ECN

Energy research Centre of the Netherlands

Global PV research

preparing for impact

Wim Sinke

ECN Solar Energy, Utrecht University & European PV Technology Platform

www.ecn.nl

Contents

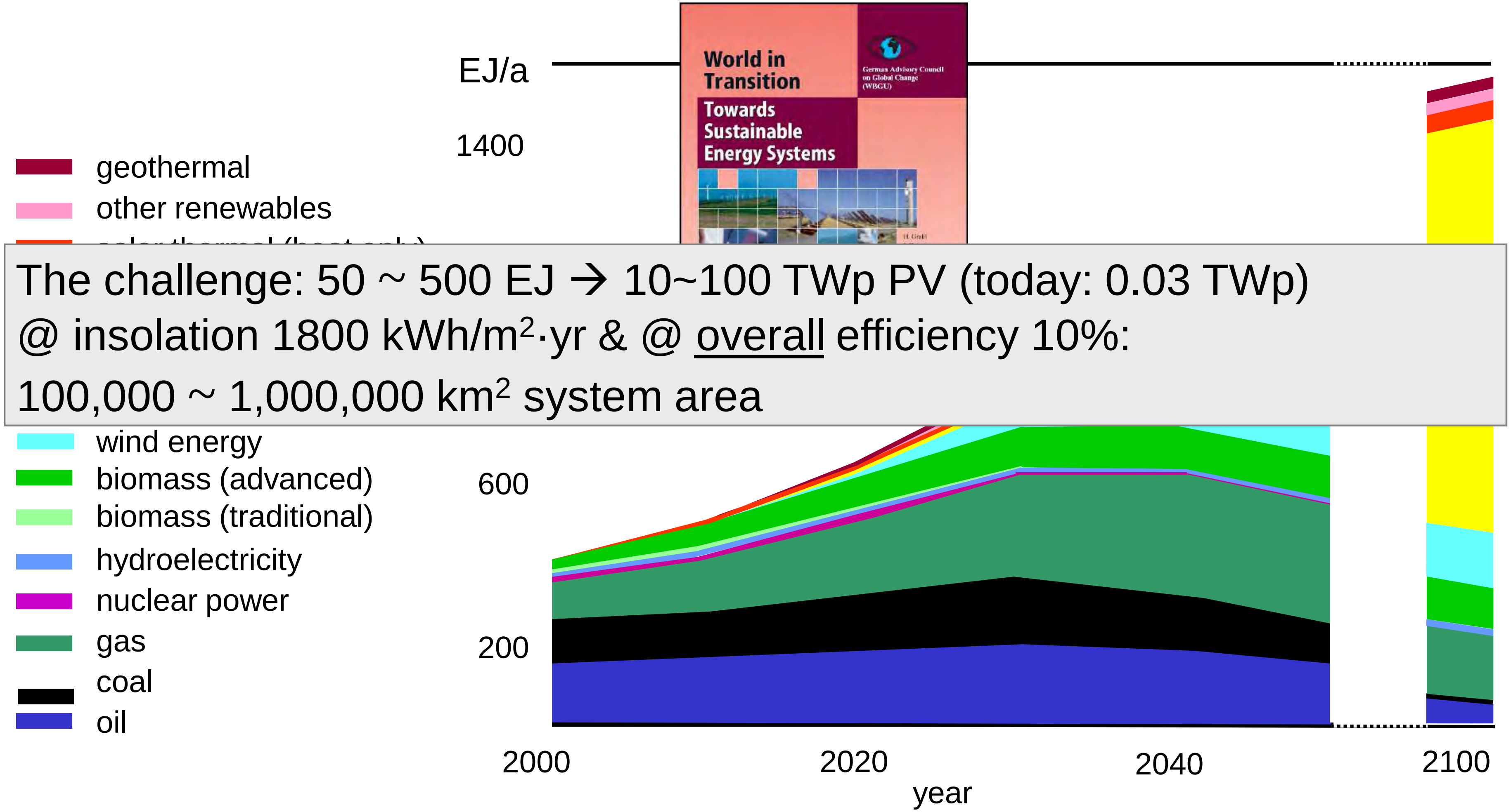
- **What is (needed for) very large-scale application of PV?**
  - The challenge quantified
- **Where are we?**
  - State of the art in technology and market
- **Visions, scenarios and roadmaps**
  - Technology and implementation targets
  - About modules & systems, cost & price, kWp & kWh
- **Approaches**
  - The technology portfolio and corresponding R&D areas
  - Environmental and societal issues
- **Outlook**

Contents

- **What is (needed for) very large-scale application of PV?**
  - The challenge quantified
- **Where are we?**
  - State of the art in technology and market
- **Visions, scenarios and roadmaps**
  - Technology and implementation targets
  - About modules & systems, cost & price, kWp & kWh
- **Approaches**
  - The technology portfolio and corresponding R&D areas
  - Environmental and societal issues
- **Outlook**

ECN

Solar energy: the challenge quantified



The challenge: 50 ~ 500 EJ → 10~100 TWp PV (today: 0.03 TWp)
@ insolation 1800 kWh/m²·yr & @ overall efficiency 10%:
100,000 ~ 1,000,000 km² system area

Source: German Advisory Council on Global Change, 2003, www.wbgu.de (example scenario)

Typical specific requirements for TW scale use

- **Electricity generation costs <<0.10 €/kWh**

- **→ turn-key system price <1 €/Wp (now >2.5 €/Wp)**
  - low-cost modules at high efficiency (typically 20~30+%)
  - or: very low-cost modules at moderate efficiency (typically 10~15%)
  - *and*: low-cost Balance-of-System (components + labor)

- **Use of non-toxic, abundantly available materials and closed cycles**

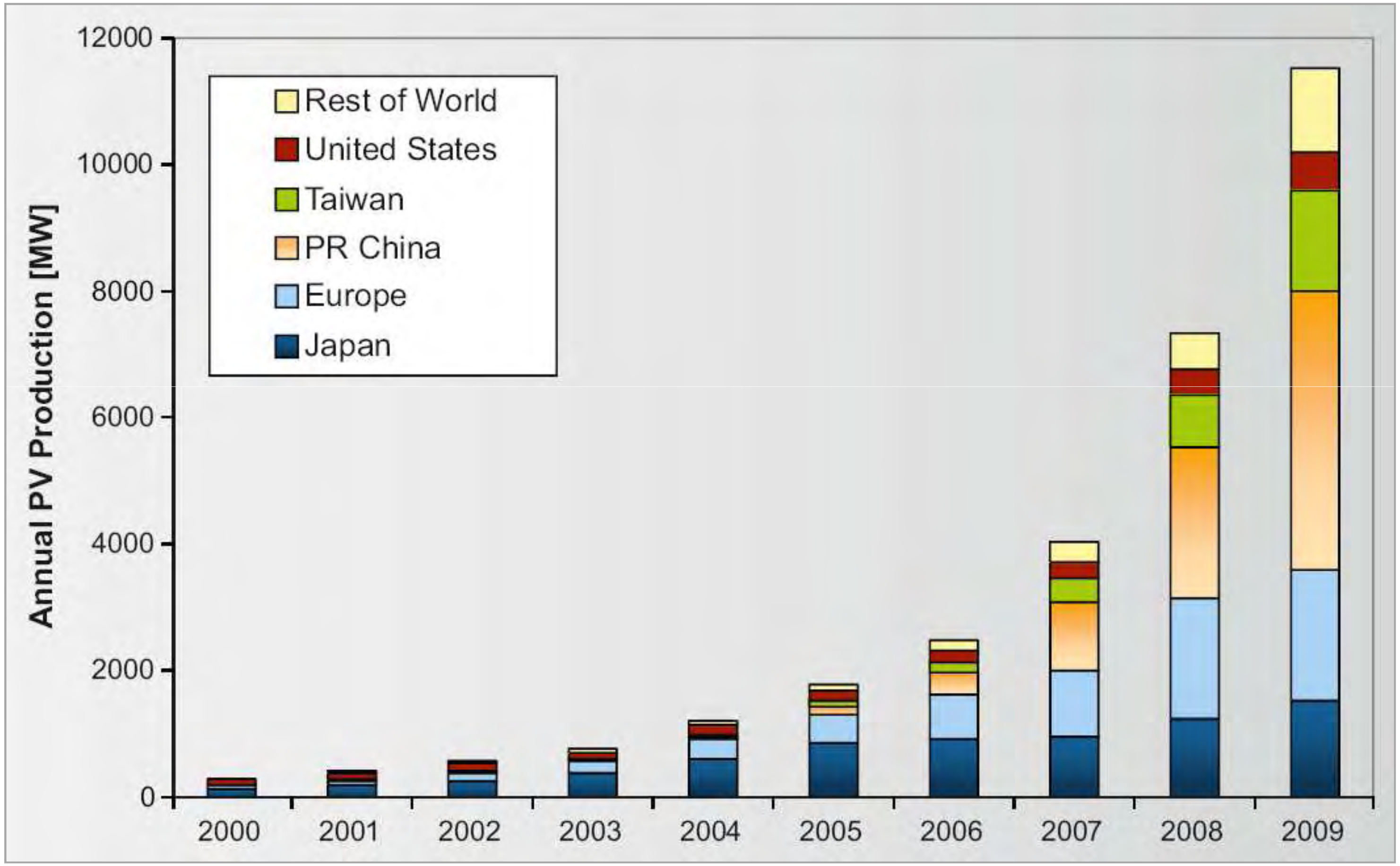
- **20 ~ 40+ years lifetime**

- **But:**
  - also need *transition* technologies, to develop the market and to demonstrate scientific/technical and economic potential

