Photovoltaics

Introduction

INTRODUCTION

This course - contents

- Solar **resource**
- **Physics** of solar cells
- PV **technologies**
- **Grid connected** PV systems
- **Stand alone** systems
- **Building** integrated systems
- **Vehicle** integrated systems
- **Floatvoltaics** and **Agriphotovoltaics**
- **Concentrated** solar power

INTRODUCTION

This course - grading

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

and/or

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

INTRODUCTION

This course – main references

- Geoff Stapleton, Grid-connected Solar Electric Systems: The Earthscan Expert Handbook for Planning, Design and Installation, Routledge; 1 edition, 2012
- Messeger, Photovoltaics system engineering, 4th ed., 2017
- Bowden et al, PV CD ROM [pvcdrom.pveducation.org]

Other references

- Pereira & Oliveira, Curso técnico instalador de energia solar fotovoltaica, Pubindustria, 2ª edição, 2015
- Luque et al, Handbook of PV Science and Engineering, 2003

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

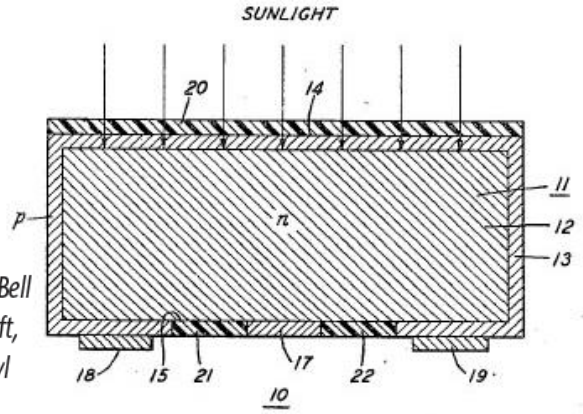
The inventors of the Bell Solar Battery, from left, Gerald Pearson, Daryl Chapin, and Calvin Fuller, check devices for the amount of solar electricity derived from sunlight, here simulated by a lamp.

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

SOLAR ENERGY CONVERTING APPARATUS

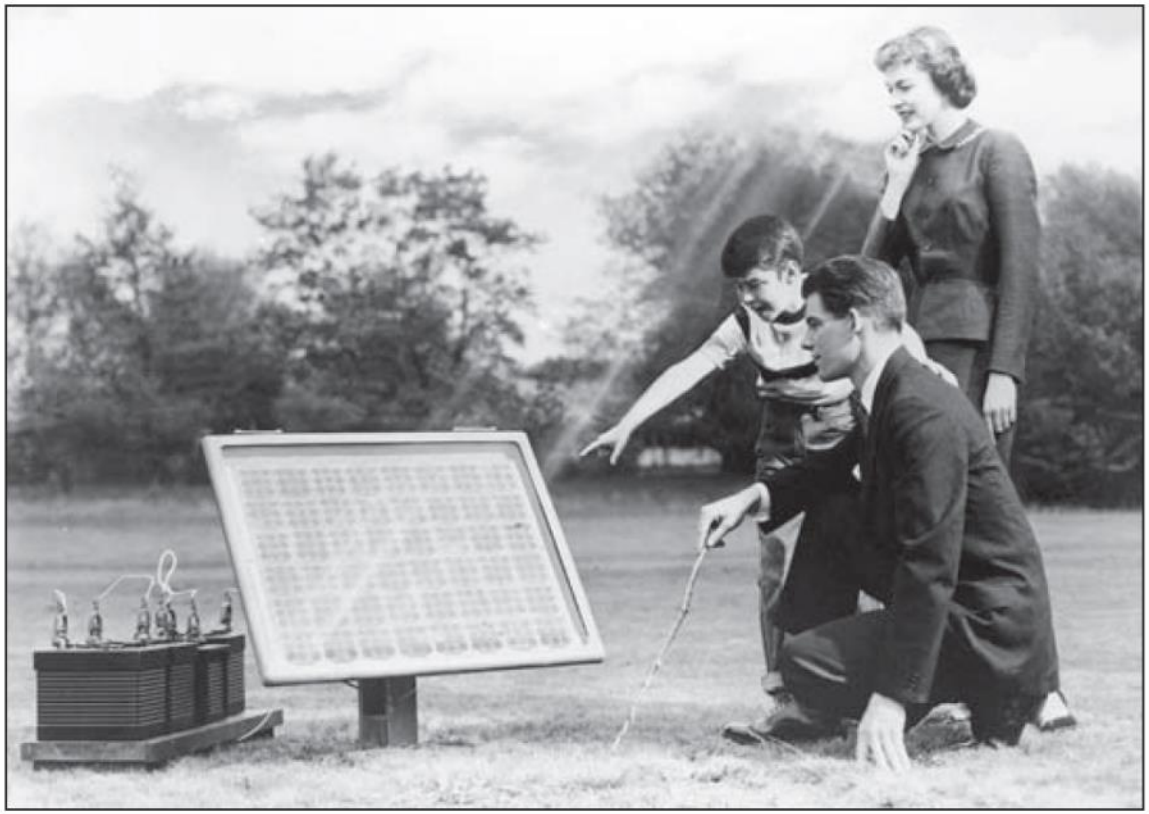
Filed March 5, 1954

FIG. 1



INTRODUCTION

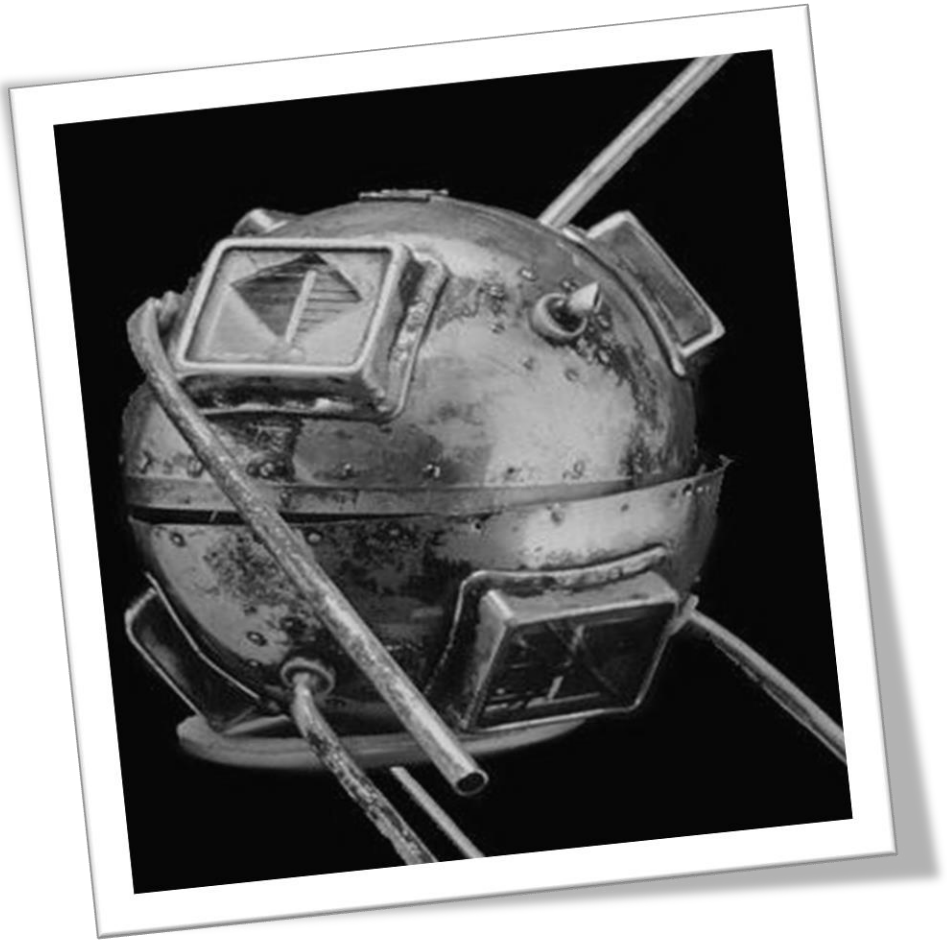
Brief history of photovoltaics



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.

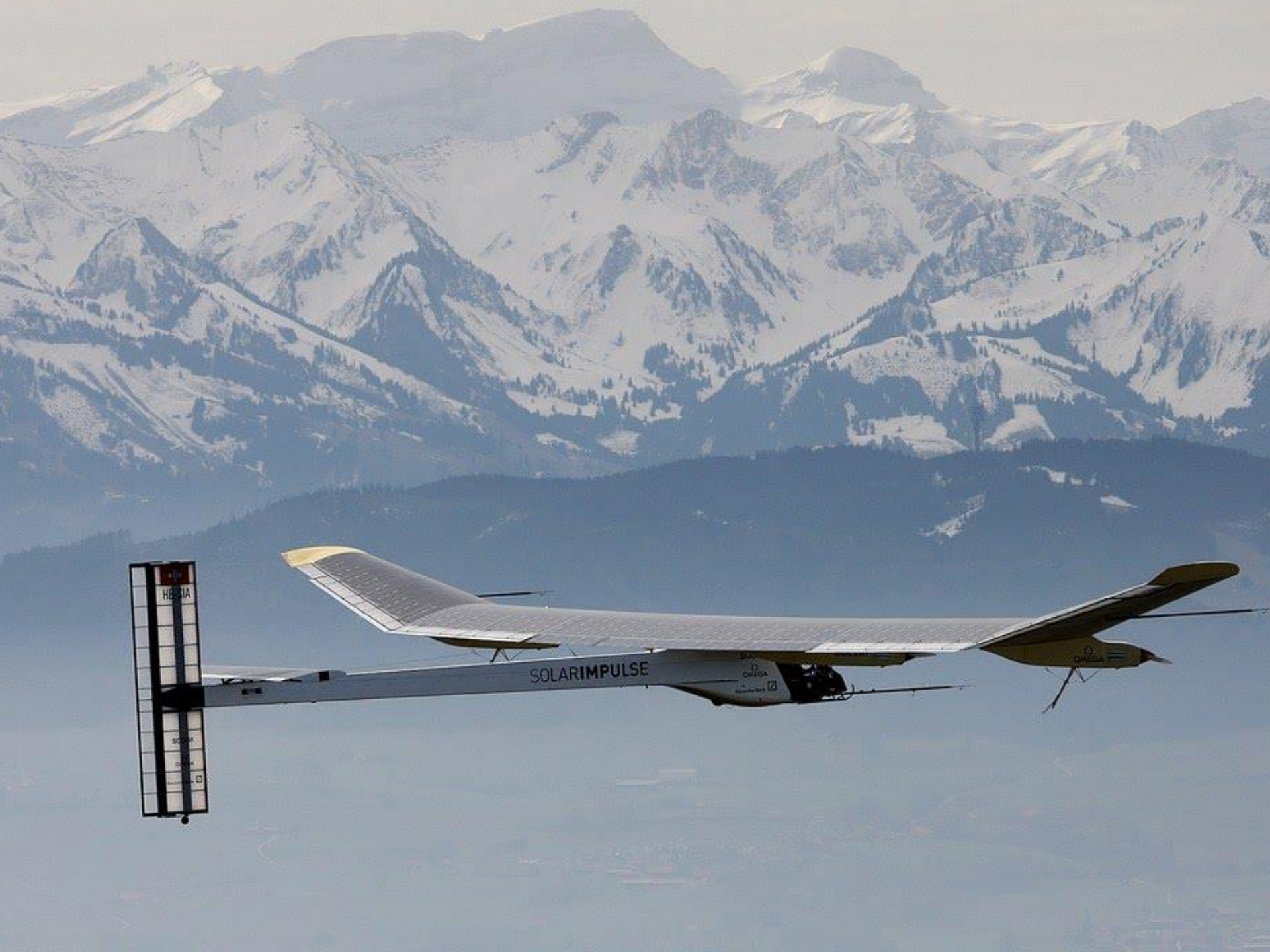
INTRODUCTION

Brief history of photovoltaics



INTRODUCTION

Brief history of photovoltai


SOLARIMPULSE


TÛRANOR PlanetSolar


ENGINEERING
UNSW

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

INTRODUCTION

Cost per Watt-peak

Units: **€/W**

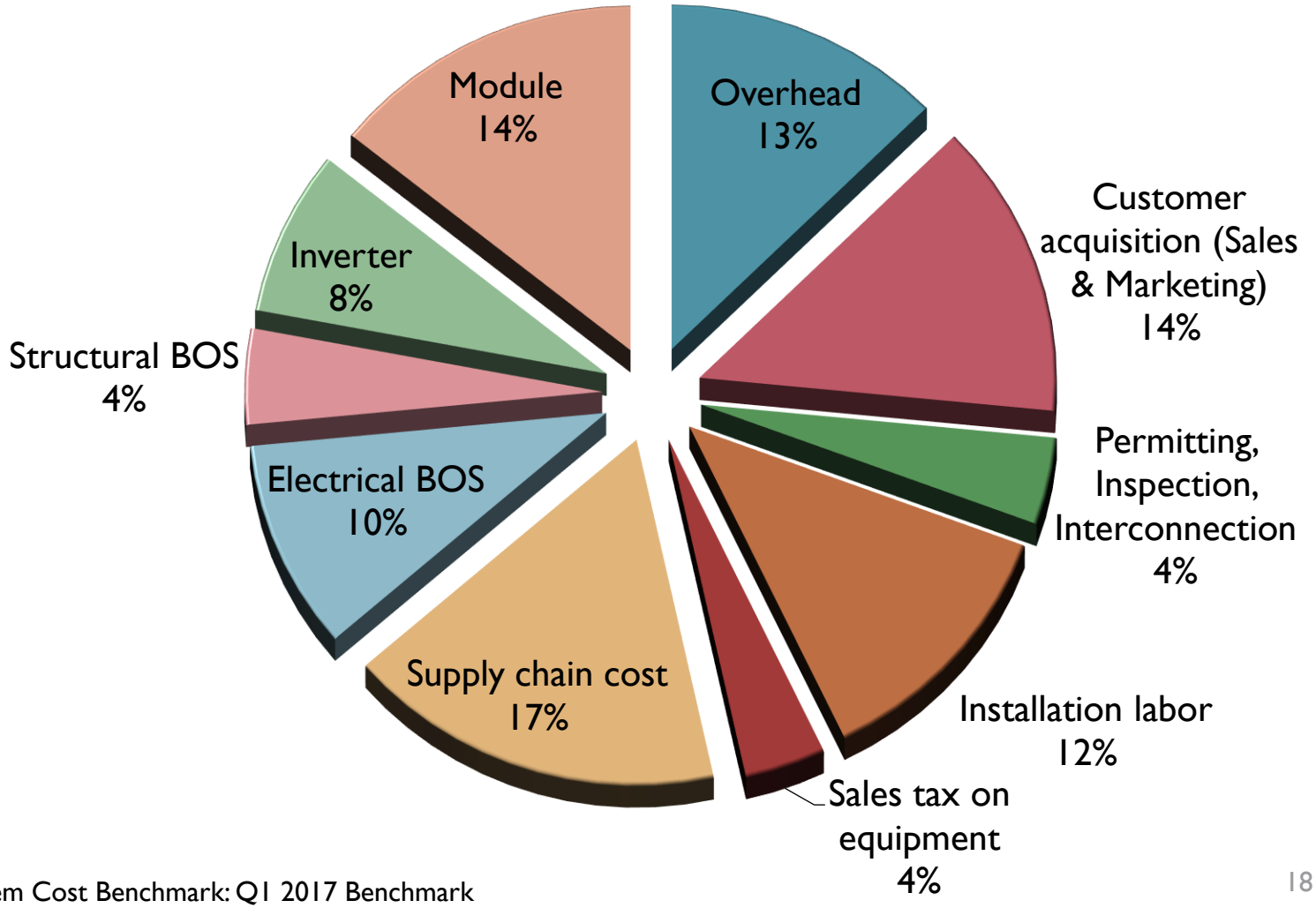
Simple and objective to determine, usually refers to module cost (Spot market? Factory gate? End user?) and thus it does not represent full installation system cost.

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



U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017 Benchmark

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.

