



# Photovoltaics

## Introduction

# Today

- Brief history of photovoltaics
- PV global market
- PV in Portugal

# 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.

# Brief history of photovoltaics

Feb. 5, 1957

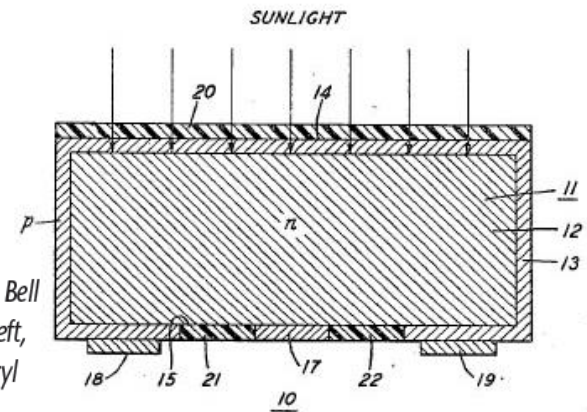
D. M. CHAPIN ET AL  
SOLAR ENERGY CONVERTING APPARATUS

2,780,765

Filed March 5, 1954



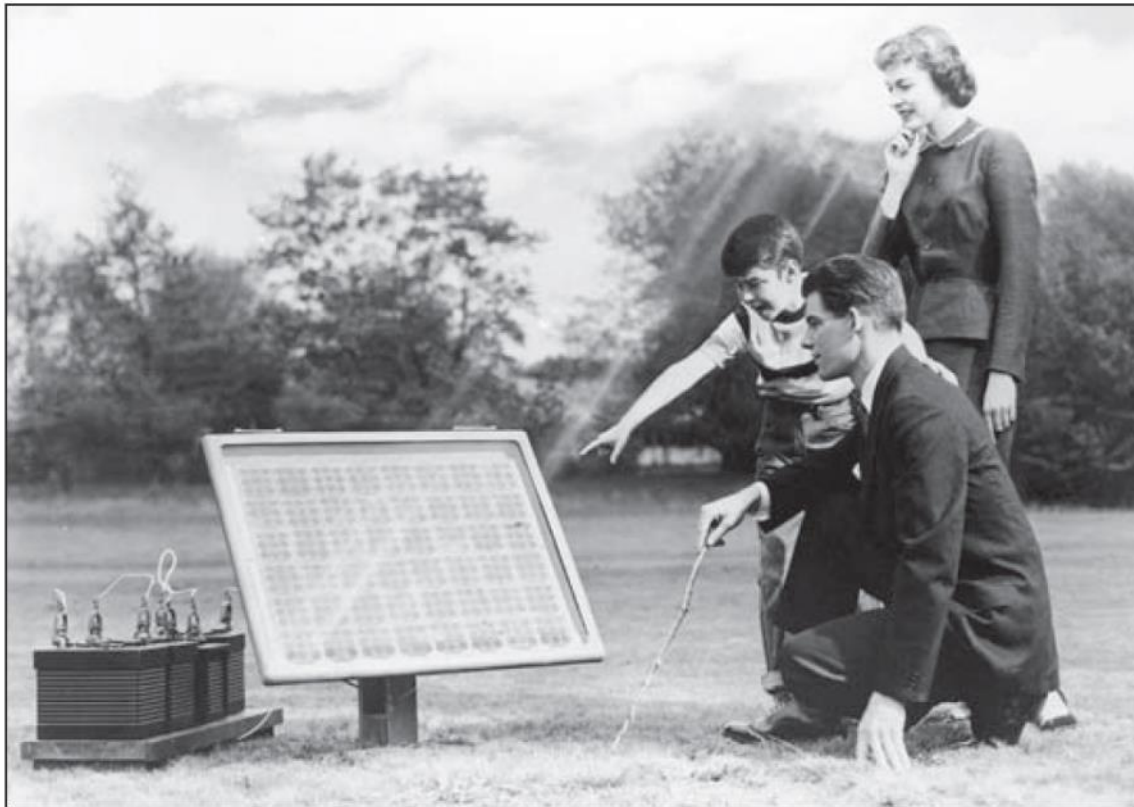
FIG. 1



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.

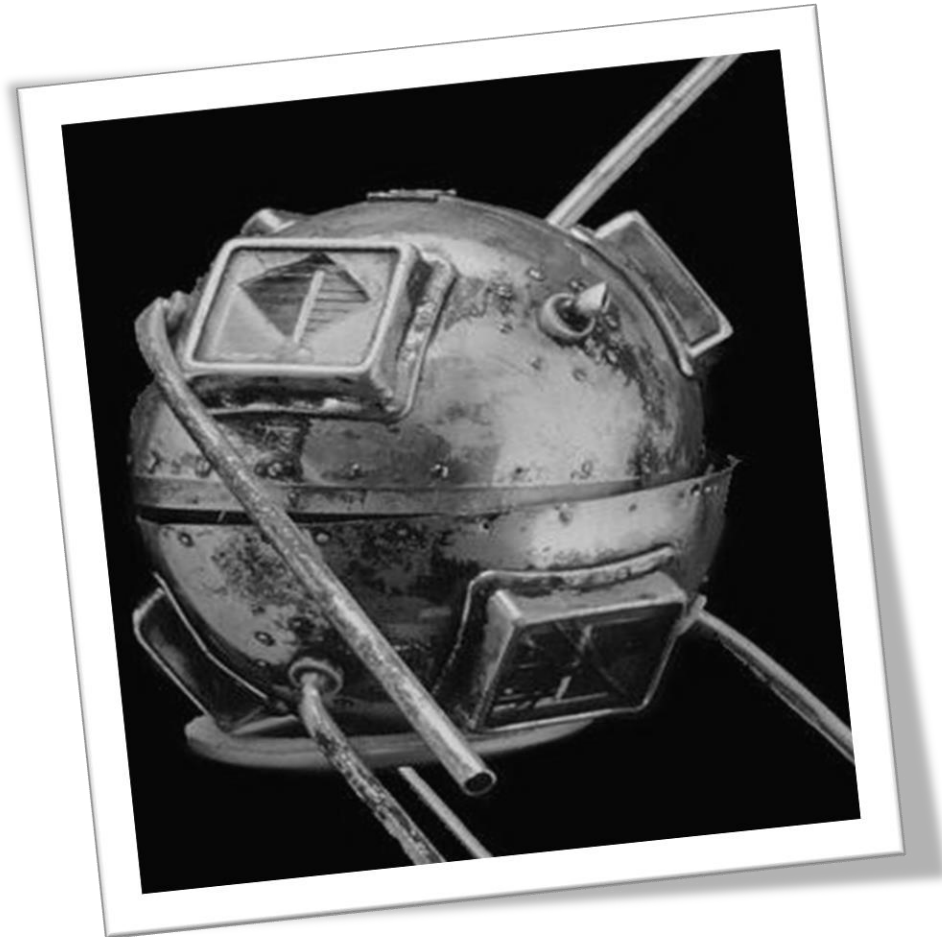


# Brief history of photovoltaics

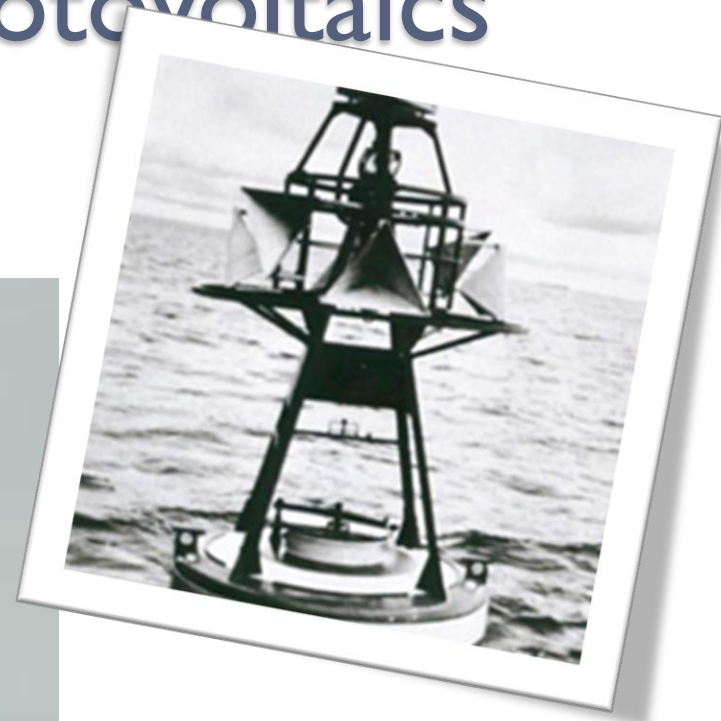


*Advertisement photos, such as this one that appeared in the 1956 issue of Look Magazine, show off the "Bell Solar Battery" to the American public.*