Contents

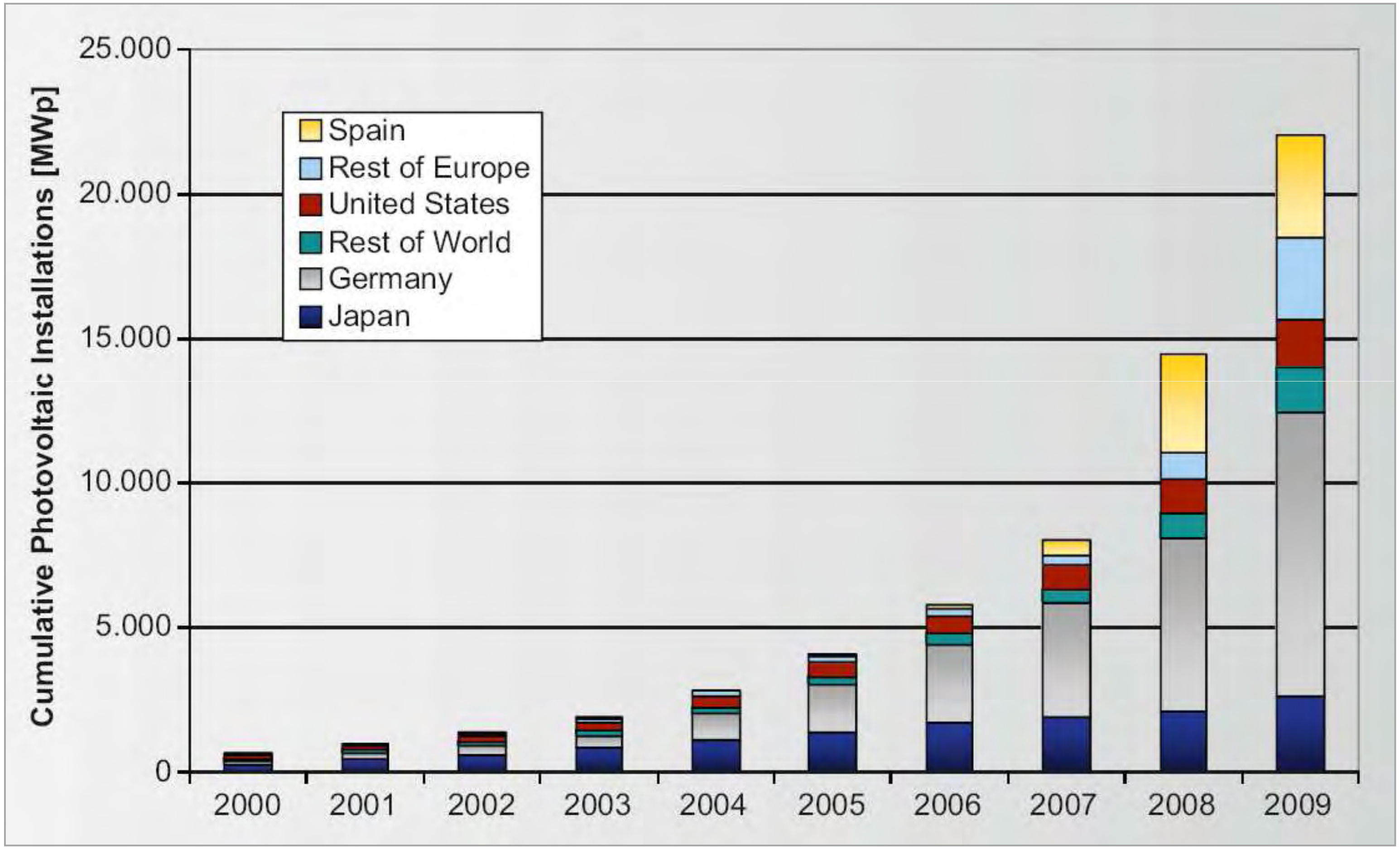
- What is (needed for) very large-scale application of PV?
  - The challenge quantified
- **Where are we?**
  - State of the art in technology and market
- Visions, scenarios and roadmaps
  - Technology and implementation targets
  - About modules & systems, cost & price, kWp & kWh
- Approaches
  - The technology portfolio and corresponding R&D areas
  - Environmental and societal issues
- Outlook

World annual solar cell and module production



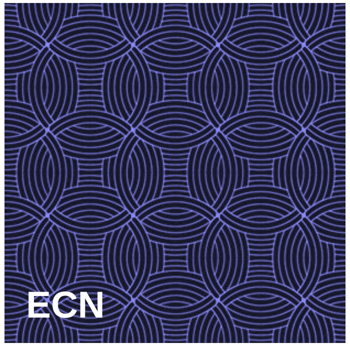
Source: PV Status Report 2010

World cumulative systems installations



Source: PV Status Report 2010

Cell & module technologies (“flat plate”)

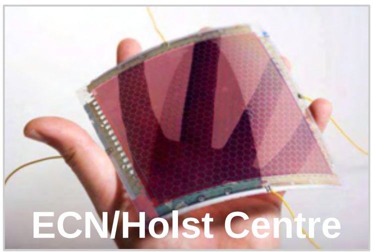


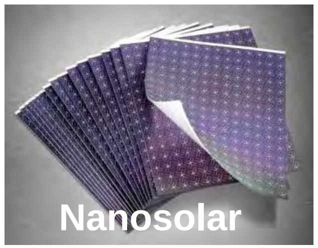
<u>Commercial:</u> wafer-based crystalline silicon
- monocrystalline (cut)
- multicrystalline (cut)
- ribbons

(2009: 82% of global market)

<u>Commercial:</u> thin films
- silicon
- copper-indium/gallium-diselenide (CIGS)
- cadmium telluride (CdTe)

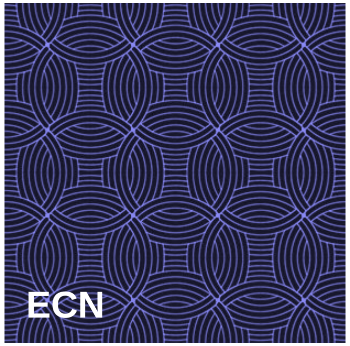
(2009: 18% of global market)





<u>Pilot production and laboratory:</u>
emerging and novel technologies
- super-low-cost concepts
  (printed organic & inorganic, etc.)
- super-high-efficiency concepts
  (many approaches for full spectrum utilisation)

Cell & module technologies ("flat plate")

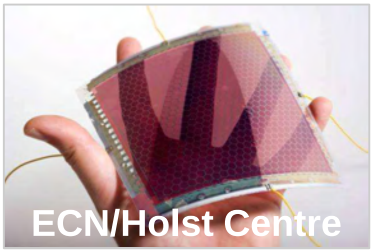


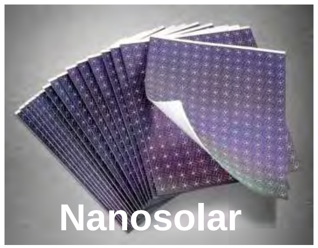
<u>Commercial:</u> wafer-based crystalline silicon

module efficiencies 13 ~ 19%

<u>Commercial:</u> thin films

module efficiencies 6 ~ 12%



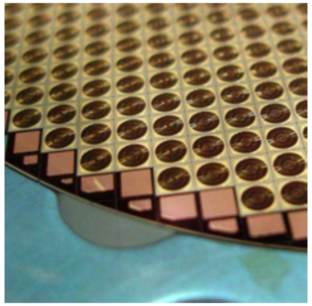


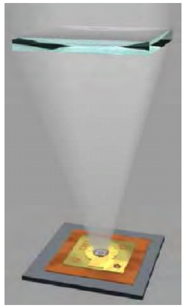
<u>Pilot production and laboratory:</u>
emerging and novel technologies

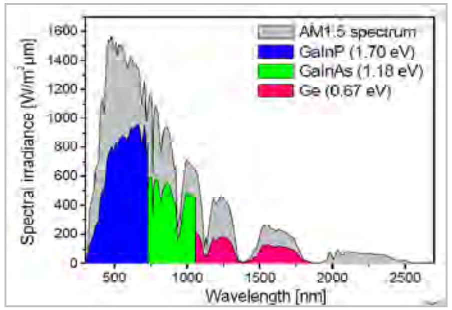
(various efficiencies)

ECN

Concentrator technology



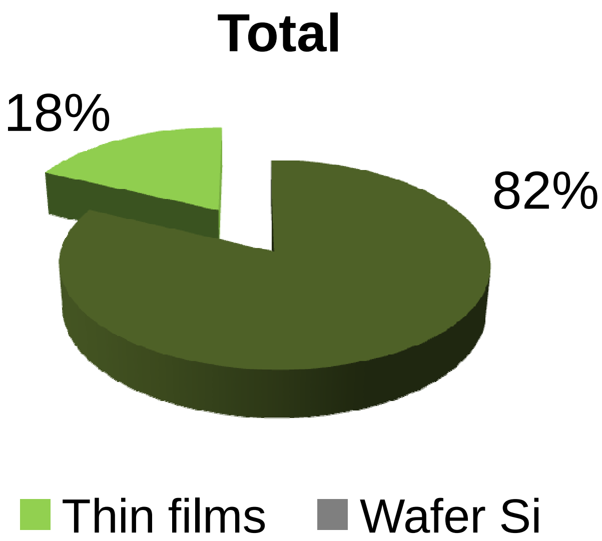


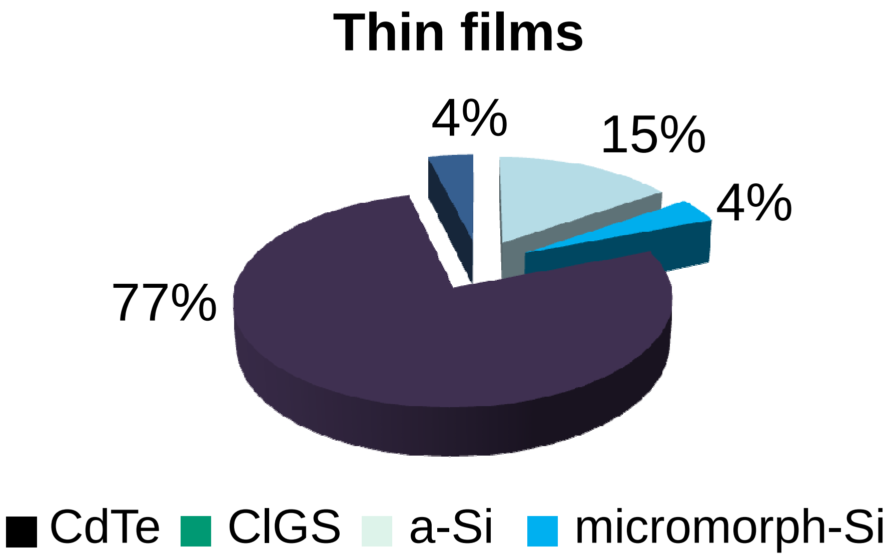


Courtesy
Andreas Bett
FhG-ISE

- application form of choice for expensive (per m^2) super high efficiency cells
- uses direct (i.e. not diffuse) sunlight:
  - requires sun tracking
  - mainly suited for sunbelt regions
- initially based on Si, now on III-V (GaAs-family) materials
- world record efficiency PV conversion: 42% for a triple-junction cell (Spectrolab, USA)
- *system* efficiency ≈25%, potential >40%

Technology shares in production (2009)





Courtesy Joachim Luther, SERIS

Contents

- **What is (needed for) very large-scale application of PV?**
  - The challenge quantified
- **Where are we?**
  - State of the art in technology and market
- **Visions, scenarios and roadmaps**
  - Technology and implementation targets
  - About modules & systems, cost & price, kWp & kWh
- **Approaches**
  - The technology portfolio and corresponding R&D areas
  - Environmental and societal issues
- **Outlook**

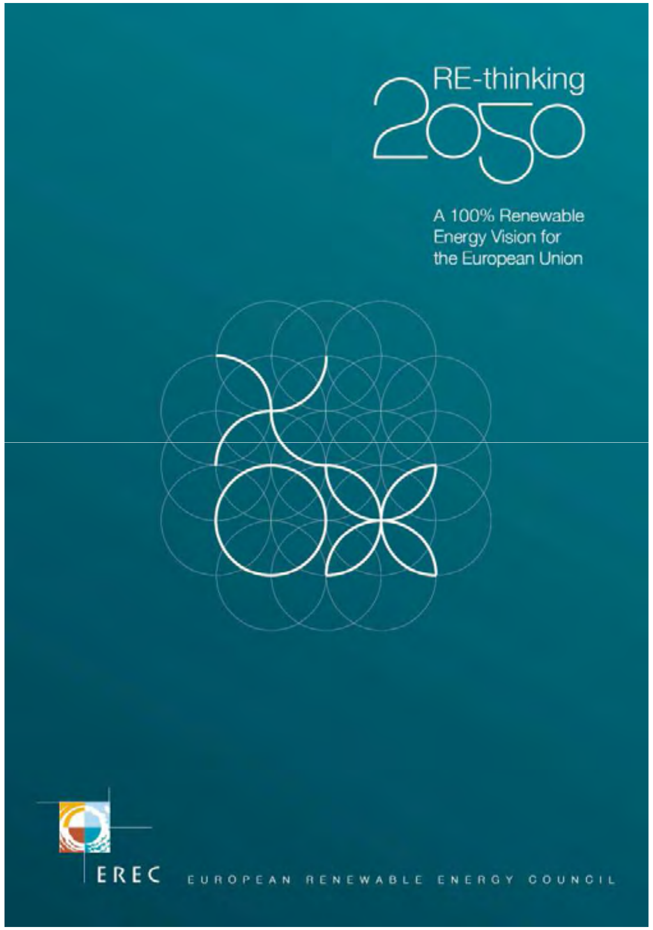
Visions, scenarios and roadmaps – examples

