Photovoltaics

Introduction

INTRODUCTION

This course - contents

- Solar **resource**
- **Physics** of solar cells
- PV **technologies**
- **Grid connected** PV systems
- **Stand alone** systems
- **Building** integrated systems
- **Concentration** photovoltaics

INTRODUCTION

This course - grading

- **Test**: 50% (15 Dez 2017)
- **Lab work**: 15%
- **Home work**: System design (15%)
- **Presentation**: Advanced topics (20%)

and/or

- **Final exam**: everything (100%)

INTRODUCTION

This course – main references

- T. Markvart, *Solar electricity*, 2nd edition, John Wiley & Sons, 2000
- M. Green, *Solar* cells – *operating principles, technology and system applications*, USW 1986
- R. Messeger, *Photovoltaics system engineering*, 2nd ed., 2003
- A. Luque *et al*, *Handbook of PV Science and Engineering*, 2003
- S. Bowden *et* al, PV CD ROM [*pvcdrom.pveducation.org*]
- Photon international magazine [*www.photon-magazine.com*]

INTRODUCTION

TODAY

- (Summary of this course)
- Brief history of photovoltaics
- PV global market
- PV in Portugal

INTRODUCTION

Brief history of photovoltaics

1839: Edmund Becquerel, a French experimental physicist, discovered the photovoltaic effect.

1873: Willoughby Smith discovered the photoconductivity of selenium.

1876: Adams and Day observed the photovoltaic effect in solid selenium.

1883: Charles Fritts, an American inventor, described the first solar cells made from selenium wafers.

1904: Einstein published his paper on the photoelectric effect.

1916: Millikan provided experimental proof of the photoelectric effect.

1951: A grown p-n junction enabled the production of a single-crystal cell of germanium.

1954: Bell Labs researchers Pearson, Chapin, and Fuller reported their discovery of 4.5% efficient silicon solar cells.

INTRODUCTION

Brief history of photovoltaics

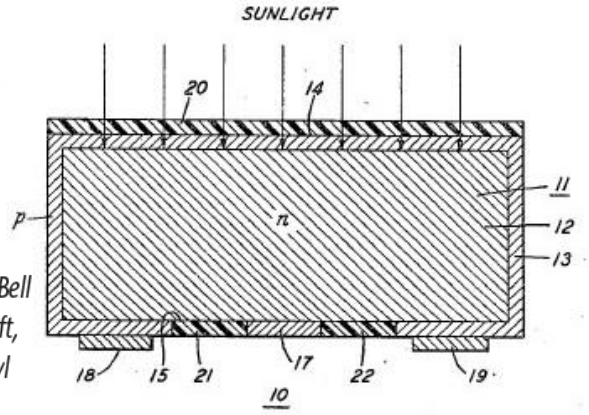
The inventors of the Bell Solar Battery, from left, Gerald Pearson, Daryl Chapin, and Calvin Fuller, check devices for the amount of solar electricity derived from sunlight, here simulated by a lamp.

Feb. 5, 1957 D. M. CHAPIN ET AL 2,780,765

SOLAR ENERGY CONVERTING APPARATUS

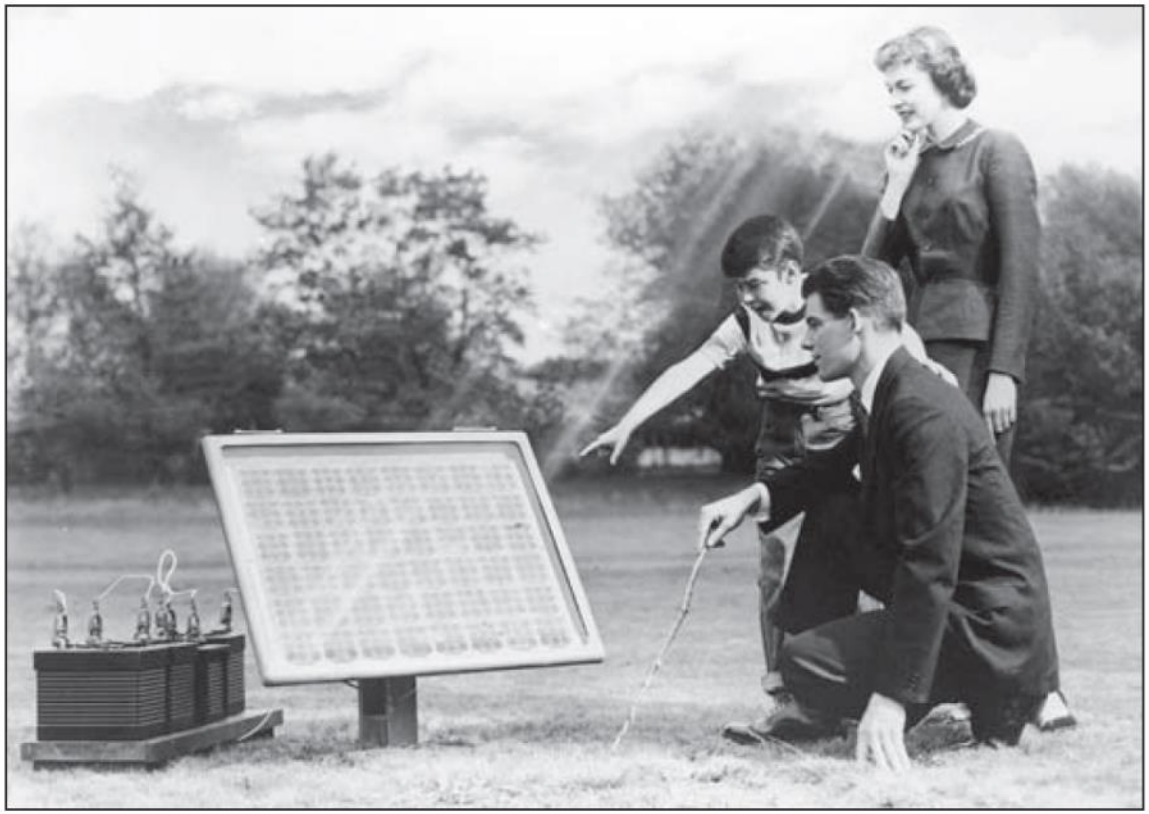
Filed March 5, 1954

FIG. 1



INTRODUCTION

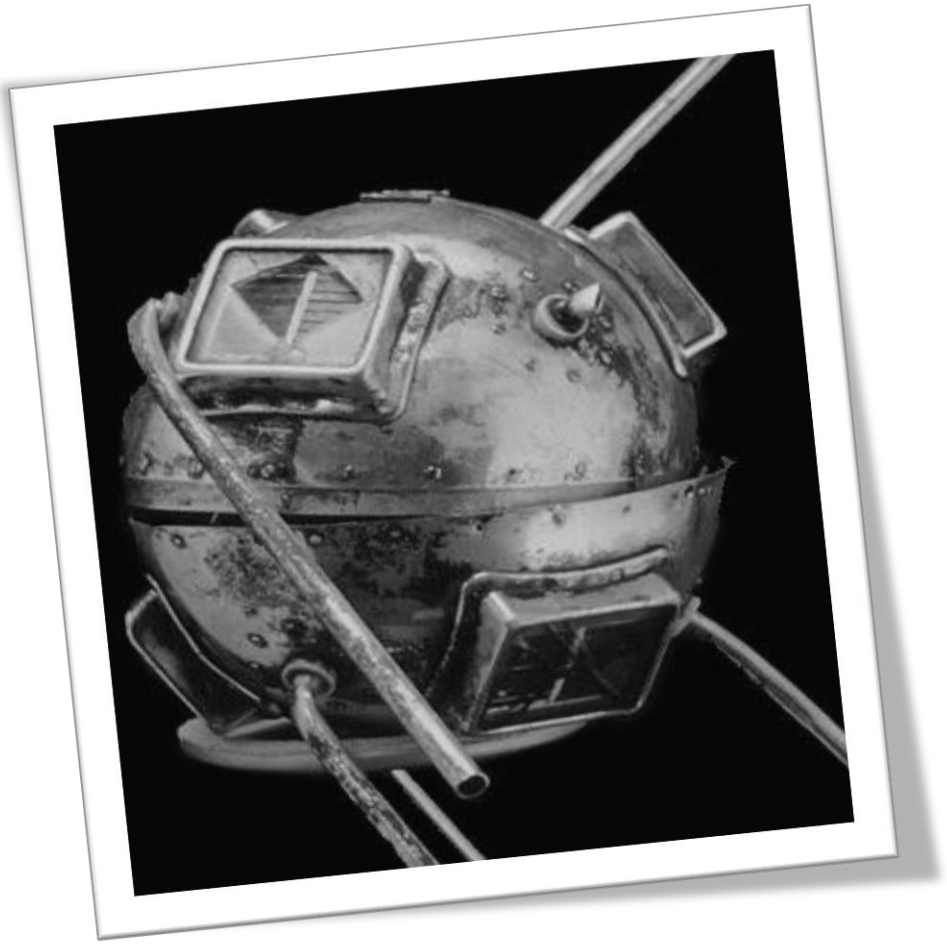
Brief history of photovoltaics

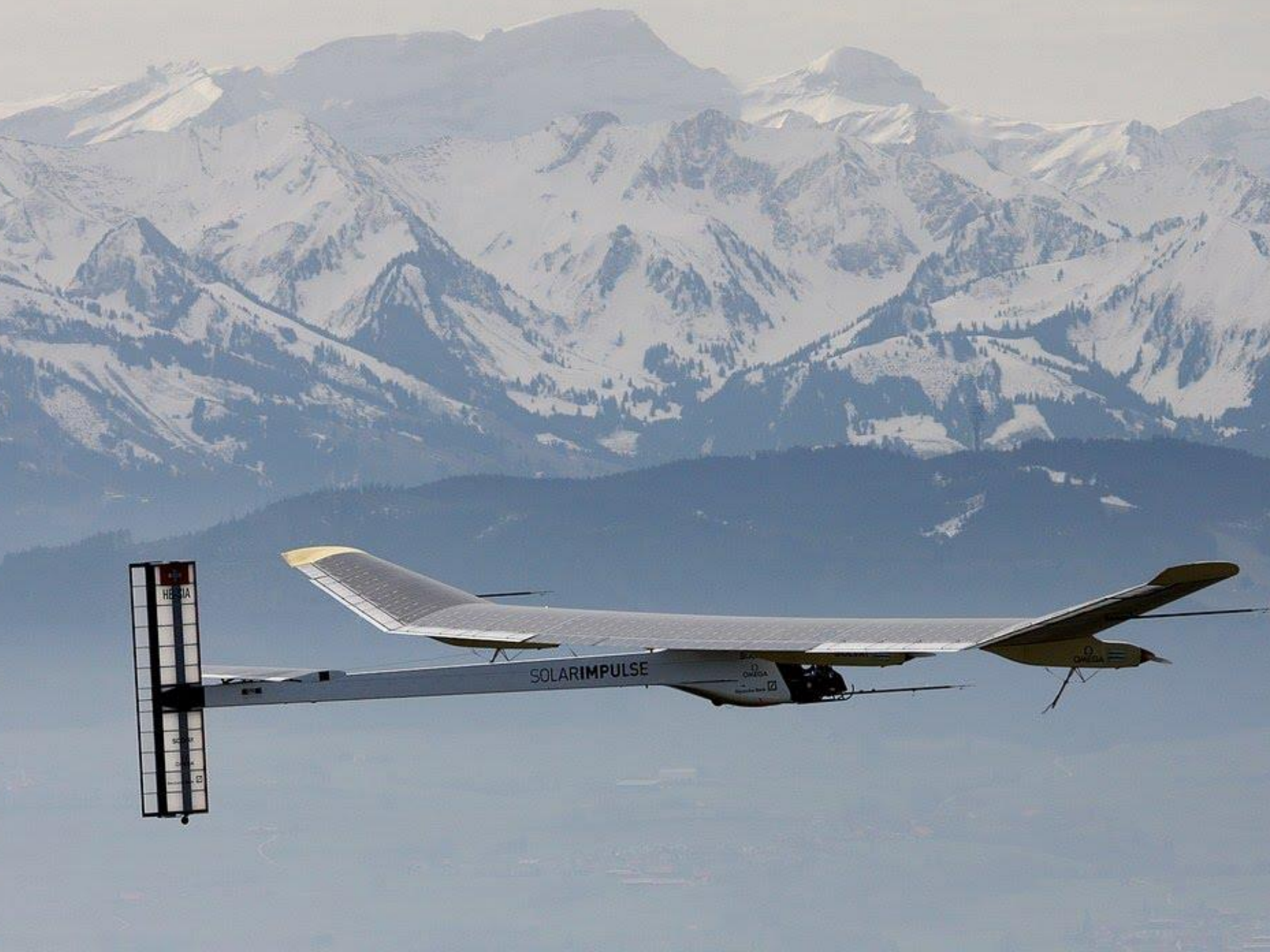


Advertisement photos, such as this one that appeared in the 1956 issue of Look Magazine, show off the "Bell Solar Battery" to the American public.

INTRODUCTION

Brief history of photovoltaics




HELVETIA
SOLARIMPULSE
OMEGA


TAFE
ENGINEERING
UNSW
TAFE


TÛRANOR PlanetSolar

PORTUGAL SOLAR CHALLENGE

INTRODUCTION

Cost of photovoltaics

Cost and **price** are very different, often not even correlated!

There are 3 traditional measures of PV cost:

- Cost per Watt-peak installed
- Levelized cost of electricity
- Grid parity

Morgan Bazilian et al, *Re-considering the Economics of Photovoltaic Power* , et, New Energy Finance working paper 2012

INTRODUCTION

Cost per Watt-peak

Units: **€/W**

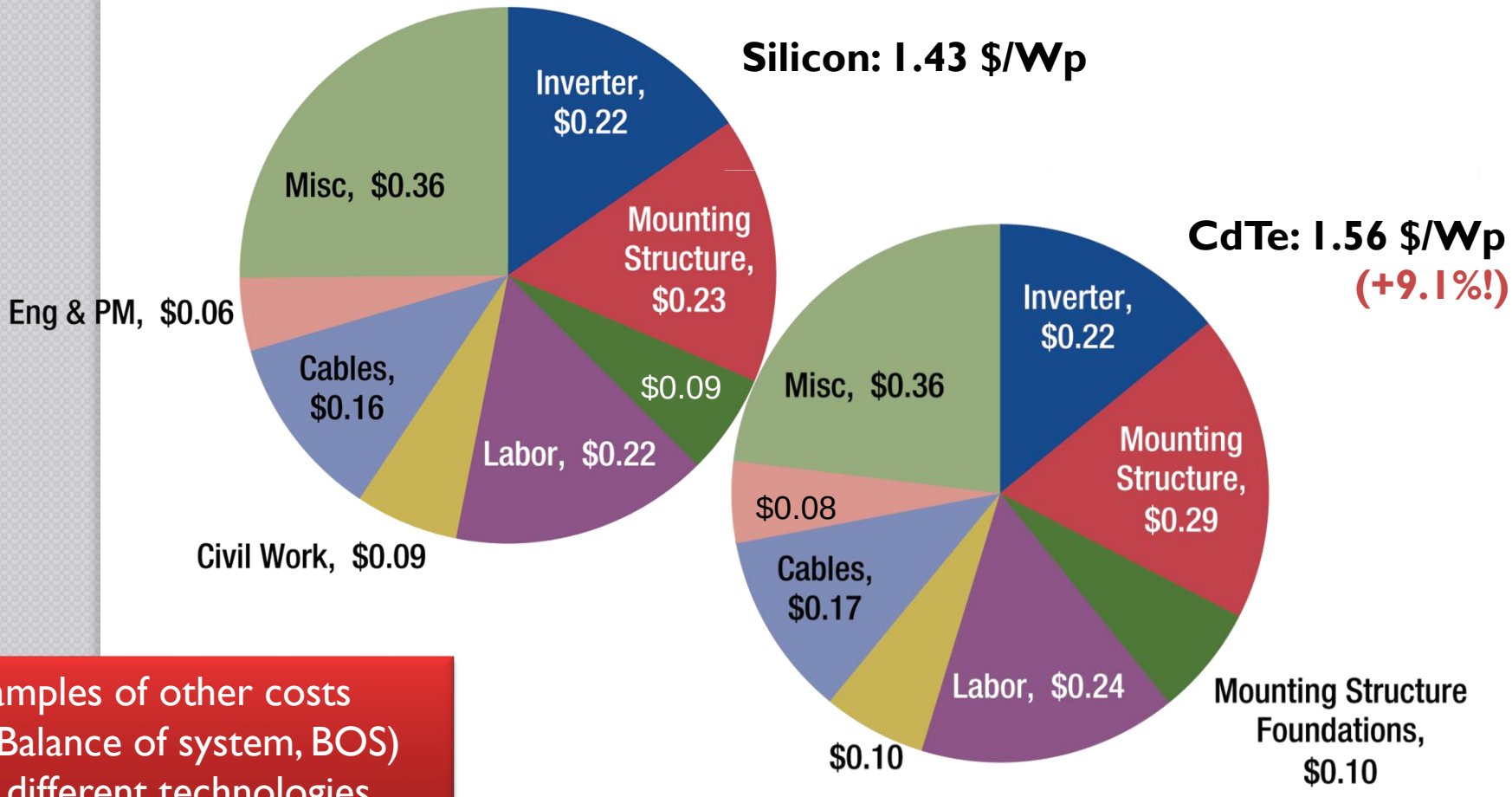
Simple and objective to determine, usually refers to module cost (Spot market? Factory gate? End user?) and thus it does not represent full installation system cost.