# Brief history of photovoltaics



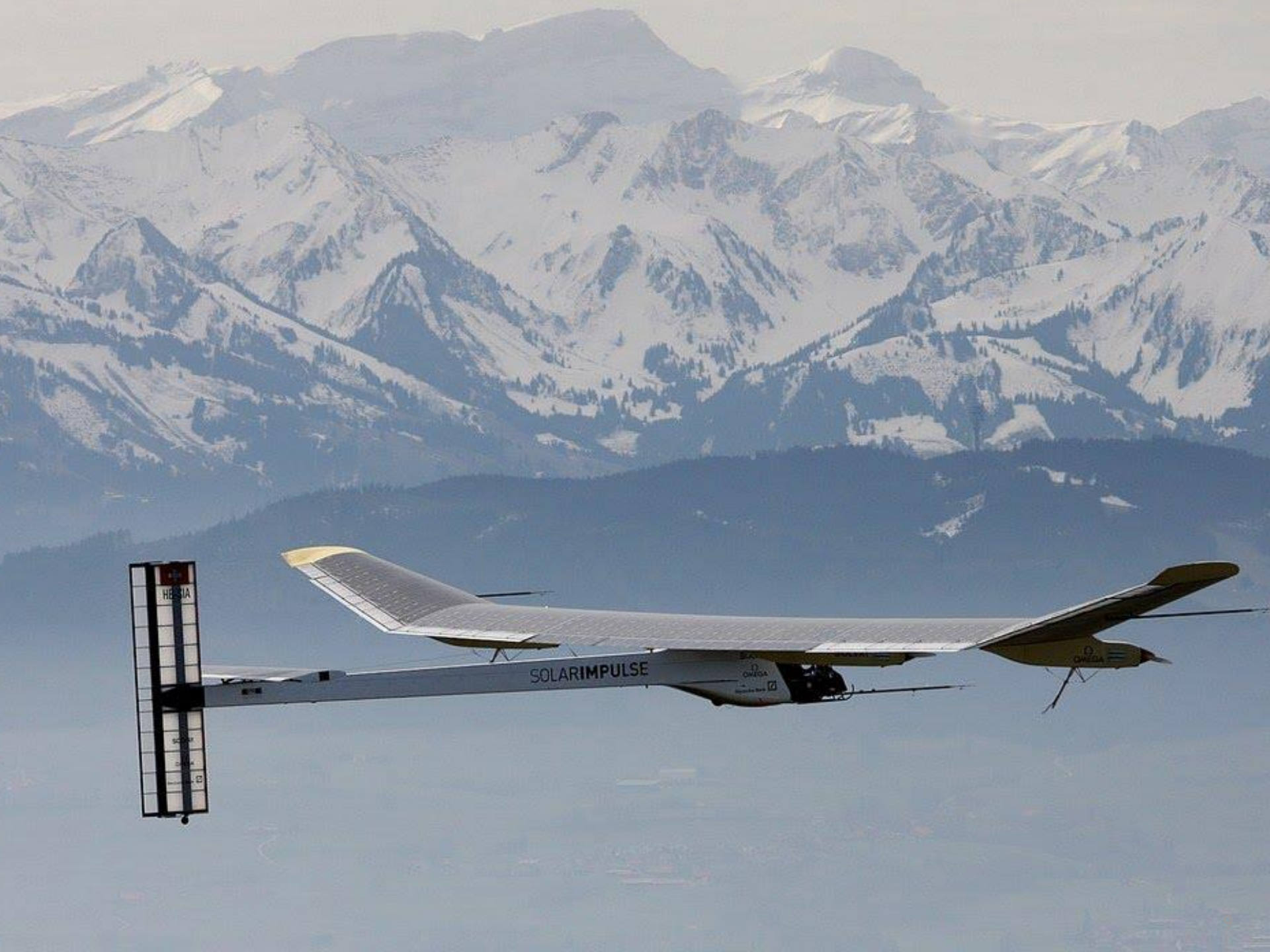
# Brief history of photovoltaics











HEBRIA

SOLARIMPULSE

OMEGA

OMEGA









UNSW  
ENGINEERING

TAPE





2

A D2990

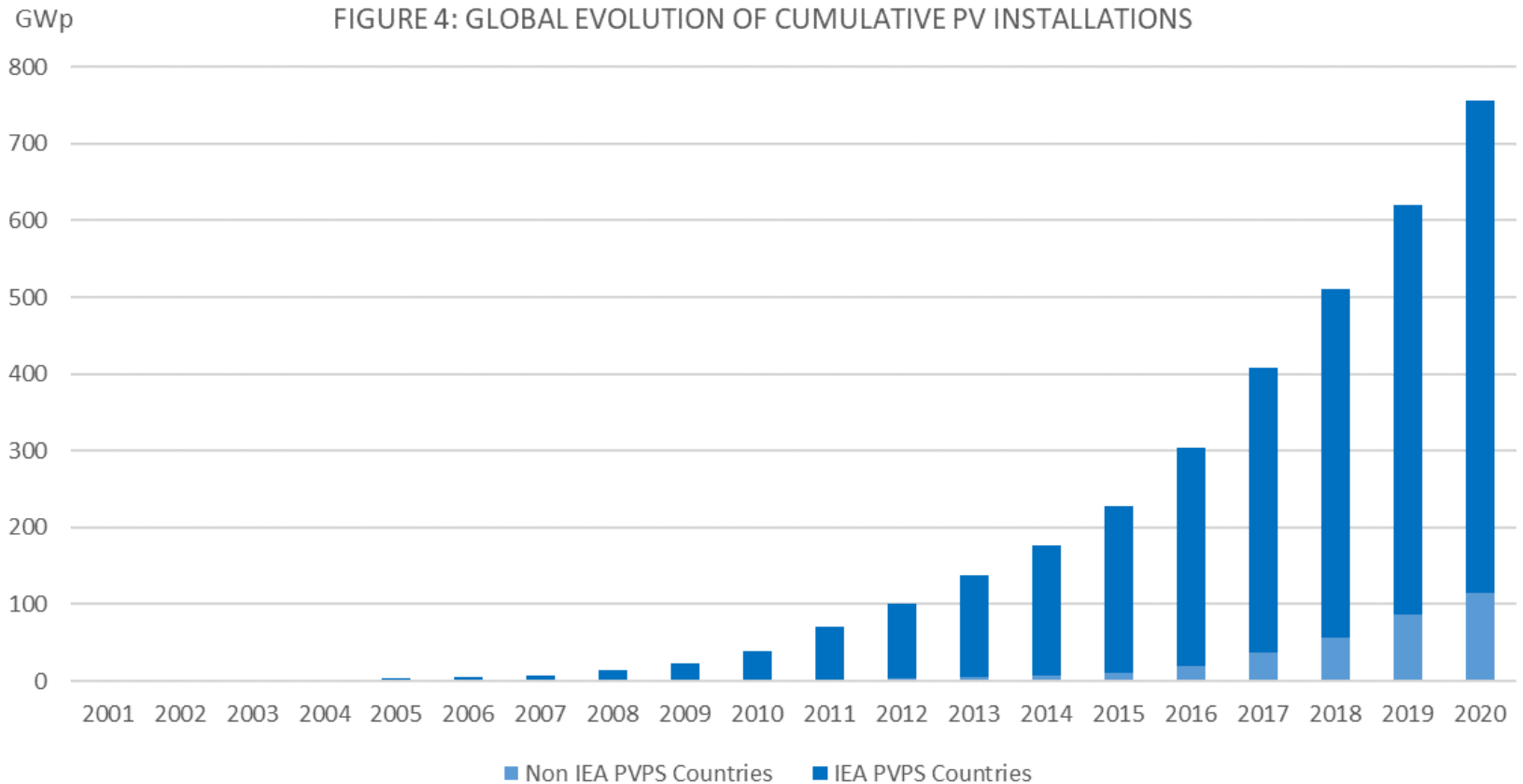
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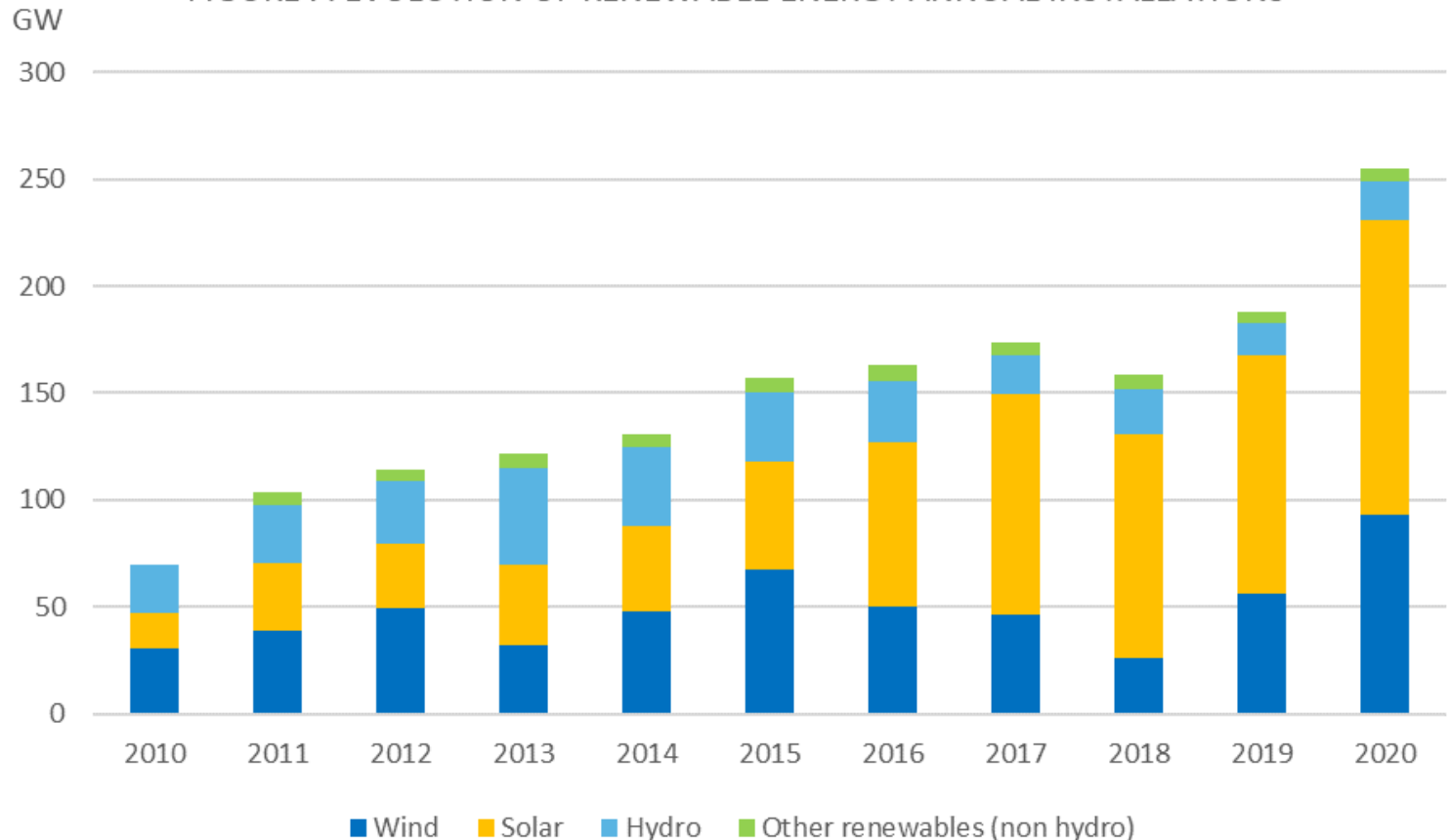
# PV fast development