Greenpeace & EREC (2010)
www.energyblueprint.info

ForschungsVerbund Erneuerbare Energien (2010)
www.fvee.de

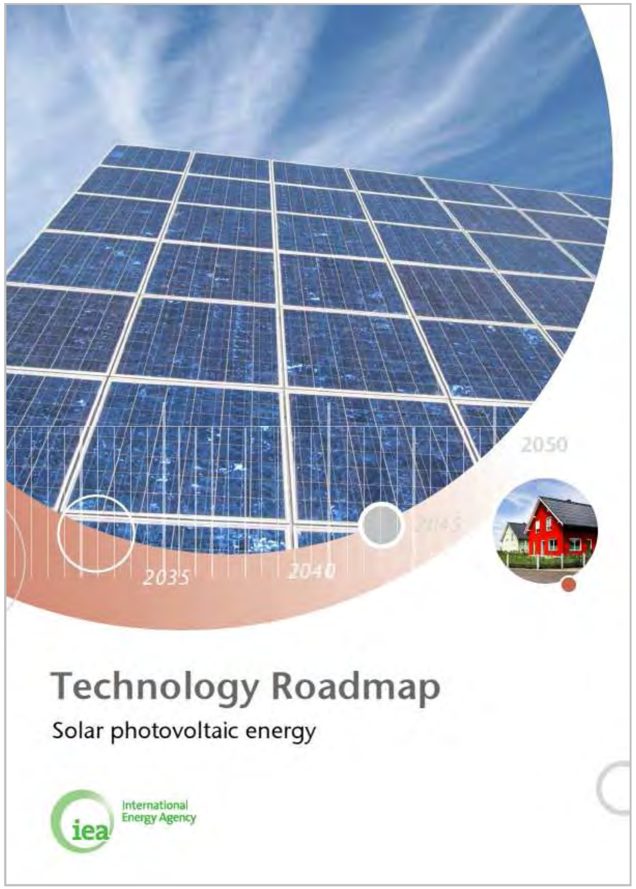
Visions, scenarios and roadmaps - examples

European Climate Foundation (2010)
www.roadmap2050.eu/downloads.html



European Renewable Energy Council (2010)

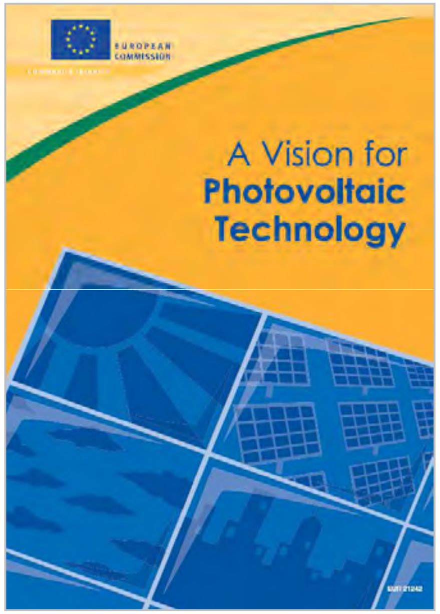
Visions, scenarios and roadmaps- examples



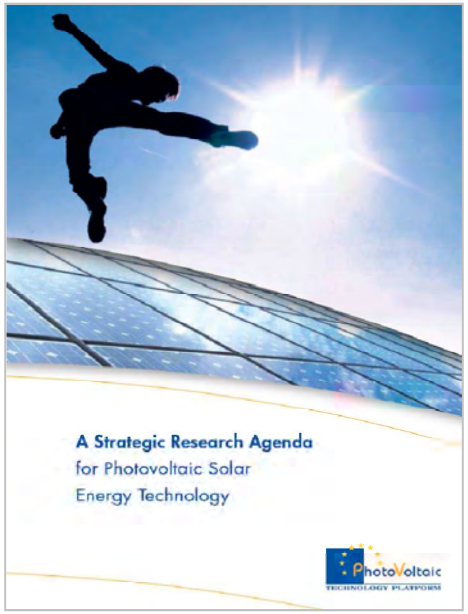
International Energy Agency
www.iea.org (2010)

New Energy Development Organisation
www.pv-era.net/doc_upload/documents/245_0108Japanese_Roadmap_PV2030plus.pdf
(2009)

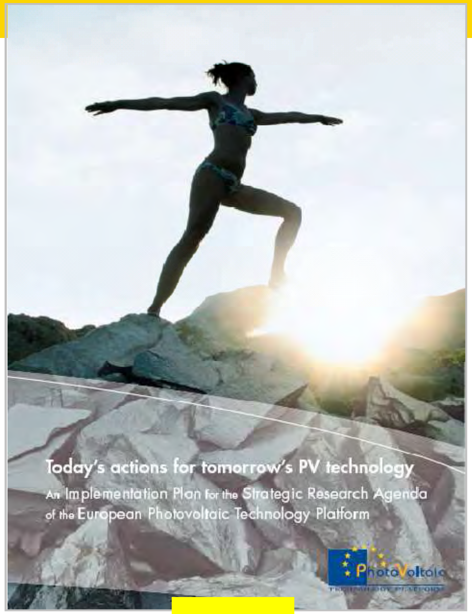
Visions, scenarios and roadmaps - examples



2005



2007



2009


EPIA
PhotoVoltaic
TECHNOLOGY PLATFORM

SOLAR EUROPE INDUSTRY INITIATIVE

IMPLEMENTATION PLAN 2010-2012

May 2010

2010

Addressing enablers for large-scale deployment

2010

2020
and beyond

COST REDUCTION

volume
+
innovation

INTEGRATION

grid
+
built environment

market deployment

R&D + demonstration

Solar Europe Industry Initiative (SEII)

PV system integration

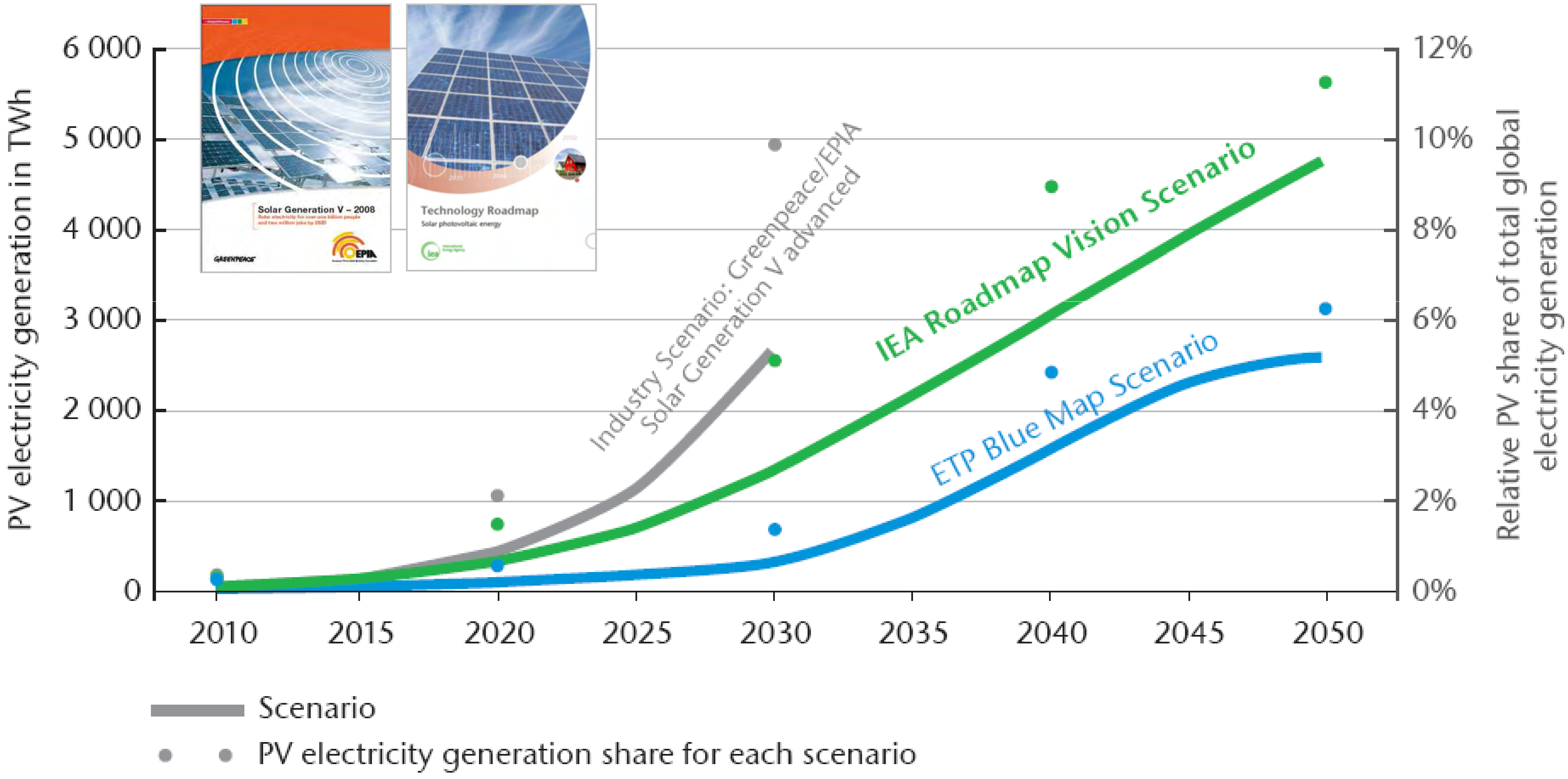
smart grids & integration of other renewables