It is not comparable to other (renewable or fossil) energy sources due to the different capacity factor.

Comparing different PV technologies not trivial.

INTRODUCTION

Cost per Watt-peak



Examples of other costs (= Balance of system, BOS) for different technologies

INTRODUCTION

Levelized cost of electricity (LCoE)

Units: **€/kWh**

The cost that really matters!

But depends on location (insolation), financial costs (discount rate, subsidies,…) and assumptions on lifetime (25 or 40 years?) or O&M costs (10 or 30$/kW/year)

INTRODUCTION

Grid parity

Electricity prices will increase

PV costs will decrease

… PV **WILL BE** COST COMPETITIVE.

Wholesale or end-user electricity price?

Socket parity – defined as the point where a household can make 5% or more return on investment in a PV system just by using the energy generated to replace household energy consumption.

INTRODUCTION

Grid parity

Electricity prices will increase

PV costs will decrease

… PV **WILL BE** COST COMPETITIVE.

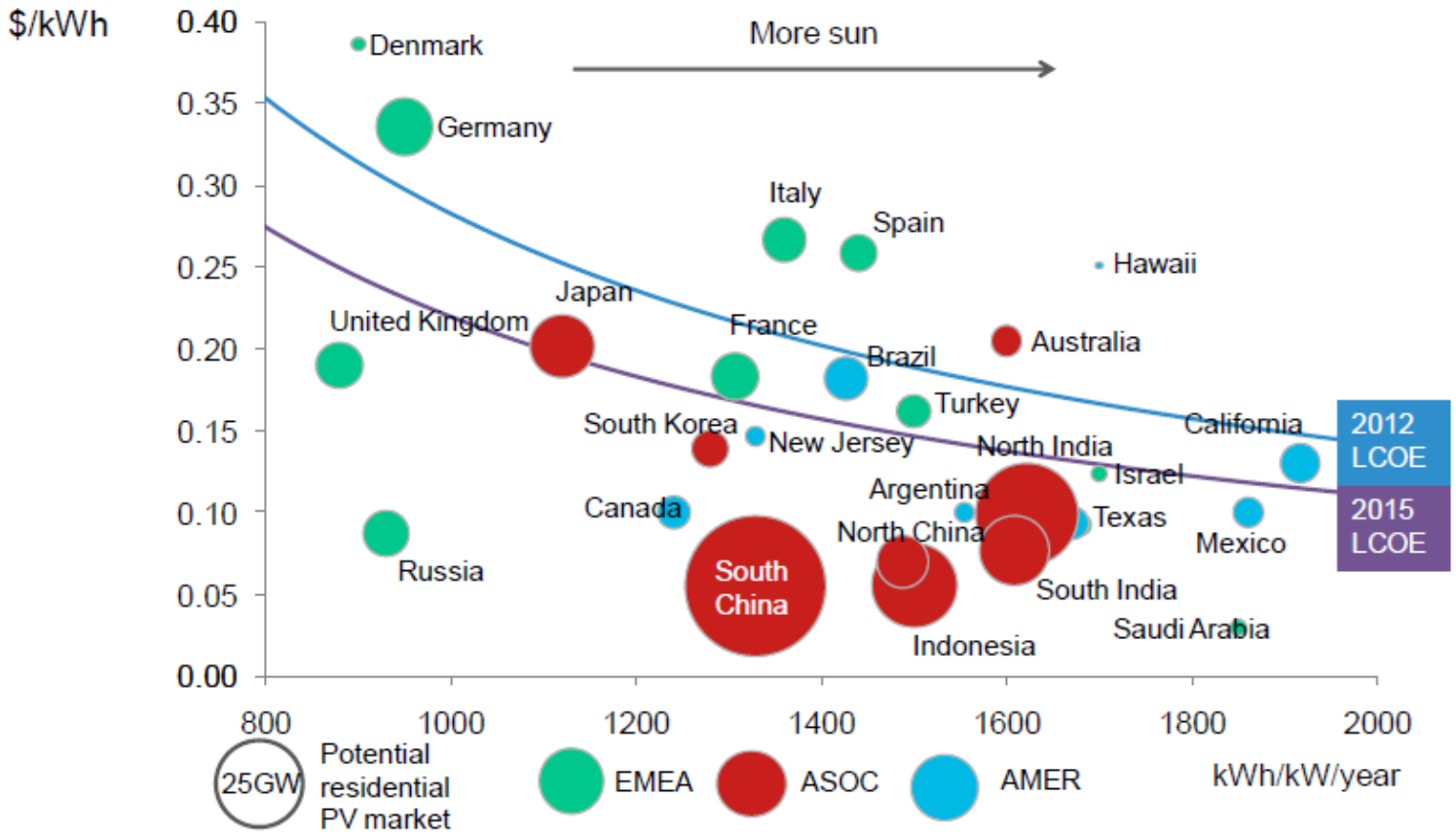
When?

Where?

At what time of the day/year?

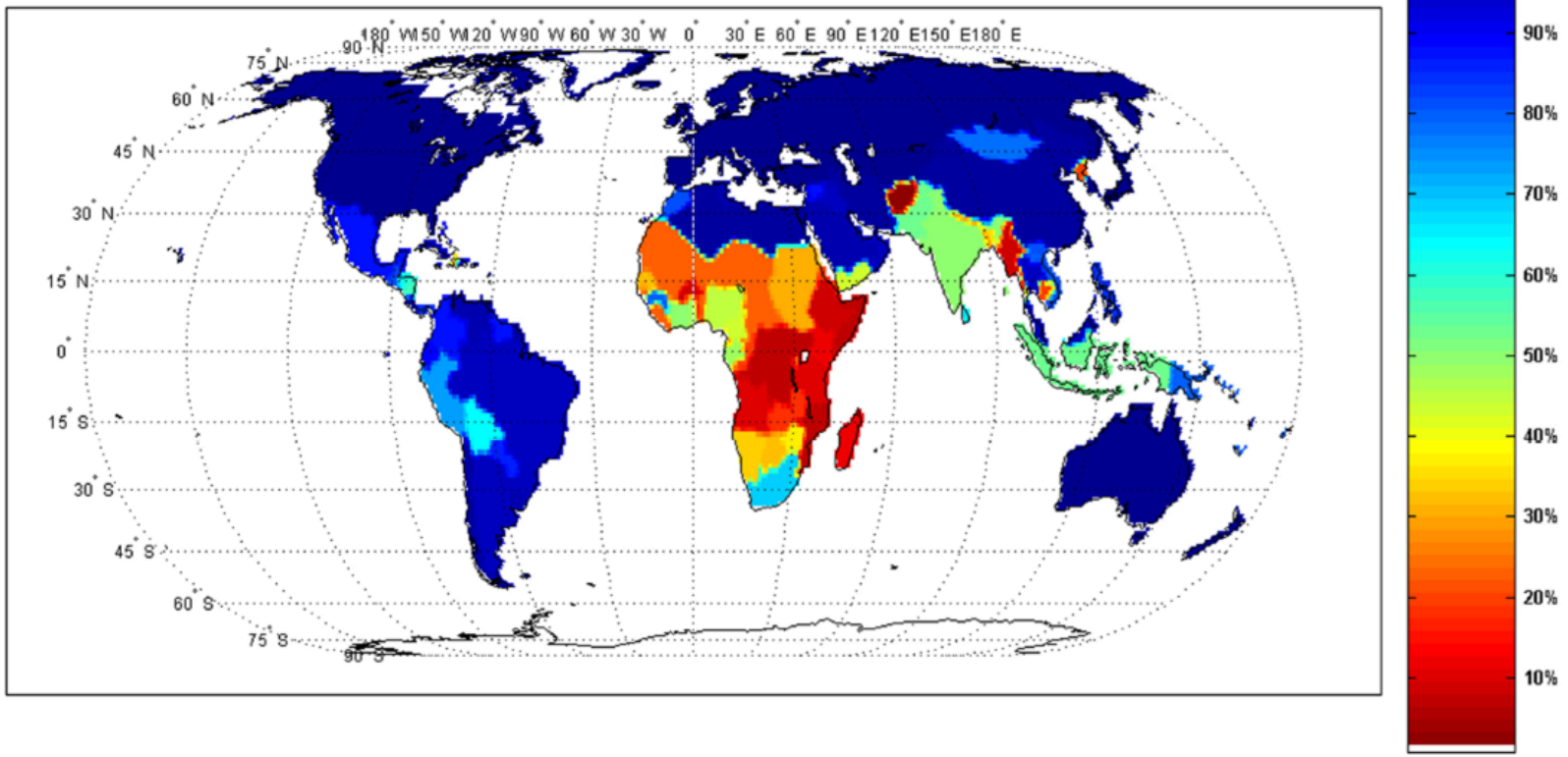
INTRODUCTION

Grid parity



INTRODUCTION

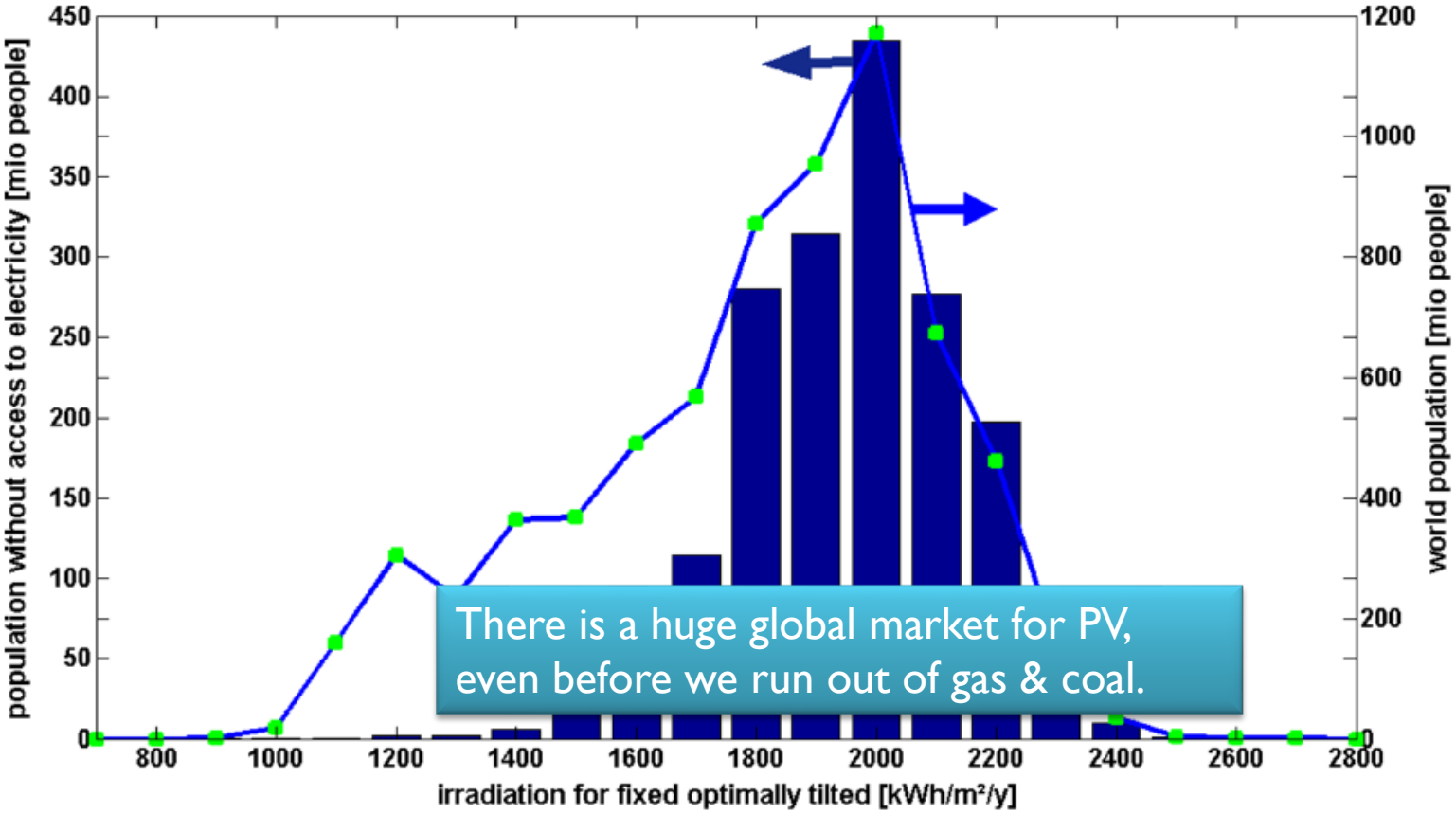
Global access to electricity in percent of local population



Christian Breyer and Alexander Gerlach, *Global overview on grid-parity,* Prog. Photovolt: Res. Appl. (2012) DOI: 10.1002/pip.1254

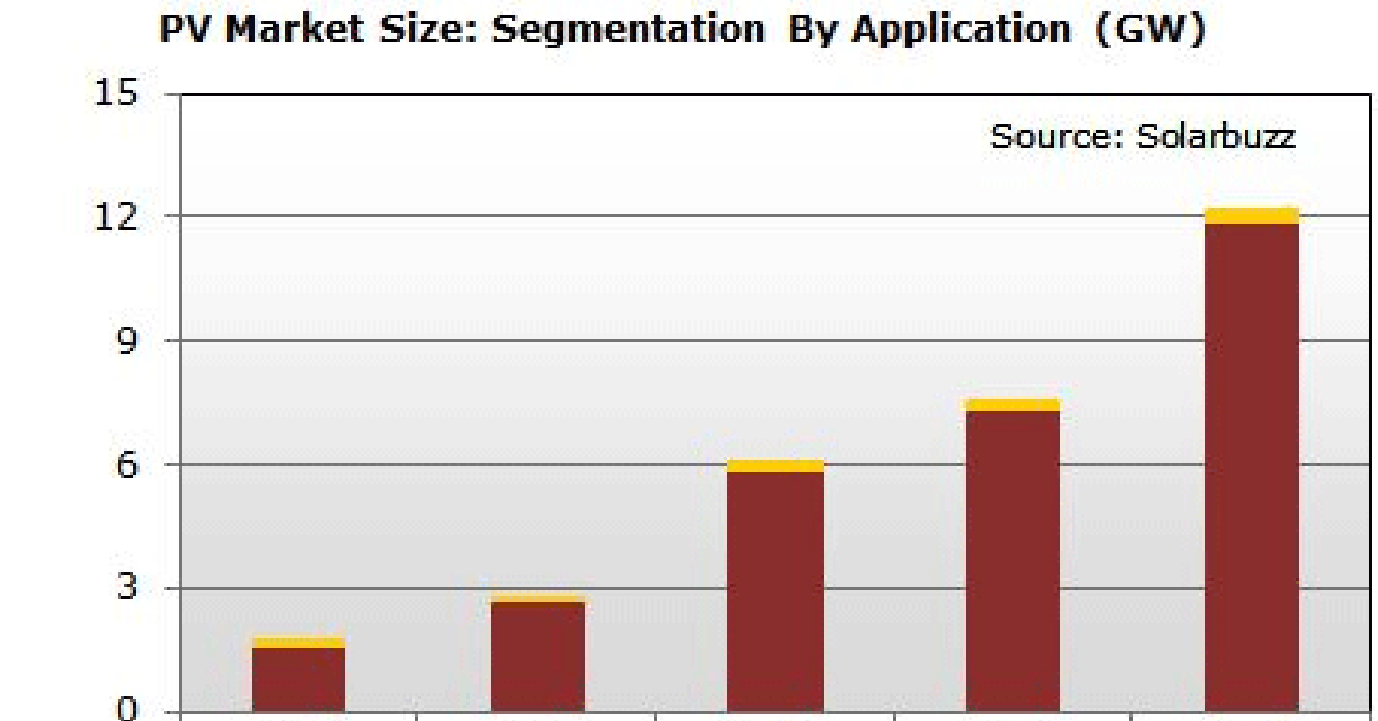
INTRODUCTION

Population without access to electricity and local irradiation



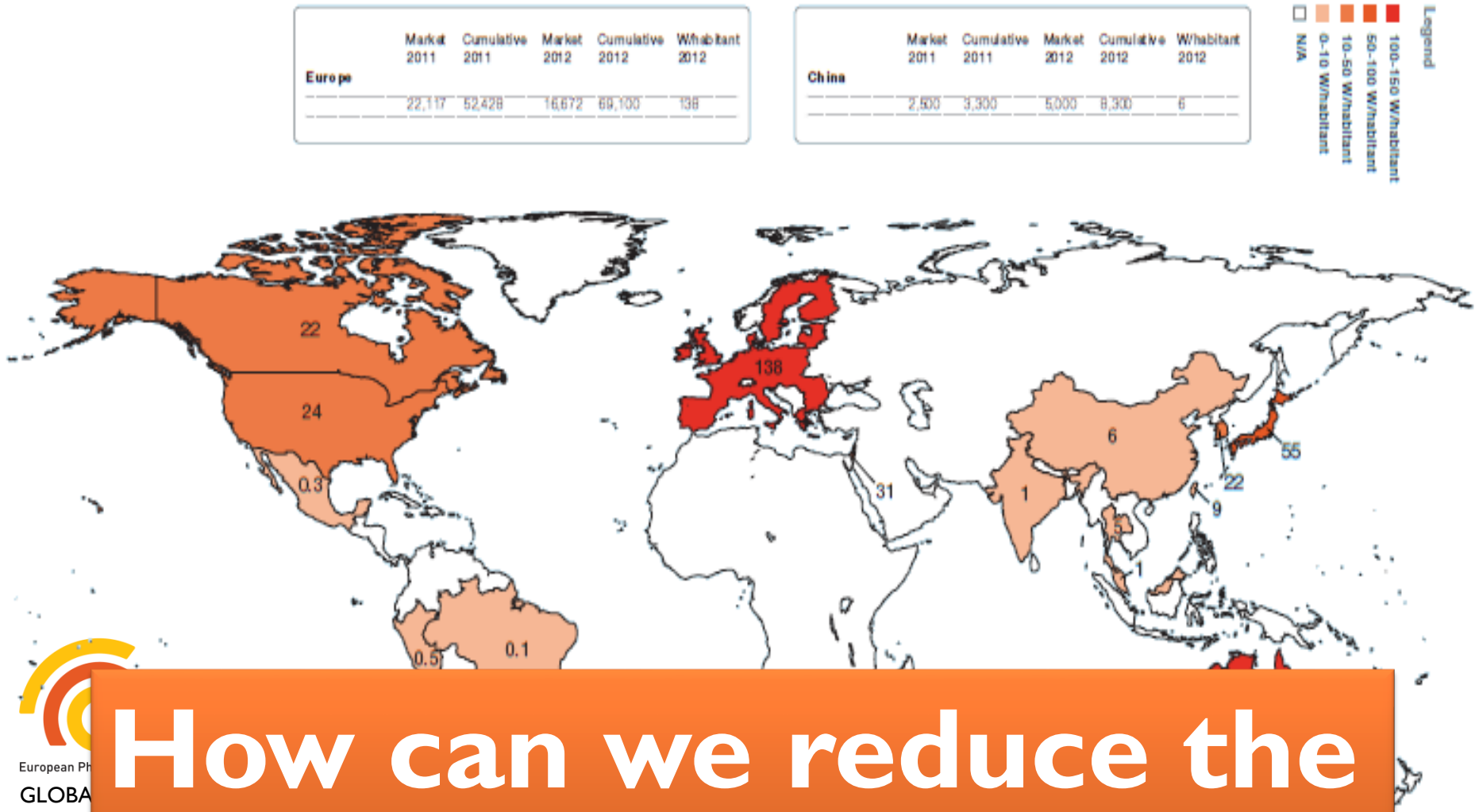
Christian Breyer and Alexander Gerlach, *Global overview on grid-parity,* Prog. Photovolt: Res. Appl. (2012) DOI: 10.1002/pip.1254