PV installed capacity growing exponentially

# PV fast development

FIGURE 7: EVOLUTION OF RENEWABLE ENERGY ANNUAL INSTALLATIONS



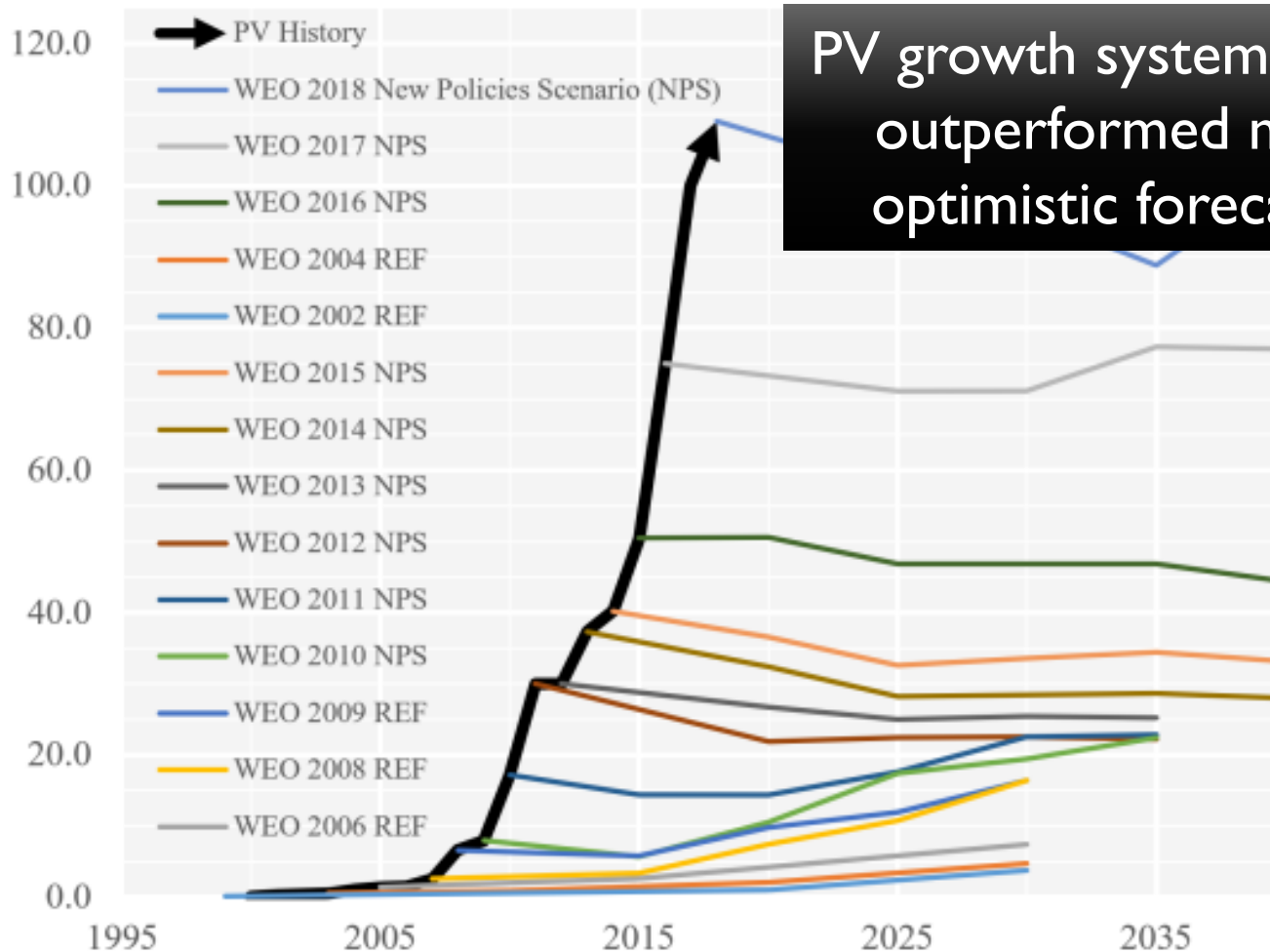
PV is the fastest growing power source worldwide



# PV fast development

## Annual PV additions: historic data vs IEA WEO predictions

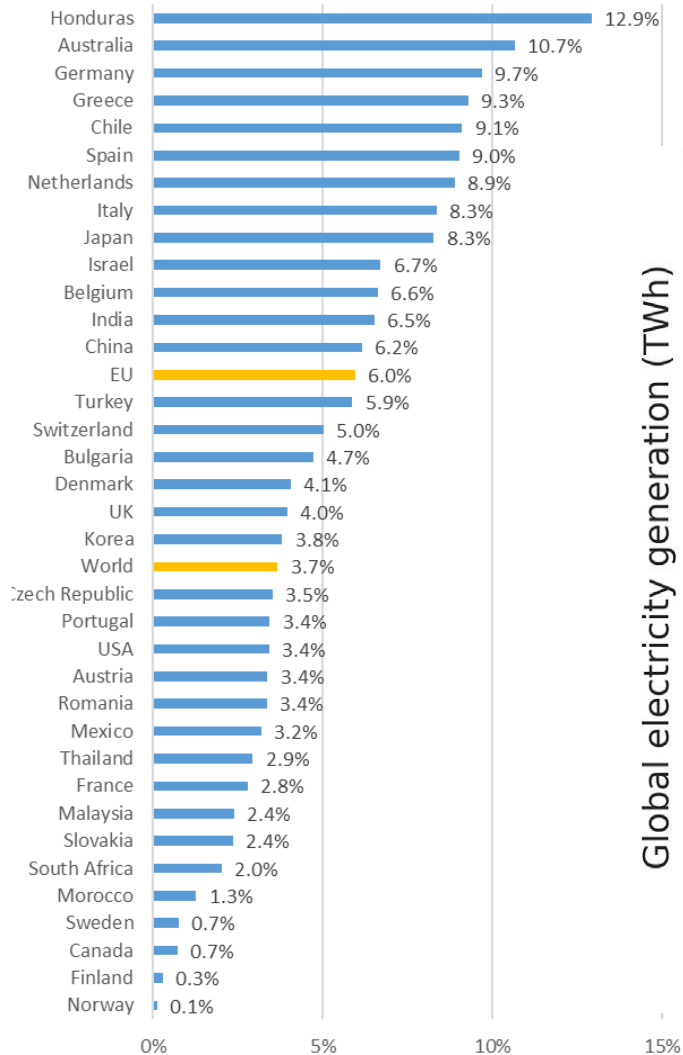
In GW of added capacity per year - source International Energy Agency - World Energy Outlook