LARGE-SCALE DEPLOYMENT

&

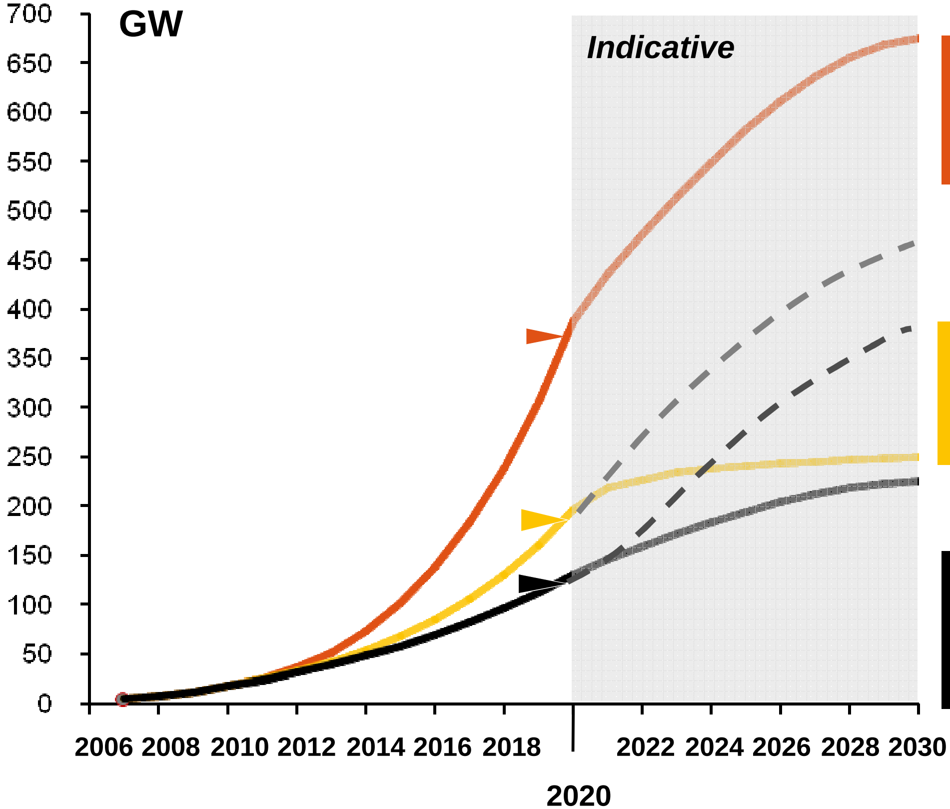
INDUSTRY COMPETITIVENESS

Visions on implementation vary: global market share of PV according to Greenpeace/EPIA and IEA



Visions on implementation vary: EU PV market share according to 'SET for 2020'

Courtesy
M. Lippert,
SAFT



Share of demand by 2020

***Paradigm Shift Scenario**: 12% (need flexible grid)*

***Accelerated Scenario**: 6%*

Baseline Scenario: 4%

ECN

Views on cost reduction largely coincide:
IEA PV Roadmap

Targets for residential sector		2008	[illegible]	2030	2050
*Typical turn-key system price (2008 USD/kW) **		6 000	[illegible]	1 800	1 200
Typical electricity generation costs (2008 USD/MWh)	2 000 kWh/kW	360	[illegible]	100	65
	1 500 kWh/kW	480	[illegible]	135	90
	1 000 kWh/kW	720	[illegible]	205	135

retail prices

Targets for commercial sector		2008	2020	2030	2050
Typical turn-key system price (2008 USD/kW)		5 000	2 250	[illegible]	1 000
Typical electricity generation costs (2008 USD/MWh)	2 000 kWh/kW	300	130	[illegible]	55
	1 500 kWh/kW	400	175	[illegible]	75
	1 000 kWh/kW	600	260	[illegible]	110

Targets for utility sector		2008	2020	[illegible]	2050
*Typical turn-key system price (2008 USD/kW) ***		4 000	1 800	[illegible]	……
Typical electricity generation costs (2008 USD/MWh)	2 000 kWh/kW	240	105	[illegible]	
	1 500 kWh/kW	320	140	[illegible]	
	1 000 kWh/kW	480	210	[illegible]	

wholesale prices

Views on cost reduction largely coincide:
EU PV TP Implementation Plan

Rounded, indicative figures	1980	1995	2009	2020	2030	Long term potential
Typical turn-key system price (2009 €/Wp)	>30	10	3 - 4.5*)	1.5 - 2.3	<1	0.5
Typical electricity generation costs @ 1300 kWh/kWp·yr**) (2009 €/kWh)	>2	0.7	0.20 – 0.30	0.10 – 0.15	<0.07	0.03
Commercial *flat-plate* module efficiencies (STC)	up to 8%	up to 12%	up to 20%	up to 23%	up to 25%	up to 40%
Commercial *concentrator* module efficiencies	(~10%)	Up to 20%	up to 30%	up to 35%	up to 40%	up to 60%
System energy pay-back time @ 1300 kWh/kWp·yr (yrs)	>10	>5	<2	<1	0.5	0.25

*) The range refers to power plants, large and small systems on buildings, respectively.

**) 25 yrs amortisation, 6% cost of capital, 1% O&M&insurance costs (PVTP NPV/FiT model).
It is noted that generation costs may be calculated to be higher or lower if other parameter values are chosen.

Views on cost reduction largely coincide:
EU PV TP Implementation Plan

Rounded, indicative figures	1980	1995	2009	2020	2030	Long term potential
Typical turn-key system price (2009 €/Wp)	>30	10	3 - 4.5*)	1.5 - 2.3	<1	0.5
Typical electricity generation costs @ 1300 kWh/kWp·yr**) (2009 €/kWh)	>2	0.7	0.20 – 0.30	0.10 – 0.15	<0.07	0.03

Views on cost reduction largely coincide:
Solar Europe Industry Initiative

		2007	2010	2015	2020
Turn-key price larger systems (€/Wp)*		≥5	2,5-3,5	2	1,5
PV electricity generation cost in Southern EU (€/kWh)**		0.30 – 0.60	0.13 – 0.25	0.10 – 0.20	0.07 – 0.14
Typical PV module efficiency range (%)	Crystalline silicon	13 - 18%	15 - 20%	16 - 21%	18 - 23%
	Thin films	5 - 11%	6 - 12%	8 - 14%	10 - 16%
	Concentrators	20%	20 - 25%	25 - 30%	30 - 35%
Inverter lifetime (years)		10	15	20	>25
Module lifetime (years)		20 - 25	20 - 25	25 - 30	35 - 40
Energy pay-back time (years)***		2 - 3	1 - 2	1	0.5
Cost of PV + small-scale storage (€/kWh) in Southern EU (grid-connected)****		--	0.35	0.22	<0.15

* System price depends on technology and market maturity

** LCoE varies with financing cost and location. Insolation range considered here 1500 - 2000 kWh/m² per year

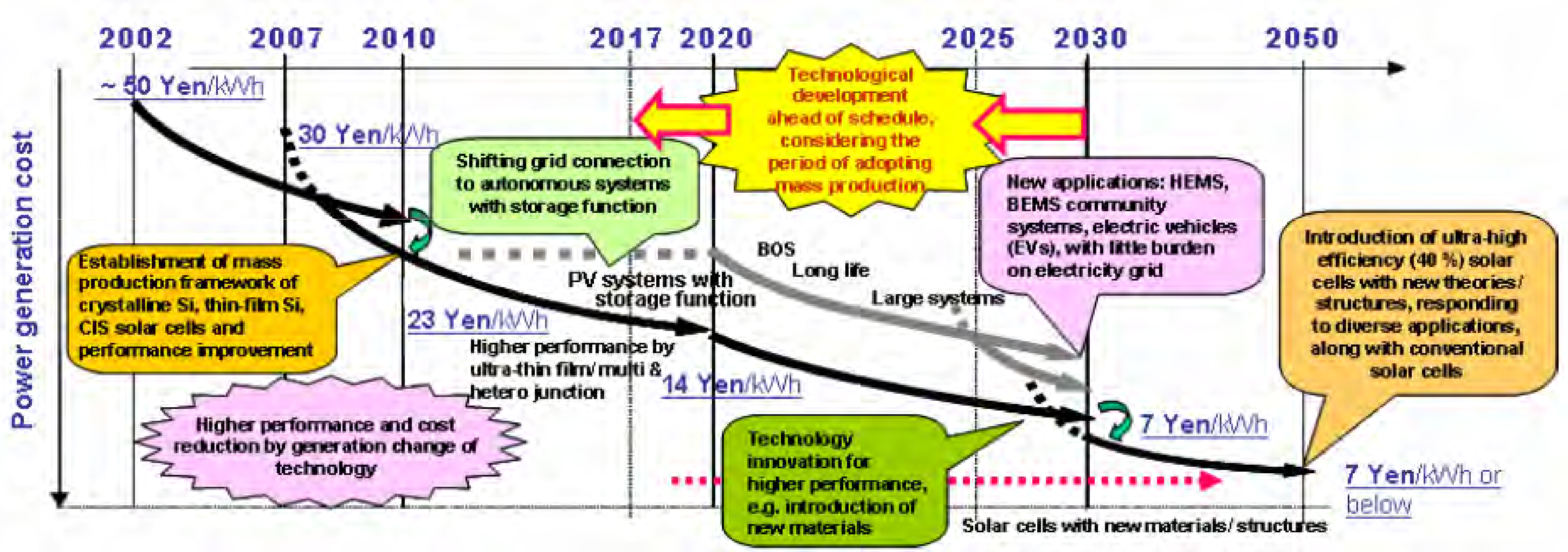
*** Best values

**** Estimated figures based on EUROBAT roadmaps

Views on cost reduction largely coincide:
Solar Europe Industry Initiative

	2007	2010	2015	2020
Turn-key price larger systems (€/Wp)*	≥5	2,5-3,5	2	1,5
PV electricity generation cost in Southern EU (€/kWh)**	0.30 – 0.60	0.13 – 0.25	0.10 – 0.20	0.07 – 0.14

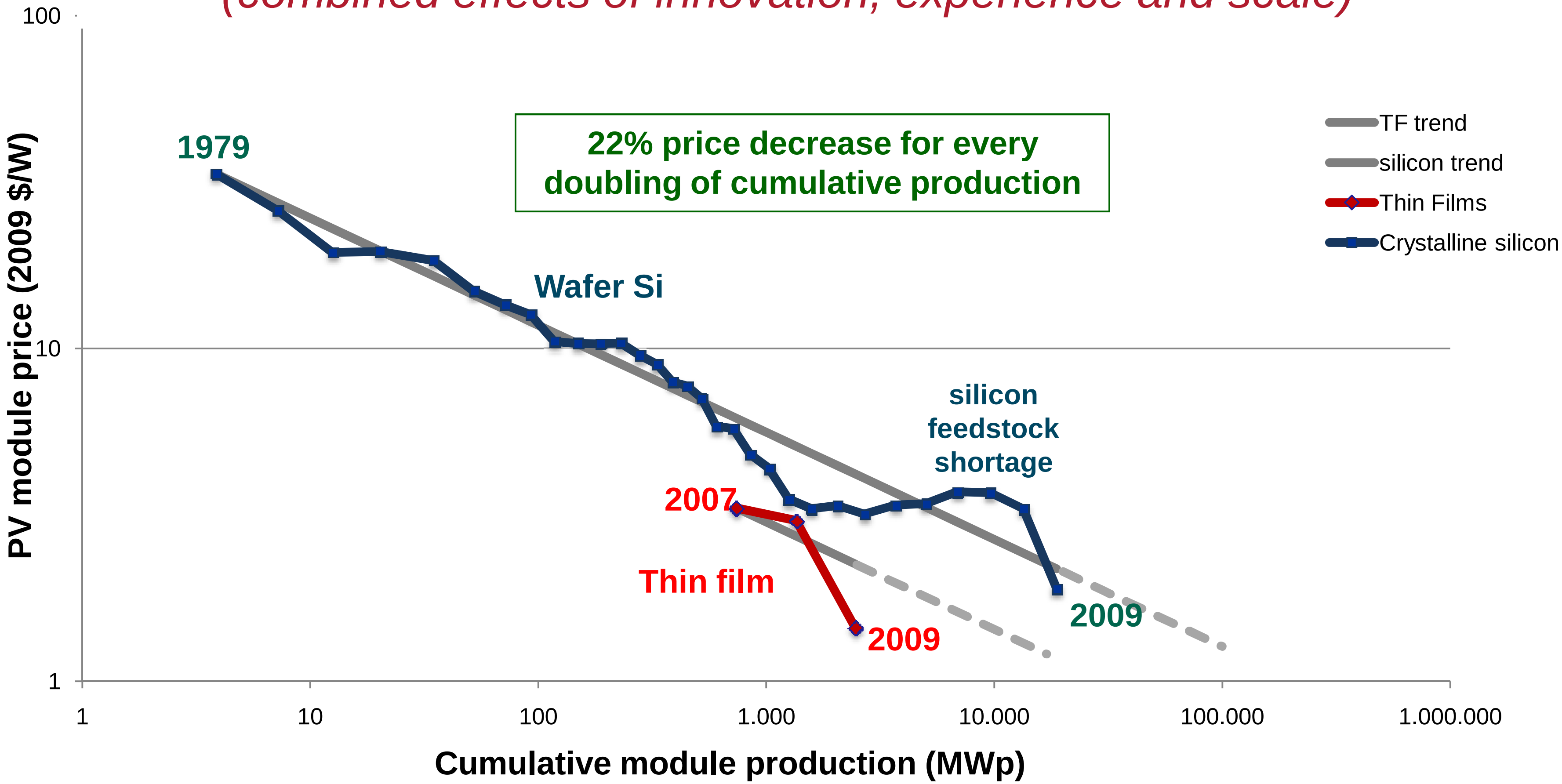
Views on cost reduction largely coincide:
PV2030+ Roadmap, Japan