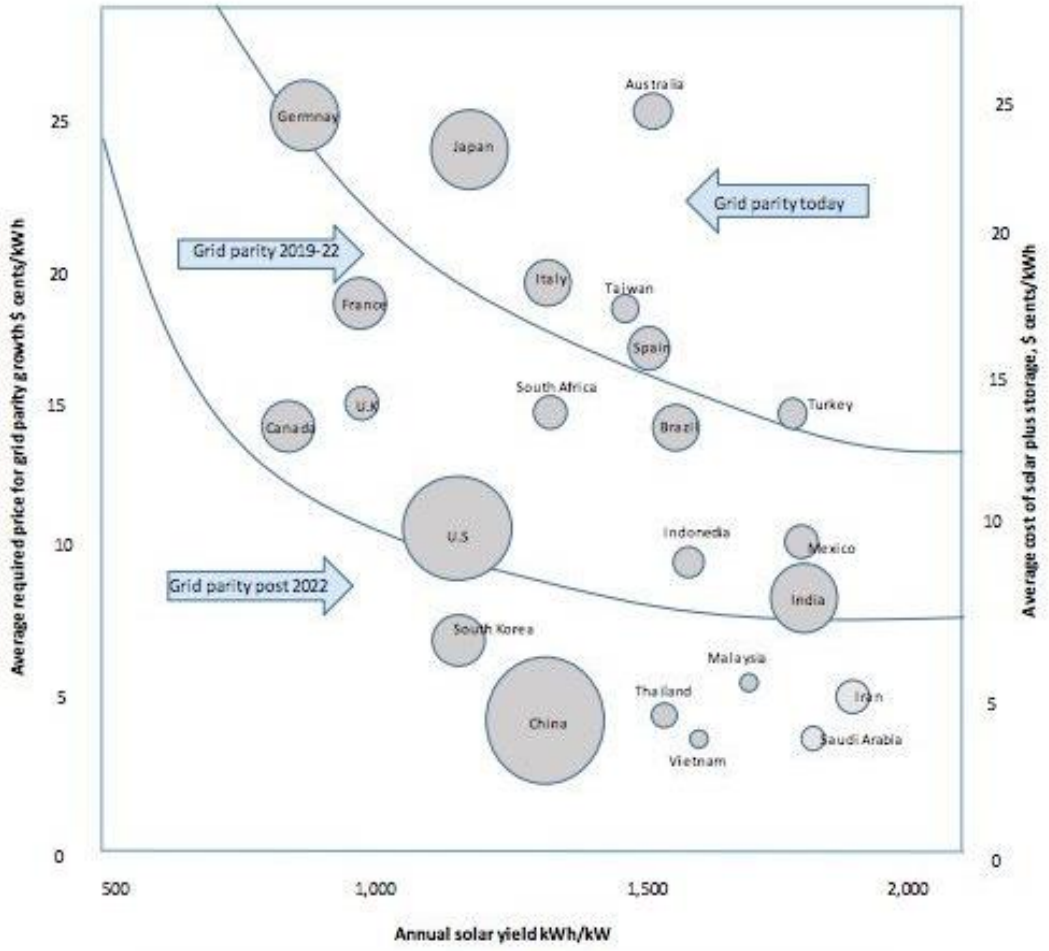
When?

Where?

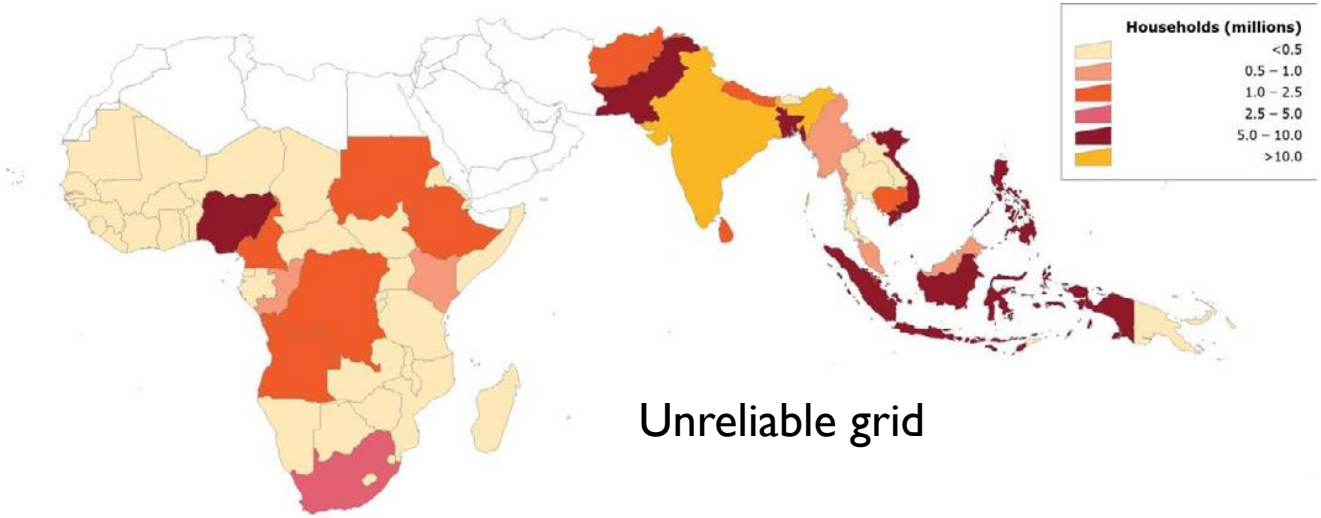
At what time of the day/year?

INTRODUCTION

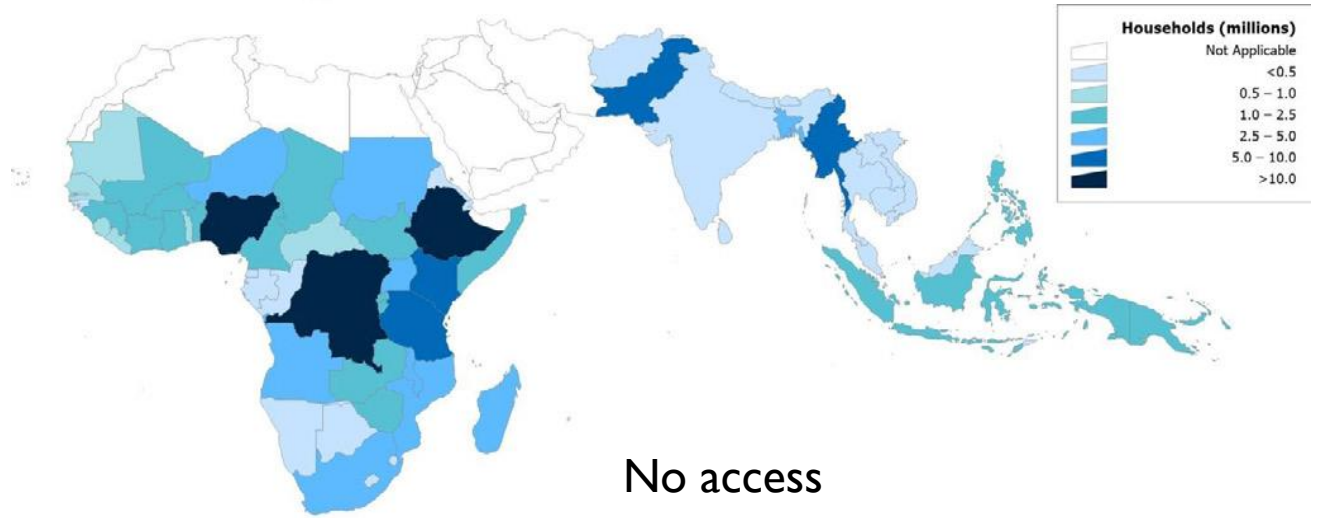
Grid parity



INTRODUCTION



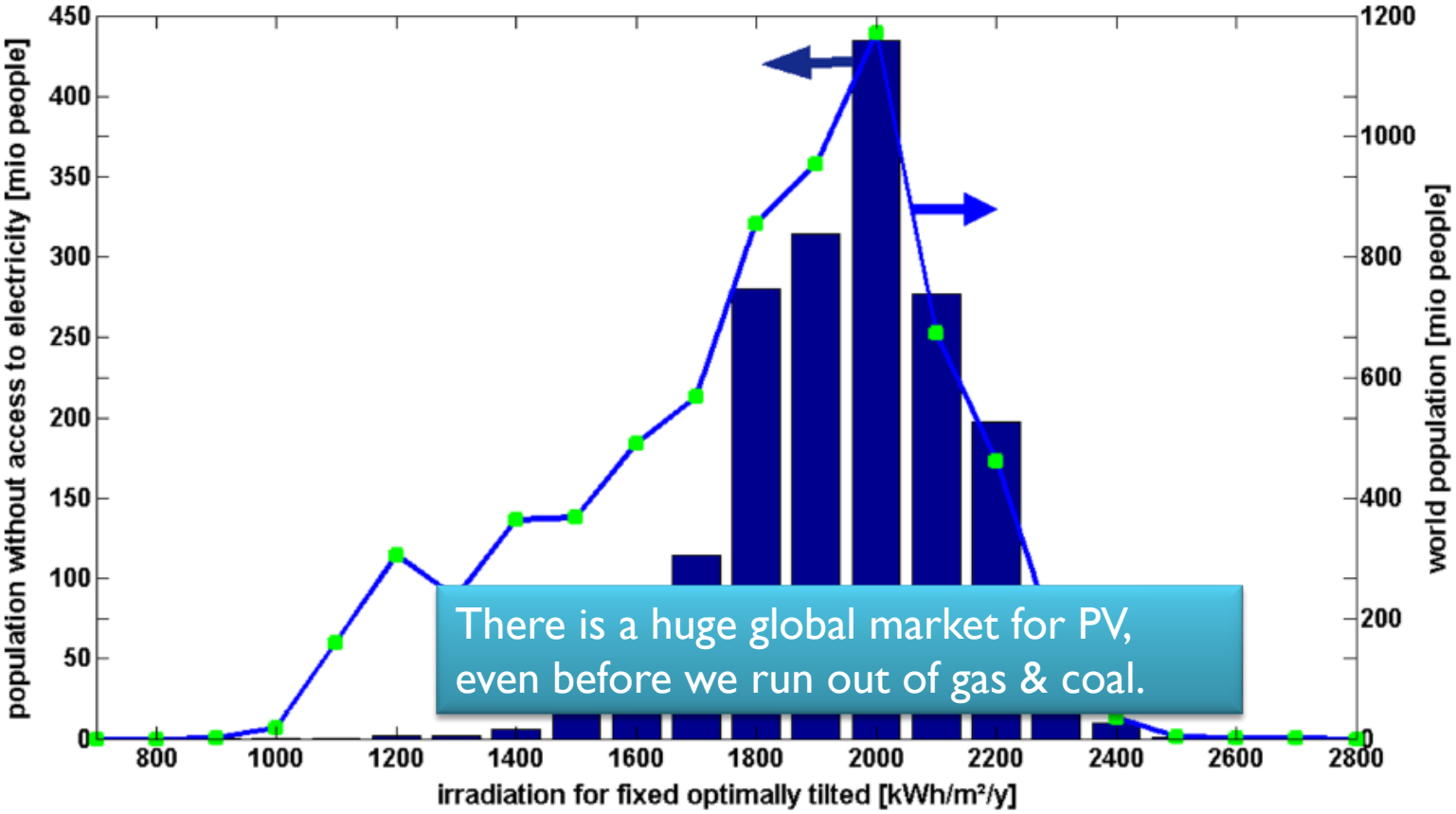
Unreliable grid



No access

INTRODUCTION

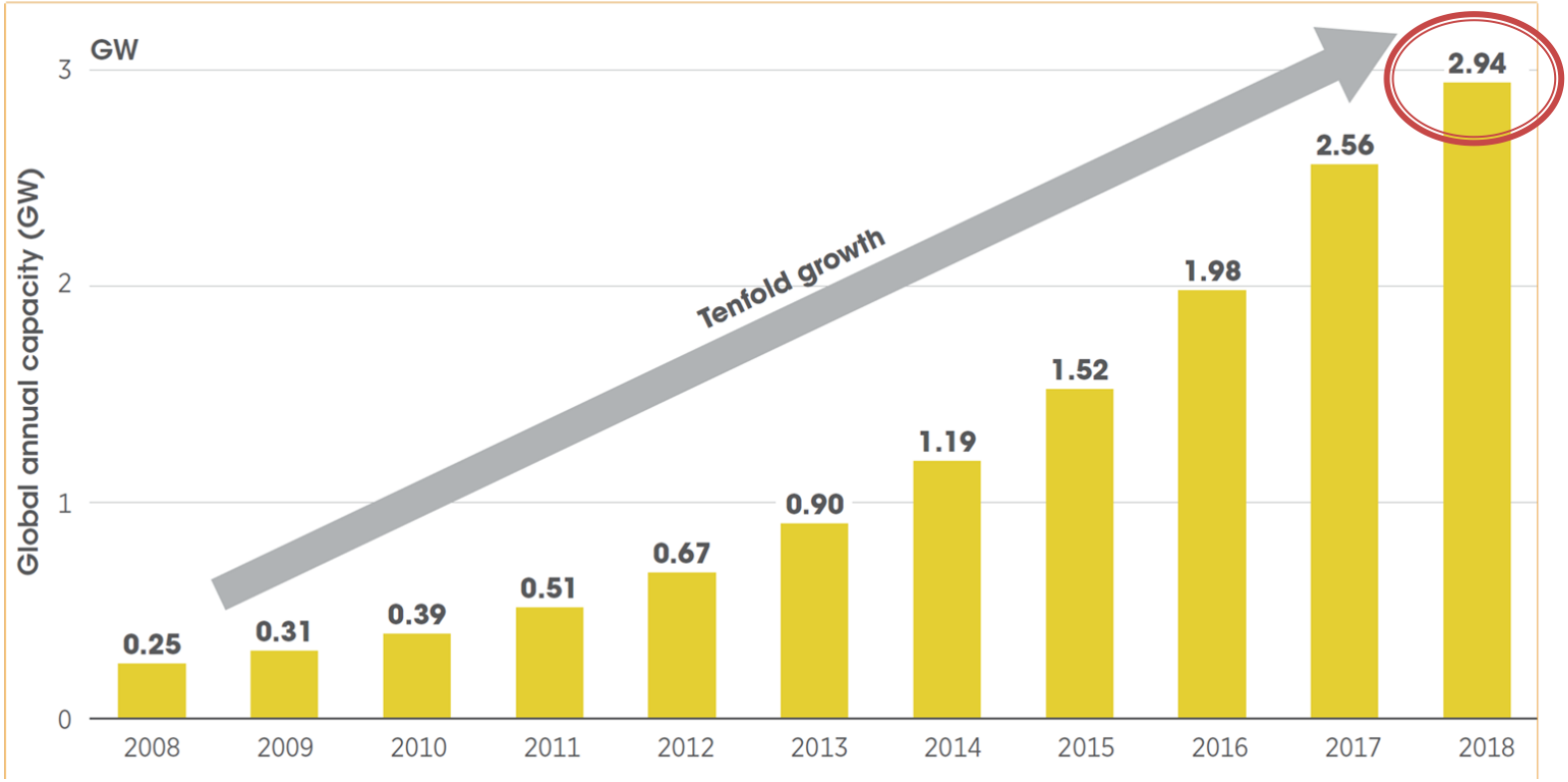
Population without access to electricity and local irradiation



INTRODUCTION

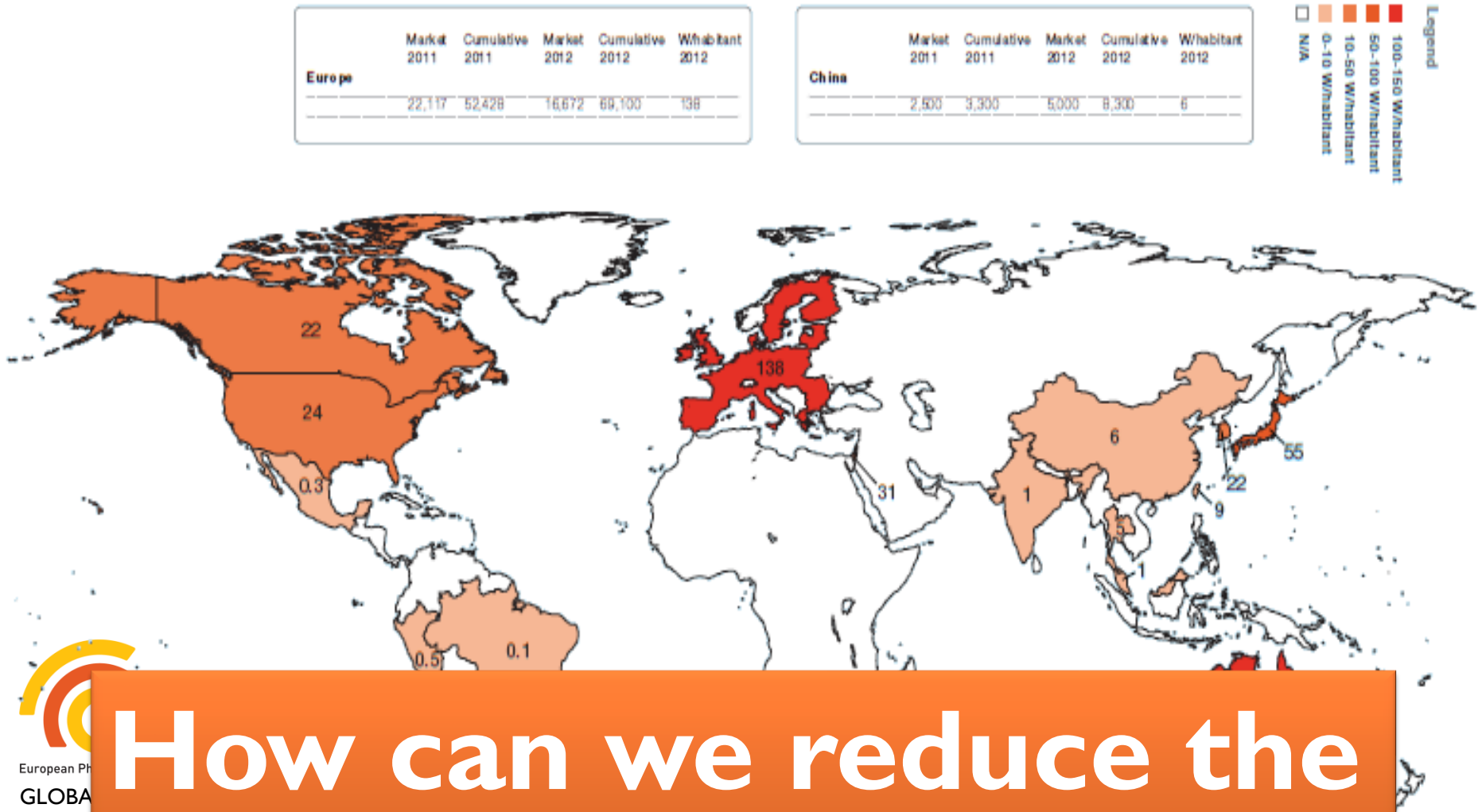
Figure 9: Global power capacity, off-grid solar PV, 2008–18

Compare with 500 GW!!