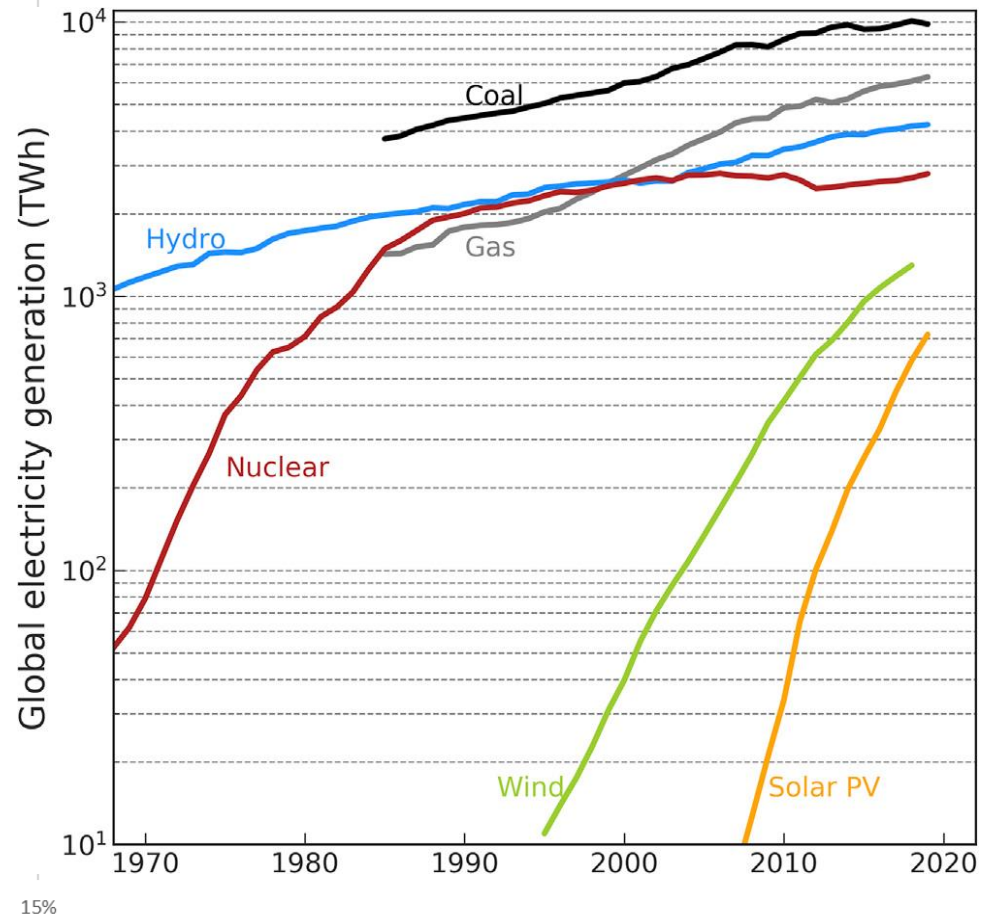
PV growth systematically outperformed most optimistic forecasts!

# PV fast development

FIGURE 6: THEORETICAL PV PENETRATION 2020



Despite growing installed capacity PV is only about 3% total demand



# PV fast development





# TOP PV MARKETS 2020



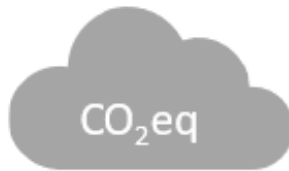
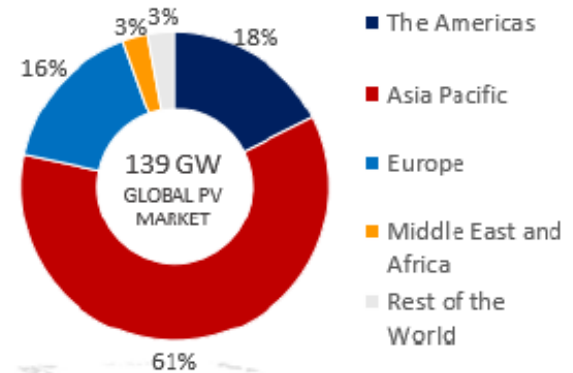
CHINA 48,2 GW



EU 19,6 GW

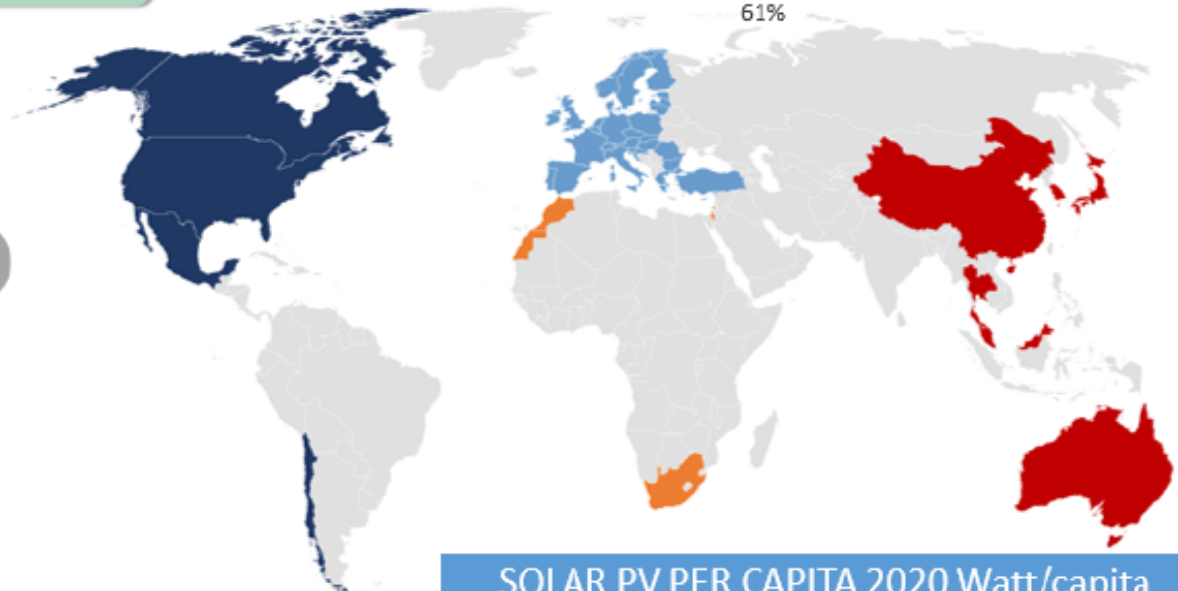


USA 19,2 GW



877 Mt

CO<sub>2</sub> emissions avoided in 2020



**760,4 GW** were installed all over the world by the end of 2020



China is the world's **#1** PV market



**20** countries installed at least **1 GW** of PV in 2020



**14** countries have installed at least **10 GW** of cumulative capacity at the end of 2020

## SOLAR PV PER CAPITA 2020 Watt/capita



# 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

# Cost of photovoltaics

## 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.



# Cost of photovoltaics

## 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)

# Cost of photovoltaics

## 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.

# Cost of photovoltaics

## Grid parity

Electricity prices will increase

PV costs will decrease

... PV **WILL BE** COST COMPETITIVE.