INTRODUCTION



	2006	2007	2008	2009	2010
Off-grid	0.19	0.20	0.23	0.28	0.37
On-grid	1.55	2.63	5.85	7.31	11.86

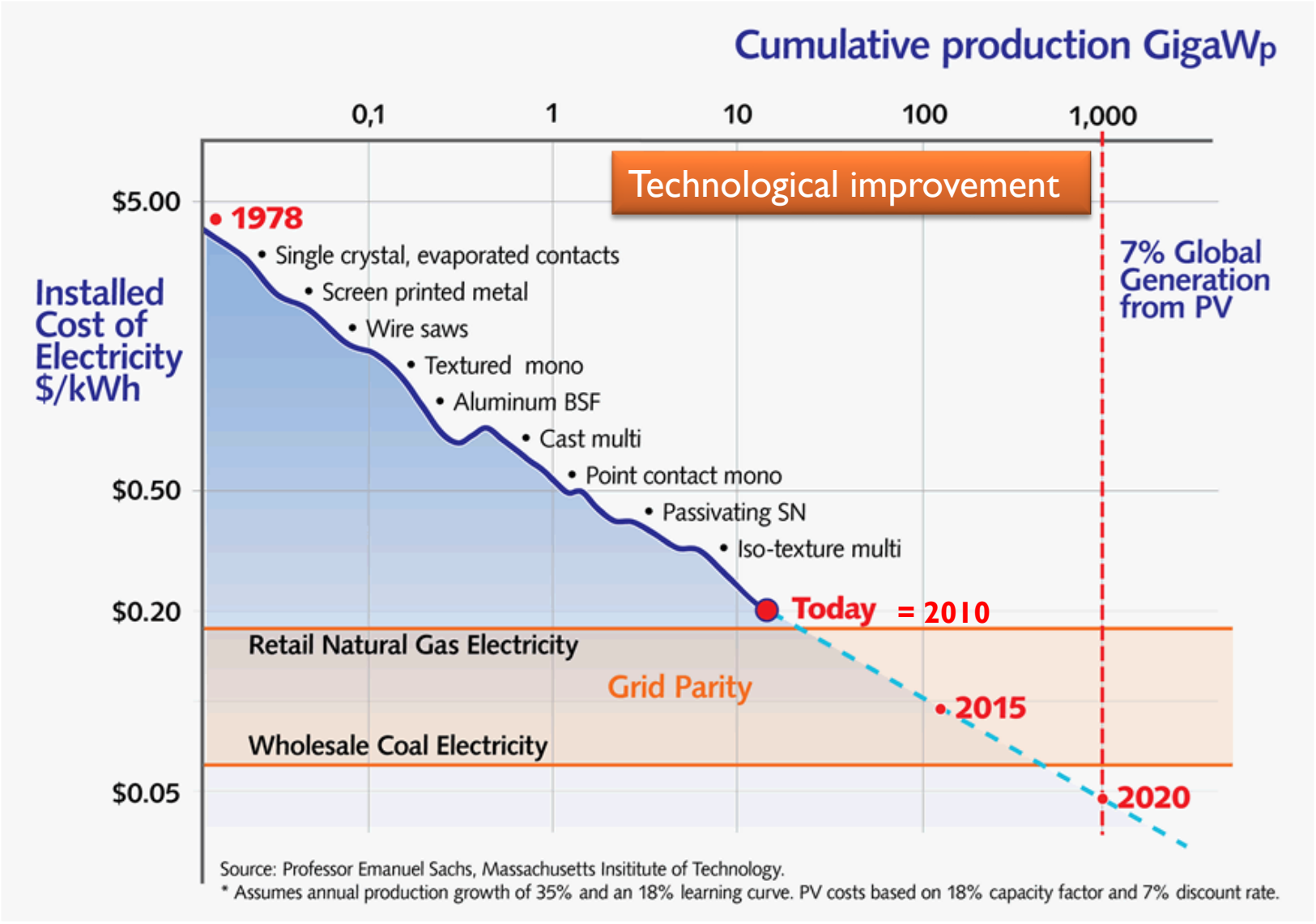
Although the best spots for PV applications are in the developing world, most systems are installed in the **developed** world. Why? Because it is **expensive**!



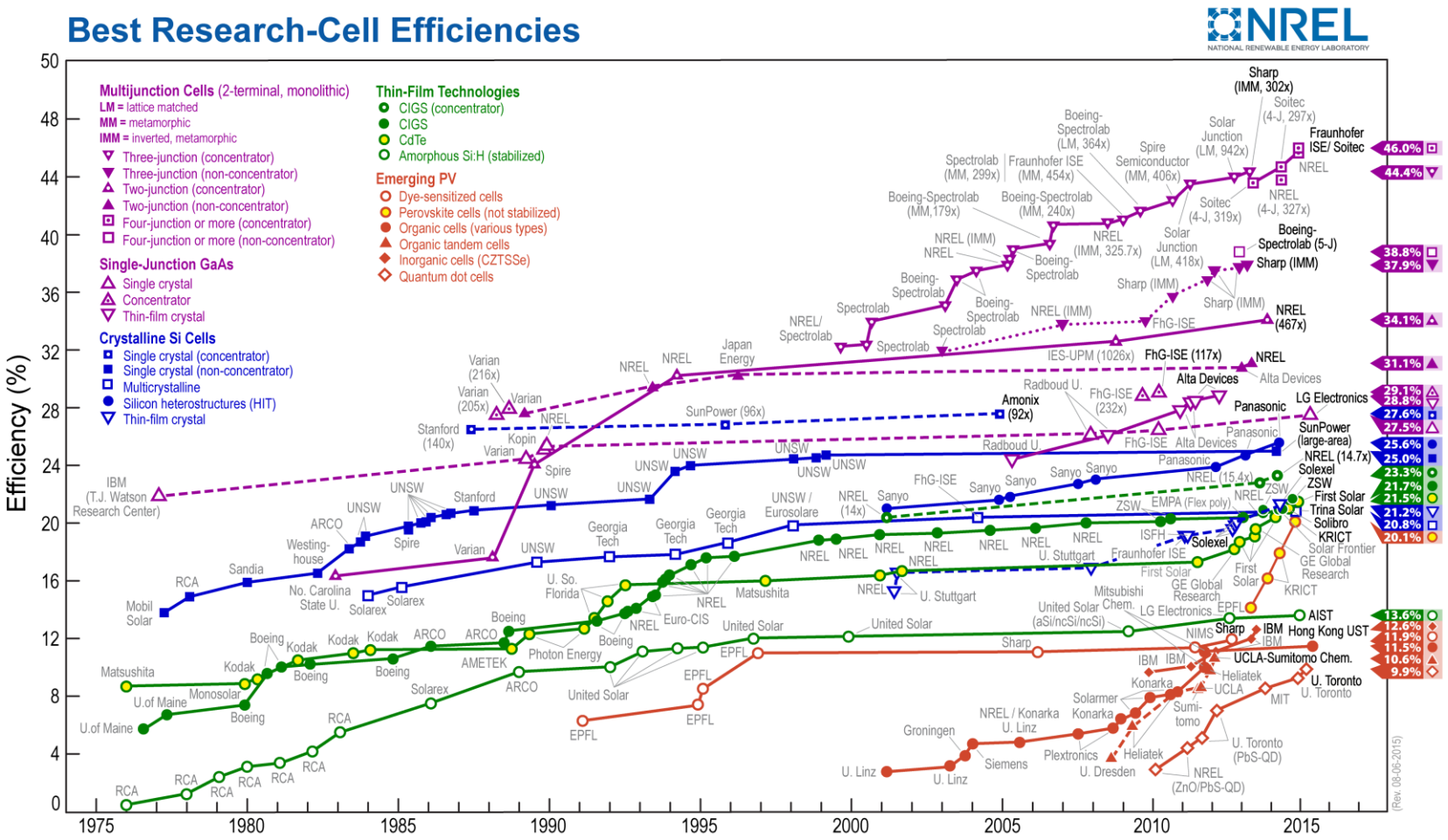
How can we reduce the cost of photovoltaics?

Although the best spots for PV applications are in the developing world, most systems are installed in the **developed** world. Why? Because it is **expensive**!

INTRODUCTION



INTRODUCTION



INTRODUCTION

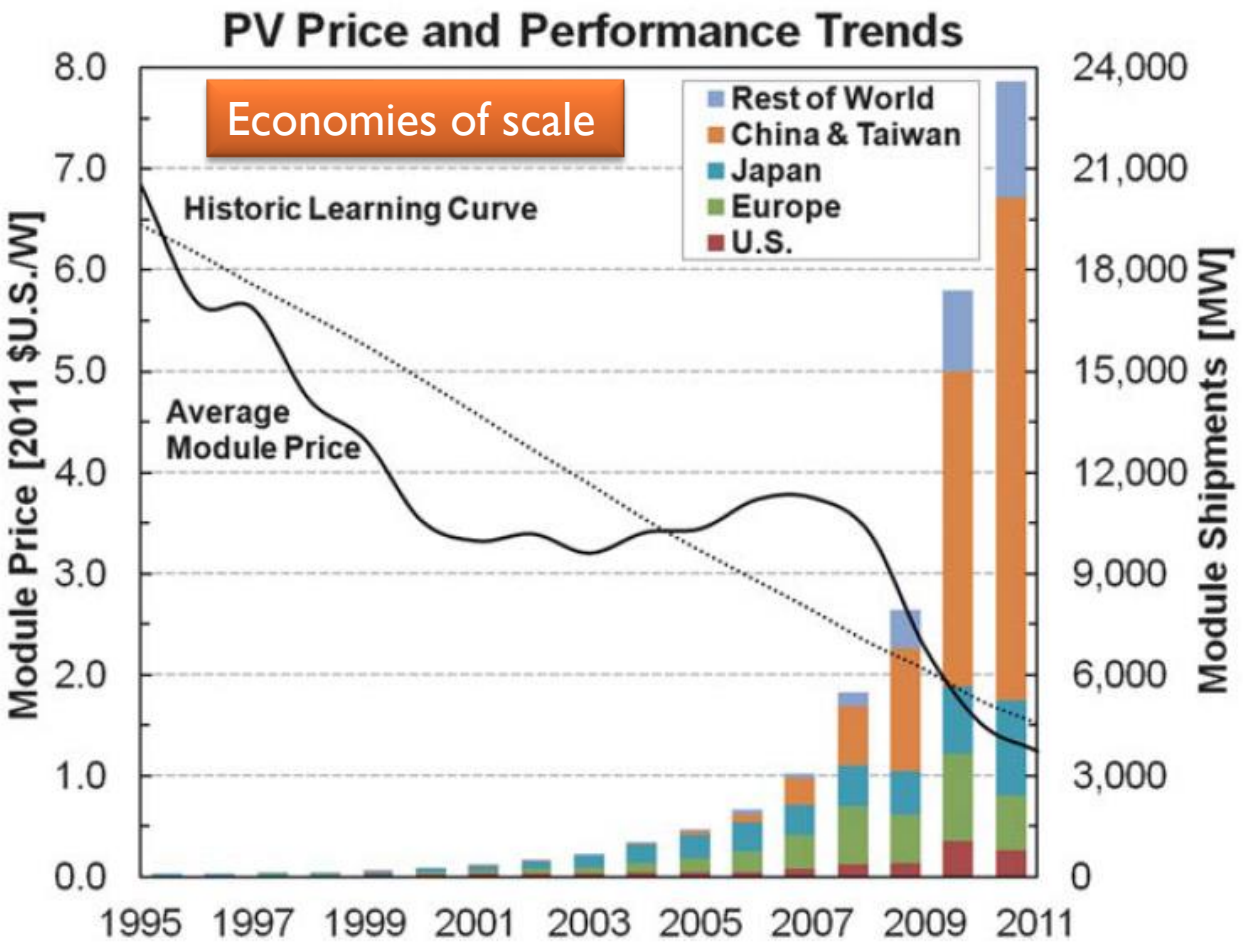
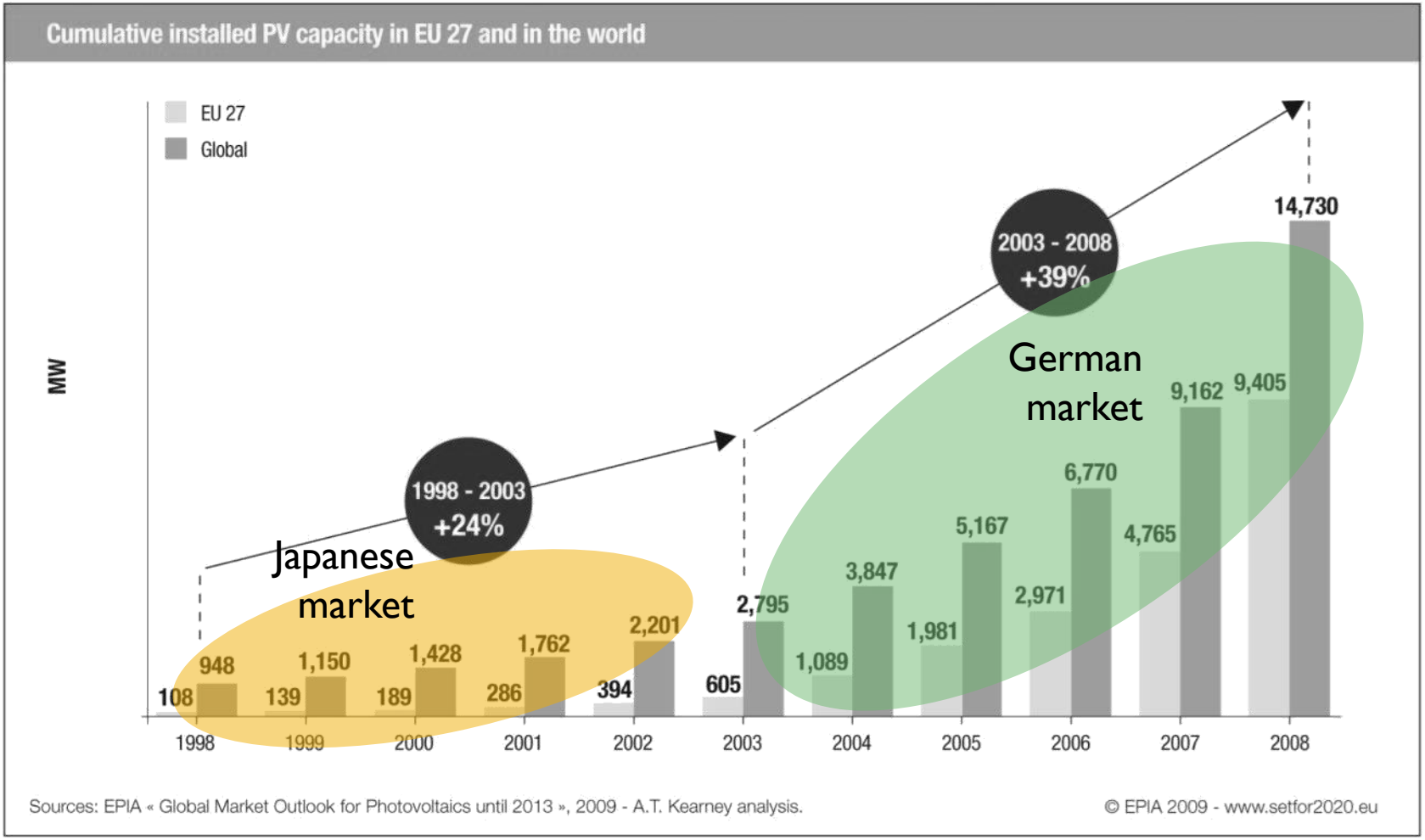