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**!

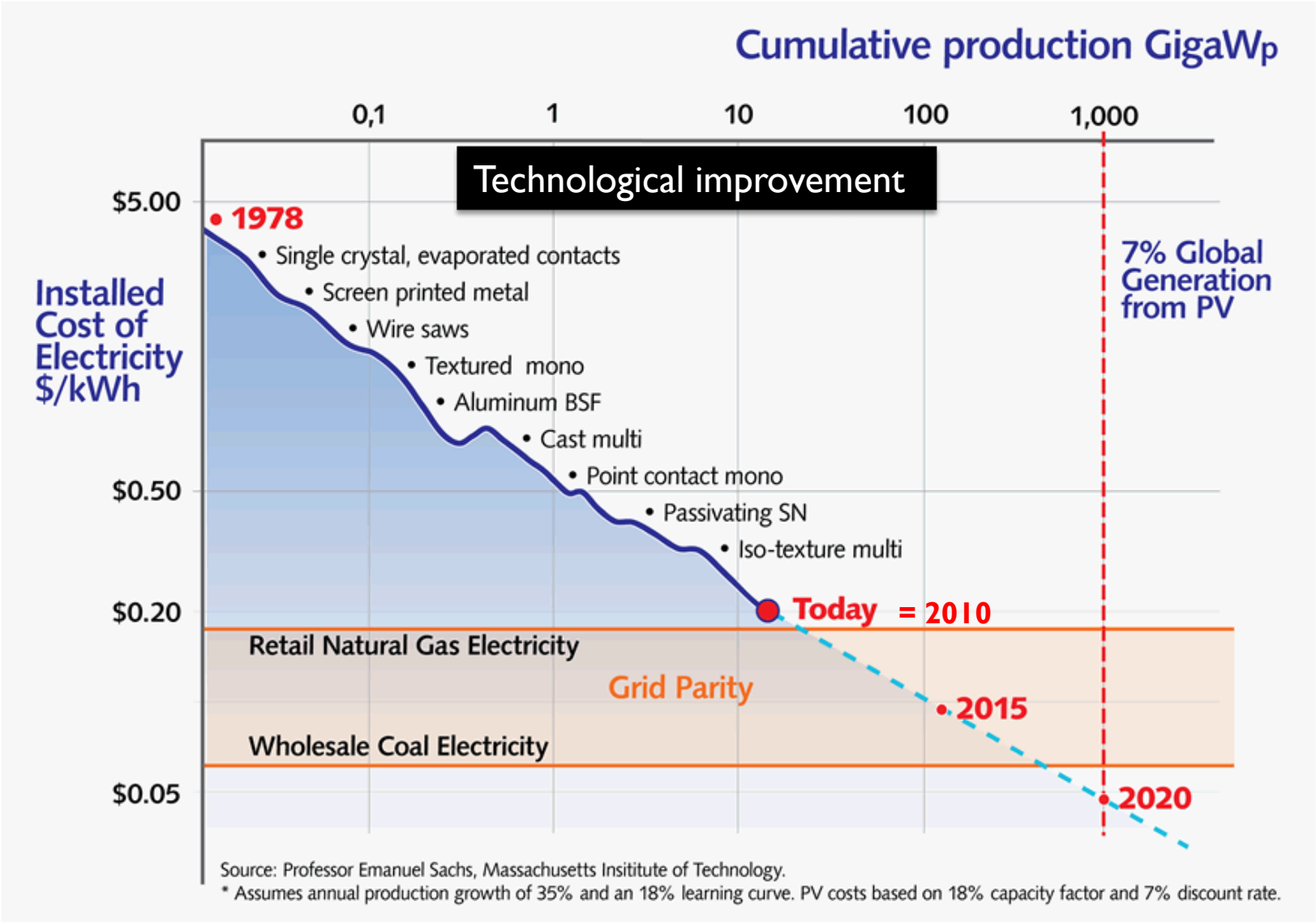
IRENA (2019), Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: paper), International Renewable Energy Agency, Abu Dhabi.



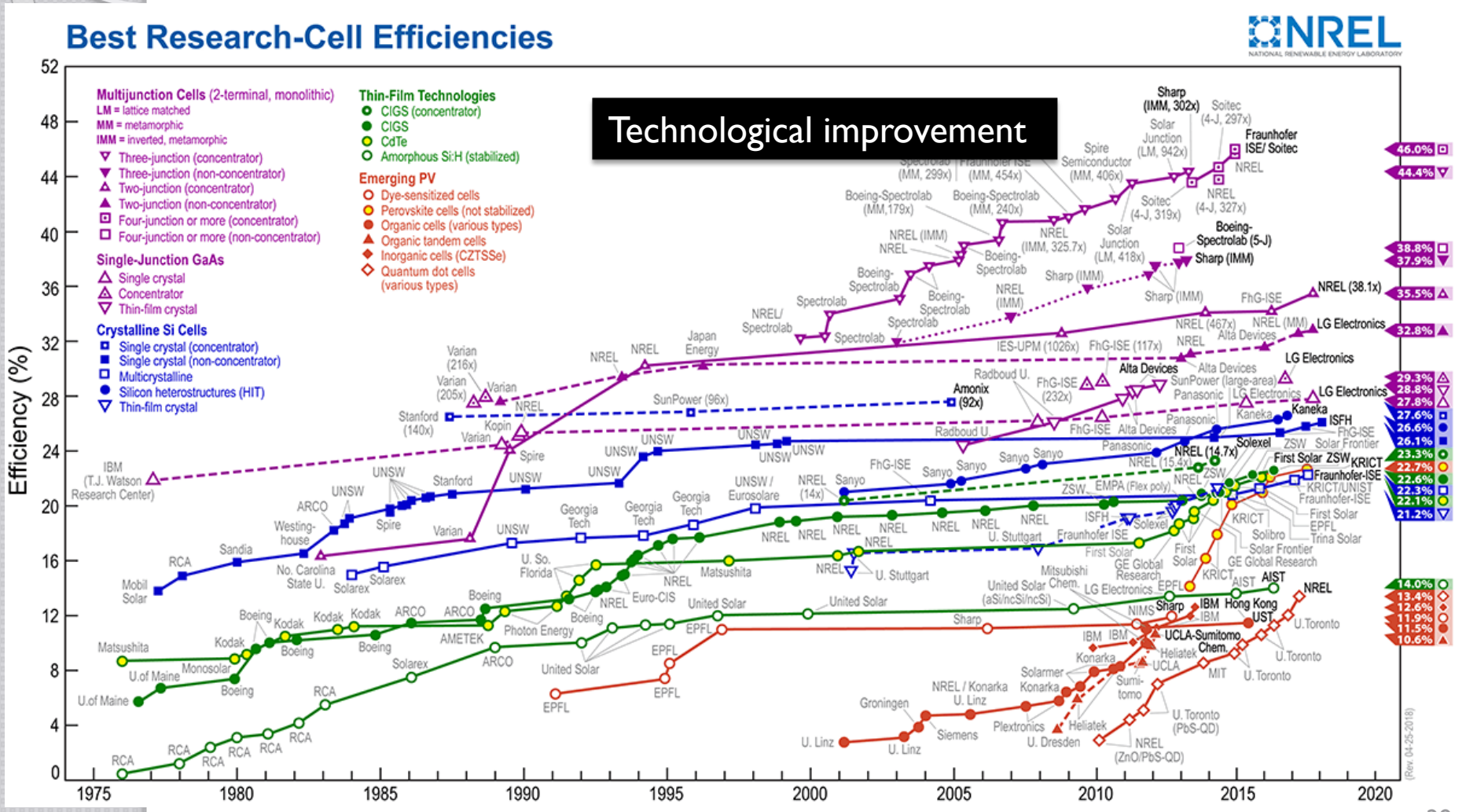
How can we reduce the cost of photovoltaics?

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**!