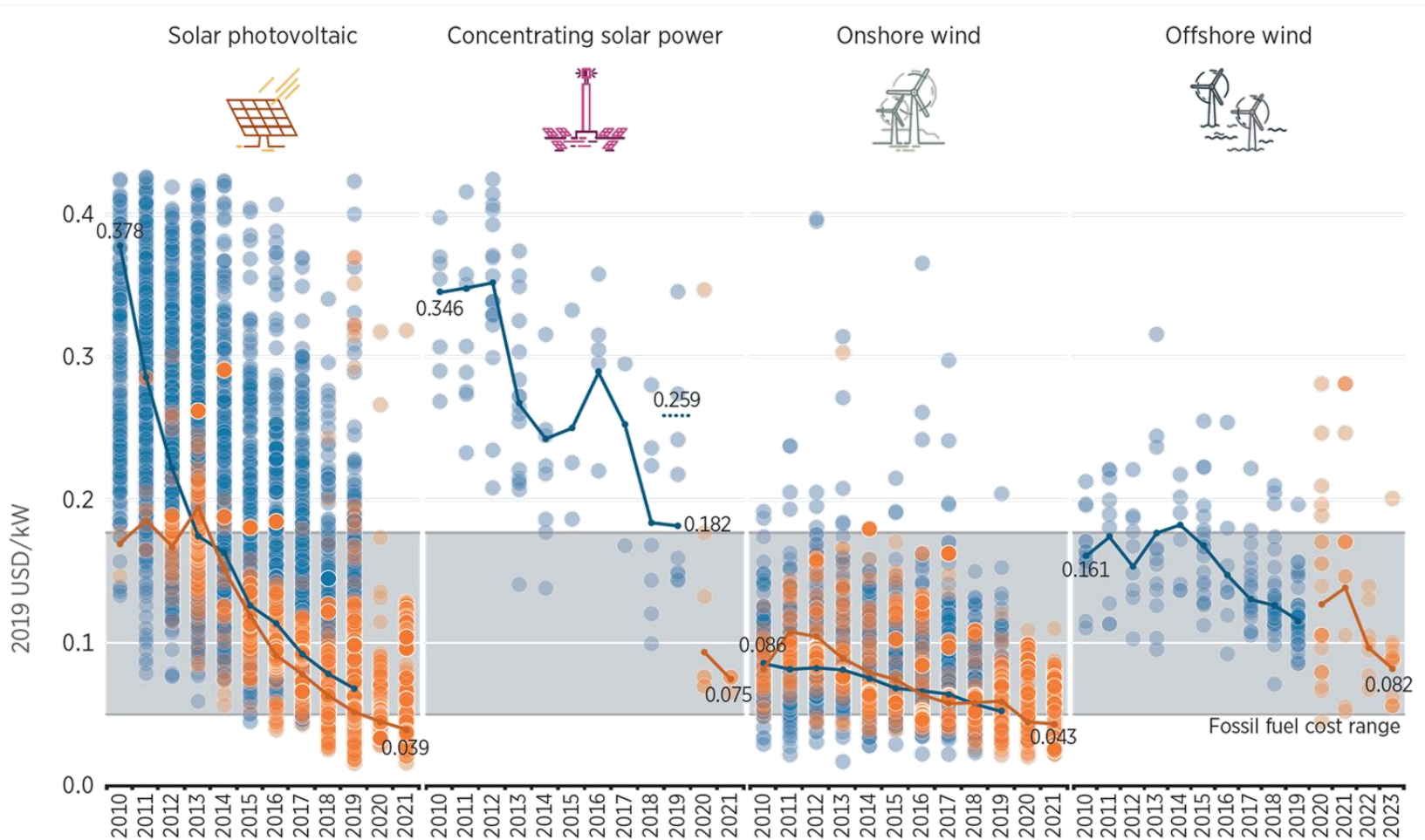
When?

Where?

At what time of the day/year?

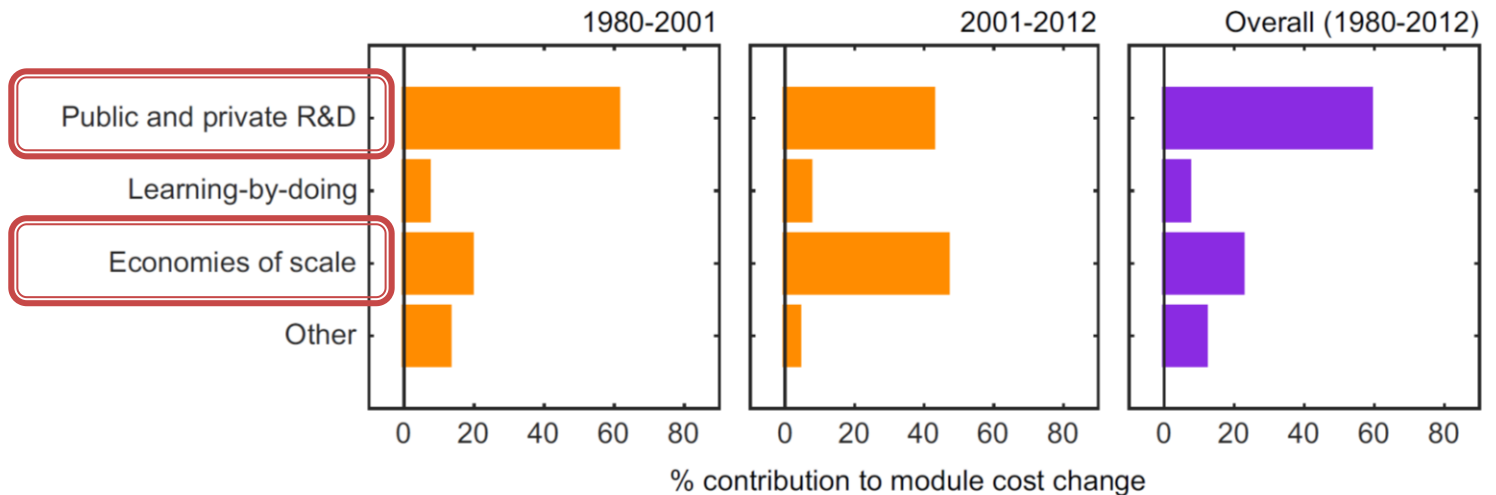
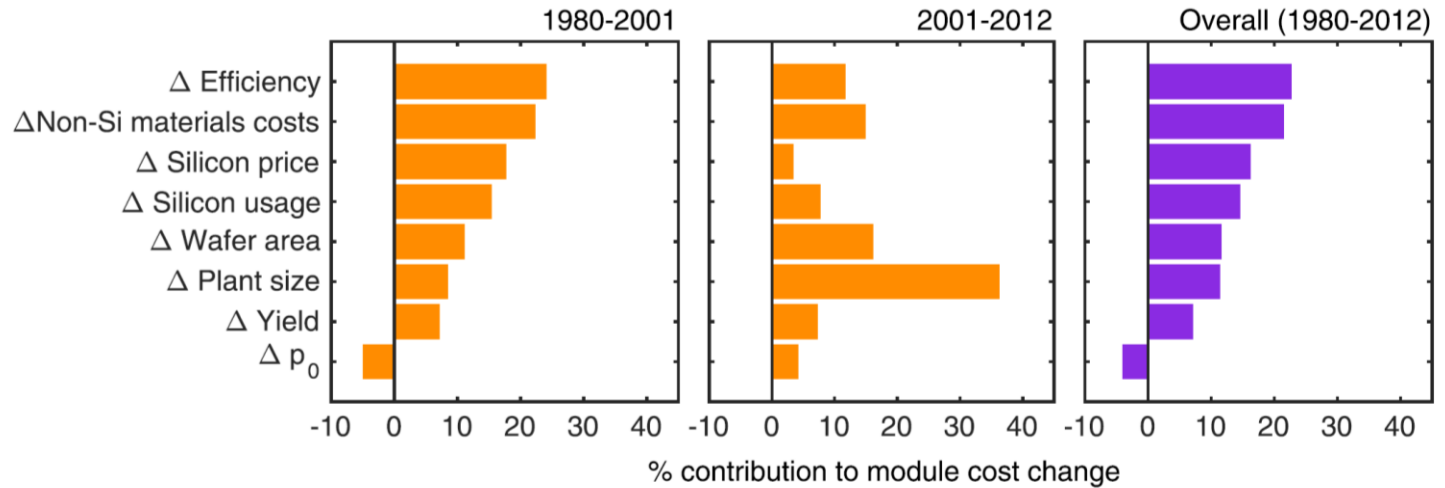