ECN

Price-experience curves of PV modules

(combined effects of innovation, experience and scale)



Source: EPIA, October 2009

From module price to generation cost

Generation cost determined by:

- **turn-key system price (€ /Wp)**
  - module price + Balance-of-System price
    (power-related part & area-related part)
- **energy output (kWh/Wp·yr)**
  - primarily dependent on annual insolation
  - influenced by system quality and design, partial shading, etc.
- **operation and maintenance cost (€/Wp·yr)**
- **cost of capital:**
  - depreciation time (yr)
  - interest rate / Return on Investment required (%)

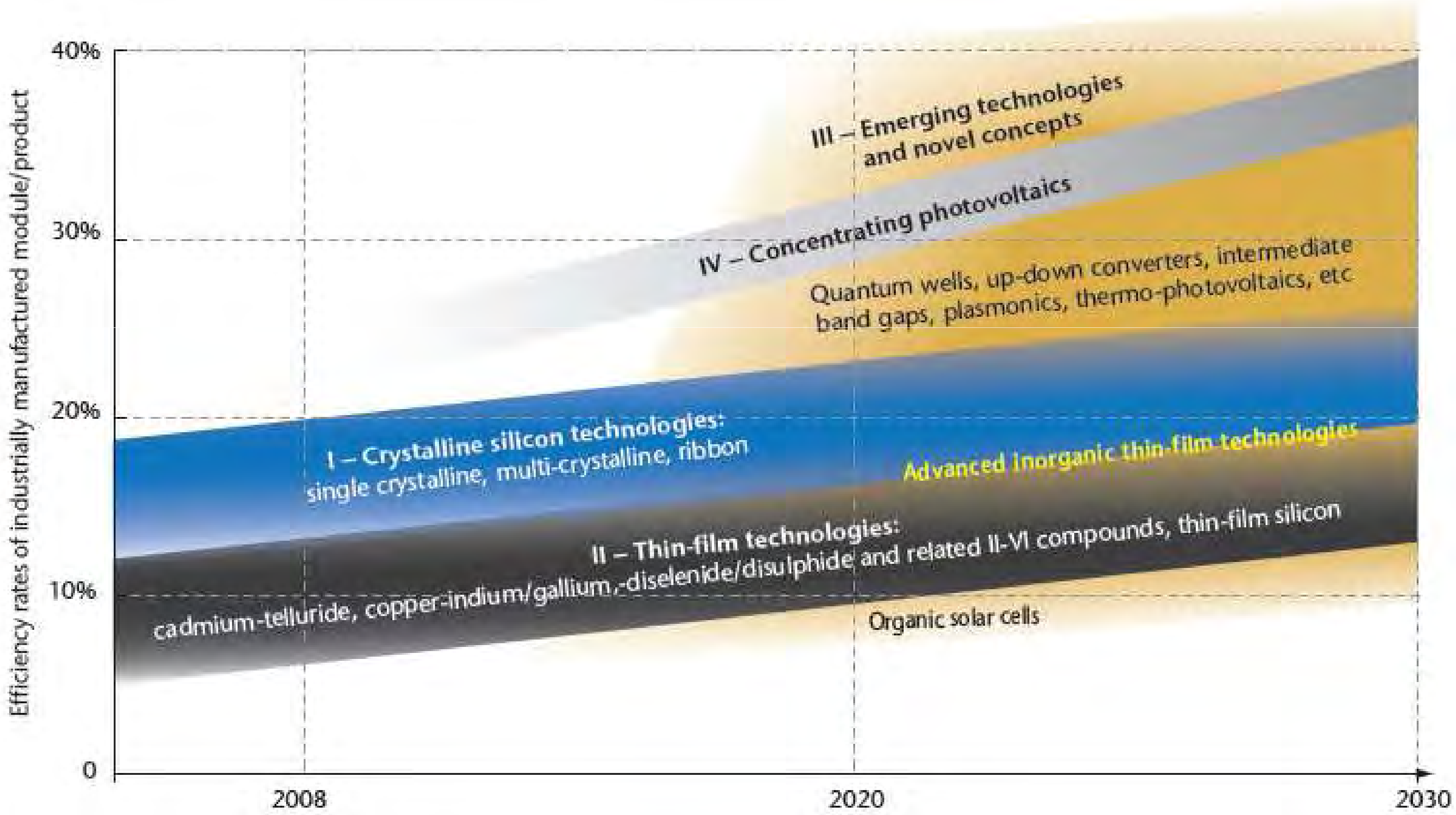
Contents

- **What is (needed for) very large-scale application of PV?**
  - The challenge quantified
- **Where are we?**
  - State of the art in technology and market
- **Visions, scenarios and roadmaps**
  - Technology and implementation targets
  - About modules & systems, cost & price, kWp & kWh
- **Approaches**
  - The technology portfolio and corresponding R&D areas
  - Environmental and societal issues
- **Outlook**

Technical requirements for low cost PV electricity generation

- High conversion efficiency at cell, module and system levels
- Low materials consumption & low-cost materials
- High-throughput, high-yield manufacturing
- Low-labour (fast & flexible) installation
- High reliability, low maintenance & long lifetime
- Intelligent grid integration

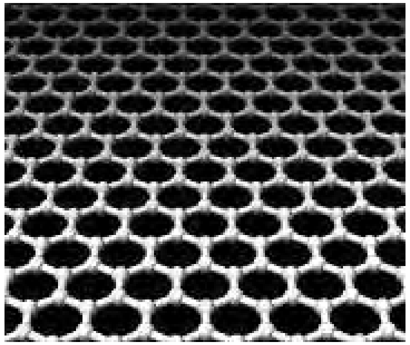
Evolution of technology portfolio and module efficiencies *(IEA PV Roadmap, 2010)*



Source: IEA PVPS.

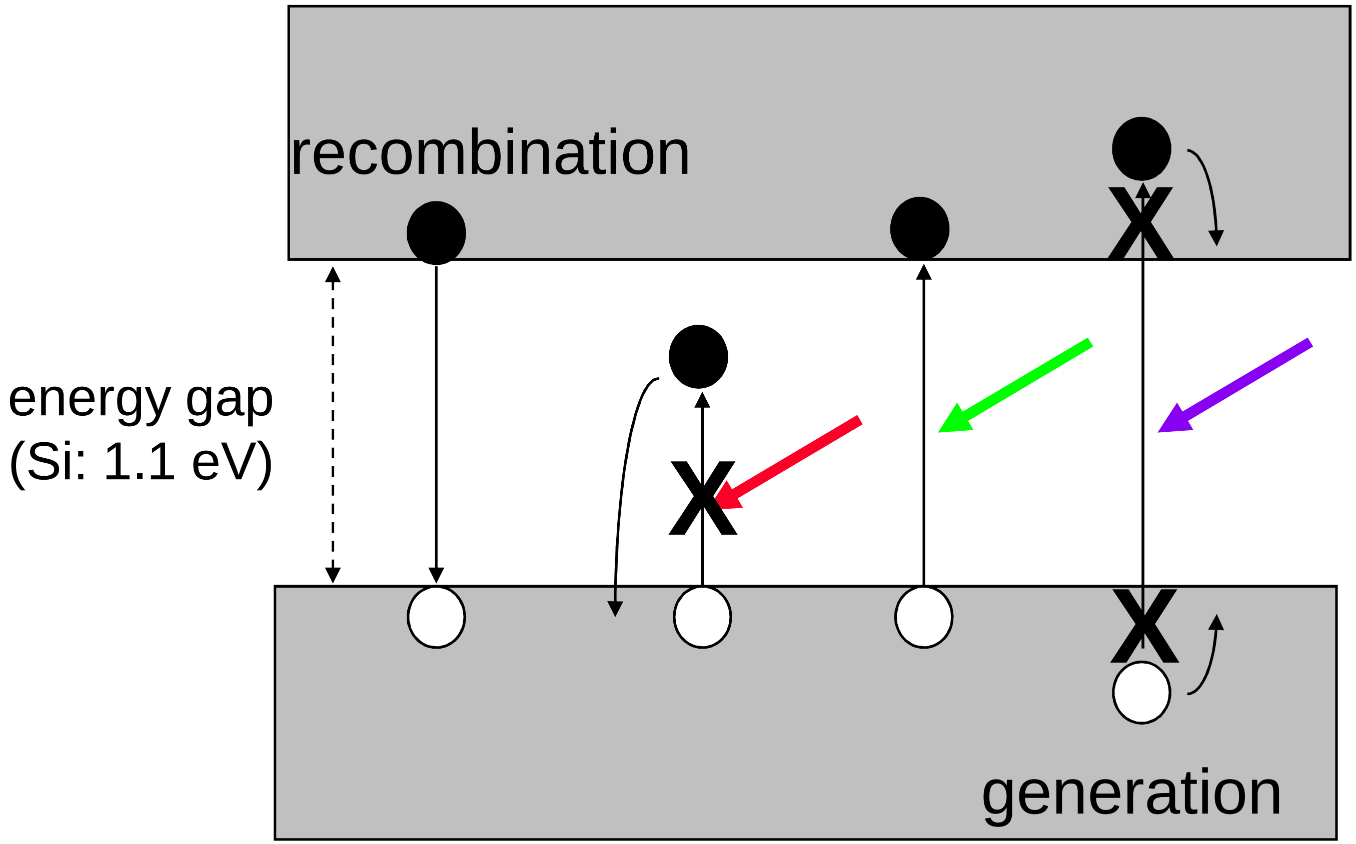
Selected hot topics in global PV R&D

- high-efficiency (20-25%) wafer silicon PV with integrated cell & module designs
- high efficiency (15-40%) thin-film multi-junction devices
- nanotechnology for very high efficiency and/or very low cost, including printed semiconductors (CIGS, Si, organic, …)
- reduction of use and replacement of non-earth-abundant, hazardous and expensive materials (In, Te, Ge, Ag, Pb, etc.)
- low-cost, high-quality encapsulants
- technology and concepts for high grid penetration
- and, of course:



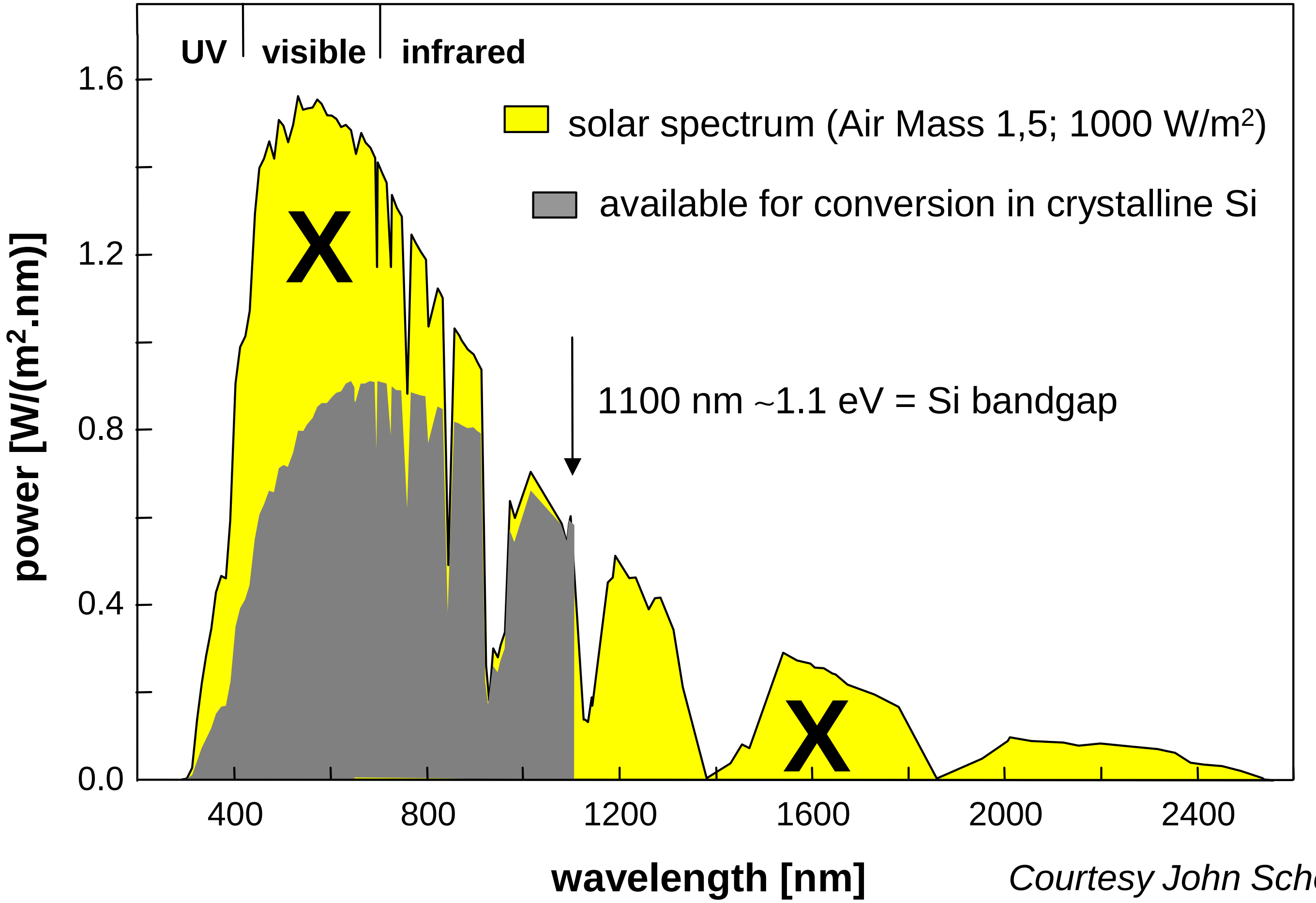
Routes to very high efficiency

Photovoltaic conversion: basic process and losses



Routes to very high efficiency

Solar spectrum and spectral losses

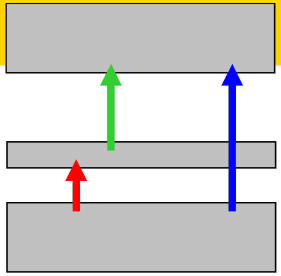


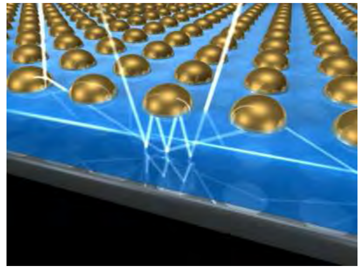
Courtesy John Schermer, RUN, NL

courtesy John Schermer, KUN

Routes to (very) high efficiency

potential & limits (simplified)





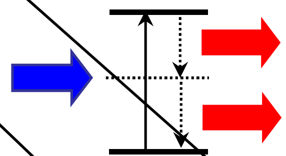
<u>Ideal</u> cells

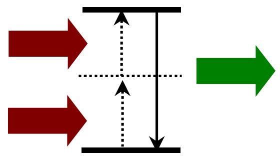
Loss factor
- **spectral losses**
- **recombination and curve loss**

η≤~30%
(1 sun)

Selected remedies
- **multi-gap & multi-band cells, spectrum shaping, hot carrier cells multi-carrier generation**
- **concentration, light management**

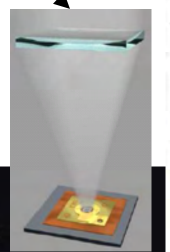
η<75~85%

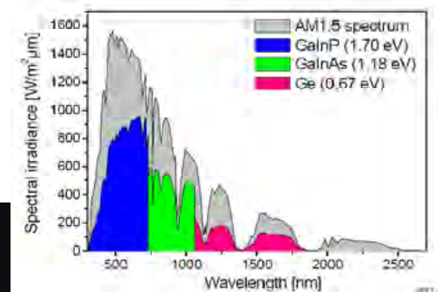




<u>Practical</u> cells and modules: add
- **extra recombination**
- **shadowing and reflection**
- **transmission**
- **resistance**
- **non-optimal band gap**

η = 0 ~ 42%
(upward potential to >60% for lab cells, >50% for commercial modules)





Routes to (very) high efficiency

potential & limits (simplified)

Ideal cells

Loss factor		*Selected remedies*	
- spectral losses - recombination and curve loss	$\eta \leq \sim 30\%$ (1 sun)	- multi-gap & multi-band cells, spectrum shaping, hot carrier cells multi-carrier generation - concentration, light management	$\eta < 75\sim 85\%$

Practical cells and modules: add

- extra recombination
- shadowing and reflection
- transmission
- resistance
- non-optimal band gap

Routes to (very) high efficiency

potential & limits (simplified)

<u>Ideal</u> cells

Loss factor		*Selected remedies*	
- spectral losses - recombination and curve loss	$\eta \leq \sim 30\%$ (1 sun)	- multi-gap & multi-band cells, spectrum shaping, hot carrier cells multi-carrier generation - concentration, light management	$\eta < 75 \sim 85\%$

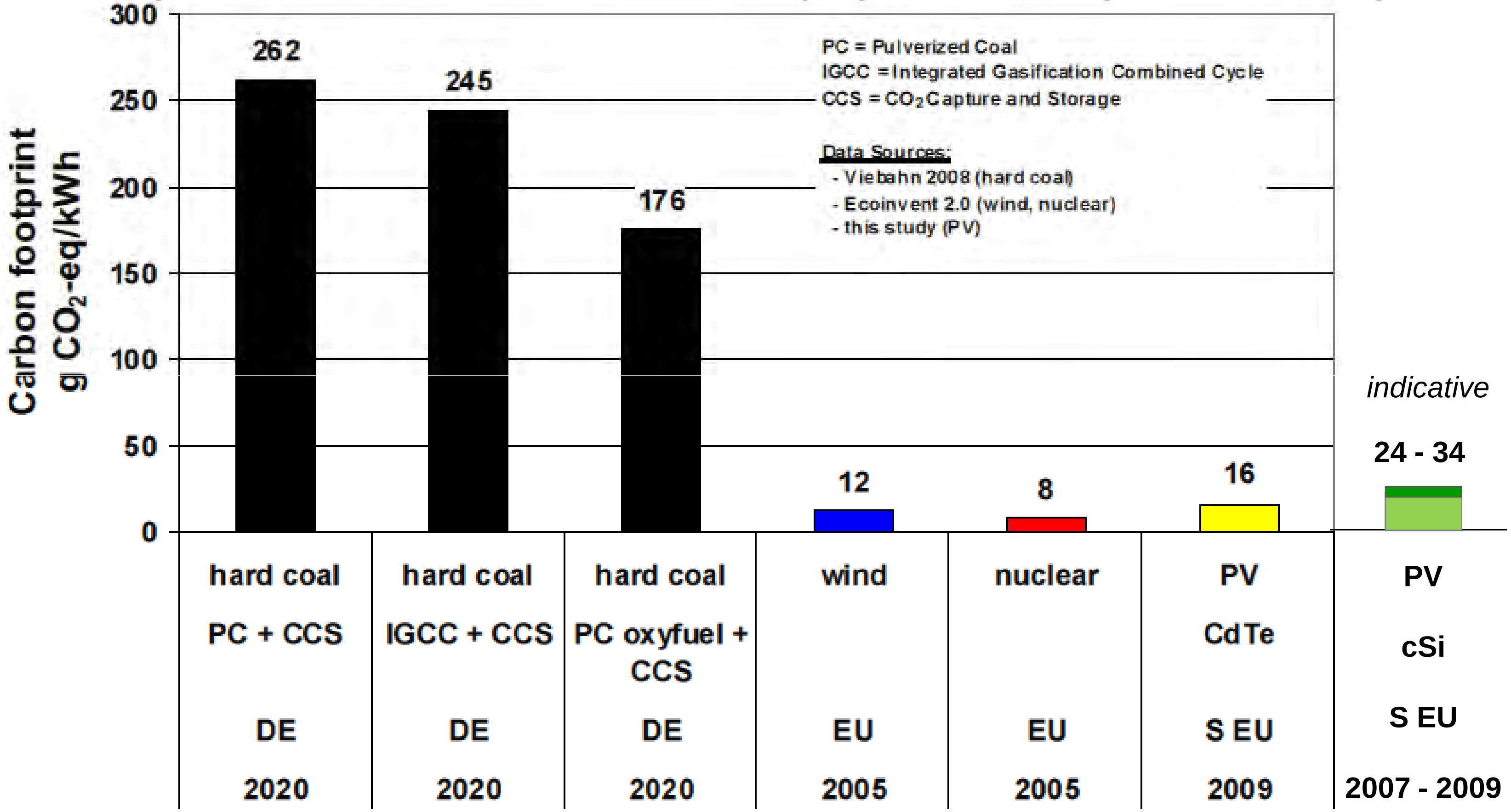
<u>Practical</u> cells and modules: add

- extra recombination
- shadowing and reflection
- transmission
- resistance
- non-optimal band gap