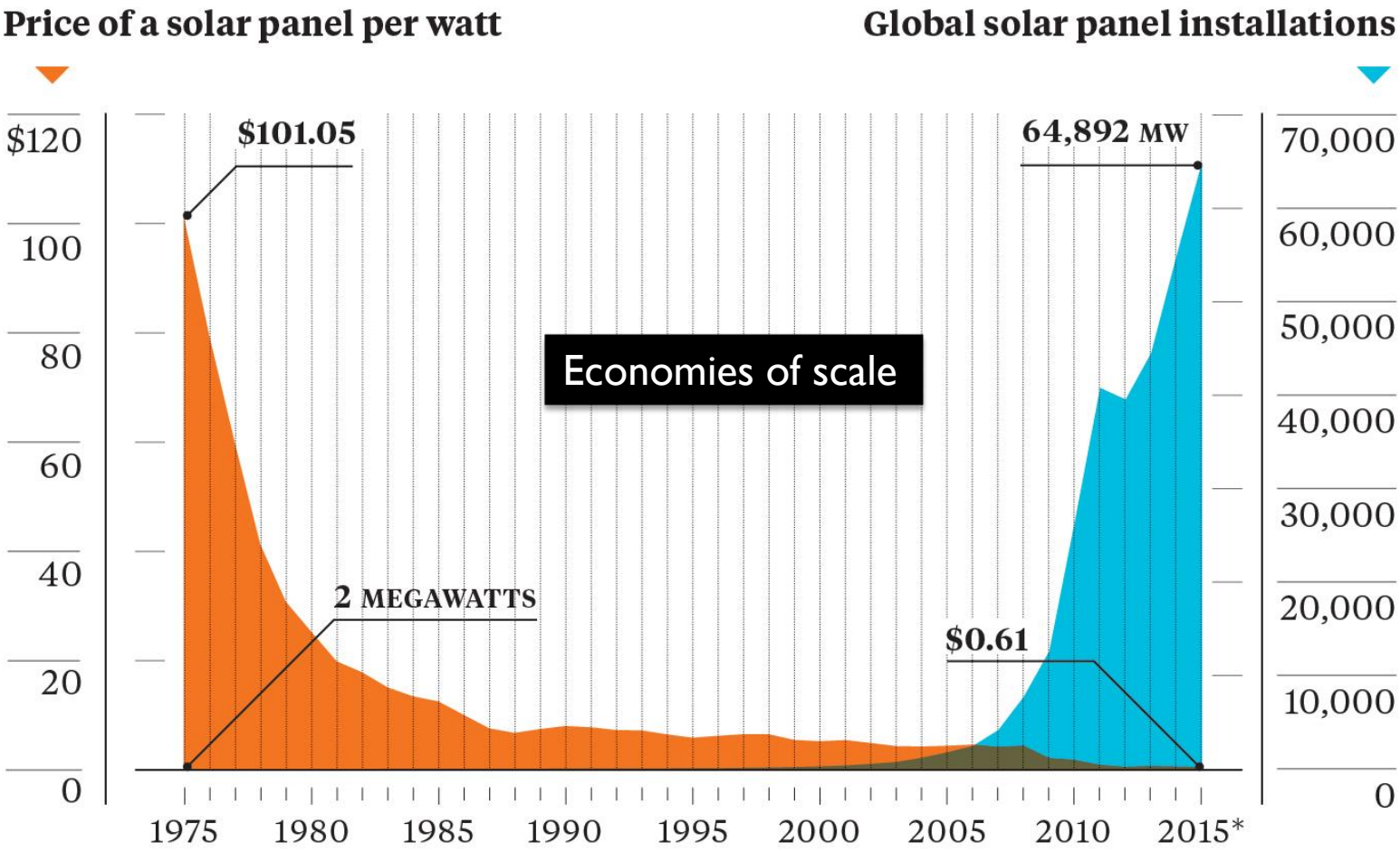
INTRODUCTION



INTRODUCTION

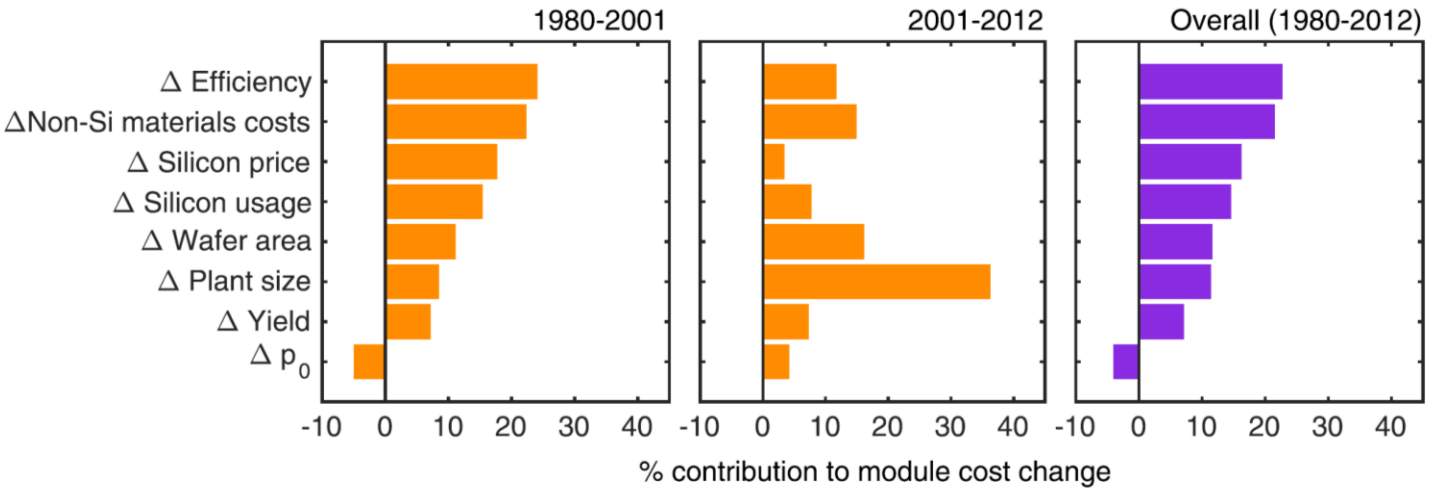


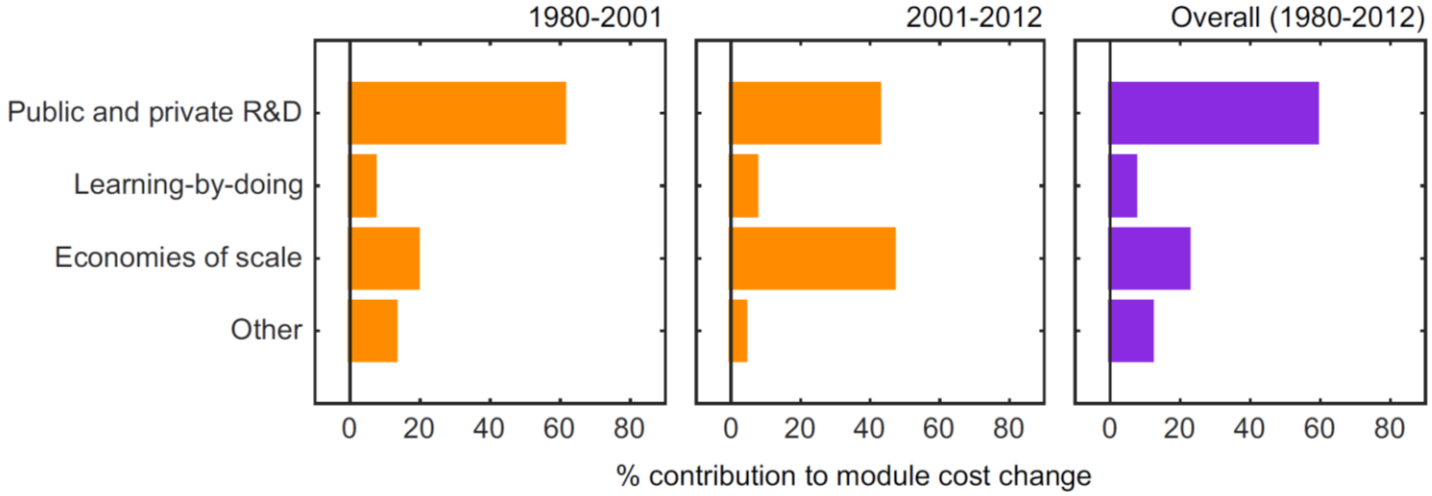
INTRODUCTION



That is why there have been incentives to the deployment of PV worldwide…

INTRODUCTION





Energy Policy 123 (2018) 700–710; 707

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…

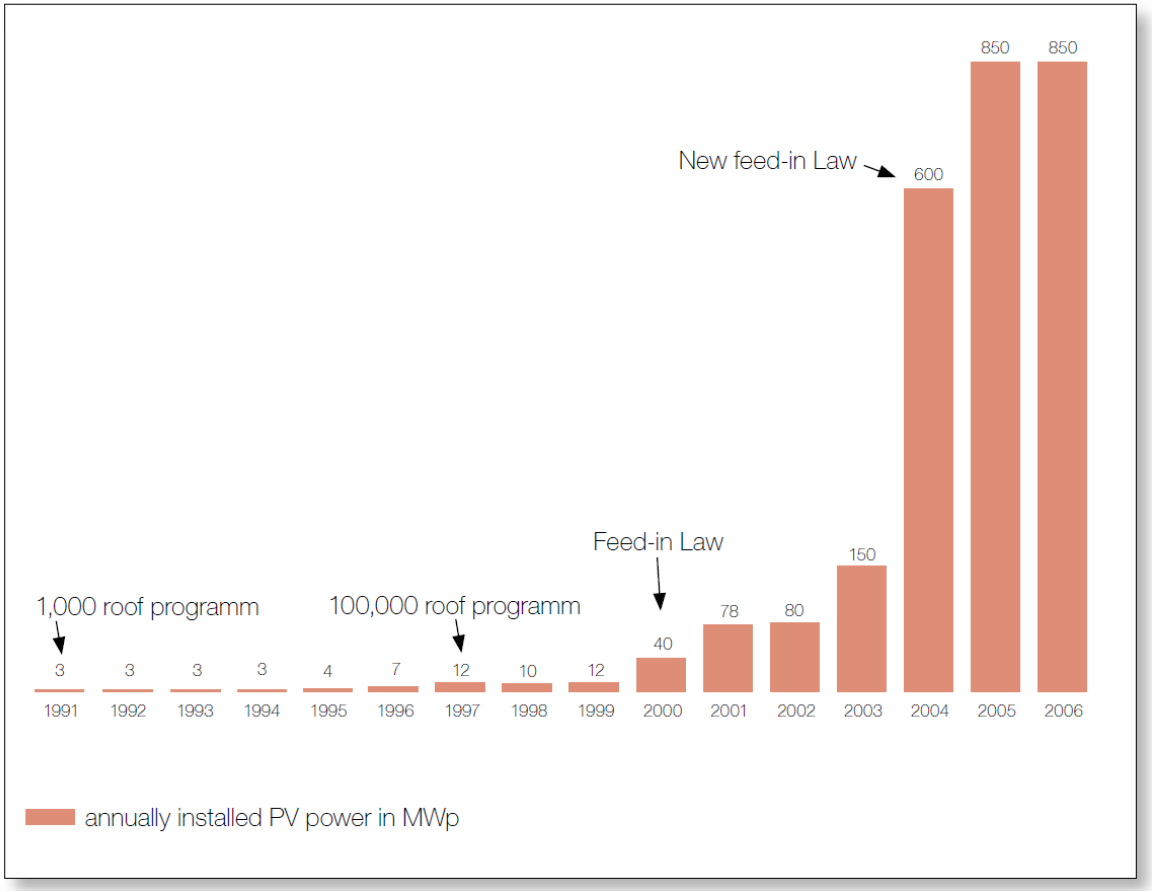
Lead to:

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

INTRODUCTION

PV market – German market in 2000s

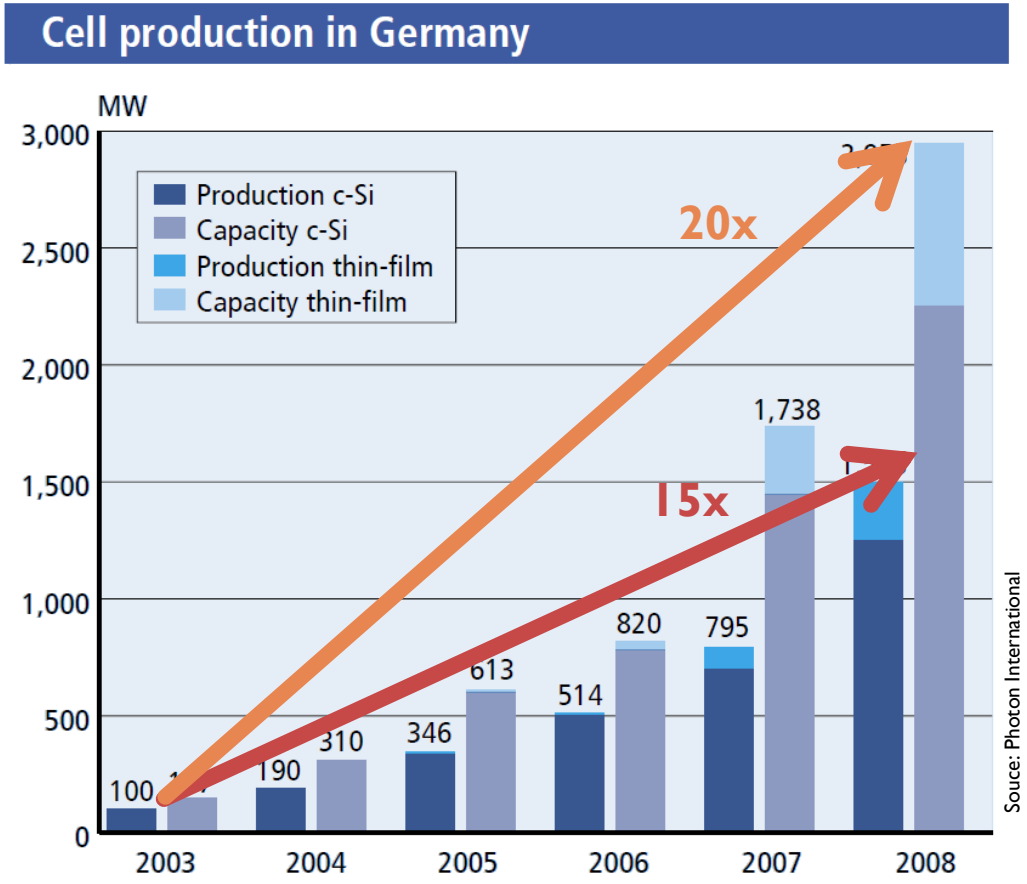
Figure 4: Influence of Feed-in Tariff on annual PV installations in Germany (MWp)



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

INTRODUCTION

PV market – German market in 2000s



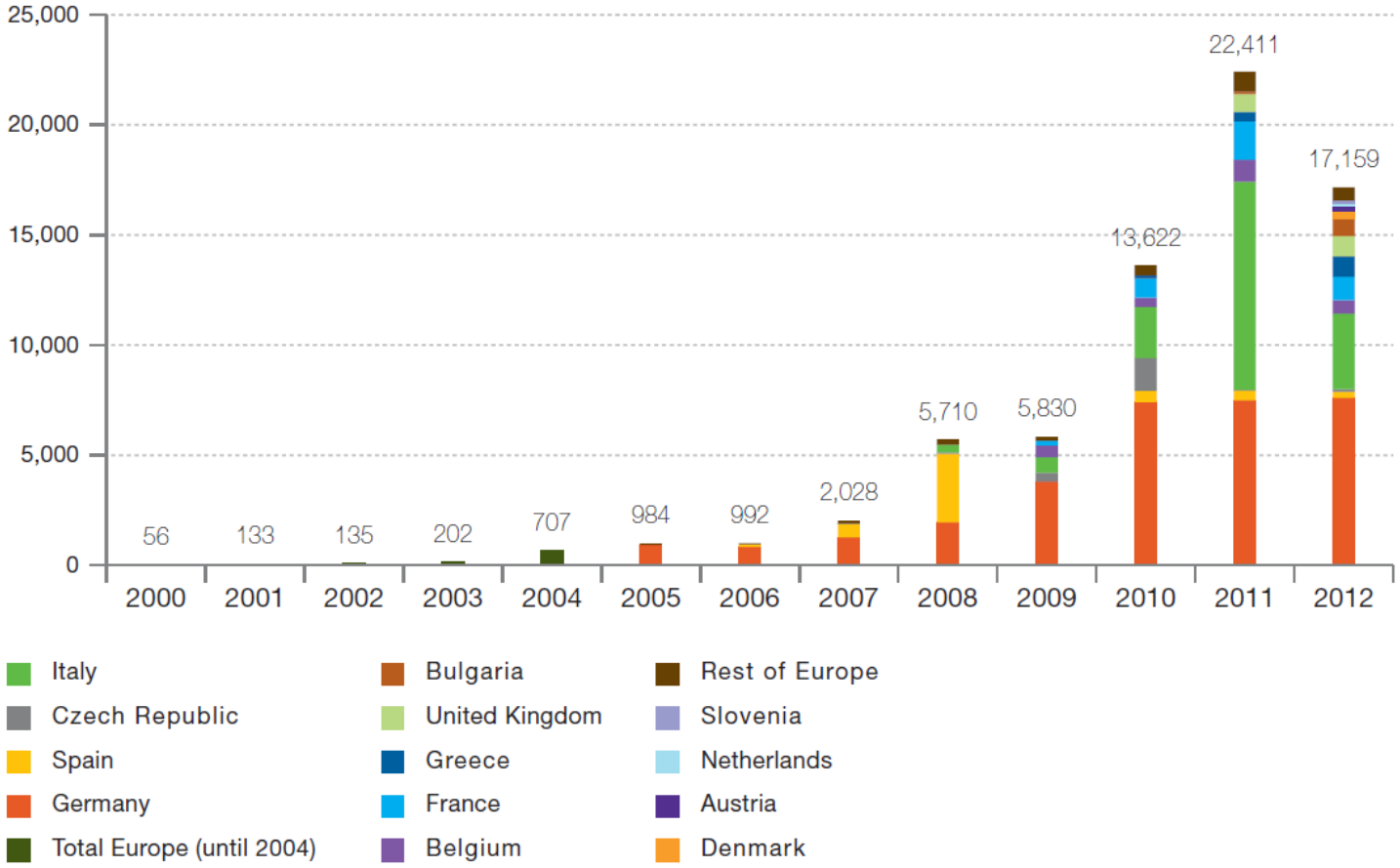
INTRODUCTION

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?*

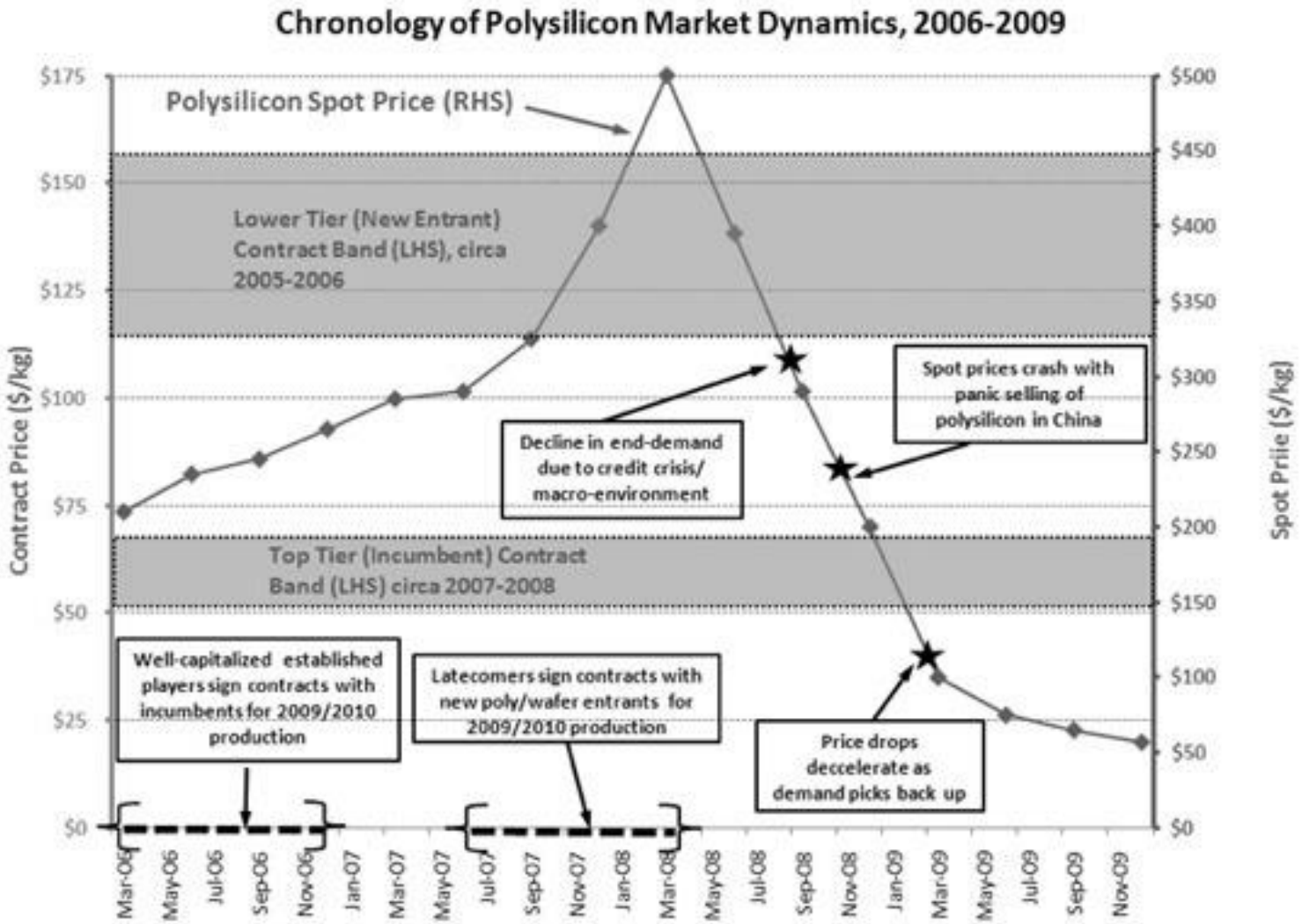
- Generous feed-in tariff
- But no maximum cap
- Overwhelming demand
- Abrupt end
- Fraud
- Huge cost to Spanish government
- Unbalanced demand/suppy for PV industry