Fig. 1 From 2008 to 2011, reductions in the average global prices of c-Si PV modules have been in line with experience, but the rise of module manufacturing in China and Taiwan has been striking.[6]

INTRODUCTION

Public subsidies for the growth of the PV global market



INTRODUCTION

PV market - Japanese market in 1990s

- **Incentives**: from 9$/W (1994) to 2$/W (2003)
  (1G€ from government + 2G€ from companies)
- High grid **electricity prices** (19c$/kWh)
- Low **interest** rates, low **inflation**, modularity of **construction** industry, large **semiconductor** industry…

Lead to:

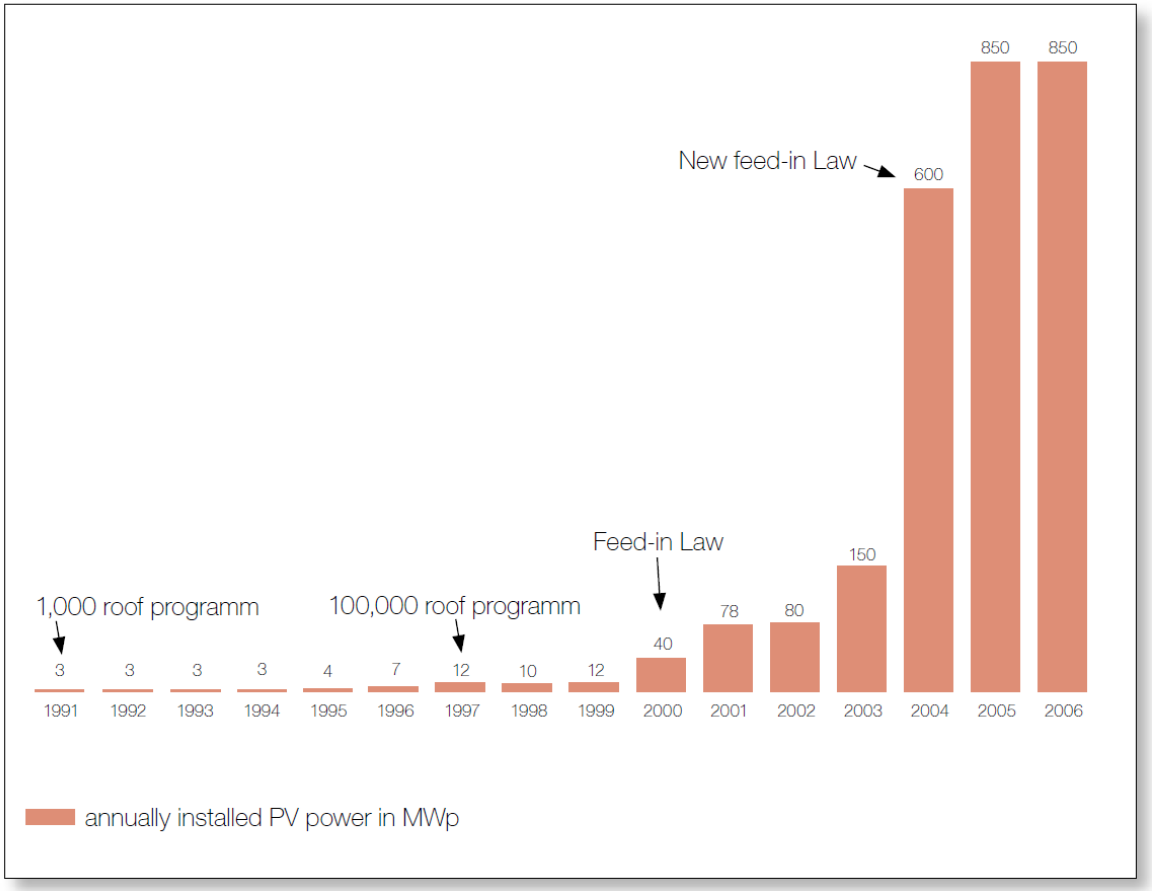
- Rapid decrease in **PV prices**
  (70% decrease from 1994 to 2003)
- 22-fold increase **production** capacity
- 32-fold increase **installed** capacity

M.G. Rogol, *Why did the solar power sector develop quickly in Japan?*, MSc Thesis, MIT 2007

INTRODUCTION

PV market – German market in 2000s

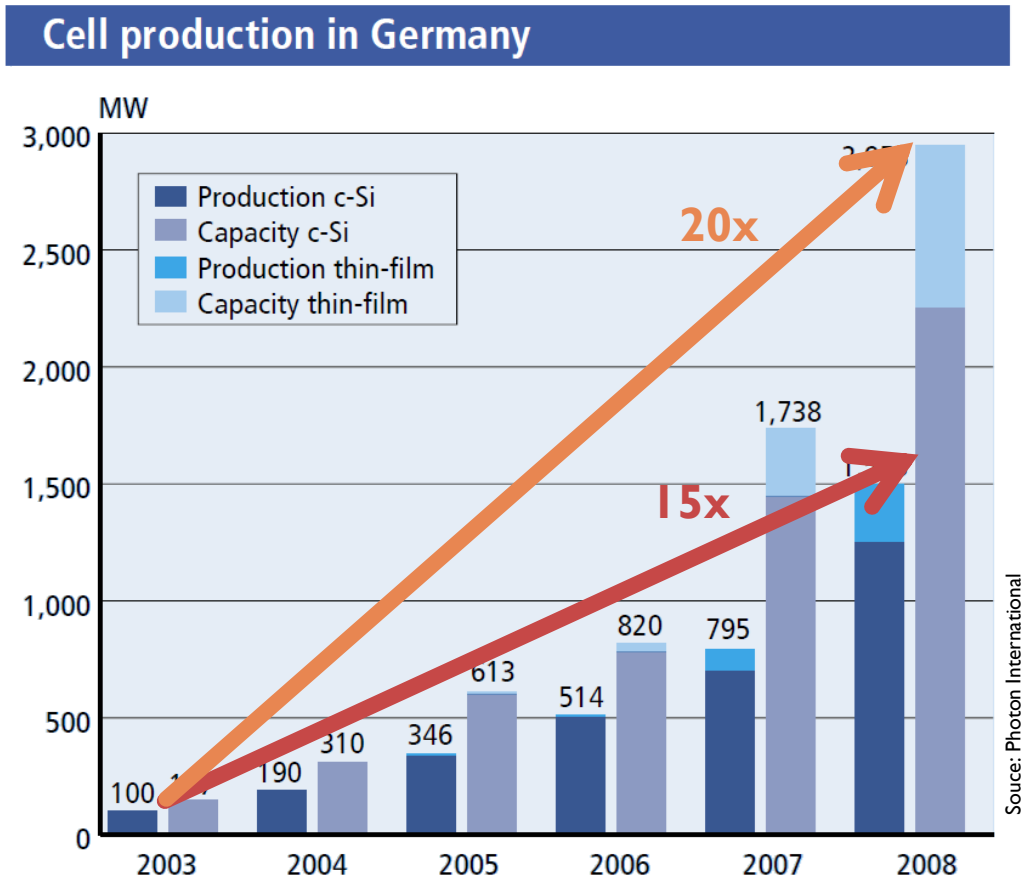
Figure 4: Influence of Feed-in Tariff on annual PV installations in Germany (MWp)



EPIA Brochure: *Supporting Solar Photovoltaic Electricity - An Argument for Feed-in Tariffs*, January 2008

INTRODUCTION

PV market – German market in 2000s



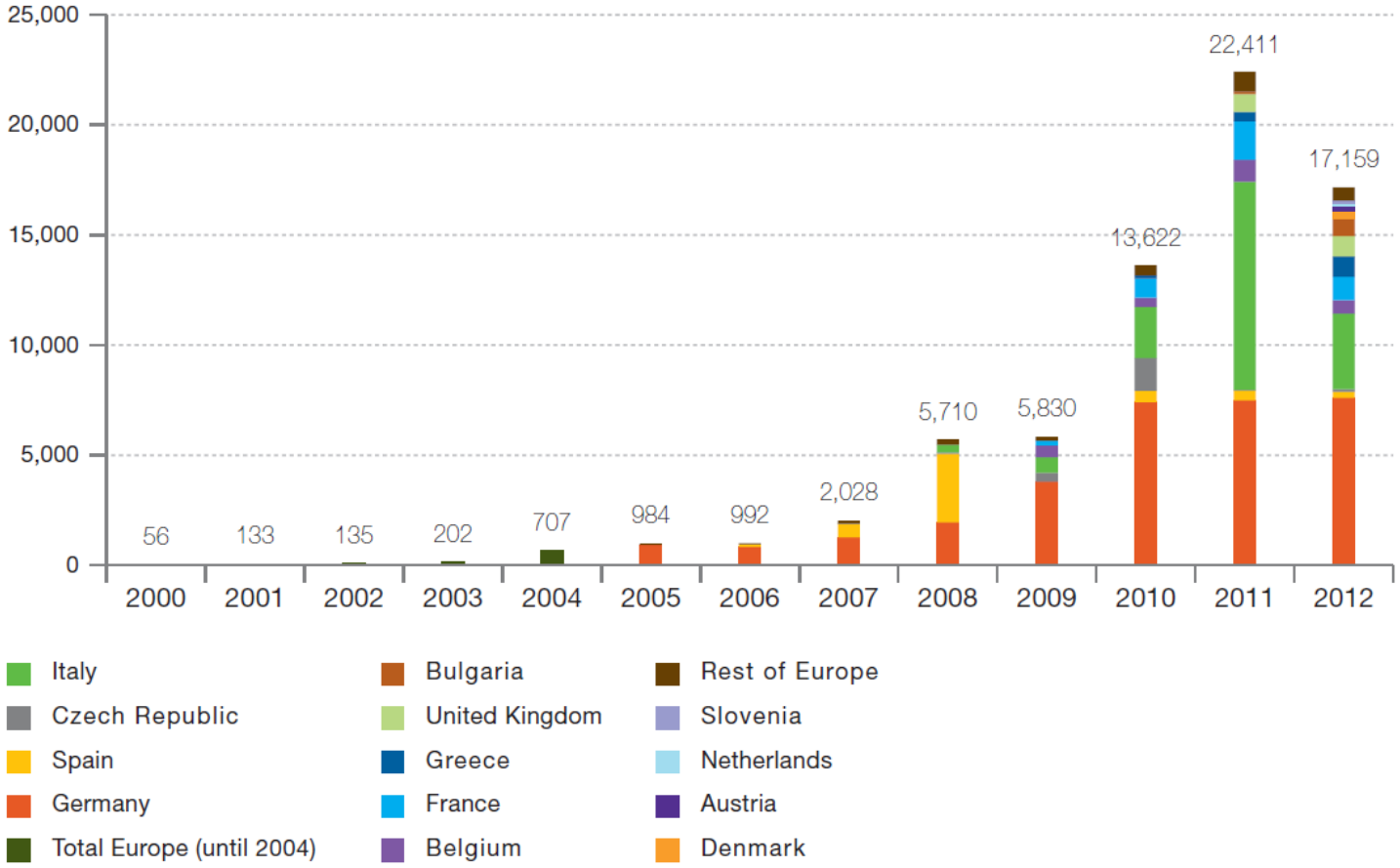
INTRODUCTION

EPIA
European Photovoltaic Industry Association

GLOBAL PV OUTLOOK 2013-2017

German model replicated across Europe, making it the largest world market

Figure 4 - Evolution of European new grid-connected PV capacities 2000-2012 (MW)



INTRODUCTION

PV market – German market in 2000s

- PV electricity production today not relevant for German electricity: <0.5% (2007)
- CO_2 abatement cost: 760€/ton
- Massive invoice to be paid over 20 years: 63T€
- German PV industry deficit: ~50% import
- 205k€/year/new job created

Recommendations:

- Stop feed-in tariff support for PV
- Increase investment into R&D

A. Macintosh, D. Wilkinson, *Searching for public benefits in solar subsidies,* Energy Policy 39 (2011) 3199–3209

M. Frondel, *et al, Germany's solar cell promotion: Dark clouds on the horizon,* Energy Policy 36 (2008) 4198–4204

INTRODUCTION

Spanish market *bubble*

Case study: *what can I do wrong?*

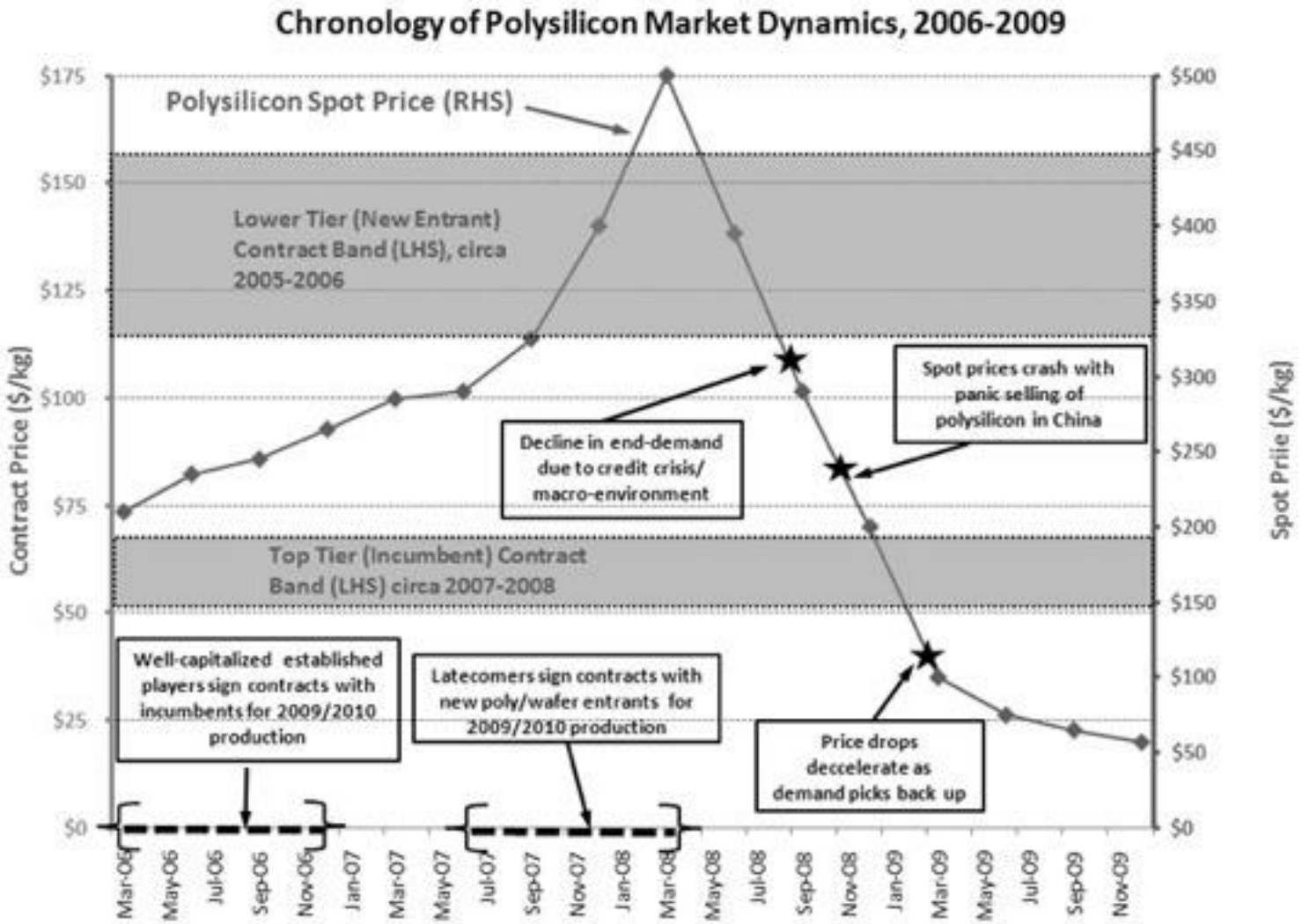
- Generous feed-in tariff
- But no maximum cap
- Overwhelming demand
- Abrupt end
- Fraud
- Huge cost to Spanish government
- Unbalanced demand/suppy for PV industry

INTRODUCTION

Polisilicon feedstock *bubble*

- Increasing demand
- Competition with 'electronic silicon'
- 'Closed' industry (high installation cost, low ramp up) with few players
- Market showed slow reaction time
- Prices skyrockted (spot market: 500$/kg)
- New players, large investments
- New polisilicon technologies window opportunity
- Huge capacity expansion
- Falling prices
- Companies bankrupting.