$\eta = 0 \sim 42\%$ (upward potential to >60% for lab cells, >50% for commercial modules)

Sustainability:

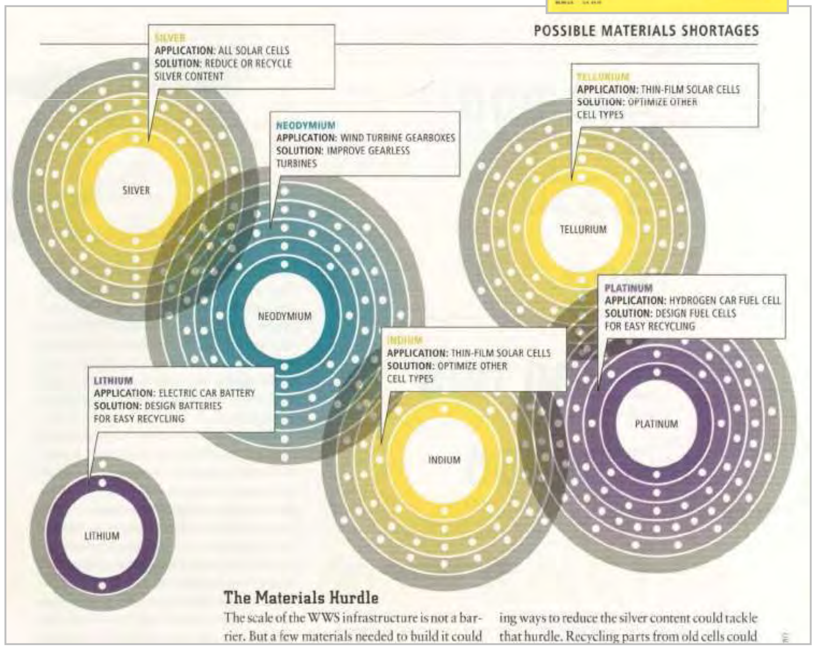
carbon footprint of selected electricity generating technologies



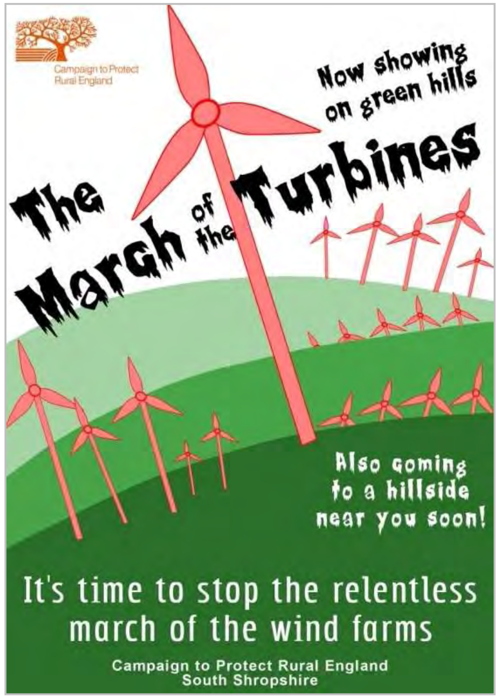
Mariska de Wild-Scholten, Environmental Sustainability of Thin Film PV
2nd EPIA International Thin Film Conference, 12 November 2009, Munich

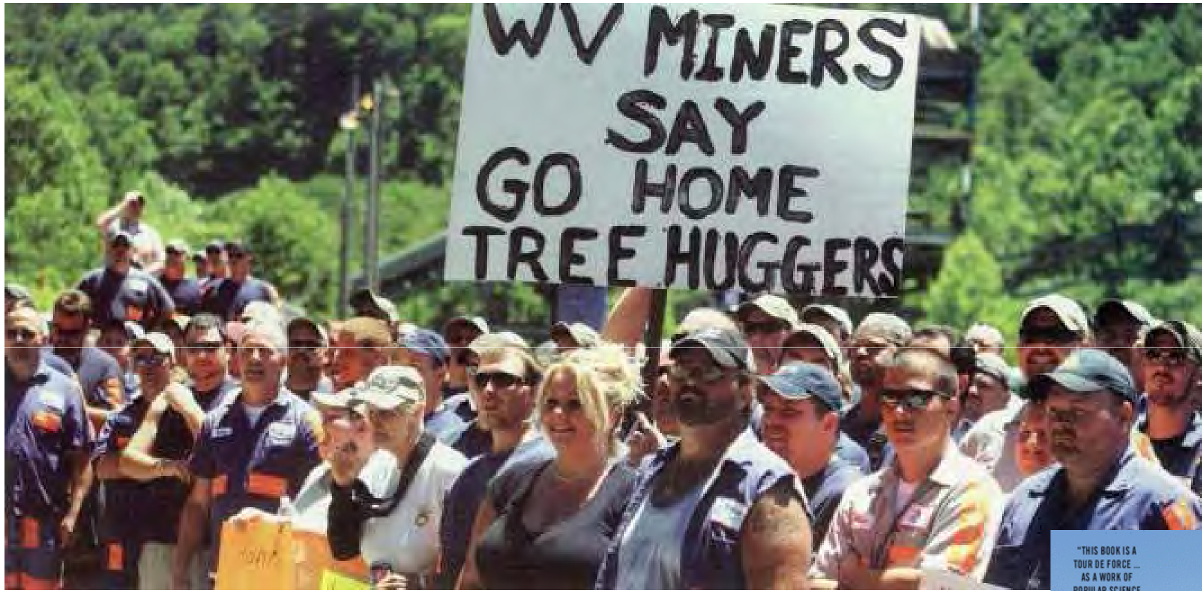
Sustainability:

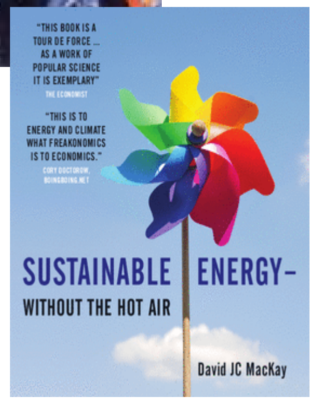
finding the best way from current to ultimate