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

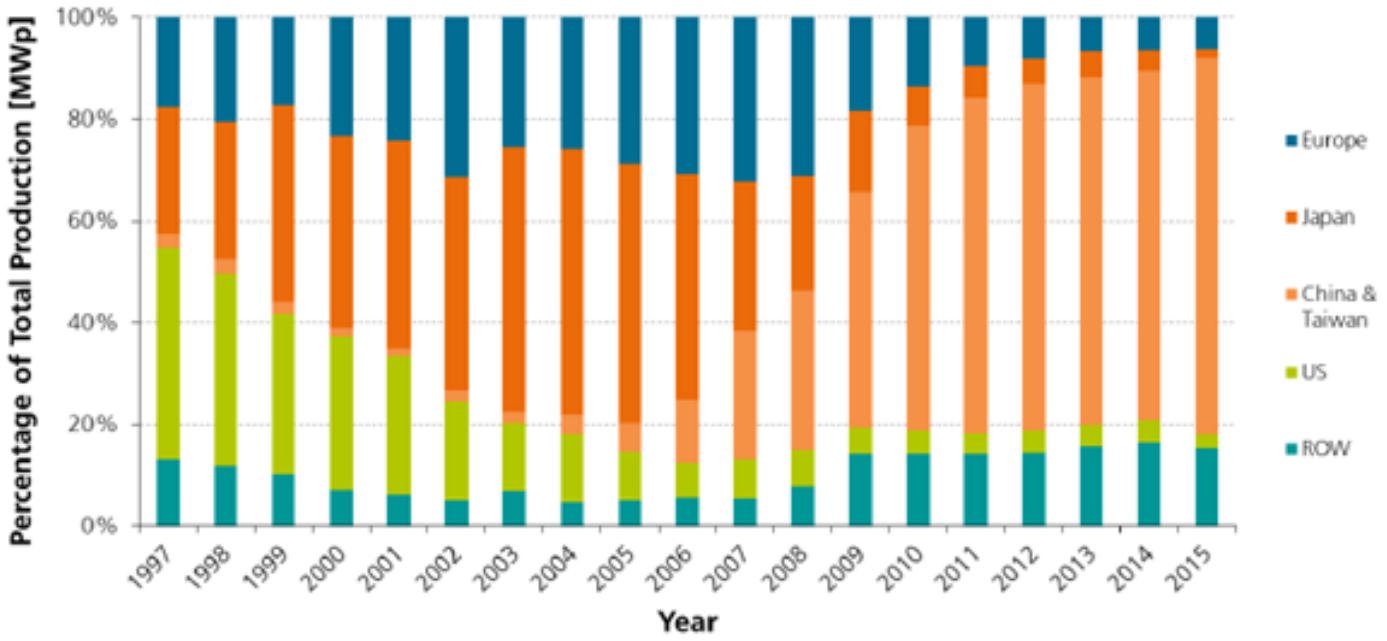


INTRODUCTION

Emergence of PV industry in China

PV Module Production by Region 1997-2015

Percentage of Total MWp Produced



INTRODUCTION

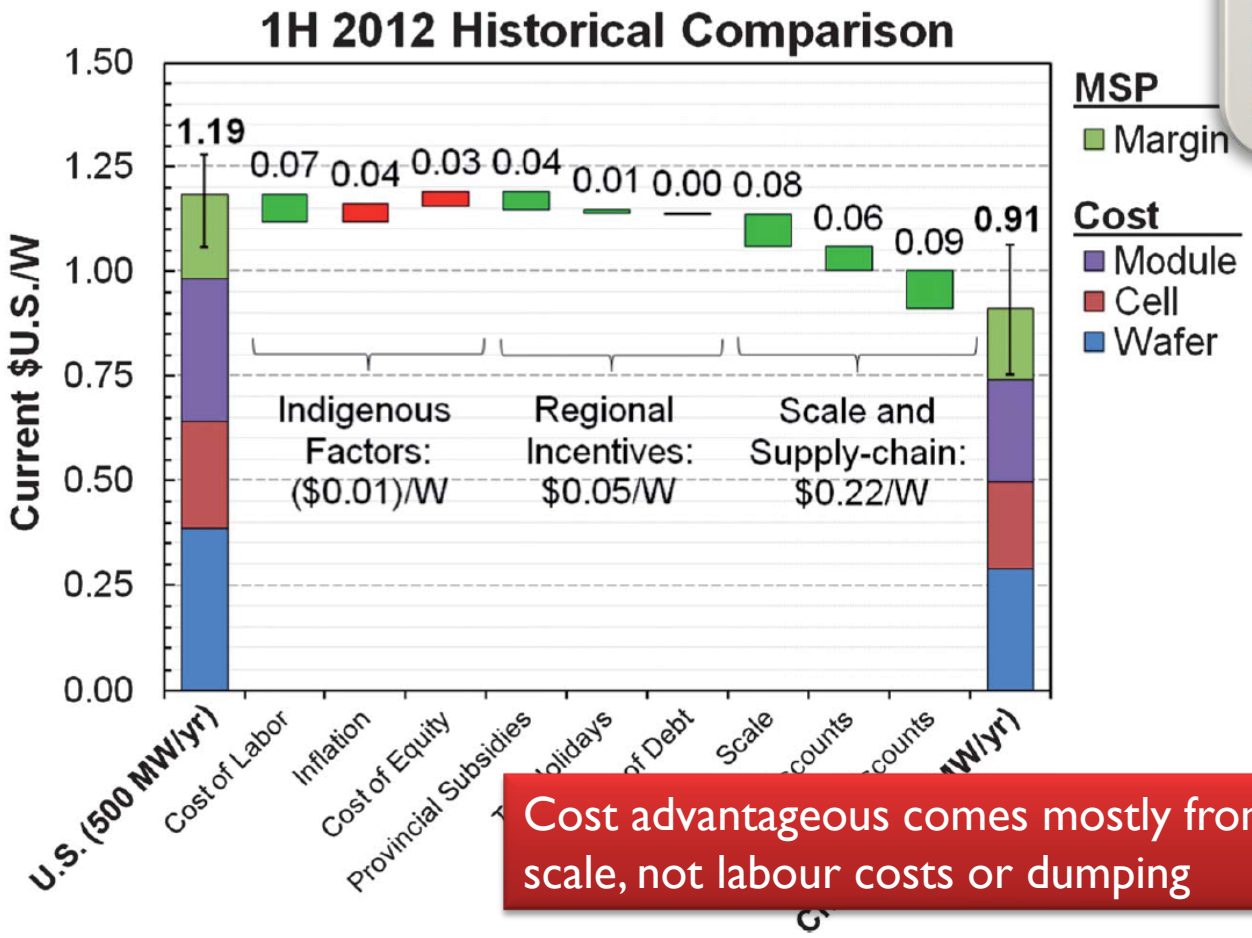
Emergence of PV industry in China

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.

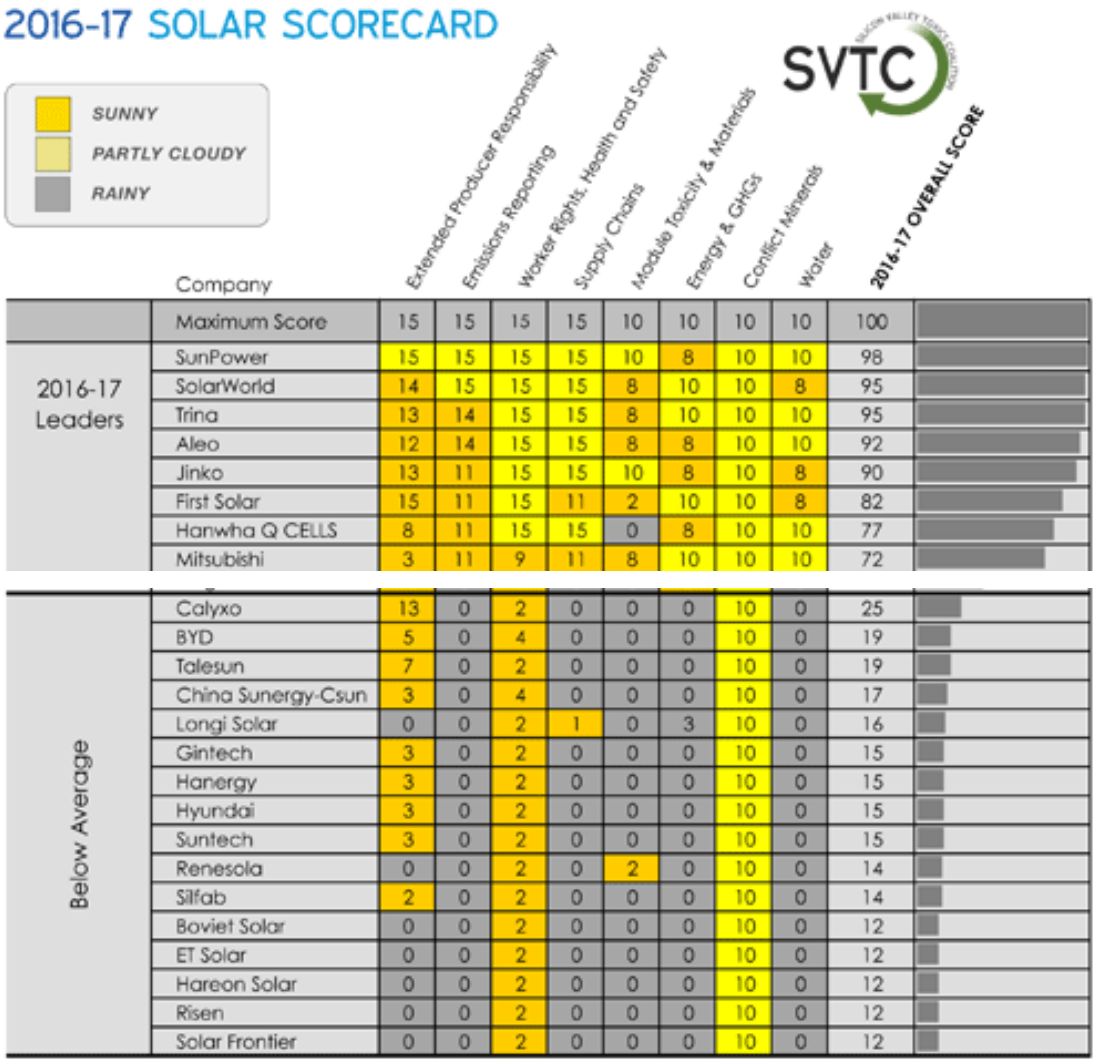
This ritual has been going on almost every day for nine months, Li and other villagers said.

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!

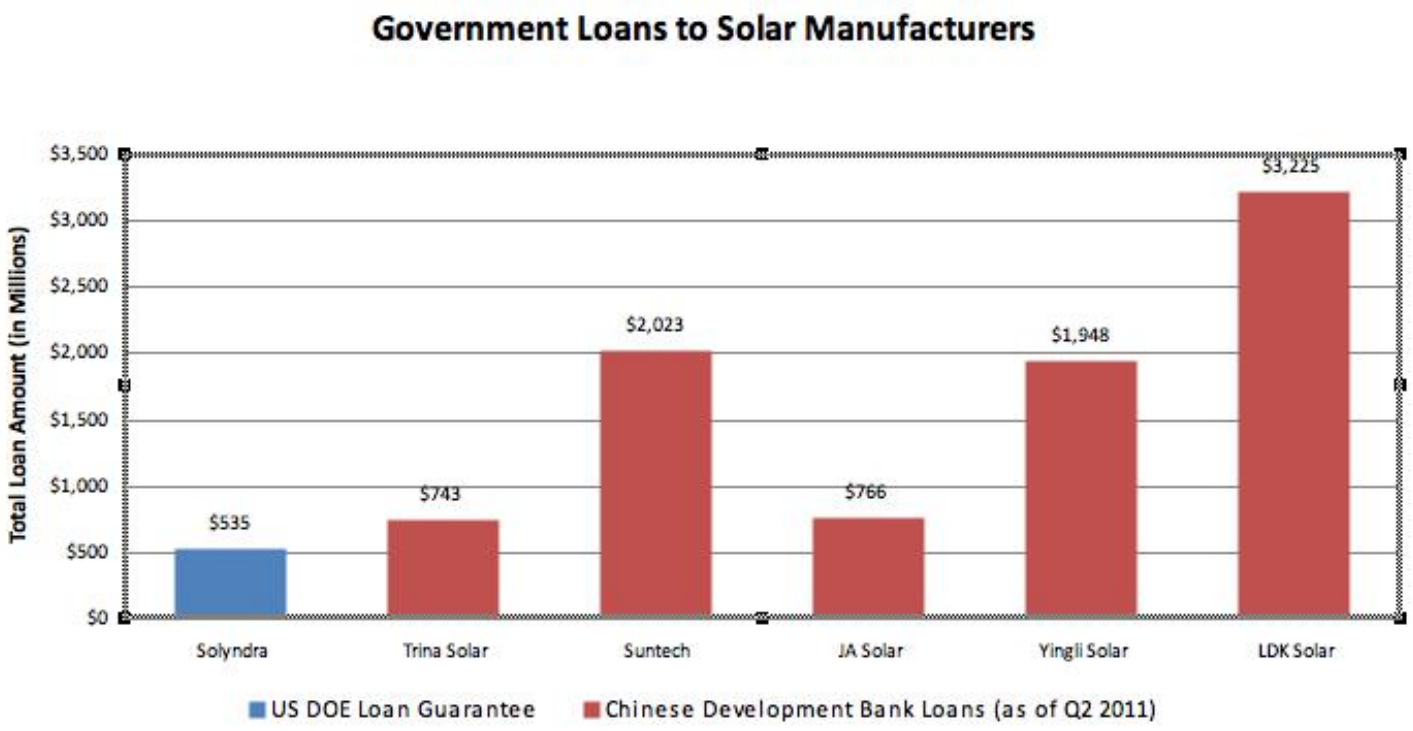
INTRODUCTION



	Company	Extended Producer Responsibility	Emissions Reporting	Worker Rights, Health and Safety	Supply Chains	Module Toxicity & Materials	Energy & GHGs	Conflict Minerals	Water	2016-17 OVERALL SCORE
	Maximum Score	15	15	15	15	10	10	10	10	100
2016-17 Leaders	SunPower	15	15	15	15	10	8	10	10	98
	SolarWorld	14	15	15	15	8	10	10	8	95
	Trina	13	14	15	15	8	10	10	10	95
	Aleo	12	14	15	15	8	8	10	10	92
	Jinko	13	11	15	15	10	8	10	8	90
	First Solar	15	11	15	11	2	10	10	8	82
	Hanwha Q CELLS	8	11	15	15	0	8	10	10	77
	Mitsubishi	3	11	9	11	8	10	10	10	72
Below Average	Calyxo	13	0	2	0	0	0	10	0	25
	BYD	5	0	4	0	0	0	10	0	19
	Talesun	7	0	2	0	0	0	10	0	19
	China Sunergy-Csun	3	0	4	0	0	0	10	0	17
	Longi Solar	0	0	2	1	0	3	10	0	16
	Gintech	3	0	2	0	0	0	10	0	15
	Hanergy	3	0	2	0	0	0	10	0	15
	Hyundai	3	0	2	0	0	0	10	0	15
	Suntech	3	0	2	0	0	0	10	0	15
	Renesola	0	0	2	0	2	0	10	0	14
	Silfab	2	0	2	0	0	0	10	0	14
	Boviet Solar	0	0	2	0	0	0	10	0	12
	ET Solar	0	0	2	0	0	0	10	0	12
	Hareon Solar	0	0	2	0	0	0	10	0	12
	Risen	0	0	2	0	0	0	10	0	12
	Solar Frontier	0	0	2	0	0	0	10	0	12

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.

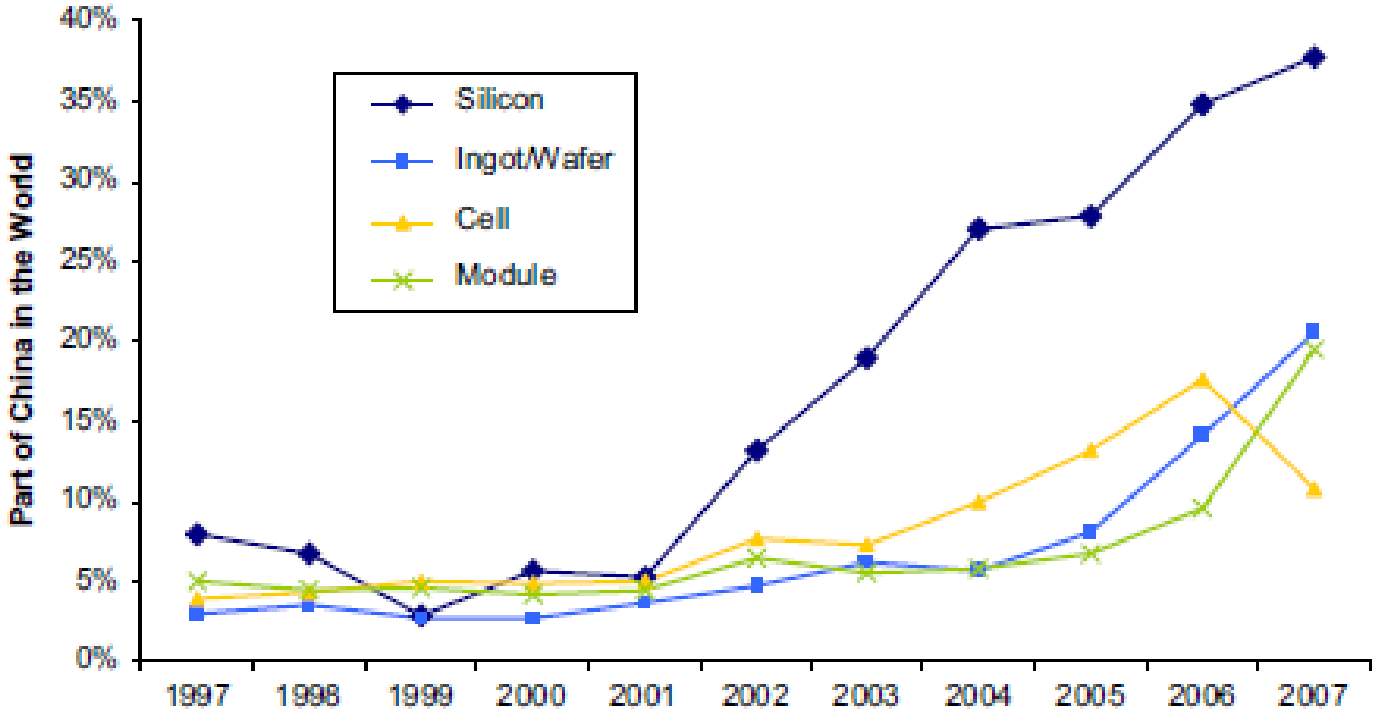
The Fraunhofer Institute of Solar Energy Systems in Germany, one of the few labs in the world whose test results are recognized by the industry, verified the efficiency of the panel. The panel rolled off a new factory line China-based Suntech set up to start shipping Pluto panels earlier this year.