INTRODUCTION



INTRODUCTION

‘First Solar’ emergence

- Silicon-less technology
- Opportunity window for financial capitals
- Long R&D development
- Lower efficiency but lower cost for high throughput

INTRODUCTION

‘First Solar’ emergence

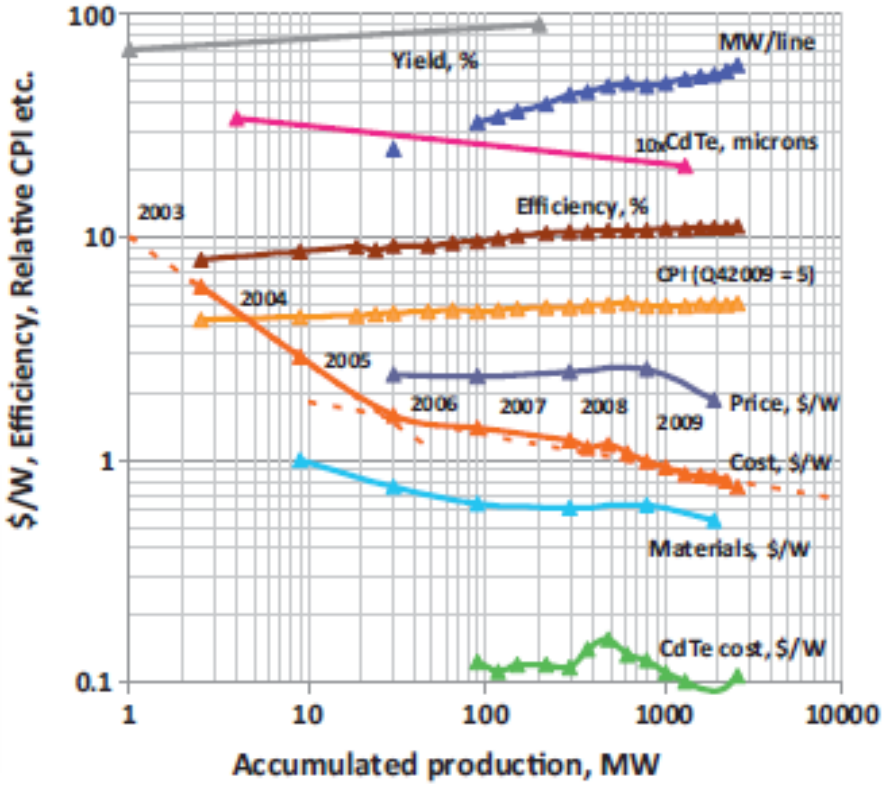


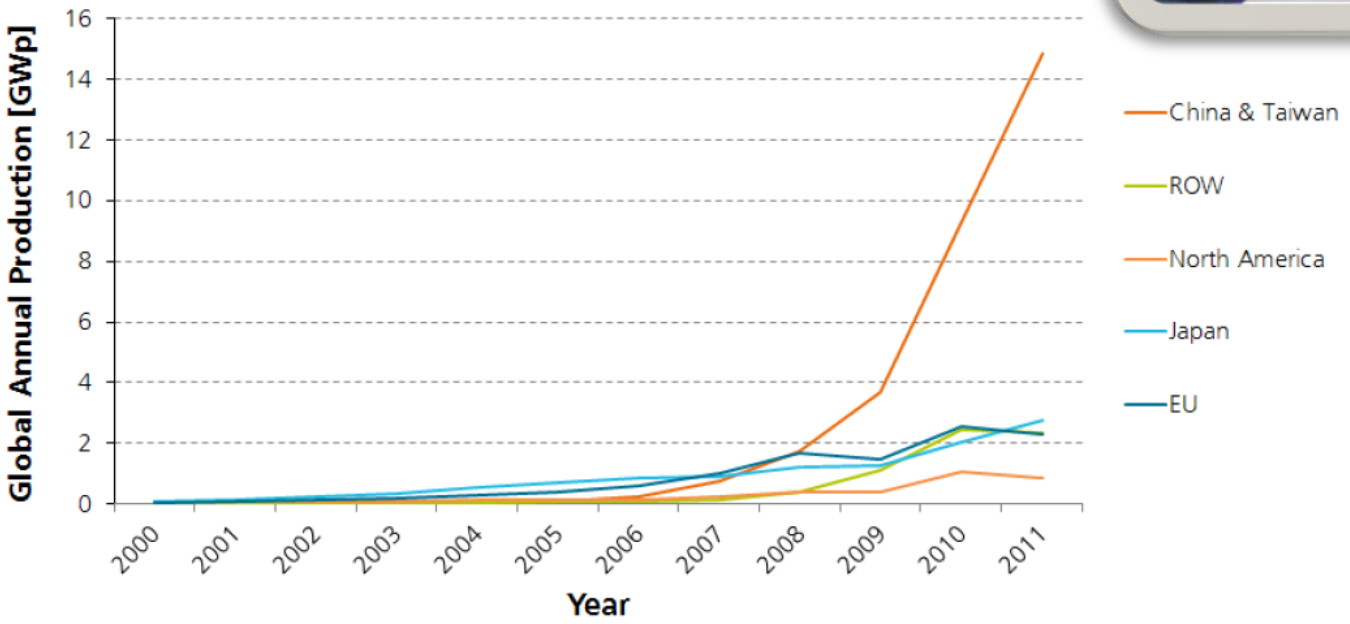
Figure 1. Learning curves for First Solar module yield, throughput (MW/line), CdTe layer thickness, aperture area efficiency (%), average selling price, manufacturing cost, direct material cost and estimated cost of pure CdTe source material (all costs and prices in $/W where the dollars are US dollars of the day). The variation of the consumer price index (CPI) is also shown with the Q4 2009 index arbitrarily set equal to 5.

M. Green, *Learning experience for thin-film solar modules: First Solar, Inc. case study,* Prog. Photovolt: Res. Appl. (2010) DOI: 10.1002/pip.1057

INTRODUCTION

Emergence of PV industry in China

PV Industry Production by Region (2000-2011)



Data: Navigant Consulting Graph: PSE AG 2012

INTRODUCTION

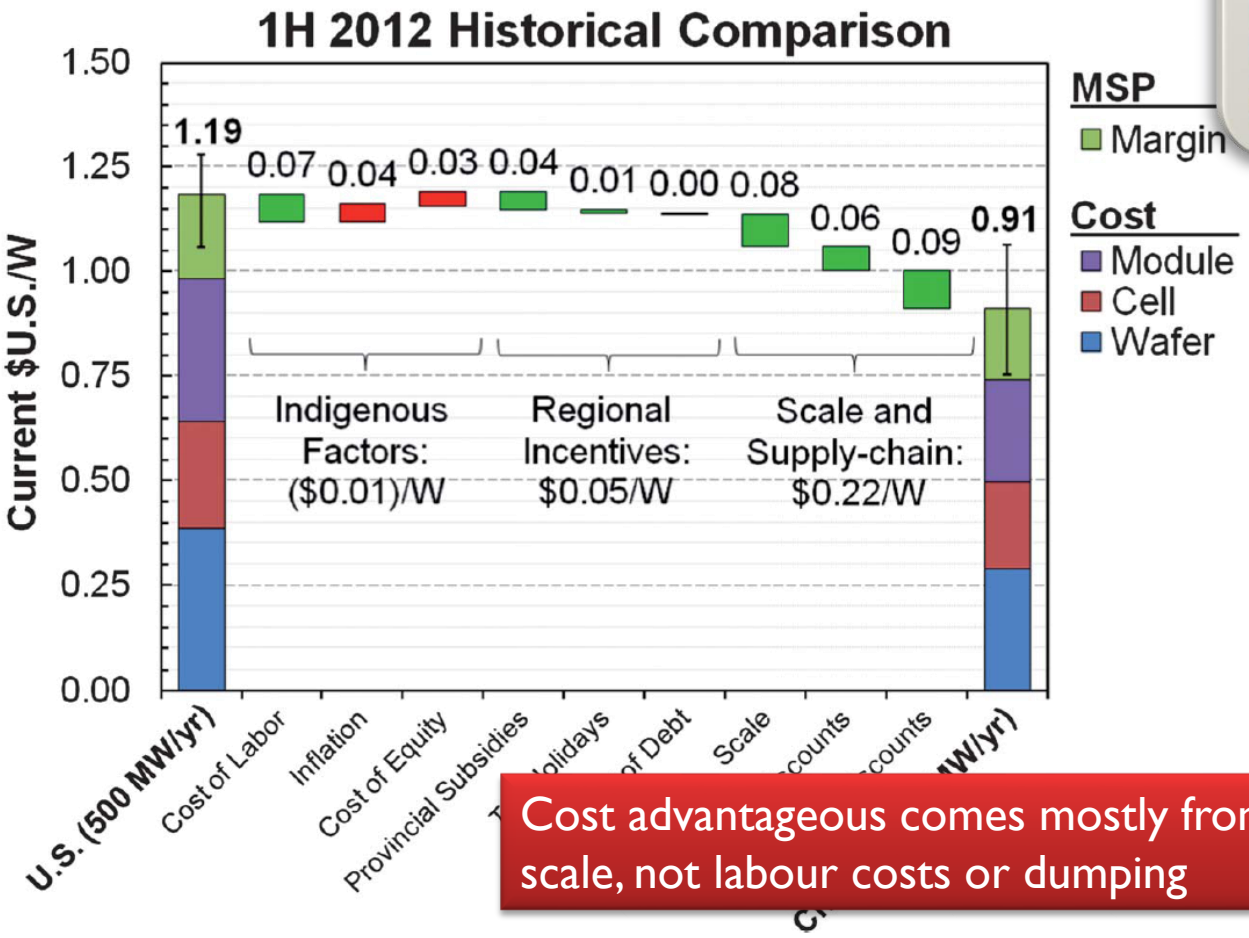
Emergence of PV industry in China

Timeline of PV development in China

1. Low cost silicon wafers, cells and modules for the German (and other EU) market(s)
1. Stricter environmental and comparable quality products
2. Large scale and innovation
3. Creation of an internal market

INTRODUCTION

Emergence of PV industry in China



Cost advantageous comes mostly from economies of scale, not labour costs or dumping

INTRODUCTION

The Washington Post

In the News | Rick Perry | Wisconsin recall | Pierre de Fermat | Sherlock Holmes | PlayStation 3

washingtonpost.com > Business

POST BUSINESS | Japan tsunami spares major economic zones

Solar Energy Firms Leave Waste Behind in China

By Ariana Eunjung Cha
Washington Post Foreign Service
Sunday, March 9, 2008

GAOLONG, China -- The first time Li Gengxuan saw the dump trucks from the nearby factory pull into his village, he couldn't believe what happened. Stopping between the cornfields and the primary school playground, the workers dumped buckets of bubbling white liquid onto the ground. Then they turned around and drove right back through the gates of their compound without a word.

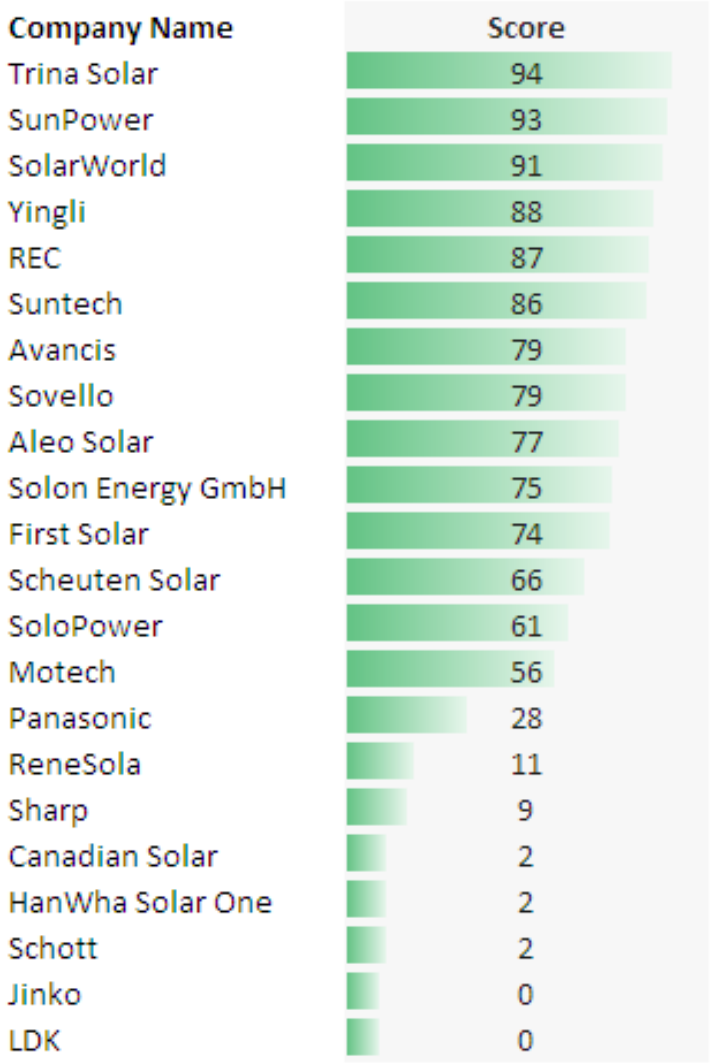
This ritual has been going on almost every day for nine months, Li and other villagers said.

PHOTOS Previous Next

"It's poison air. Sometimes it gets so bad you can't sit outside. You have to close all the doors and windows," says Qiao Shi Peng, 28, shown in front of a dumping site in his village, who worries about his 1-year-old son's health. (Zhang Quanfeng - Photo By Zhang Quanfeng)

But has been blamed on **environmental** record!

INTRODUCTION



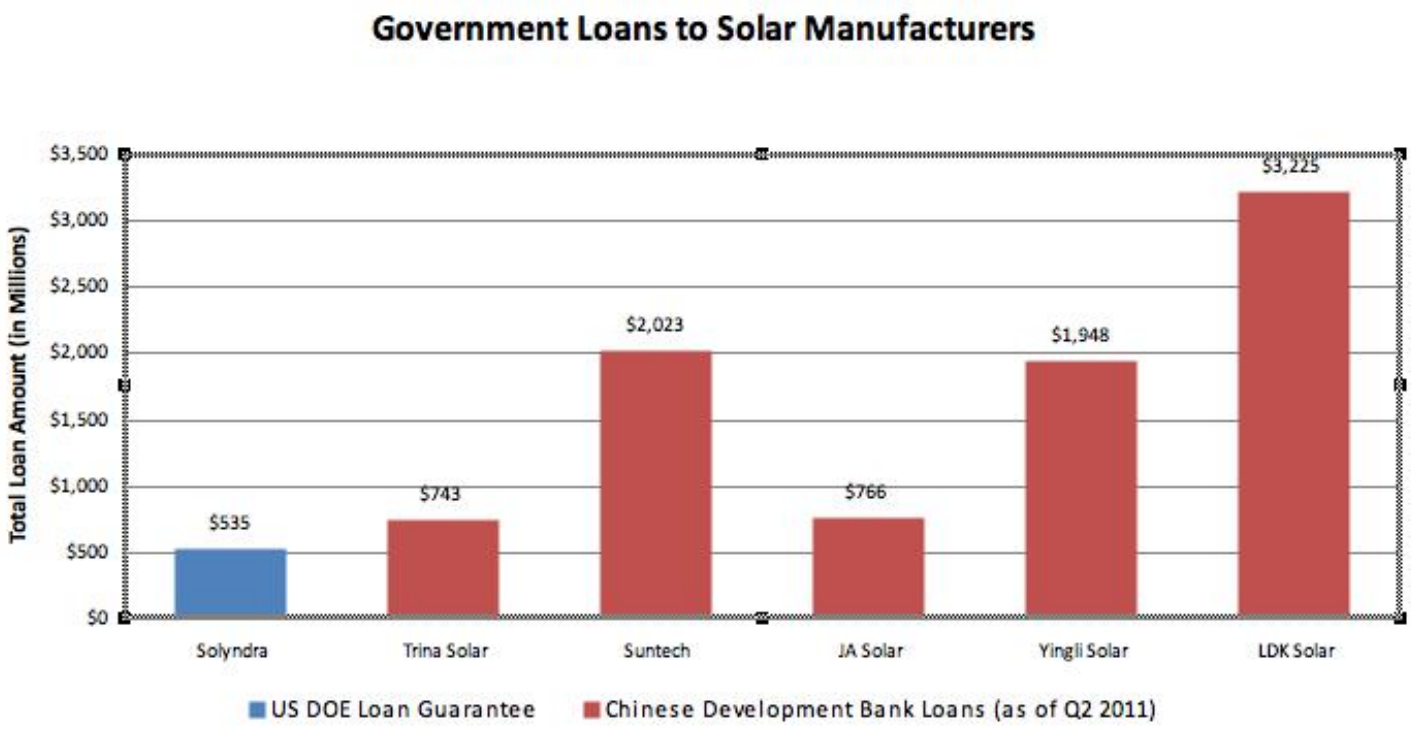
Company Name	Score
Trina Solar	94
SunPower	93
SolarWorld	91
Yingli	88
REC	87
Suntech	86
Avancis	79
Sovello	79
Aleo Solar	77
Solon Energy GmbH	75
First Solar	74
Scheuten Solar	66
SoloPower	61
Motech	56
Panasonic	28
ReneSola	11
Sharp	9
Canadian Solar	2
HanWha Solar One	2
Schott	2
Jinko	0
LDK	0

2012 SOLAR SCORECARD

SOLARSCORECARD.COM | A PROJECT OF THE SILICON VALLEY TOXICS COALITION

INTRODUCTION

And has been blamed on **dumping**…



INTRODUCTION

SOLAR

Share Tweet 0 2

UCILIA WANG: AUGUST 19, 2009

Suntech Claims New World Record in Silicon Panel Efficiency

The Fraunhofer Institute verifies that a Suntech Power multicrystalline silicon panel has beaten Sandia's record. Suntech intends to have a 300MW capacity to produce its new Pluto cells and panels in 2010.