# Cost of photovoltaics



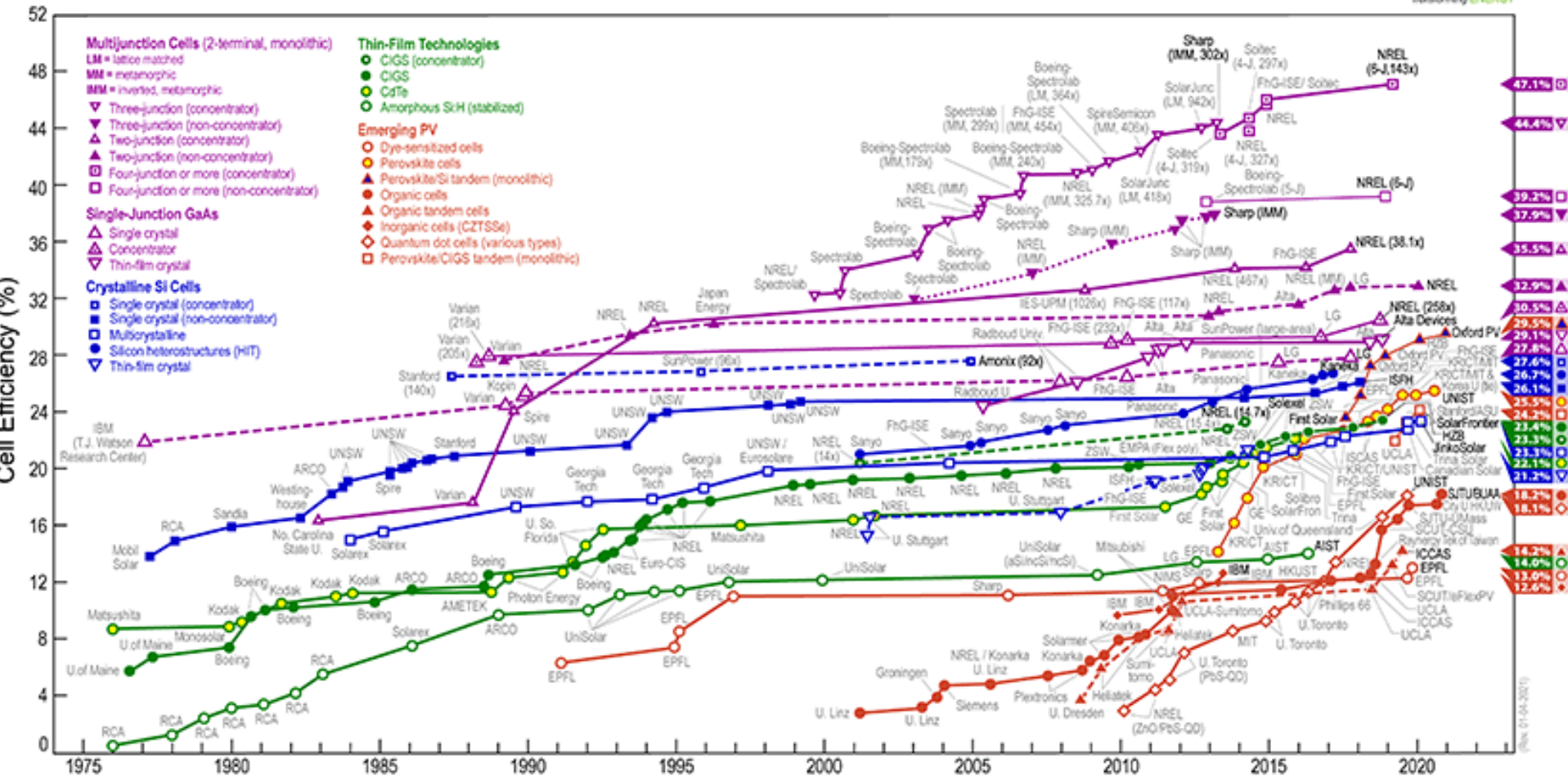
**10 times cheaper in the last 10 years!!**