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

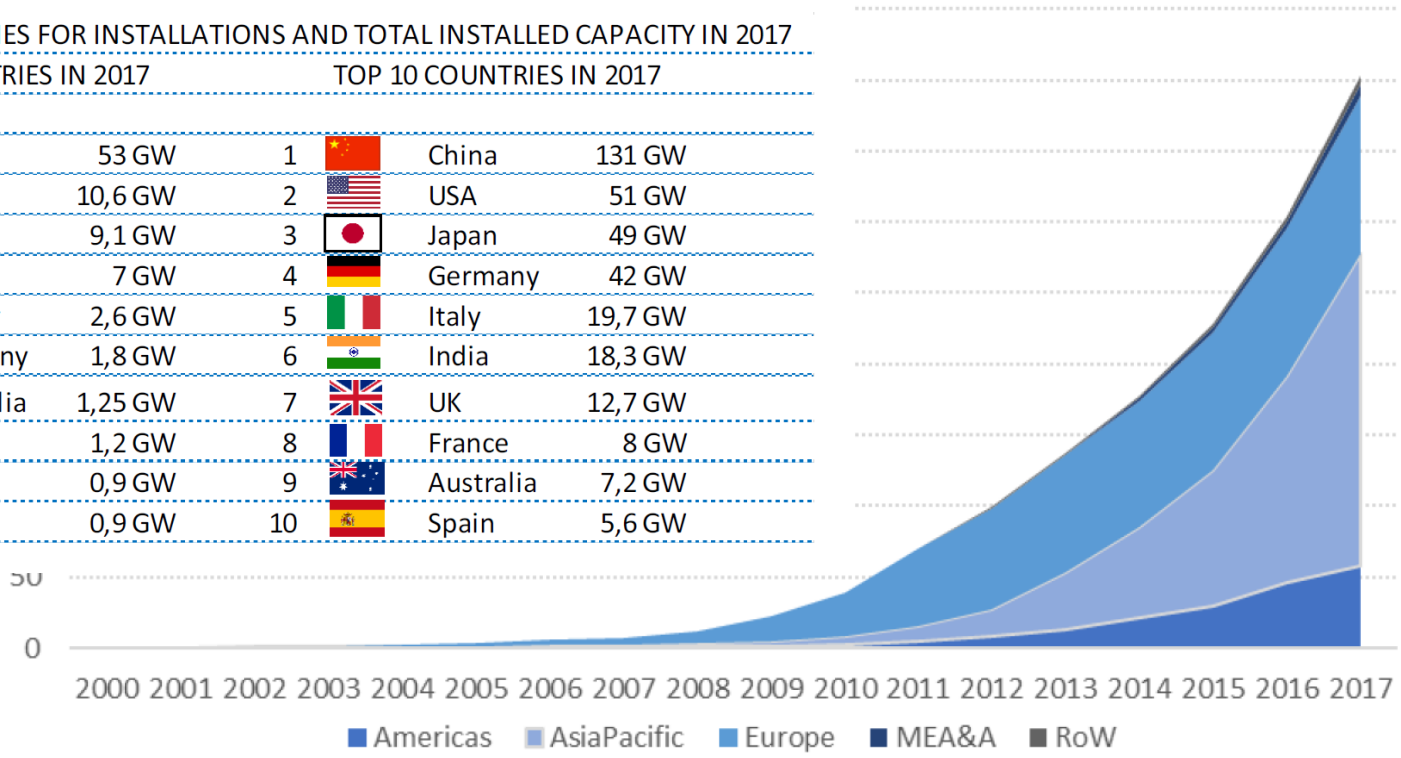
Emergence of PV industry in China

The fastest increasing PV market

TABLE 1: TOP 10 COUNTRIES FOR INSTALLATIONS AND TOTAL INSTALLED CAPACITY IN 2017

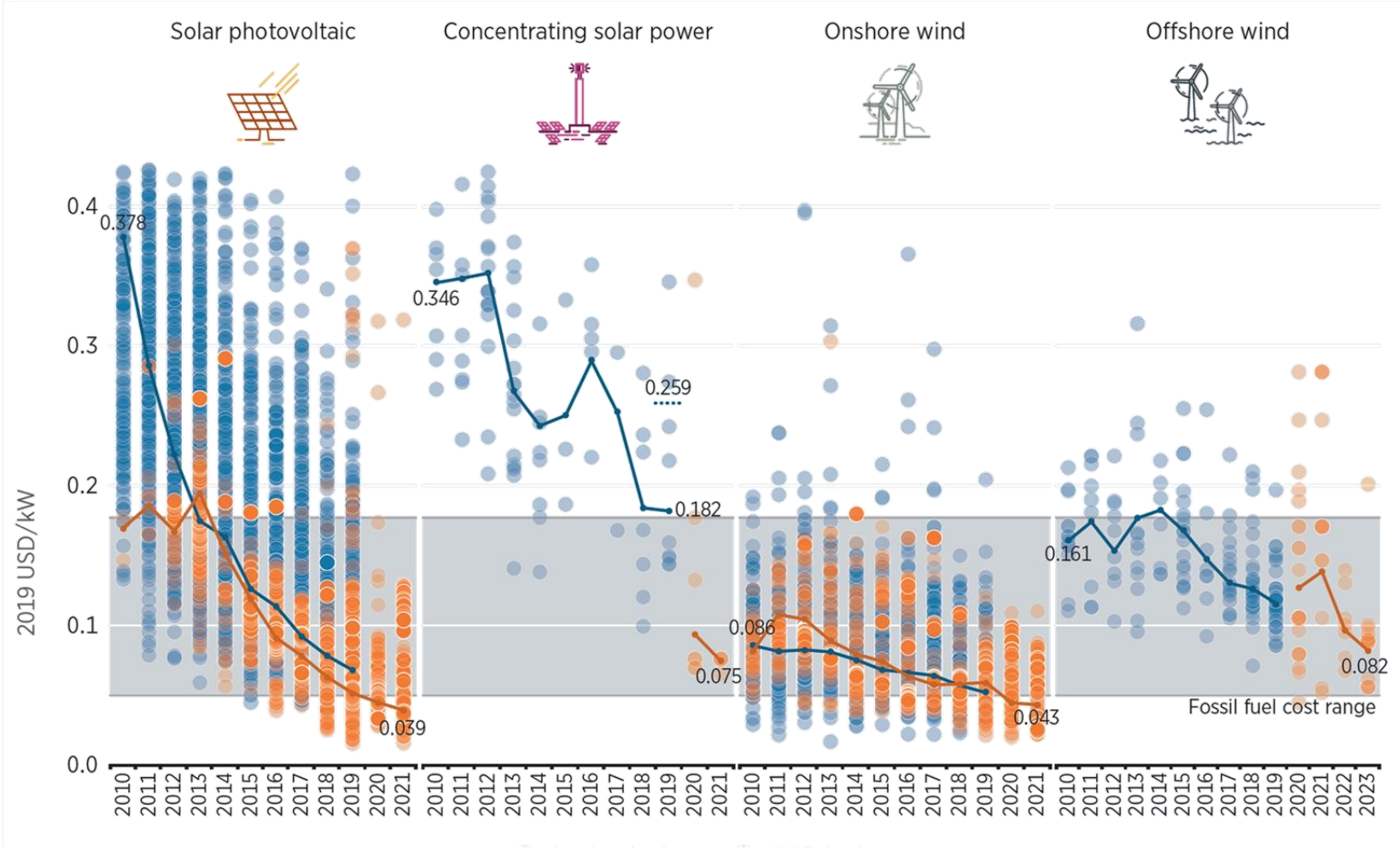
	TOP 10 COUNTRIES IN 2017			TOP 10 COUNTRIES IN 2017	
1	China	53 GW	1	China	131 GW
2	USA	10,6 GW	2	USA	51 GW
3	India	9,1 GW	3	Japan	49 GW
4	Japan	7 GW	4	Germany	42 GW
5	Turkey	2,6 GW	5	Italy	19,7 GW
6	Germany	1,8 GW	6	India	18,3 GW
7	Australia	1,25 GW	7	UK	12,7 GW
8	Korea	1,2 GW	8	France	8 GW
9	UK	0,9 GW	9	Australia	7,2 GW
10	Brazil	0,9 GW	10	Spain	5,6 GW

FIGURE 4: EVOLUTION OF REGIONAL PV INSTALLATIONS (GW - DC)



2018 SNAPSHOT OF GLOBAL PHOTOVOLTAIC MARKETS , Report IEA PVPS T1-33:2018

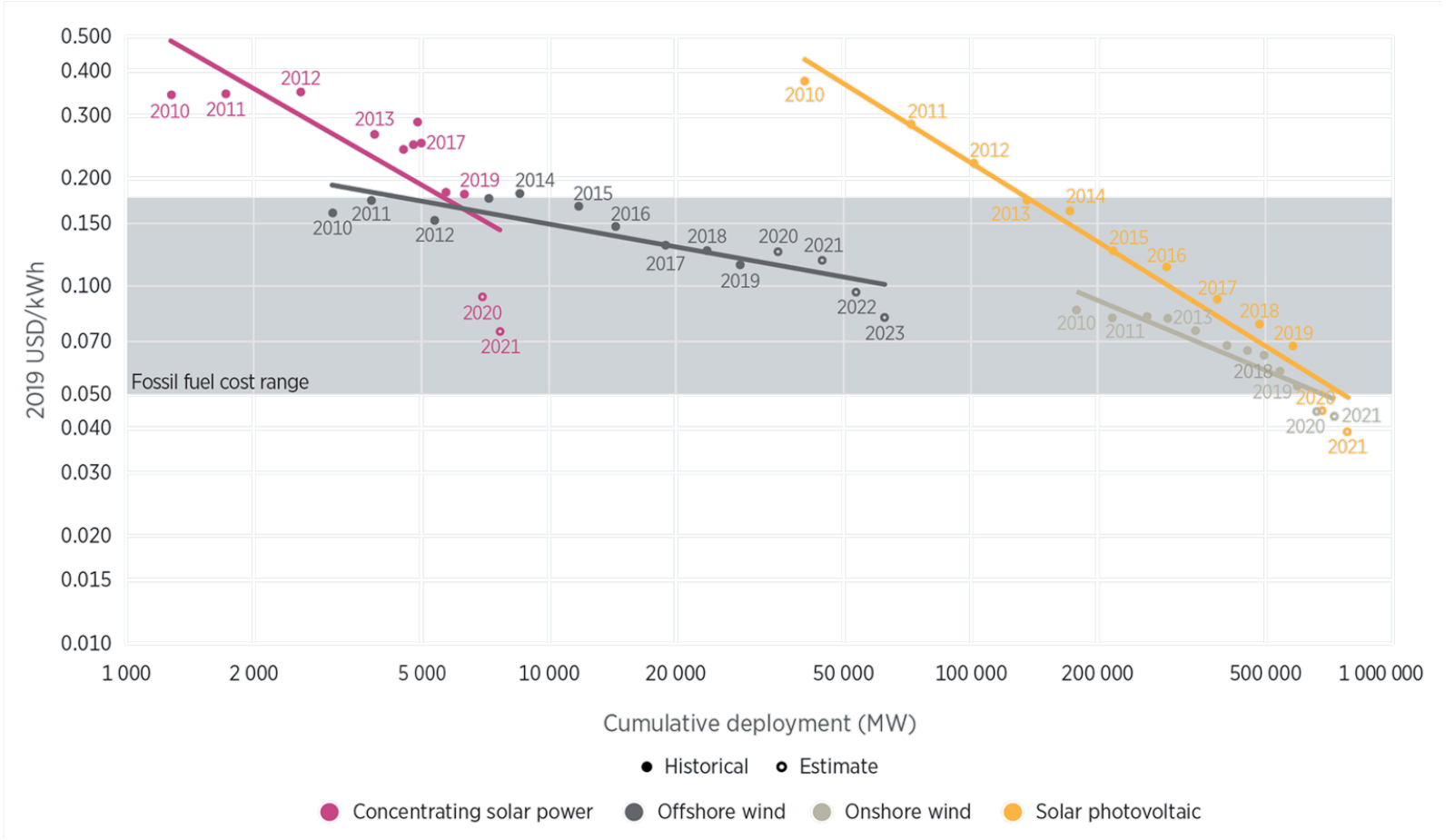
INTRODUCTION



10 times cheaper in the last 10 years!!

IRENA (2020), Renewable Power Generation Costs in 2019, International Renewable Energy Agency, Abu Dhabi.

INTRODUCTION

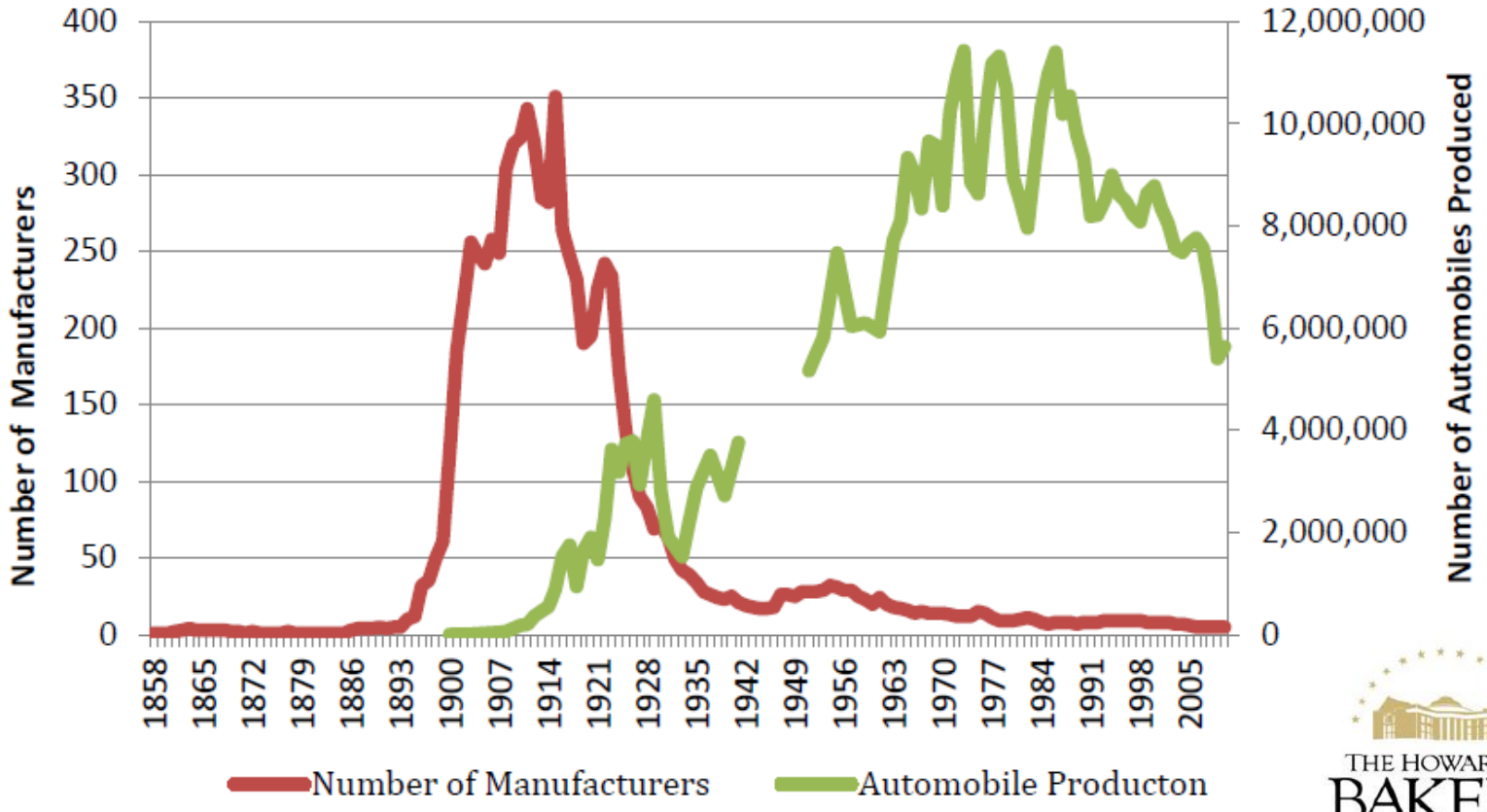


10 times cheaper in the last 10 years!!

IRENA (2020), Renewable Power Generation Costs in 2019, International Renewable Energy Agency, Abu Dhabi.