Public support, a key asset: not to be taken for granted



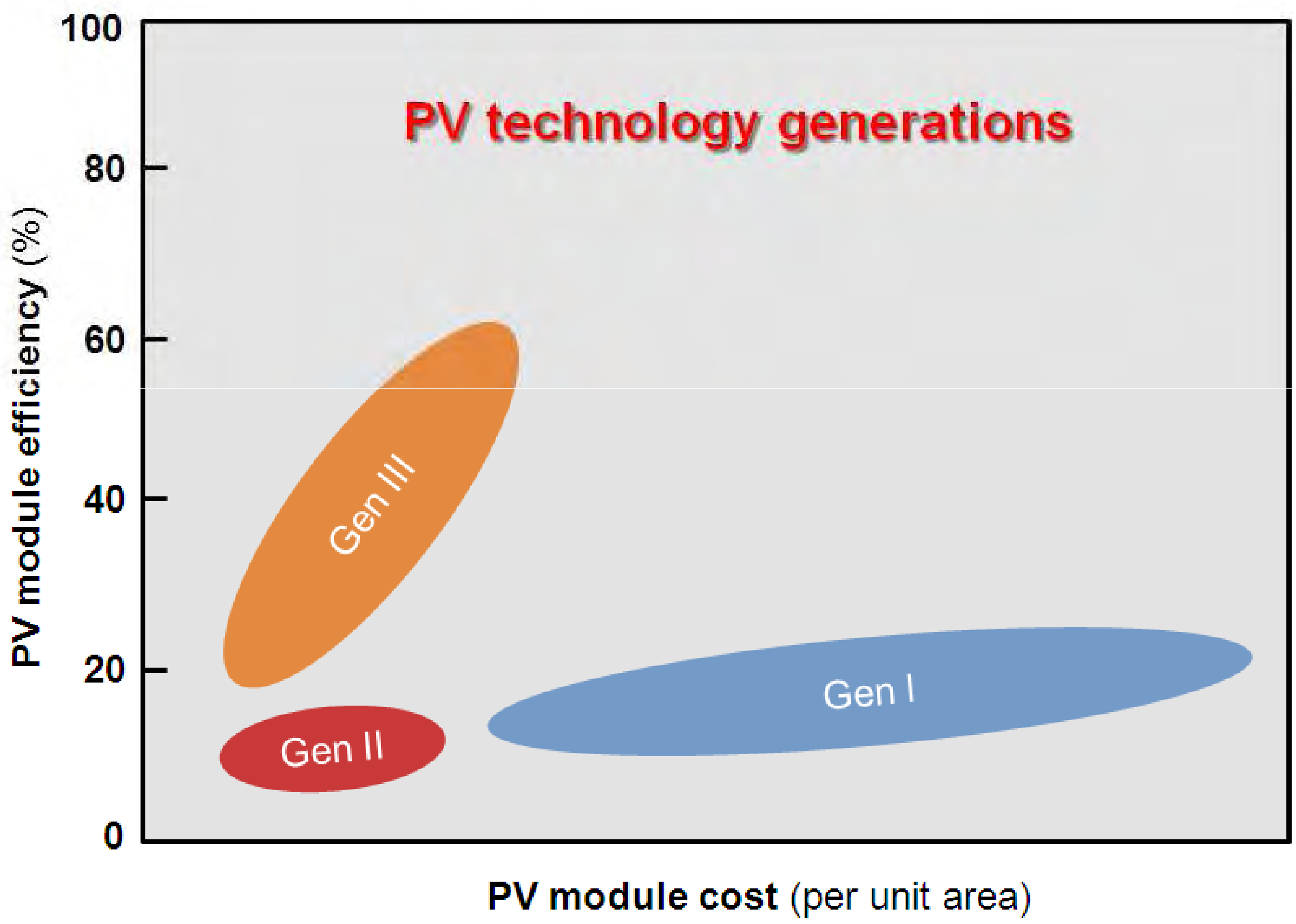




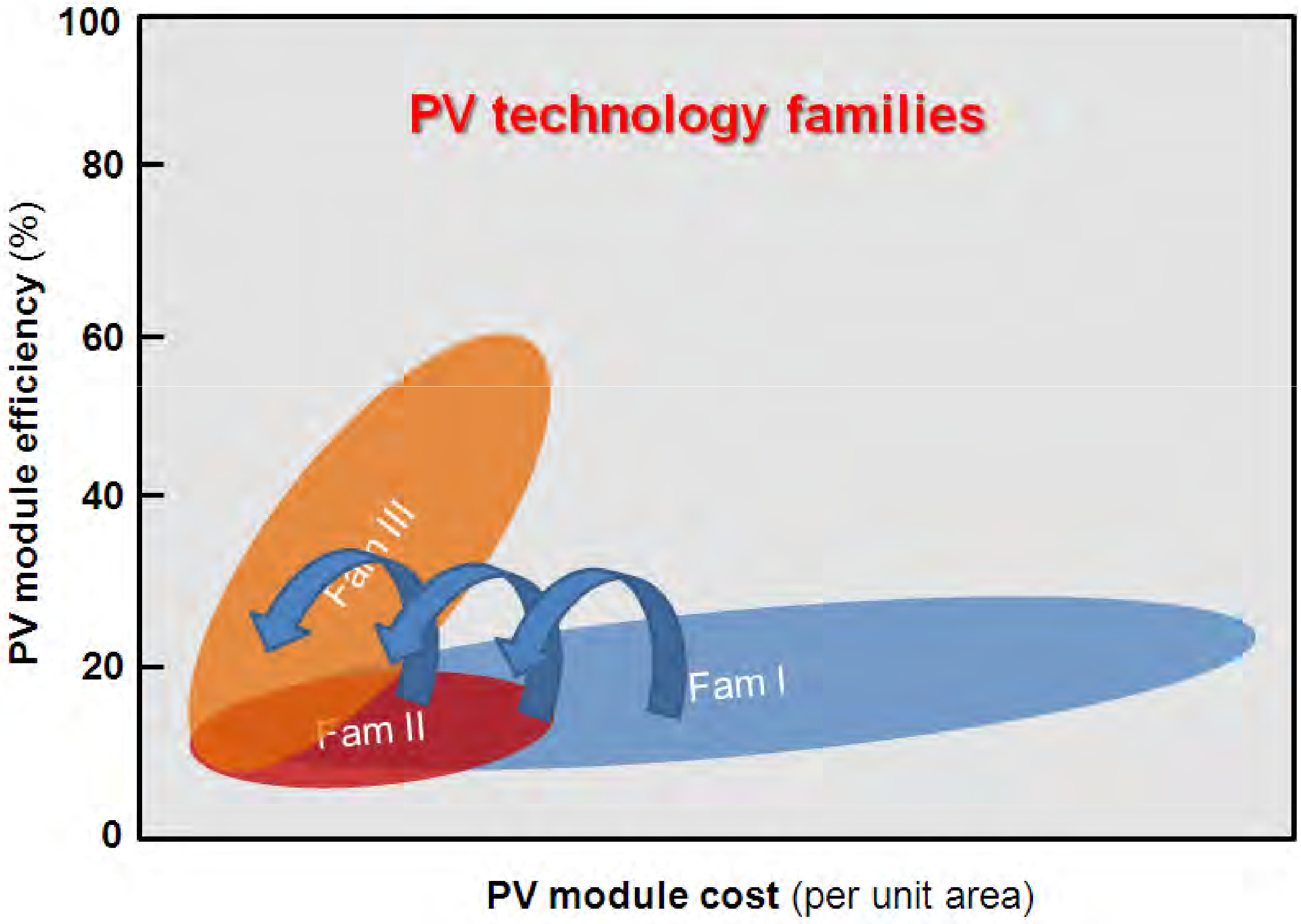
Contents

- **What is (needed for) very large-scale application of PV?**
  - The challenge quantified
- **Where are we?**
  - State of the art in technology and market
- **Visions, scenarios and roadmaps**
  - Technology and implementation targets
  - About modules & systems, cost & price, kWp & kWh
- **Approaches**
  - The technology portfolio and corresponding R&D areas
  - Environmental and societal issues
- **Outlook**

PV technologies: the common view



PV technologies: an alternative view



The research challenge summarized

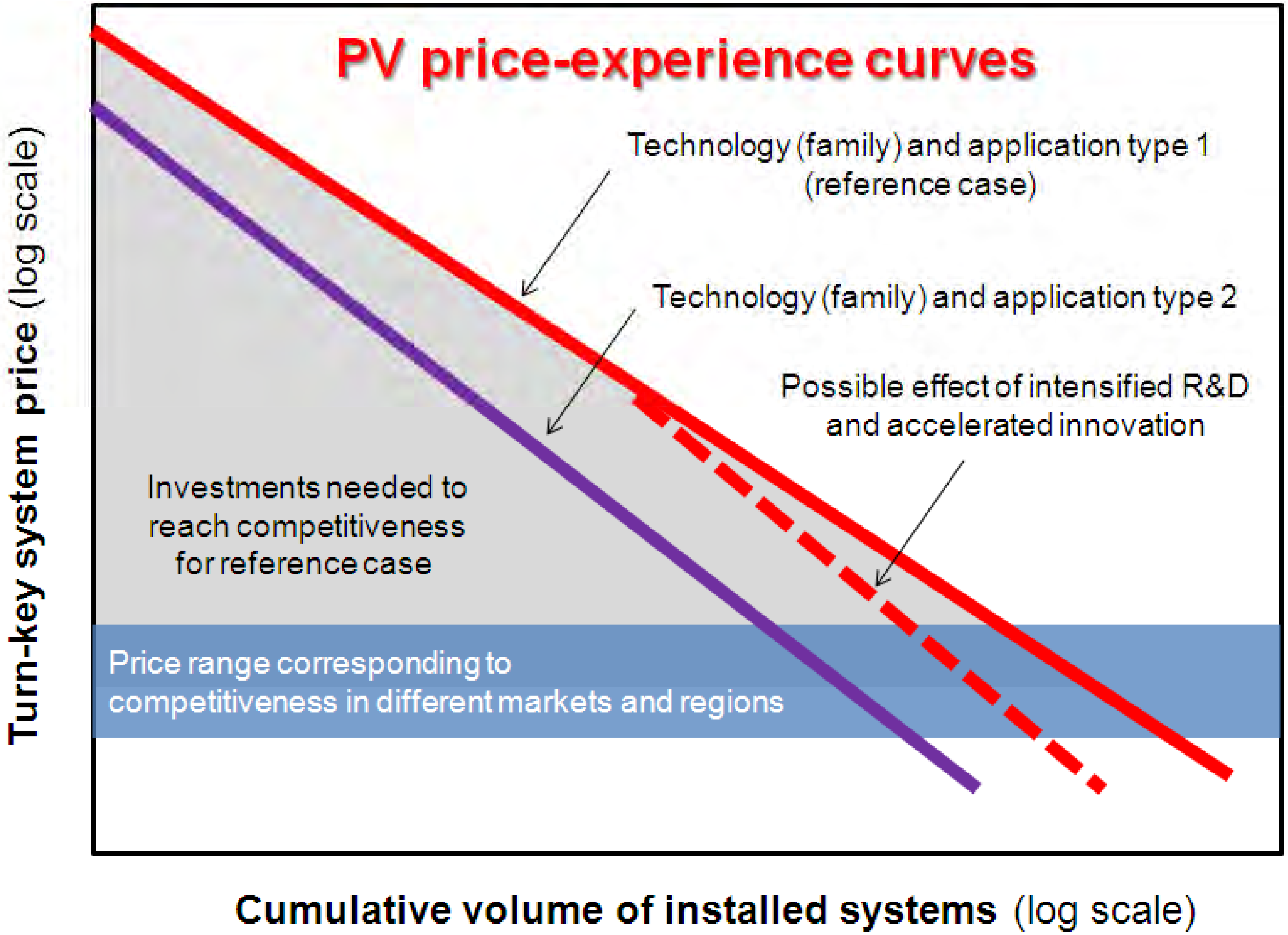
- managing the technology/topics portfolio:
  broad & robust *vs* deep & efficient

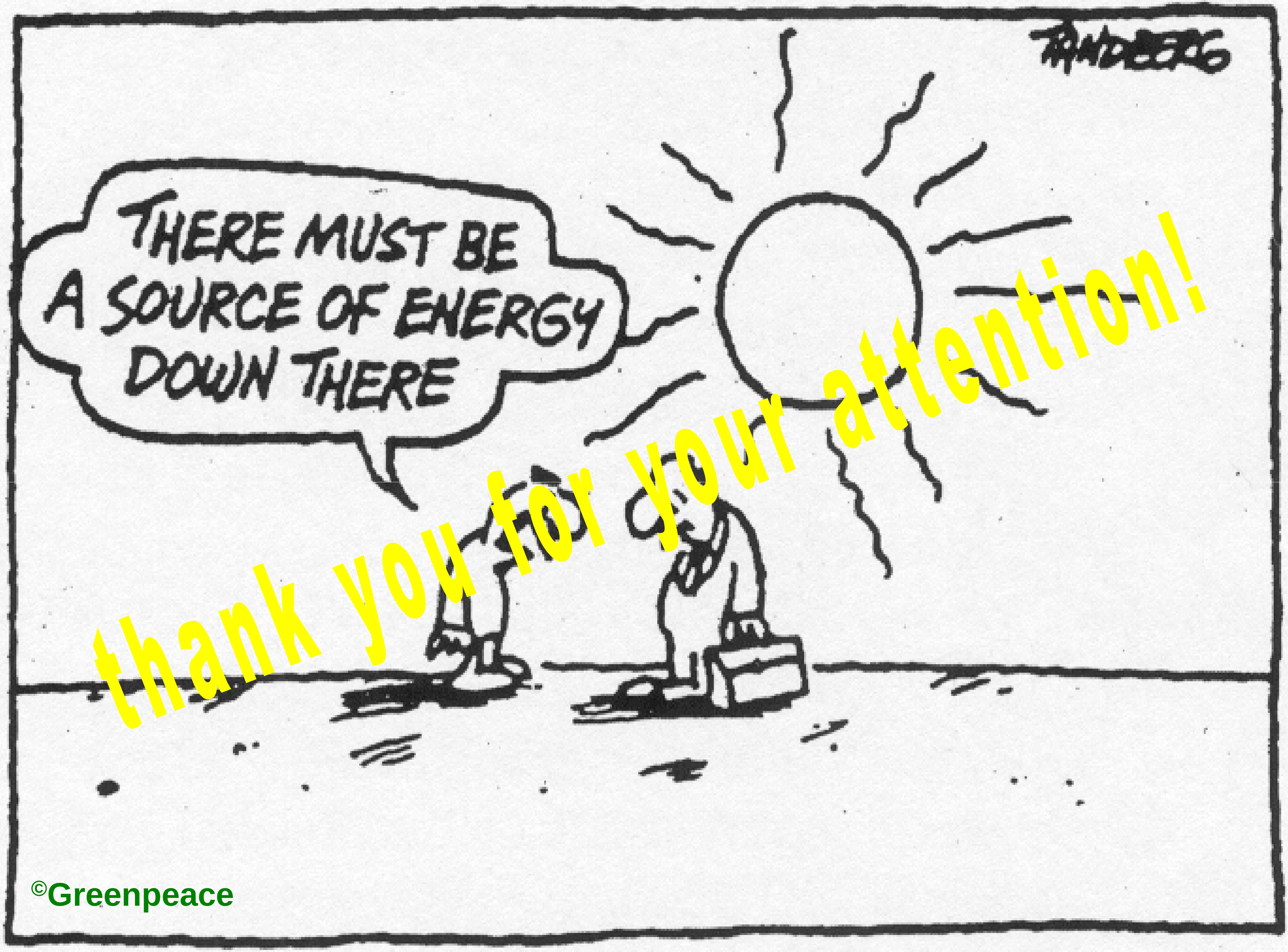
- finding the right balance between short, medium and long term / basic and applied

- crossing the ‘valley of death’ and minimizing the time from lab to fab

- finding the optimum between budgets for R&D and market development

Effects of volume and R&D on price





thank you for your attention!