# Drivers for cost reduction



# Drivers: technology

## Best Research-Cell Efficiencies

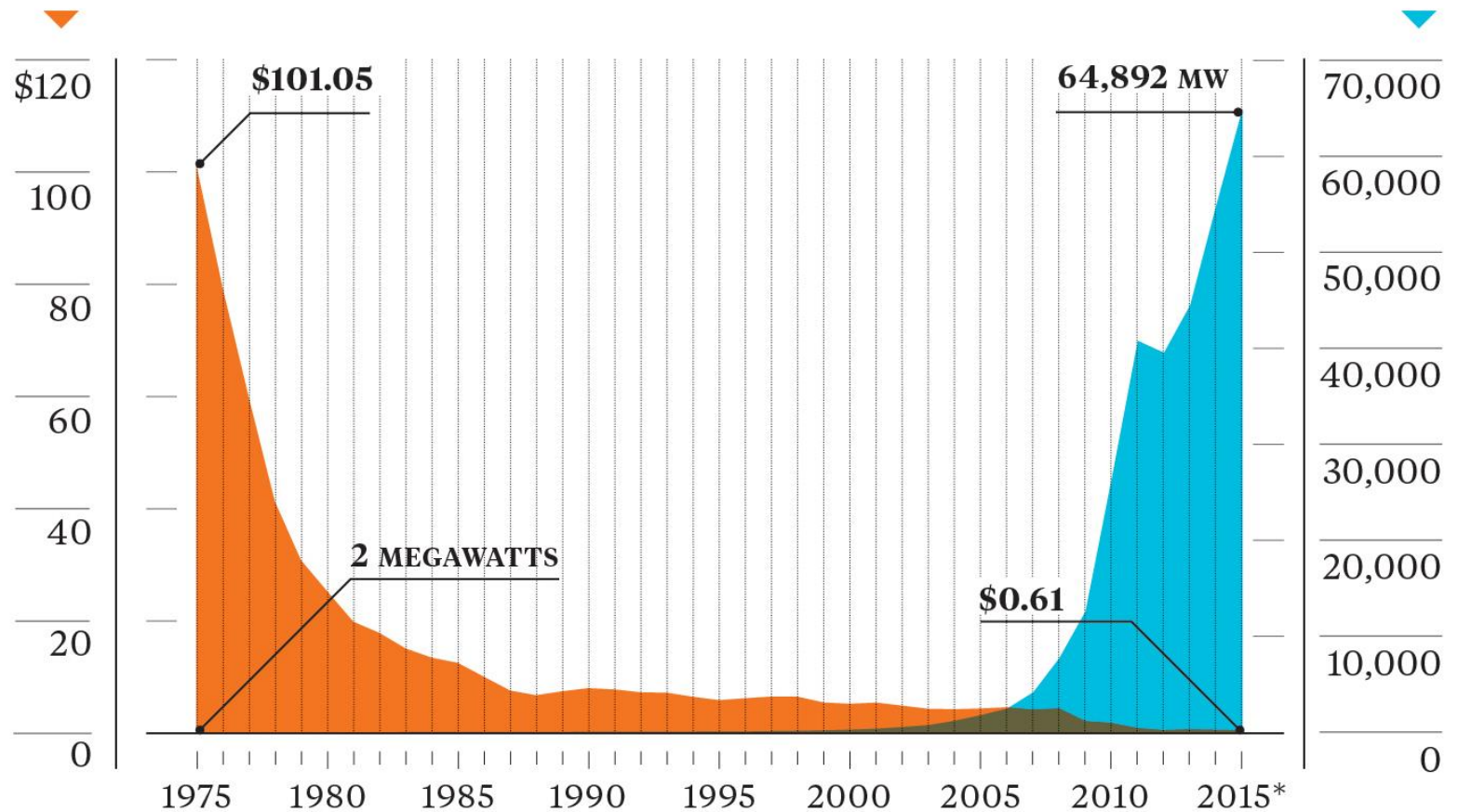




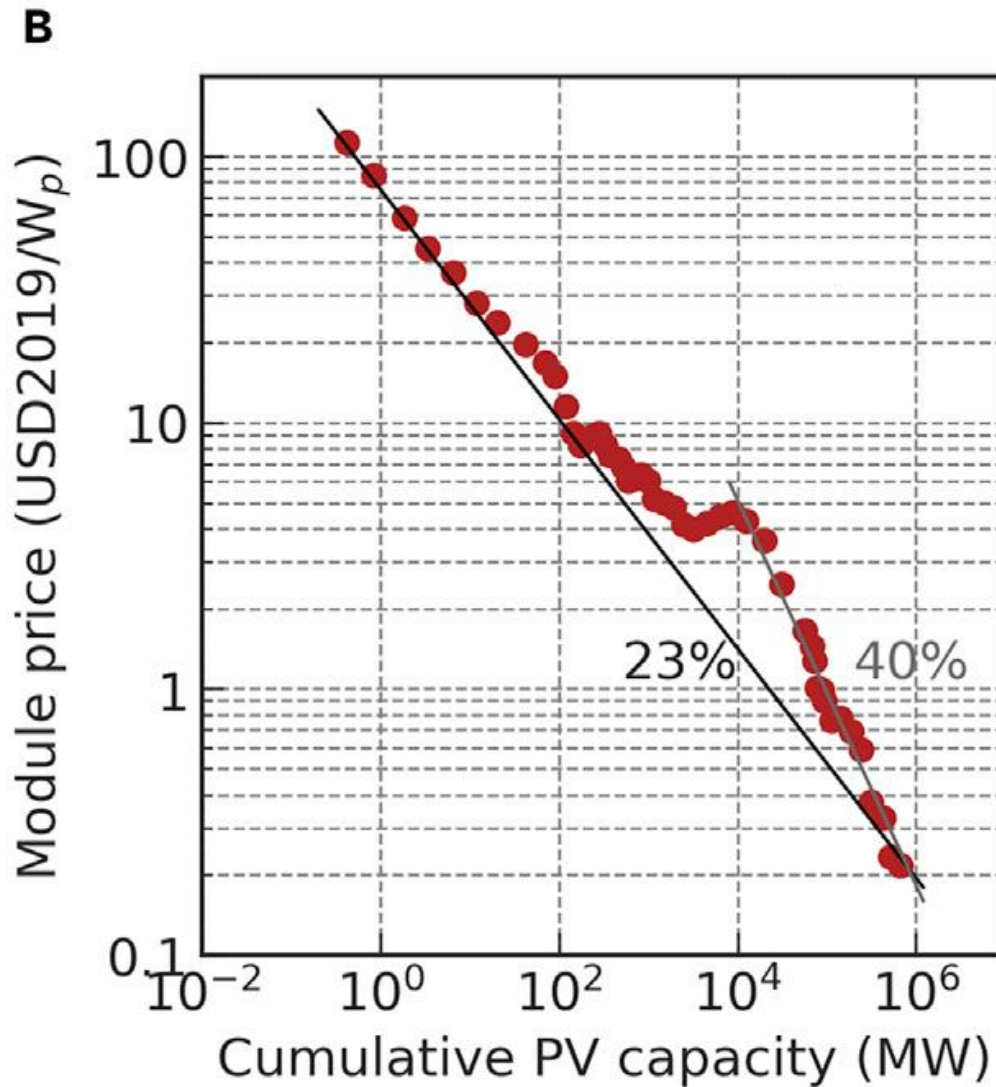
# Drivers: economies of scale

Price of a solar panel per watt

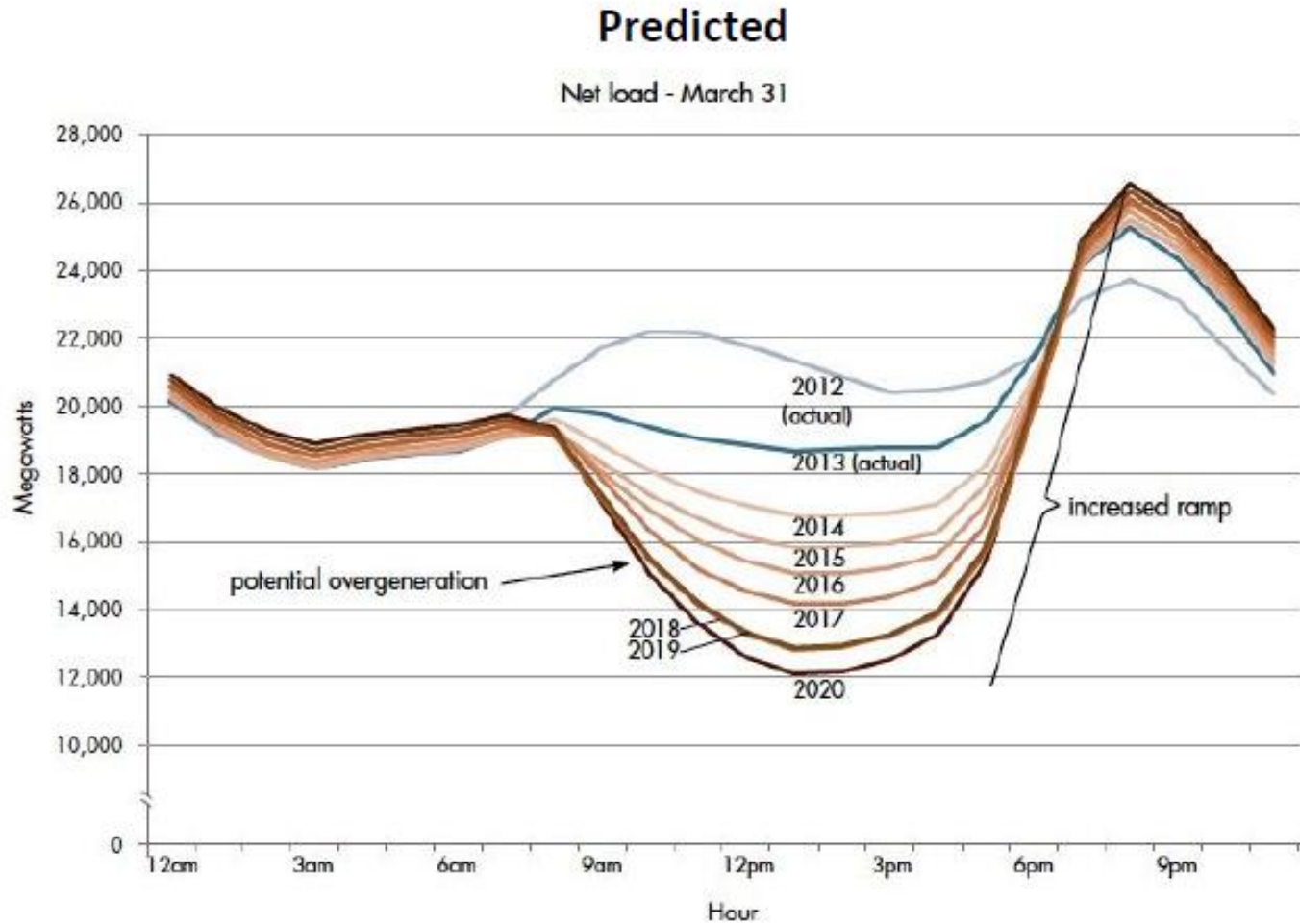
Global solar panel installations



# Drivers: economies of scale



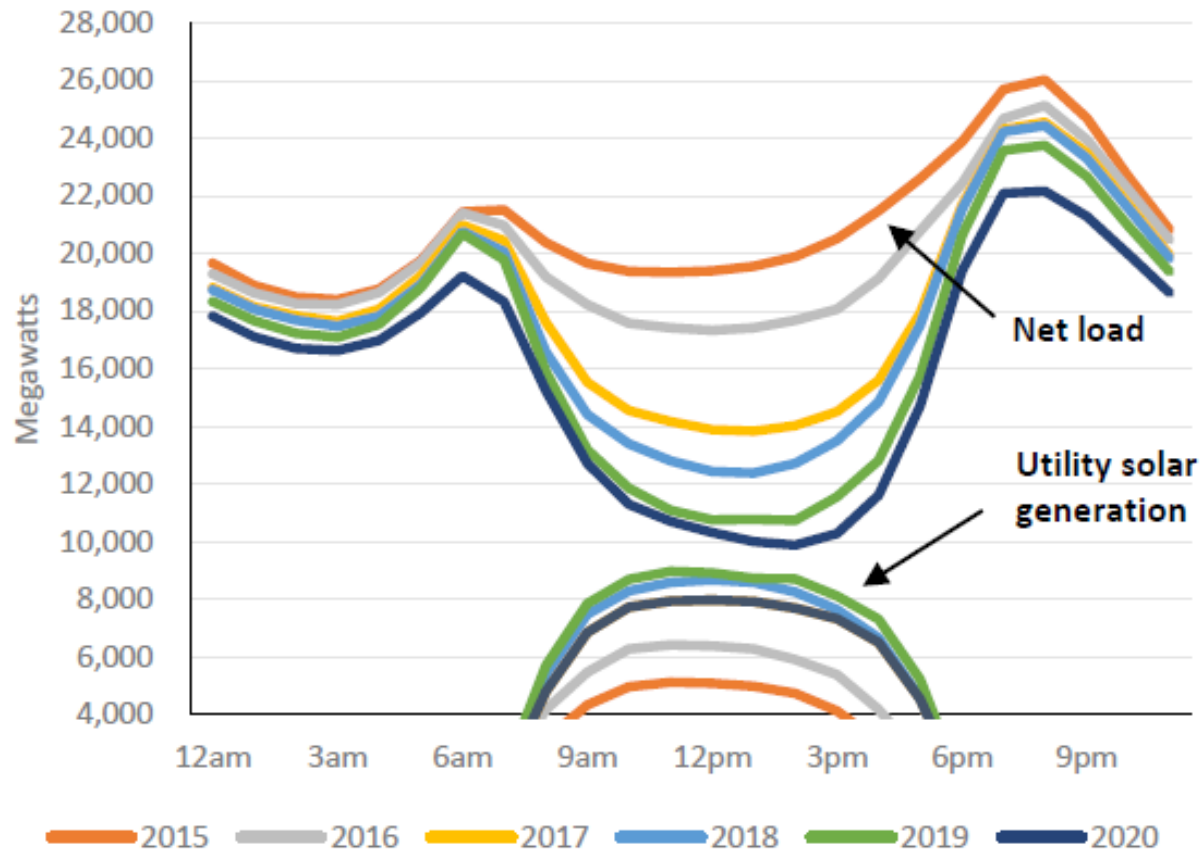
# Impacts of lots of PV



# Impacts of lots of PV

Actual