INTRODUCTION

Consolidation of the global PV industry

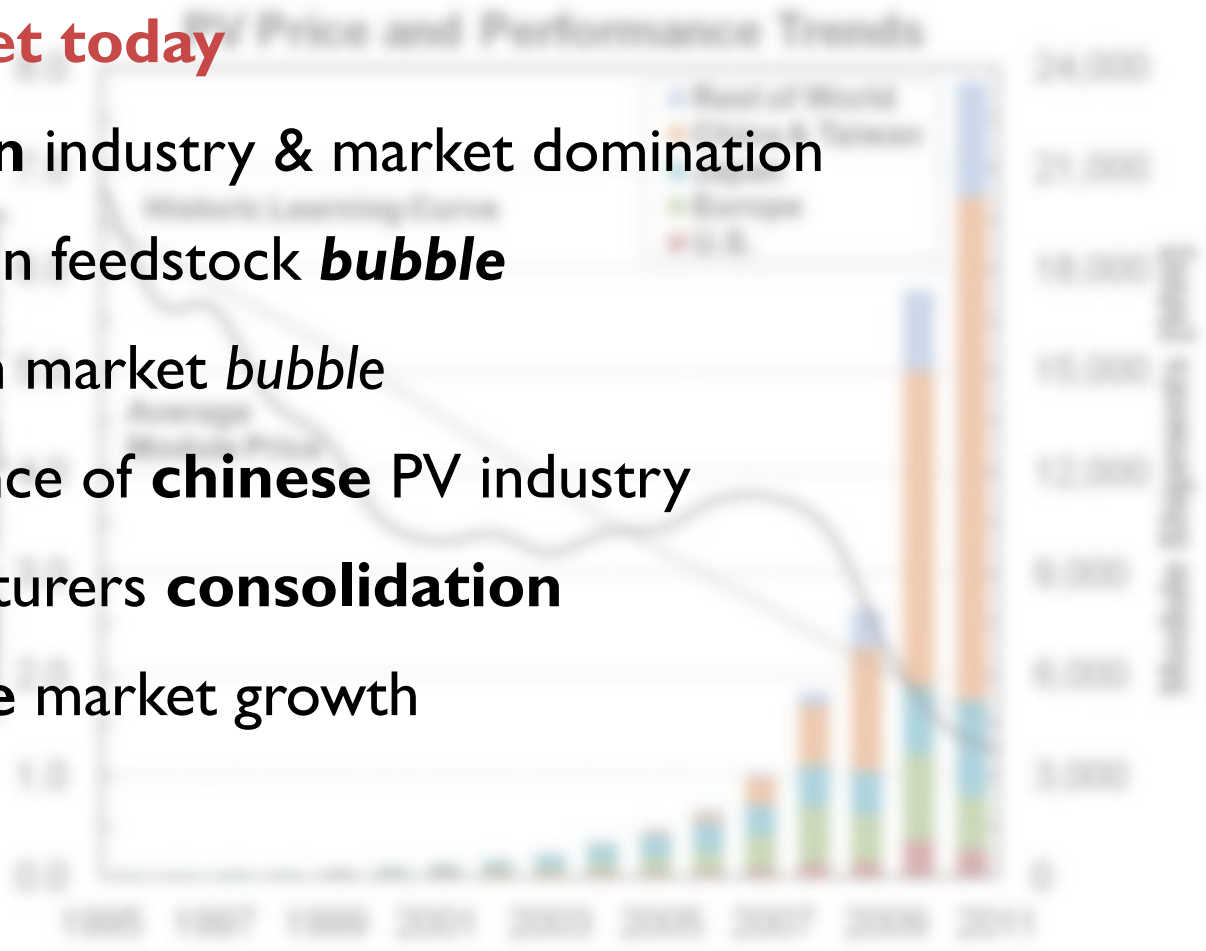


THE HOWARD H. BAKER JR CENTER for PUBLIC POLICY
THE UNIVERSITY of TENNESSEE KNOXVILLE

INTRODUCTION

PV market today

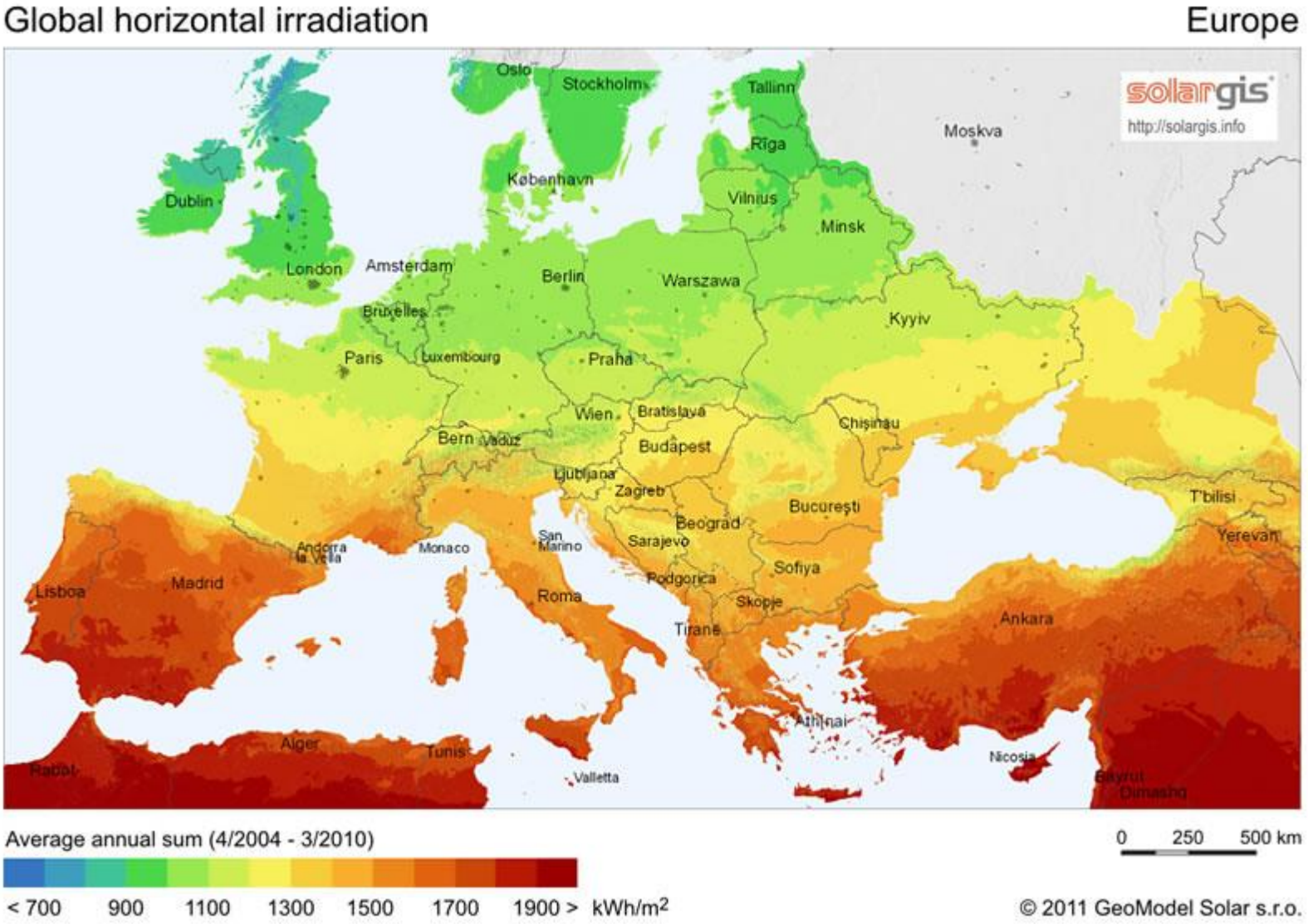
- **German** industry & market domination
- Polisilicon feedstock ***bubble***
- **Spanish** market *bubble*
- Emergence of **chinese** PV industry
- Manufacturers **consolidation**
- **Chinese** market growth



