n) break even in terms of energy and GHG [illegible]ons
- GHG emission[illegible]nd on PV cell type and location, just as GH[illegible]back time
- Imp[illegible] of direct vs. indirect emissions
- [illegible] green" energy for producing PV

PV has paid its carbon debt, and will continue to do so

1982: Solarex, solar breeder

Thank you for your attention

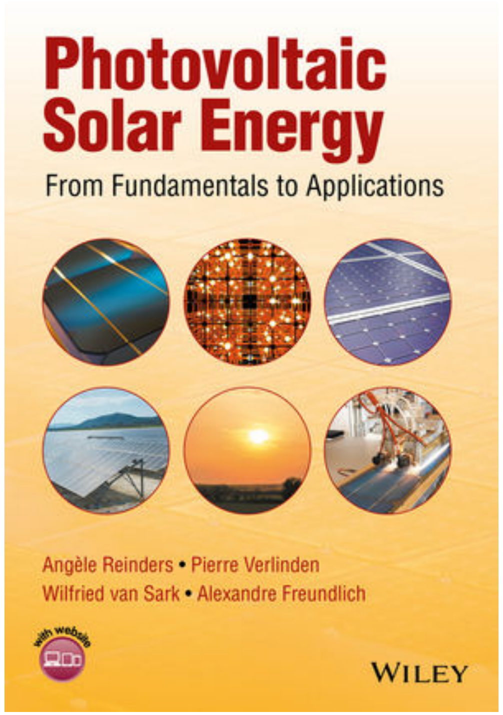
PV Group - Section Energy & Resources

Copernicus Institute of Sustainable Development, Utrecht University

Atse Louwen, Boudewijn Elsinga, Arjen de Waal, Bhavya Kausika,
Mart van der Kam, Panos Moraitis, Odysseas Tsafarakis,
Kostas Sinapis, Geert Litjens, Wouter Schram, Marte Gerritsma,
Sara Golroodbari, Wilfried van Sark

Utrecht Photovoltaic Outdoor Test facility

www.upot.nl



Out now!