Suntech Power said Wednesday it now holds the world record in producing the most efficiency multicrystalline silicon panels, beating a record previously held by Sandia National Laboratories.

A panel sporting the company's newly developed Pluto cells was able to convert 15.6 percent of the sunlight that strike it into electricity, Suntech said.

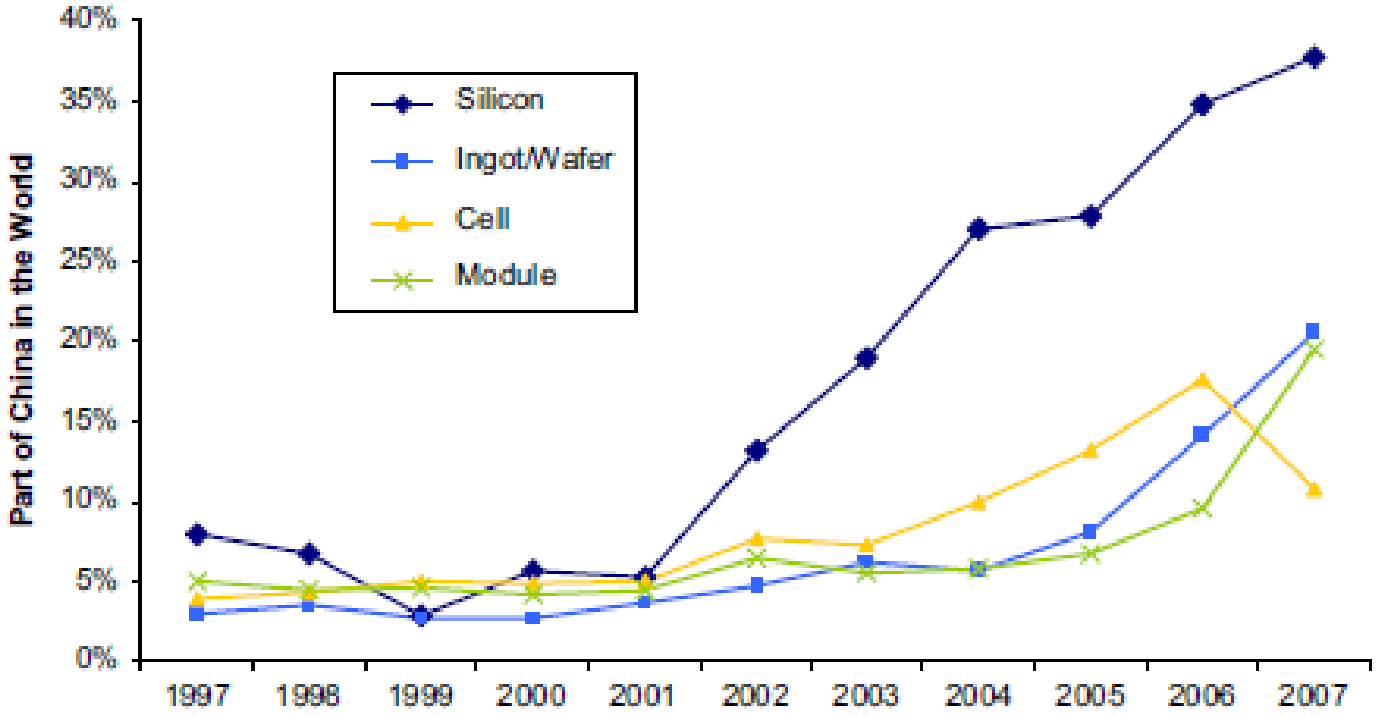
The Fraunhofer Institute of Solar Energy Systems in Germany, one of the few labs in the world whose test results are recognized by the industry, verified the efficiency of the panel. The panel rolled off a new factory line China-based Suntech set up to start shipping Pluto panels earlier this year.

The new record will be included by the science journal **Progress in Photovoltaics** (PIP) that periodically publishes a list of record-holding efficiency for different types of solar cells and panels.

Yet, the answer is also **innovation**!

INTRODUCTION

Emergence of PV industry in China

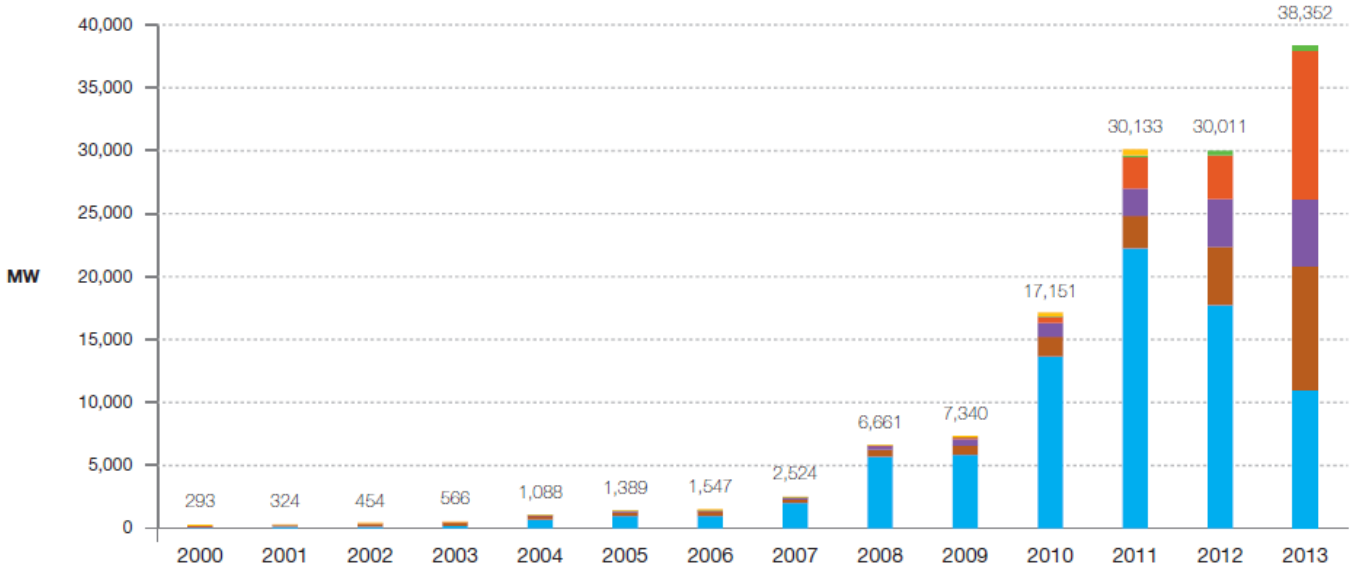


Share of China in world innovation in each segment of the PV industry [A. de la Tour *et al*, 2011]

INTRODUCTION

Emergence of PV industry in China

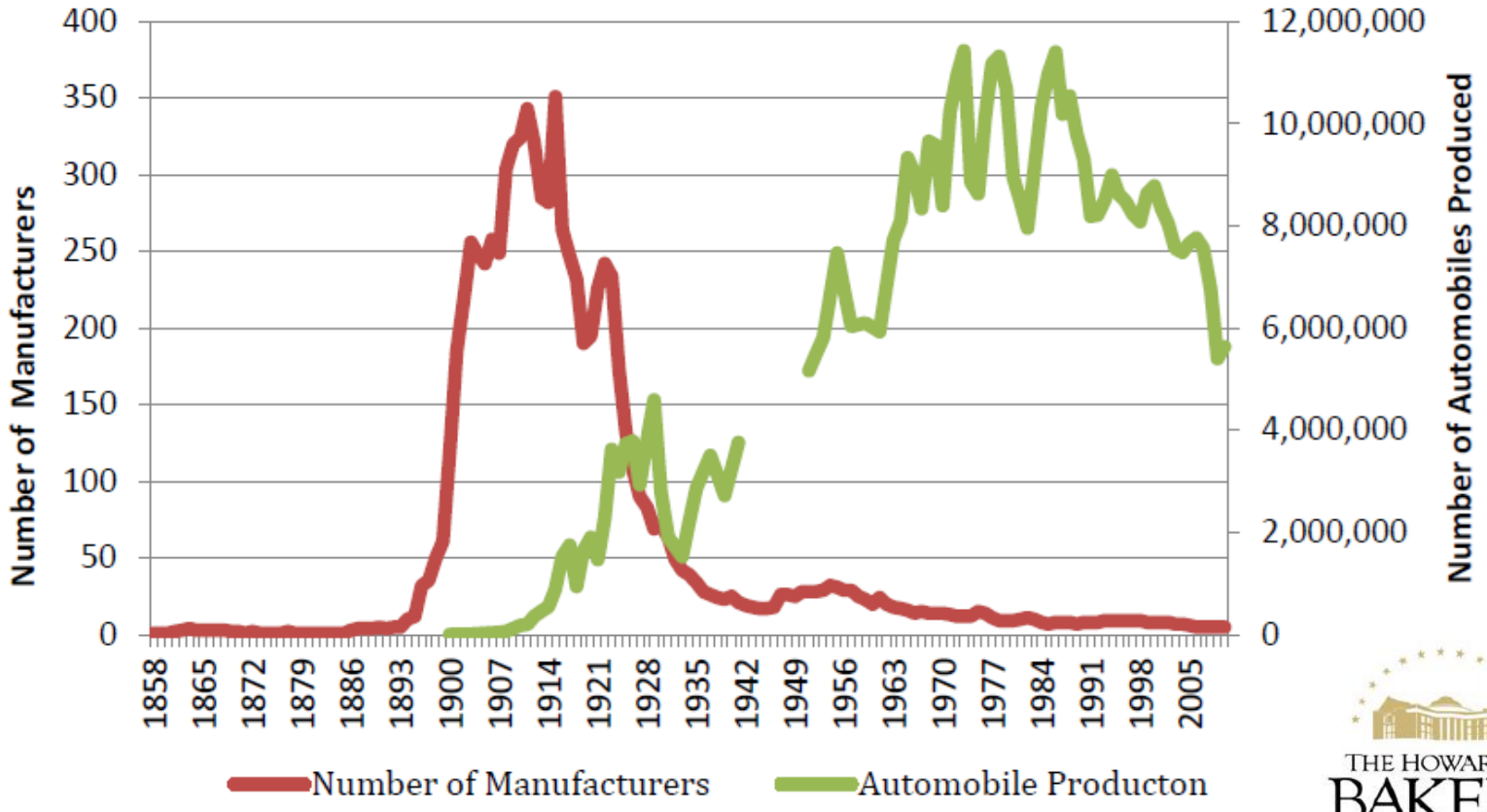
The fastest increasing PV market



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
RoW	88	56	80	77	29	10	105	42	76	80	284	508	n/a	n/a
MEA	n/a	n/a	n/a	n/a	1	0	0	1	1	22	55	125	365	383
China	19	5	19	10	10	8	10	20	40	160	500	2,500	3,500	11,800*
Americas	2	3	30	48	61	82	110	166	306	500	1,082	2,181	3,774	5,362
APAC	126	128	190	230	282	304	325	271	530	745	1,578	2,562	4,646	9,833
Europe	58	133	134	202	705	985	997	2,023	5,708	5,833	13,651	22,259	17,726	10,975
Total	**293**	**324**	**454**	**566**	**1,088**	**1,389**	**1,547**	**2,524**	**6,661**	**7,340**	**17,151**	**30,133**	**30,011**	**38,352**

INTRODUCTION

Consolidation of the global PV industry

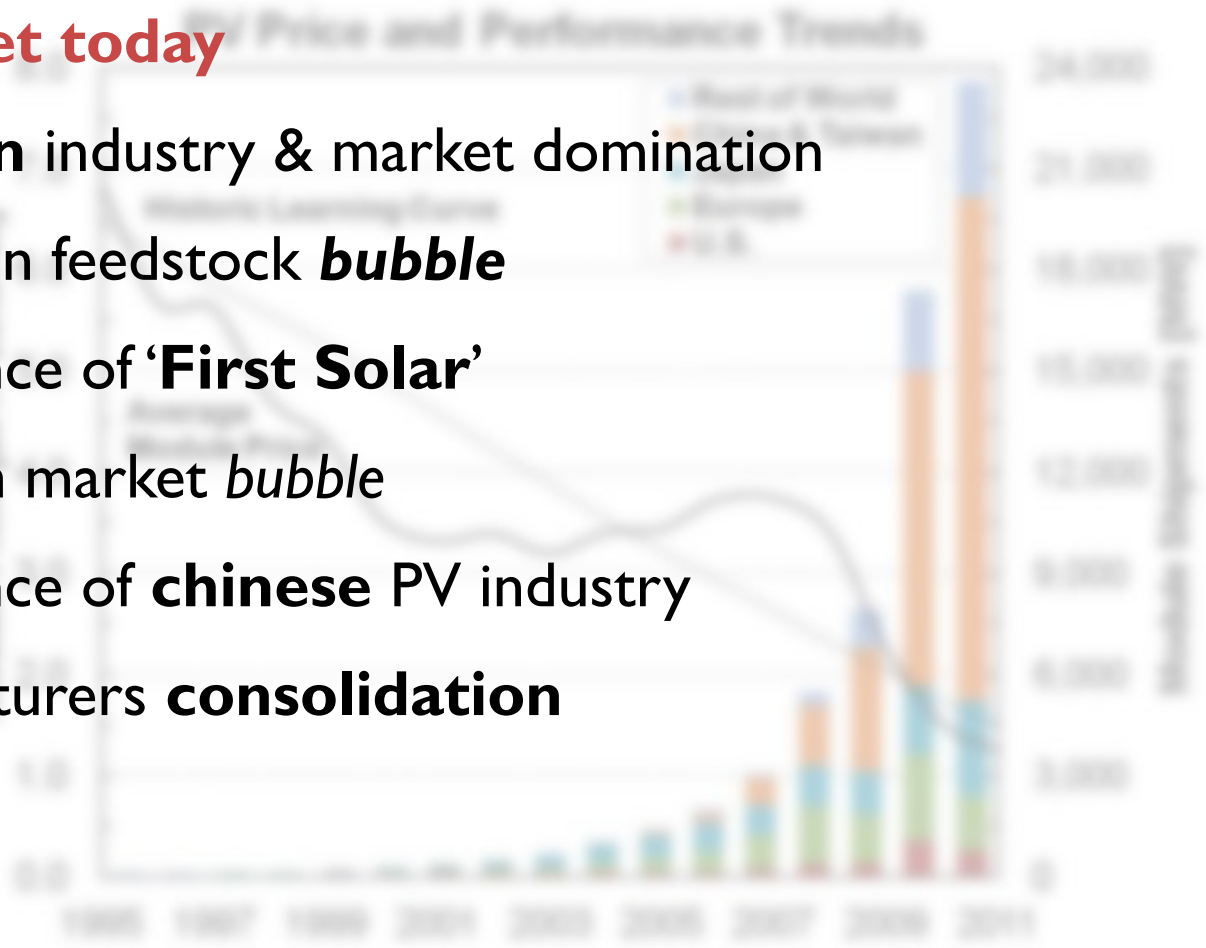


THE HOWARD H. BAKER JR CENTER for PUBLIC POLICY
THE UNIVERSITY of TENNESSEE KNOXVILLE

INTRODUCTION

PV market today

- **German** industry & market domination
- Polisilicon feedstock ***bubble***
- Emergence of '**First Solar**'
- **Spanish** market *bubble*
- Emergence of **chinese** PV industry
- Manufacturers **consolidation**