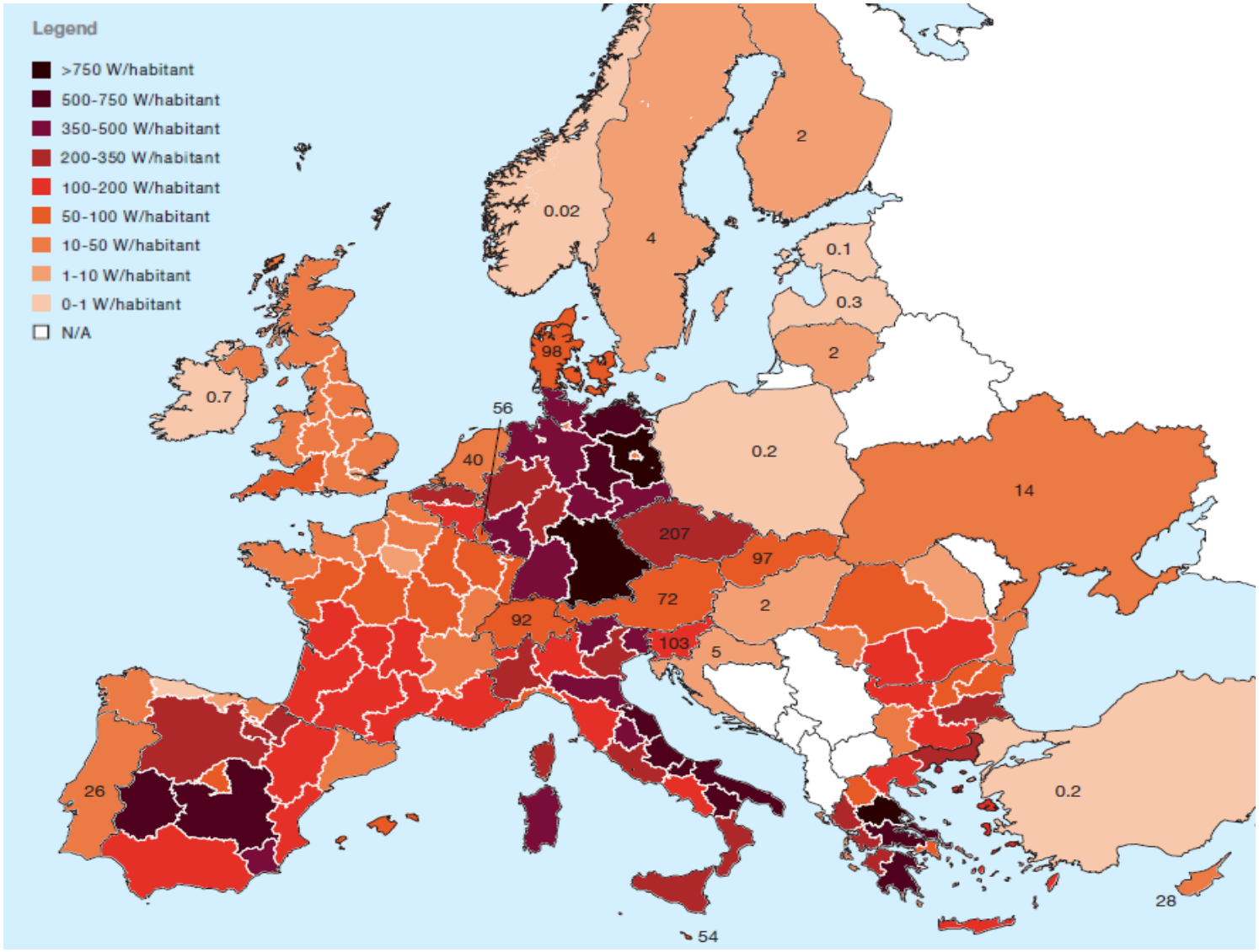
INTRODUCTION

PV in Portugal

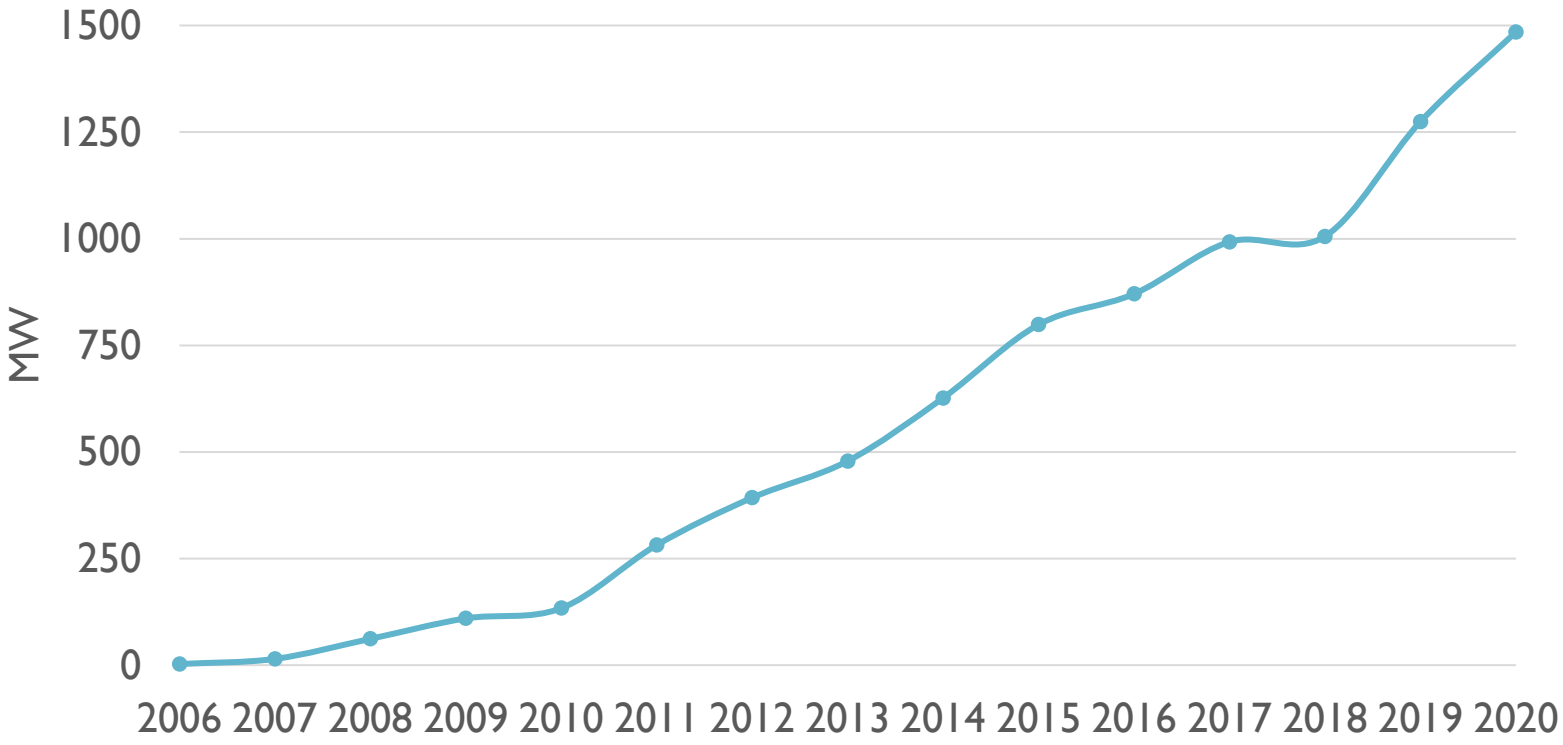
INTRODUCTION



INTRODUCTION

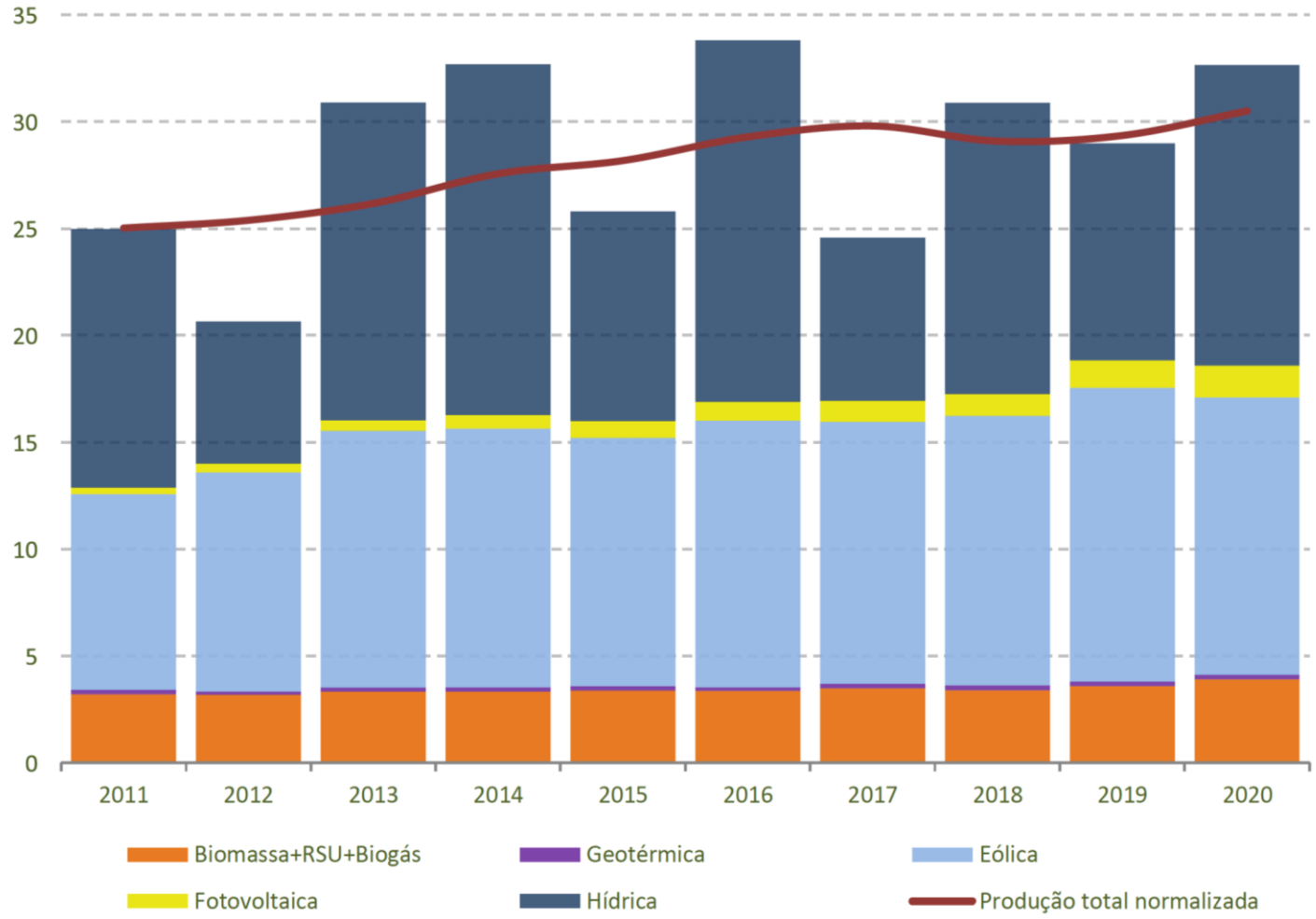


INTRODUCTION



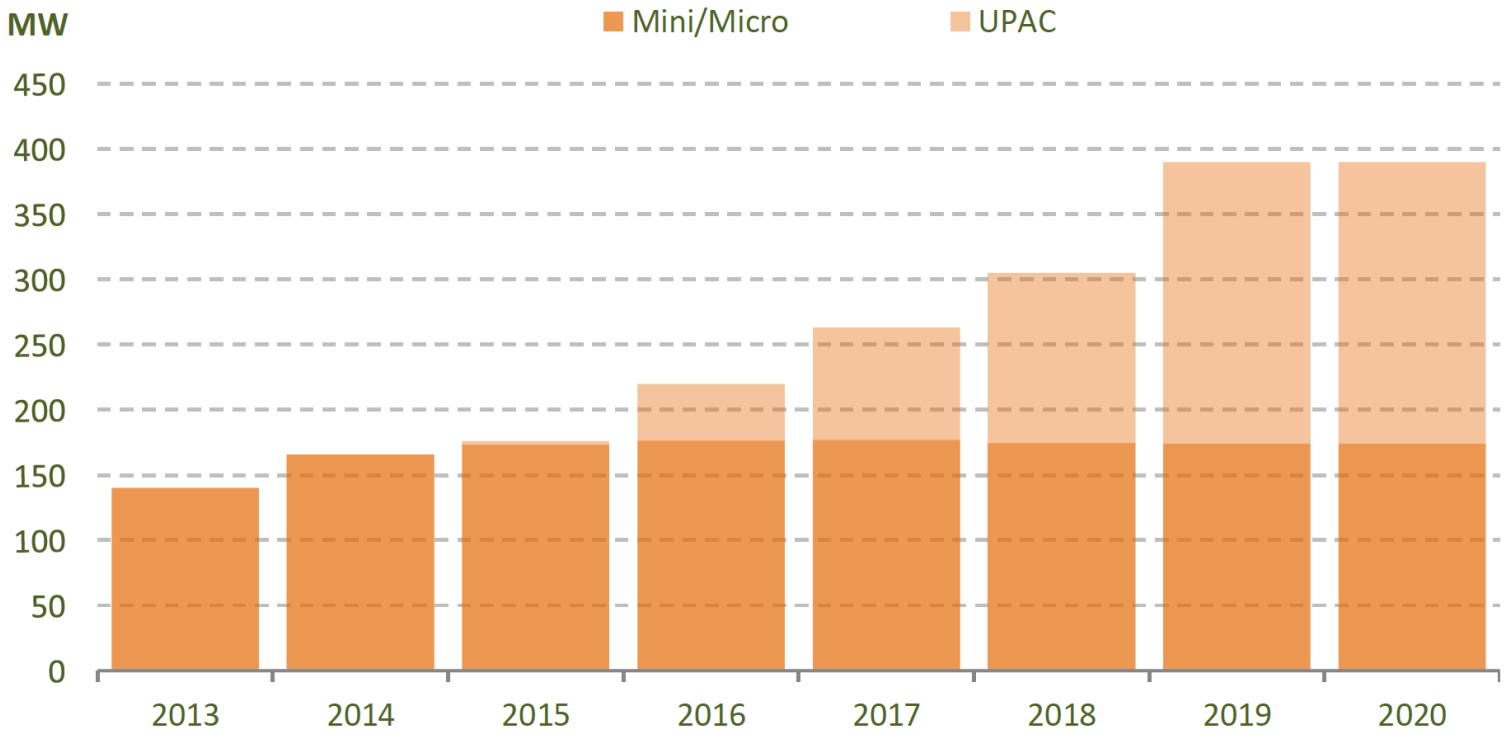
Estatísticas rápidas, DEGEG, Julho 2020

INTRODUCTION



Estatísticas rápidas, DEGEG, Julho 2020

INTRODUCTION



Estatísticas rápidas, DEGEG, Julho 2020

INTRODUCTION

PV in Portugal – **legal framework**

- Roadmaps

  2020: 1.5 W 2030: 10 GW 2050: 20 GW

- 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]

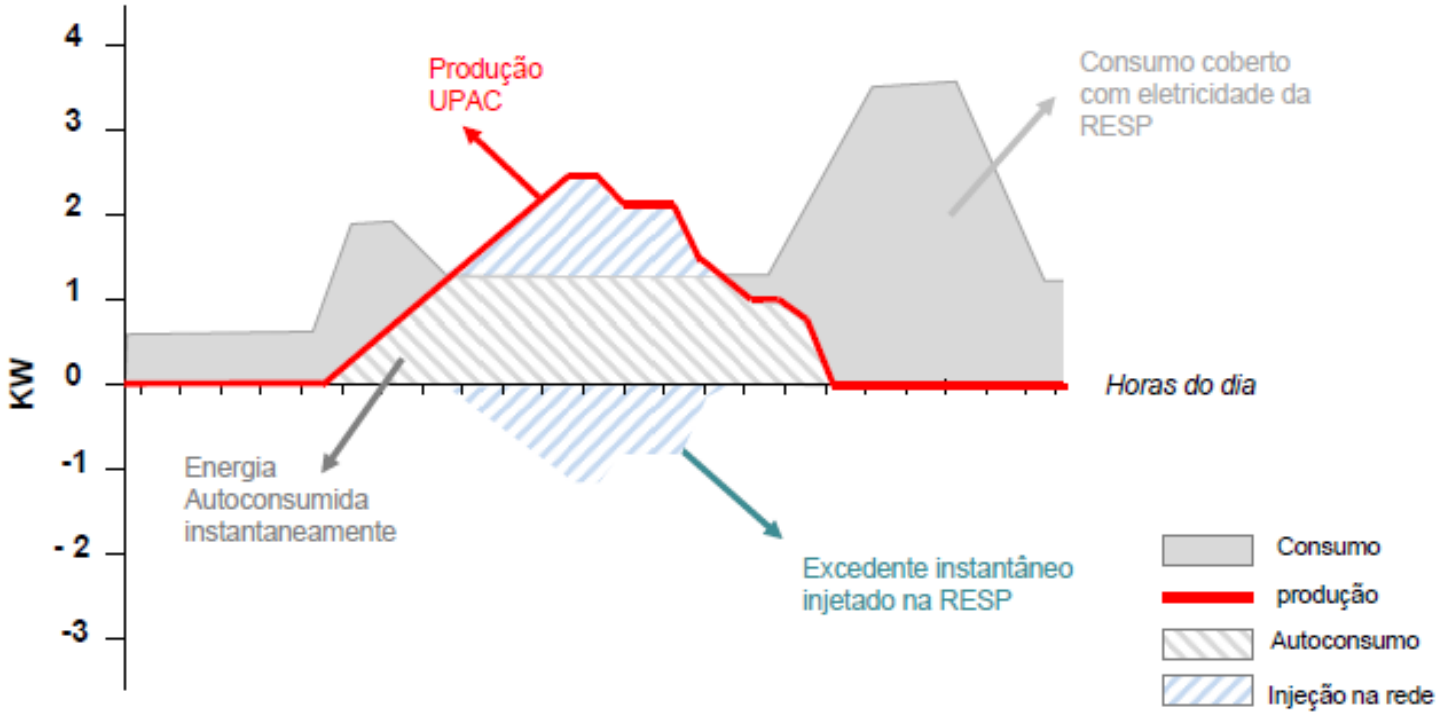
  (<20kW: 25c€/kWh; <250kW: auction)

- Self-demand |DL 153/2014 October 20th]

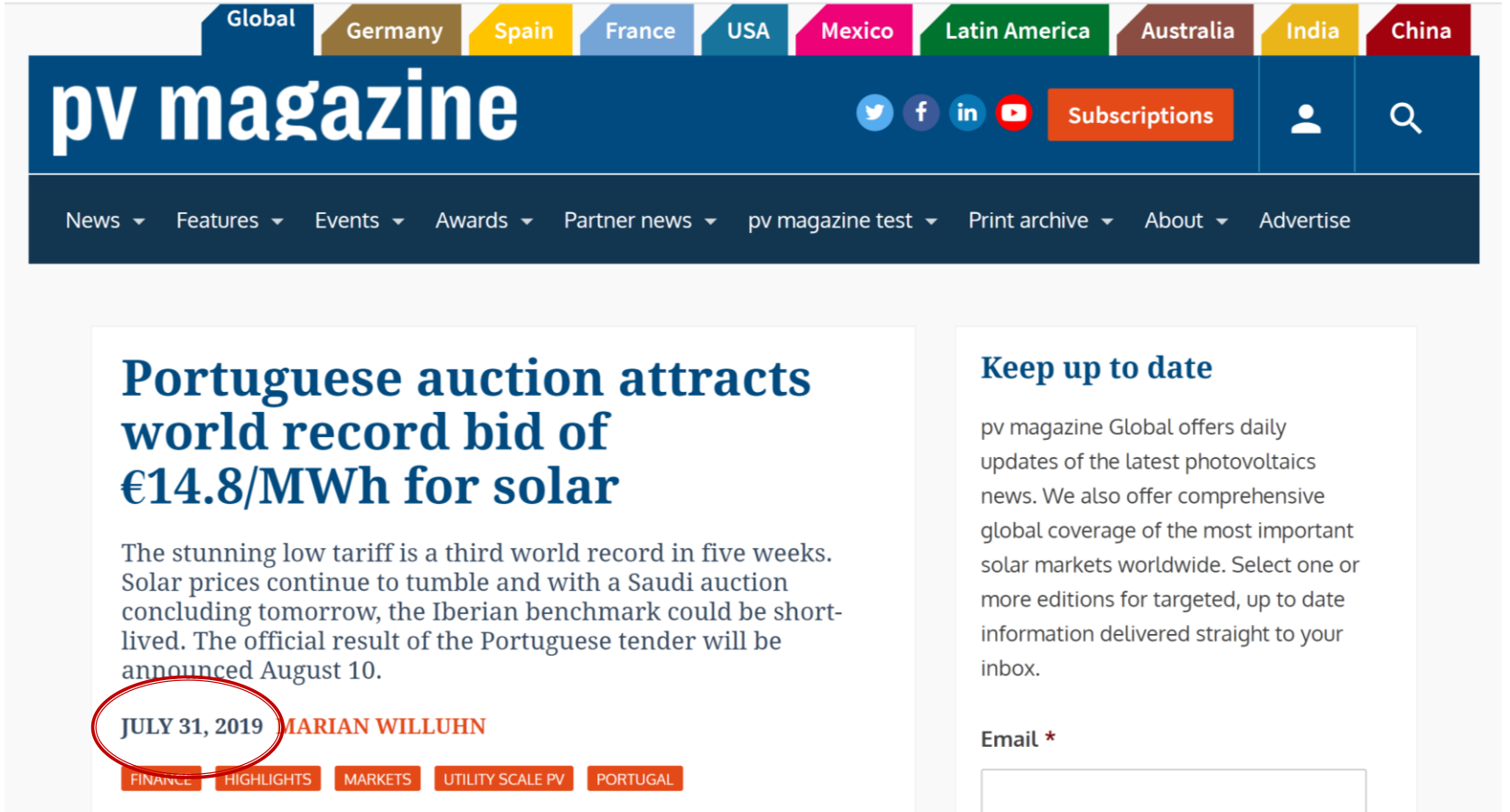
- Solar auctions (2019 & 2020)

INTRODUCTION

Self demand in Portugal



INTRODUCTION

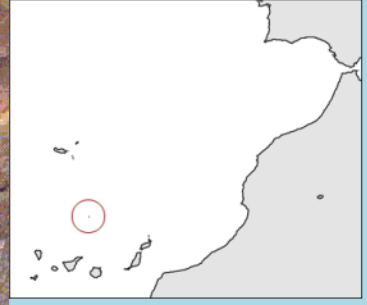


INTRODUCTION

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)

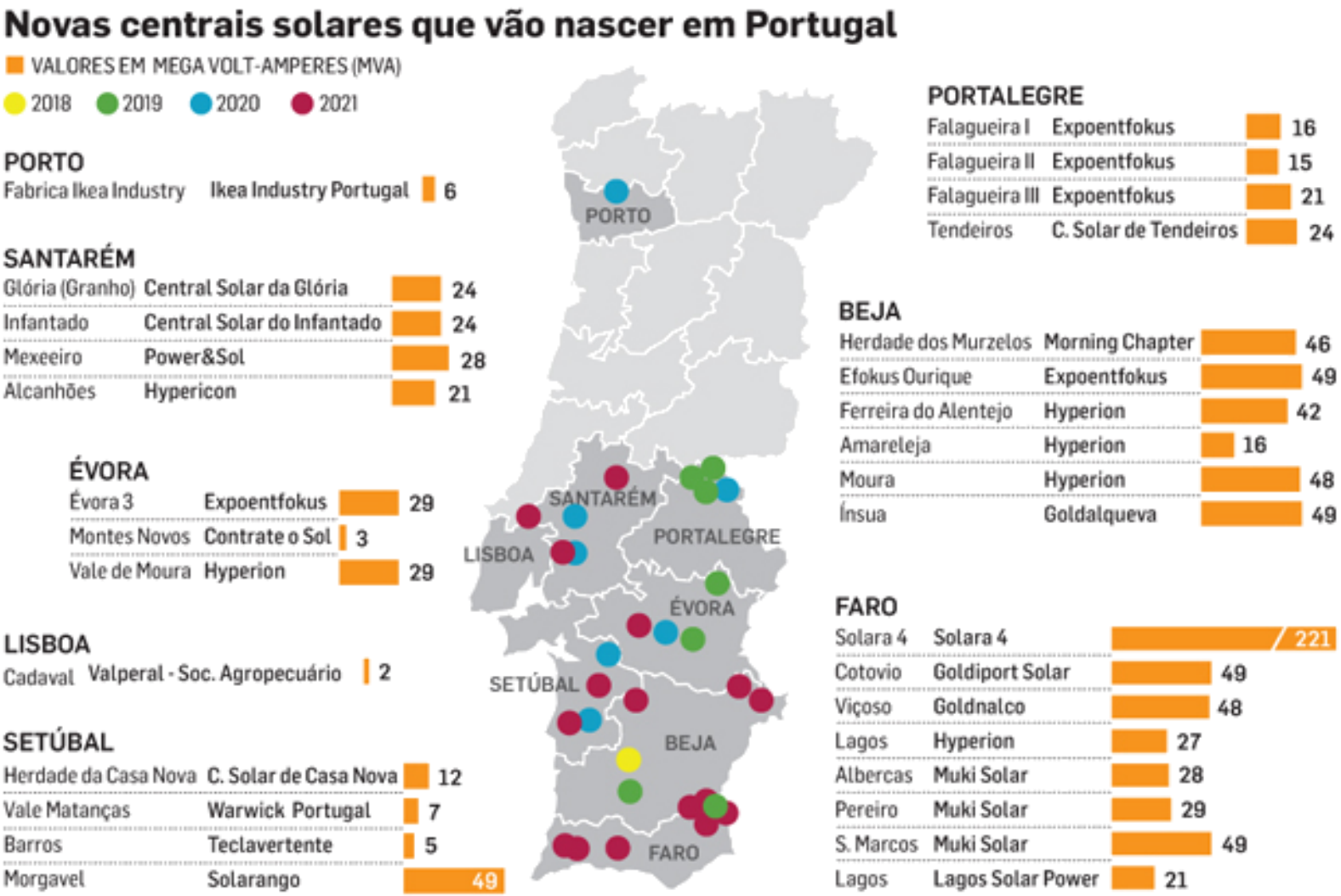


16° W
Palheiro de Terra
Palheiro do Mar
Ponta do Corgo da Areia
Ponta do Risco
Pico dos Tornozelos
Pico da Atalaia
Selvagem Grande
Enseada das Pedreiras
Enseada da Atalaia
Ilhéu Sinho
Enseada das Cagarras
Pico do Inferno
Ponta de Leste
Ponta do Inferno
Oceano Atlântico
Atlantic Ocean
Ilhéus do Norte
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



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
- Unsubsidized market is emerging, big time!
- Untapped huge solar potential