INTRODUCTION

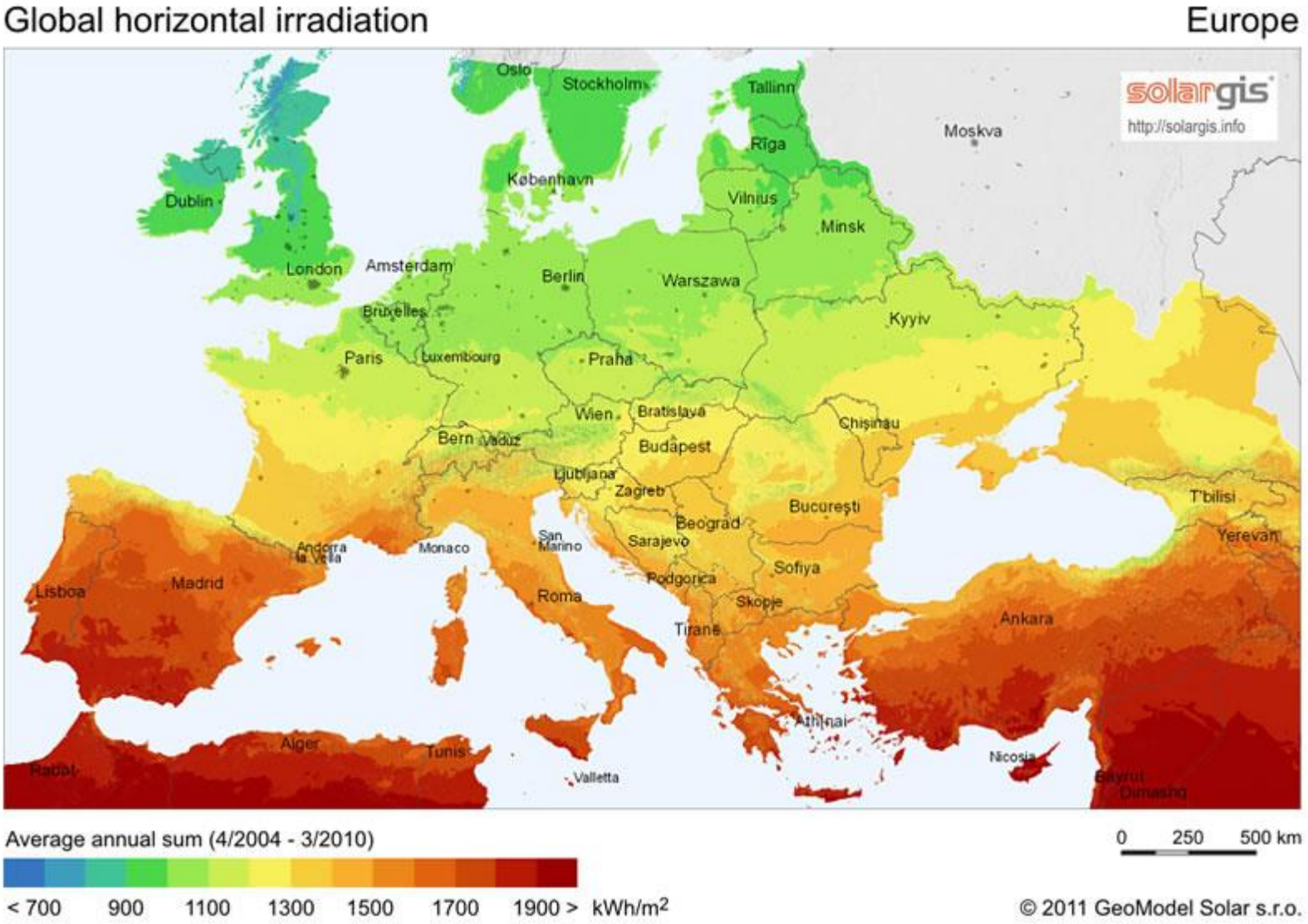
PV market today

- **German** industry & market domination
- Polisilicon feedstock ***bubble***
- Emergence of '**First Solar**'
- **Spanish** market *bubble*
- Emergence of **chinese** PV industry
- Manufacturers **consolidation**
- **Chinese** and **Japanese** market growth

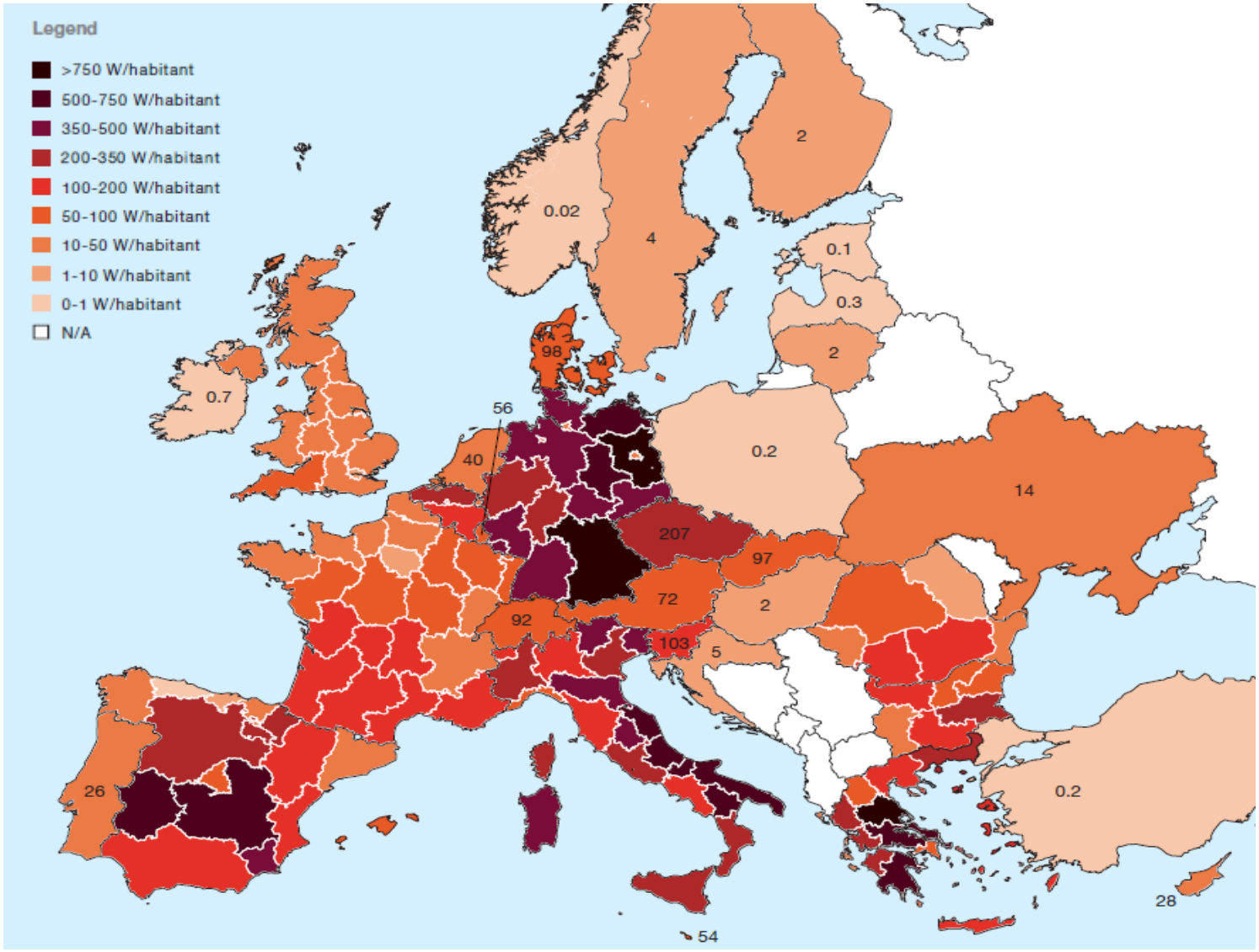
INTRODUCTION

PV in Portugal

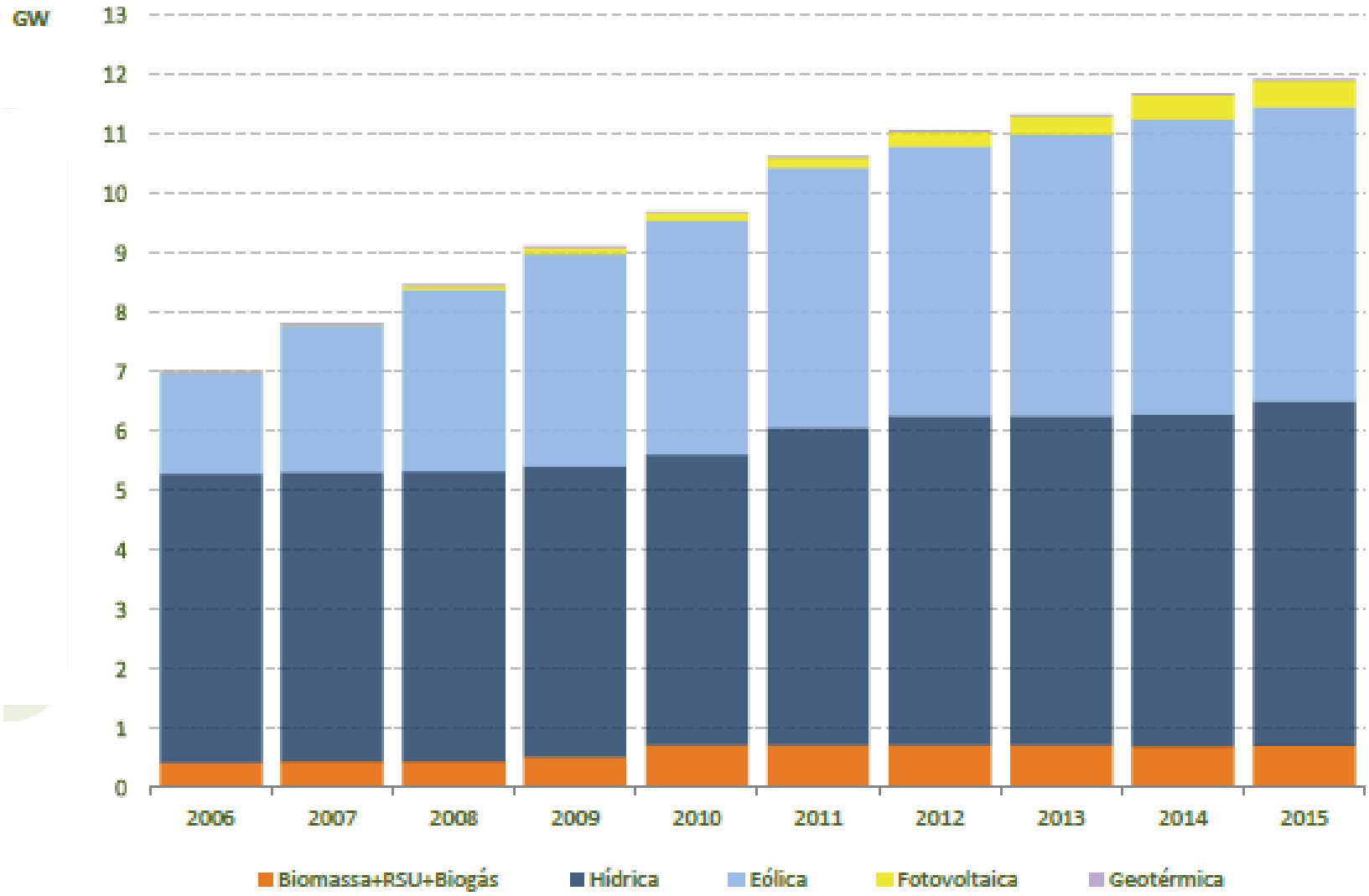
INTRODUCTION



INTRODUCTION

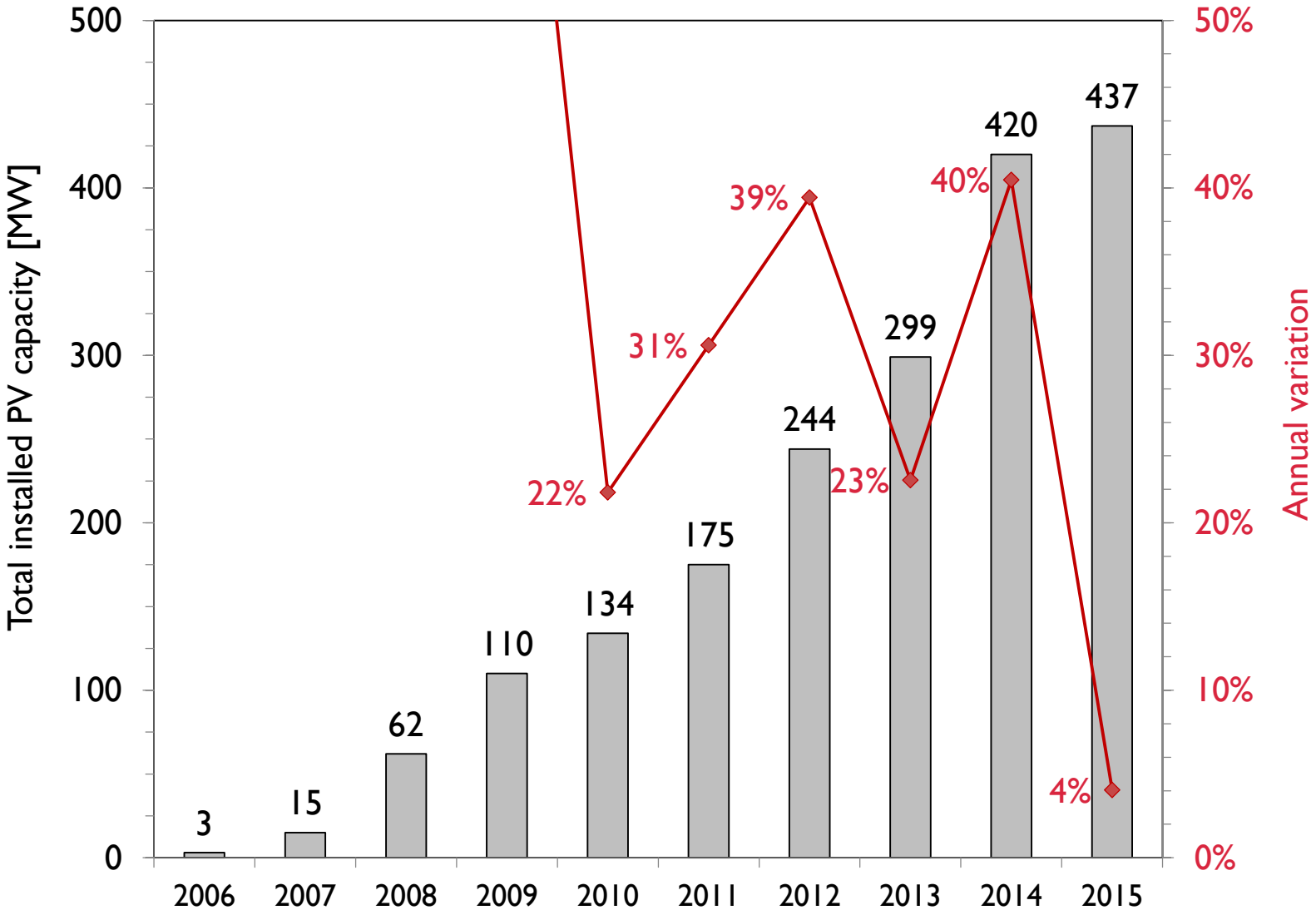


INTRODUCTION

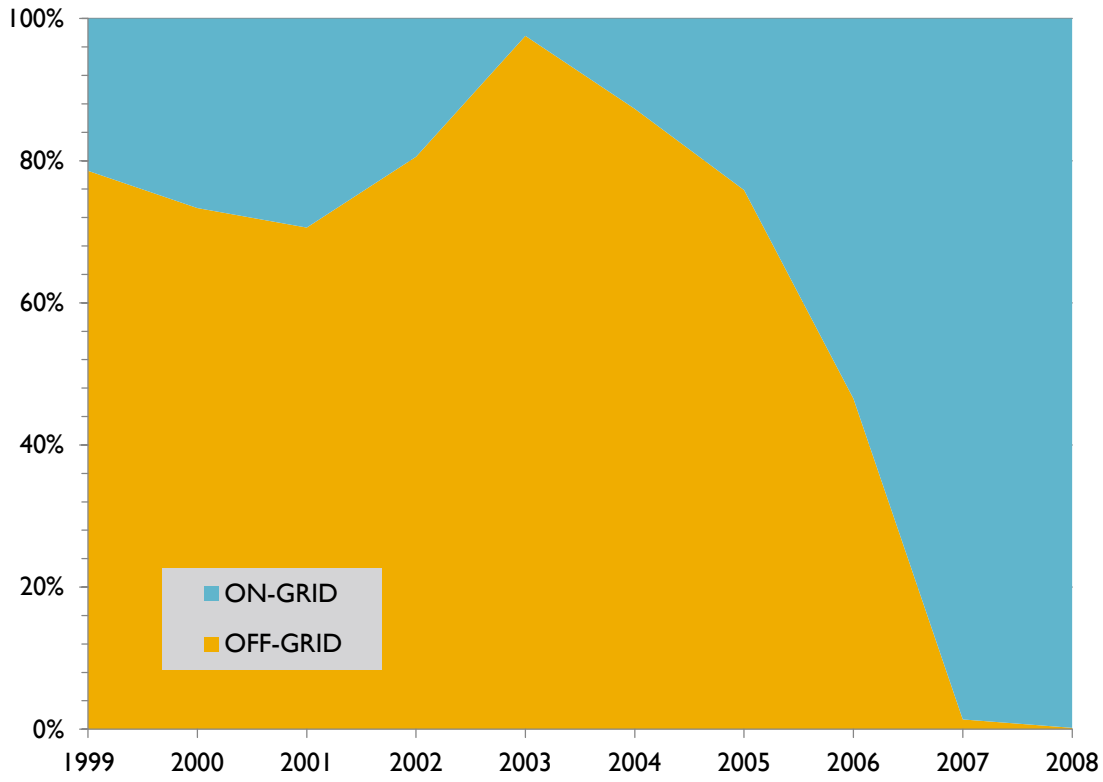


estatísticas rápidas - nº 127 - maio de 2015

INTRODUCTION



INTRODUCTION



INTRODUCTION

PV in Portugal – **legal framework**

- Roadmap: 2020: 1500MW
- Demonstration R&D projects:

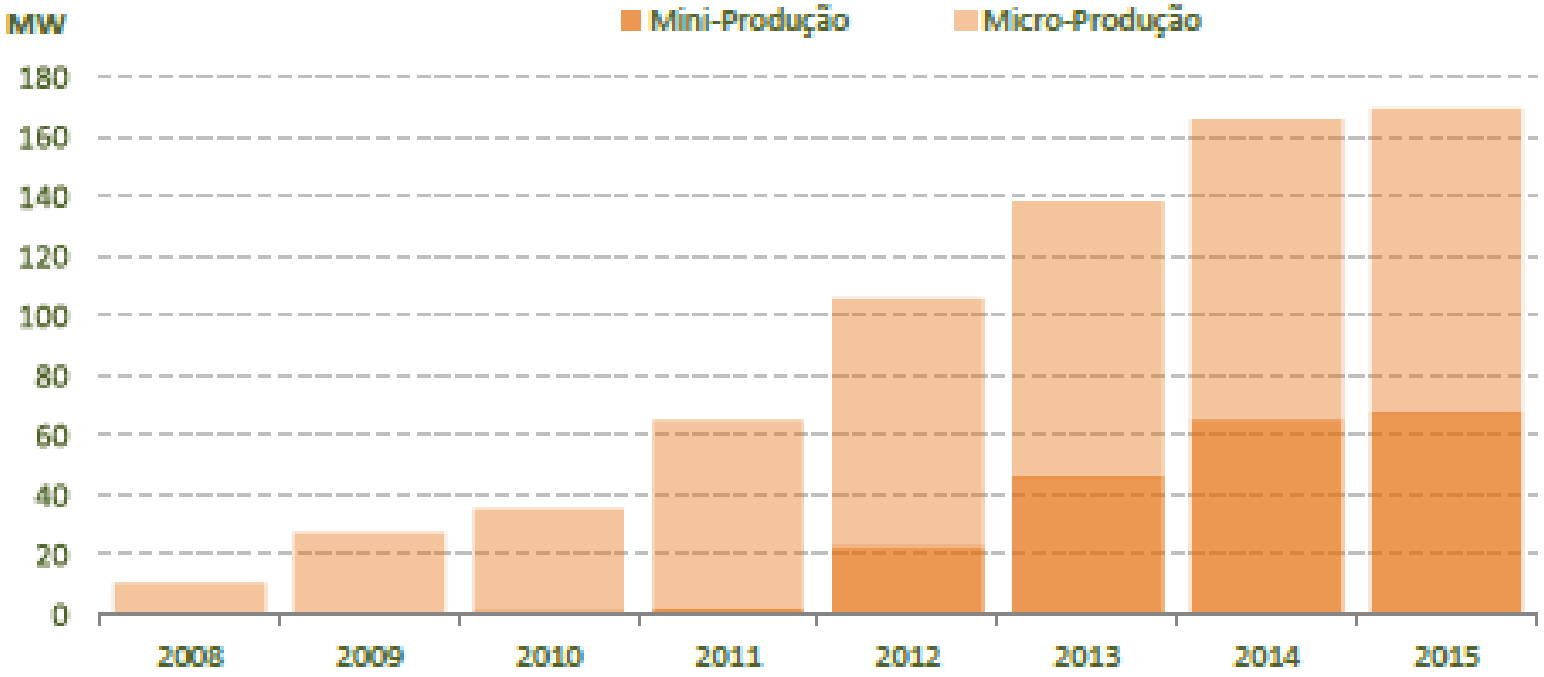
  PV concentration (28?c€/kWh) [2010]
- Micro-generation: Renewables-on-demand
  (19.6c€/kWh/8 anos + 16.5c€/kWh/7 anos)

  [2008; 2010; 2013]
- Mini-generation |DL 34/2011 March 8th]

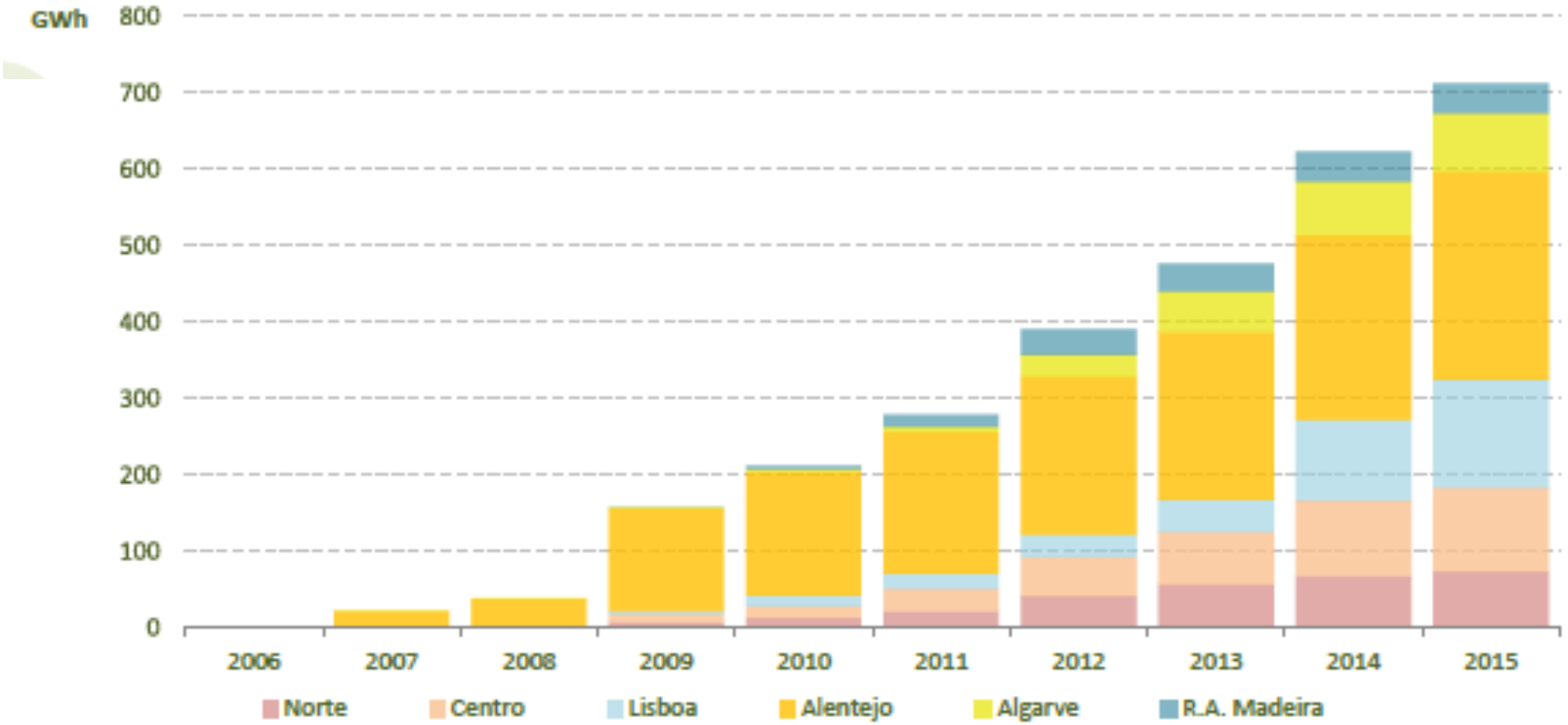
  (<20kW: 25c€/kWh; <250kW: auction)
- Self-demand |DL 153/2014 October 20th]

INTRODUCTION

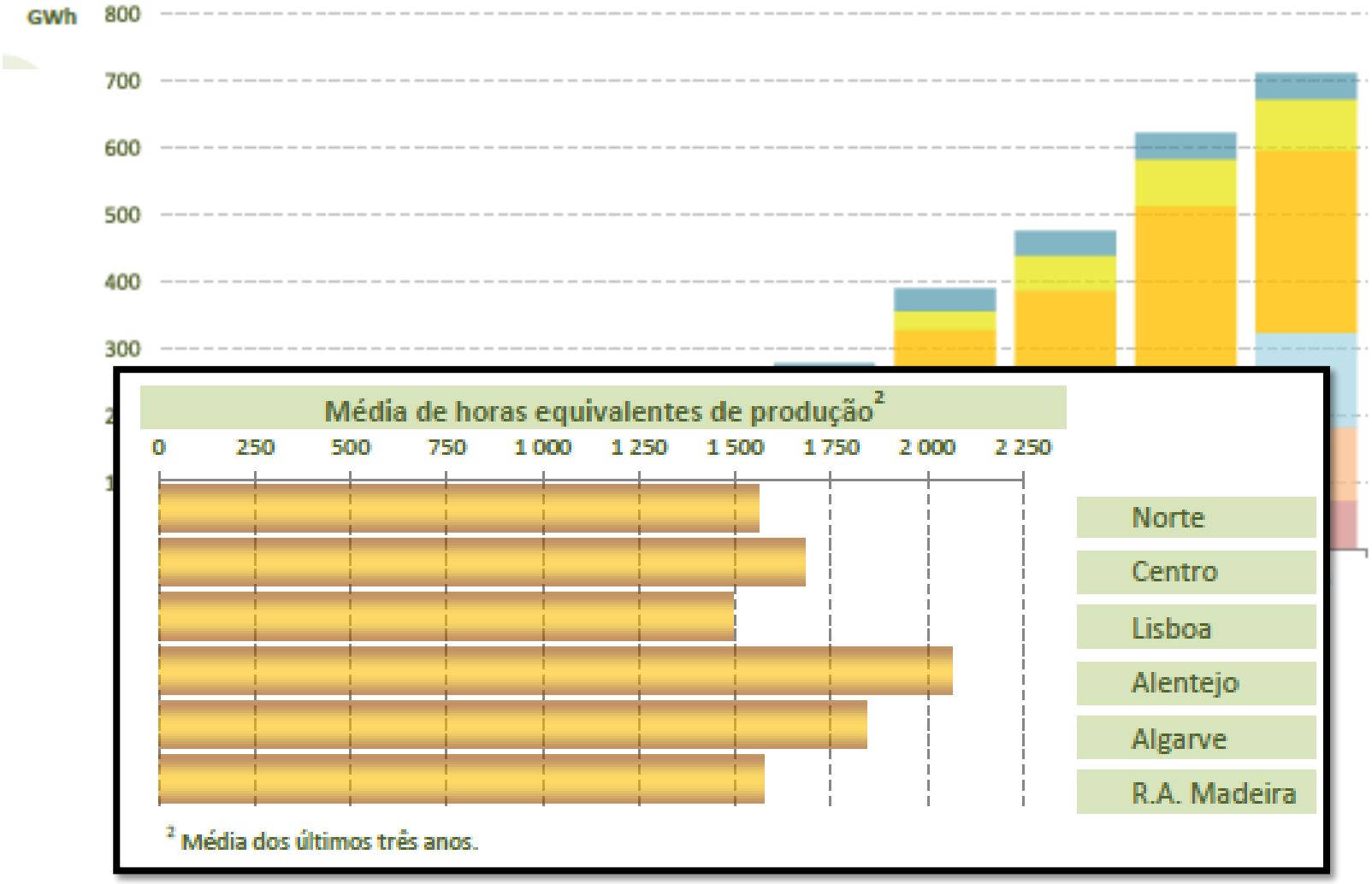
Micro-generation -
Mini-generation - Decreto Lei 363/2007



INTRODUCTION

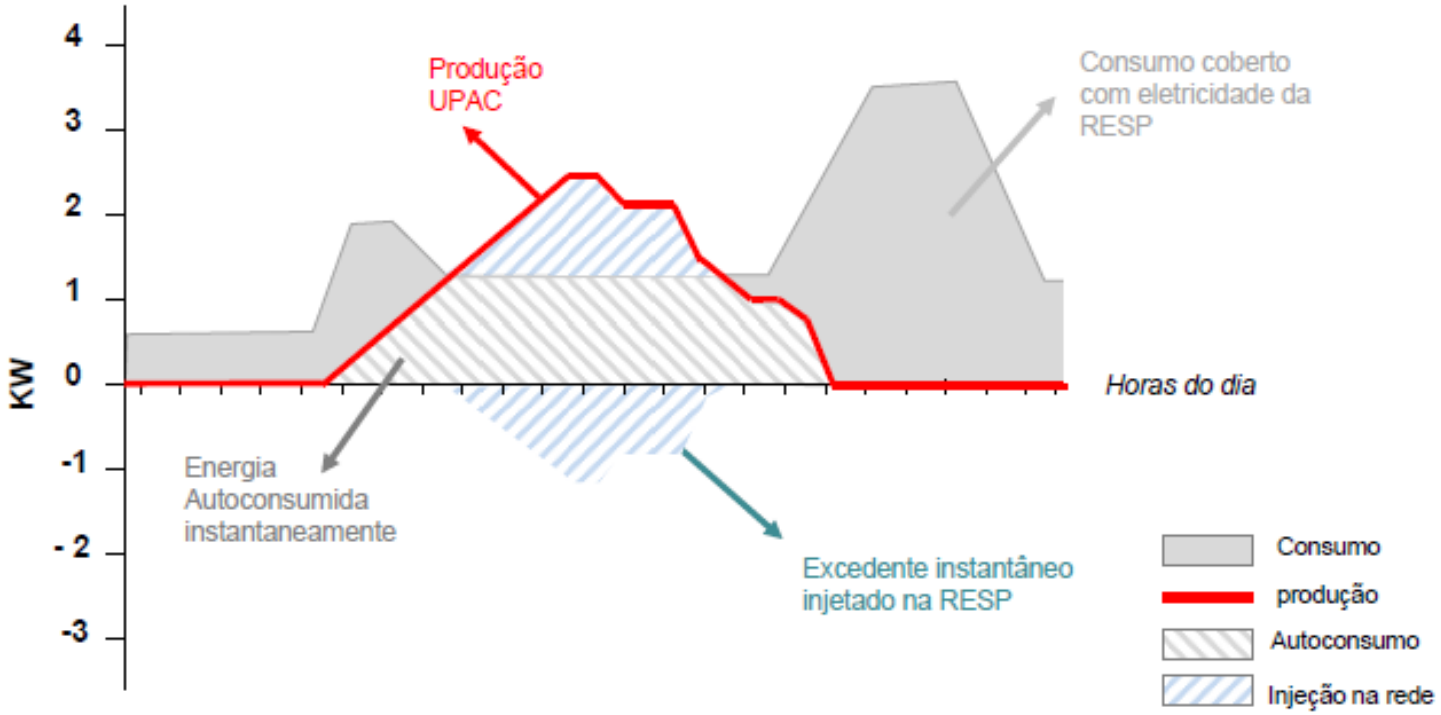


INTRODUCTION



INTRODUCTION

Self demand in Portugal



INTRODUCTION

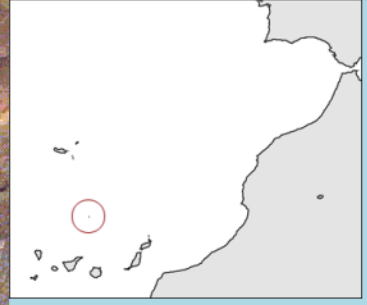
Self demand in Portugal

	Dimensão das UPAC ligadas à RESP (Potência de ligação)				s/ ligação RESP
	<200w	**200-1500 W**	**1,5k W – 1MW**	**> 1MW**	**"em ilha"**
Registo	-	Mera comunicação prévia	Controlo Prévio / Cert. Exploração	Licença de Exploração	Mera comunicação prévia
Taxas Registo	-	*isento*	✓	✓ aplicável ao respectivo regime	*Isento*
Equipamento de Contagem	-	-	Sim. Com Telecontagem	Sim. Com Telecontagem	-
Remuneração excedente ("Pool")	- (apenas se existir registo)	- (apenas se existir registo)	✓	- (Terá de ser definida com contraparte)	-
PPA	- (CUR caso exista registo)	- (CUR caso exista registo)	*CUR*	*Outro*	-
Compensação	*isento*	*isento*	✓	✓	-
Seguro. Resp. Civil	-	-	✓	✓	-

INTRODUCTION

PV in Portugal – **flagship projects**

- Selvagem Grande, Madeira (1983, 660W)
- Solar XXI, Lisbon (1989; 2.2kW)+ (2005; 12+6kW)
- Brinches, Serpa (2007; 11MW)
- Amareleja, Moura (2008; 46MW)



16° W
Palheiro de Terra
Palheiro do Mar
Ponta do Corgo da Areia
Ponta do Risco
Pico dos Tornozelos
Pico da Atalaia
Selvagem Grande
Enseada das Pedreiras
Enseada da Atalaia
Ilhéu Sinho
Enseada das Cagarras
Pico do Inferno
Ponta de Leste
Ponta do Inferno
Oceano Atlântico
Atlantic Ocean
Ilhéus do Norte
Ilhéu Redondo
Ilhéu Comprido
Ilhéu Alto
Ponta do Norte
Ponta de Oeste
Selvagem Pequena
Pico do Veado
Canal da Selvagem Pequena
Ilhéu de Fora
Ponta de Leste
Ilhéu Pequeno
Ilhéu Grande
Ponta dos Garajaus
Ponta do Sul
Ilhéu do Sul
30° N


SOLAR XXI


C1
C4

INTRODUCTION

Manufacturers

- Open renewables
- Martifer Solar
- Magpower

INTRODUCTION

Remarks - PV in Portugal

- Almost no manufacturing
- Commercialization & installation suffers from policy hesitations
- Current legal framework favors very small installations for residential users and industrial installations
- Untapped huge solar potential

INTRODUCTION

- **Further reading** (references online or available at course page)
  - **M. Green**, *Silicon Photovoltaic Modules: A Brief History of the First 50 Years*, Prog. Photovolt: Res. Appl. 2005; 13:447–455
  - **M.G. Rogol**, *Why did the solar power sector develop quickly in Japan?*, MSc Thesis, MIT 2007
  - **M. Frondel**, *et al, Germany's solar cell promotion: Dark clouds on the horizon,* Energy Policy 36 (2008) 4198–4204
  - **EPIA Brochure**: *Supporting Solar Photovoltaic Electricity - An Argument for Feed-in Tariffs*, January 2008
  - **A. Jager-Waldau**, *Photovoltaics and renewable energies in Europe*, Renewable and Sustainable Energy Reviews, 11 (2007) 1414–1437
  - www.renovaveisnahora.pt
  - pvcdrom.pveducation.org