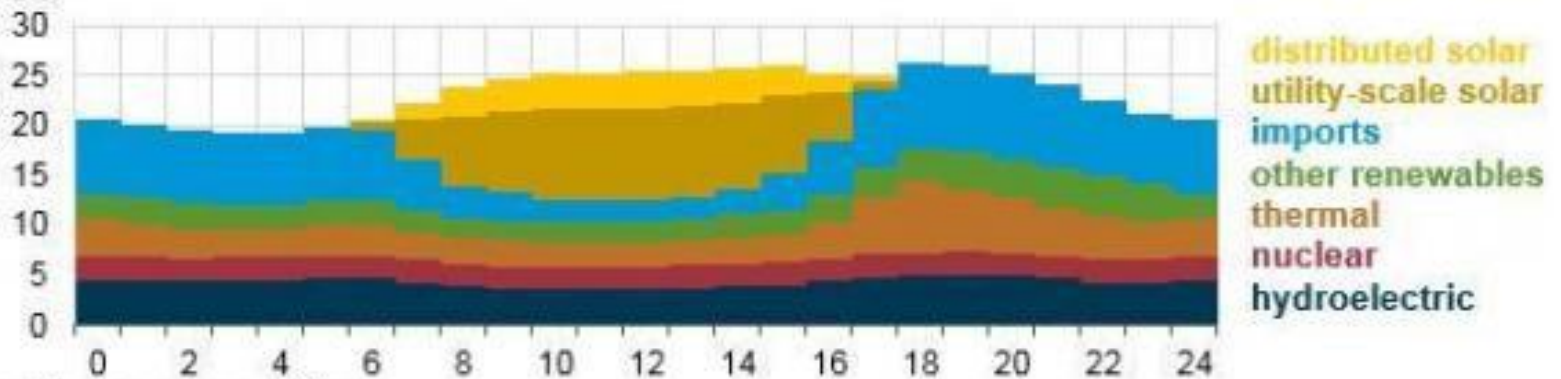
Average Hourly Net Load (March 15 - April 15)



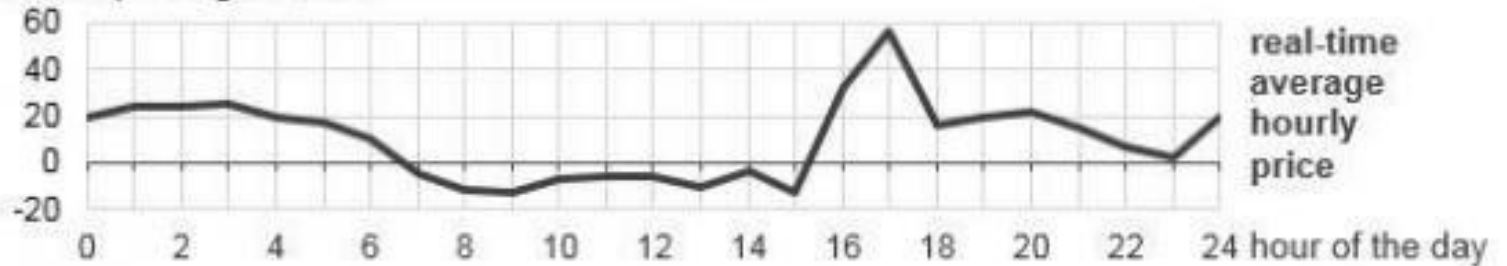


# Impacts of lots of PV

California Independent System Operator net generation, March 11, 2017  
gigawatthours



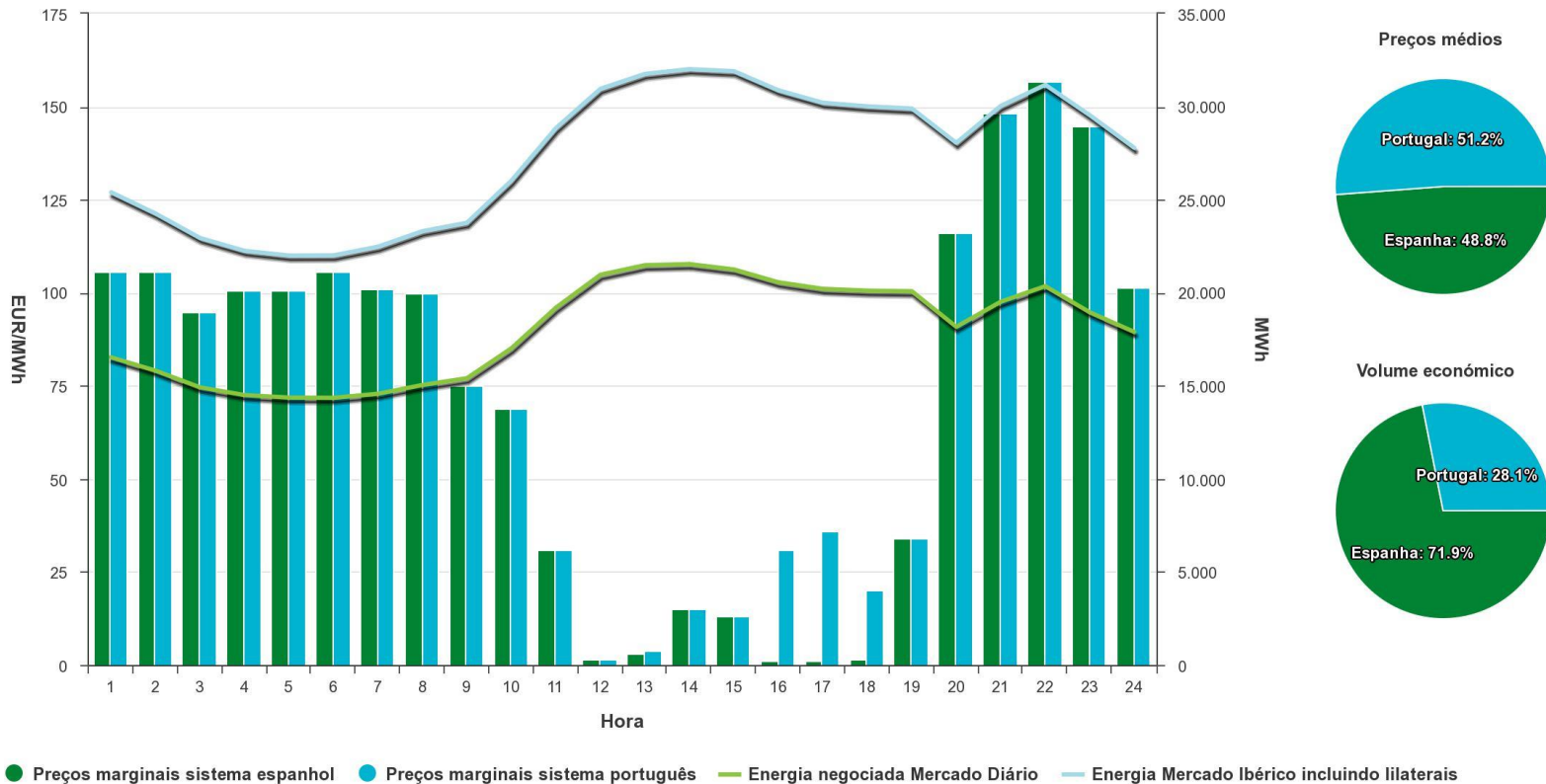
dollars per megawatthour



# Impacts of lots of PV

Preço horário do mercado diário

25/09/2022



# Impacts of lots of PV

## Solar meets 100 per cent of South Australia demand for first time

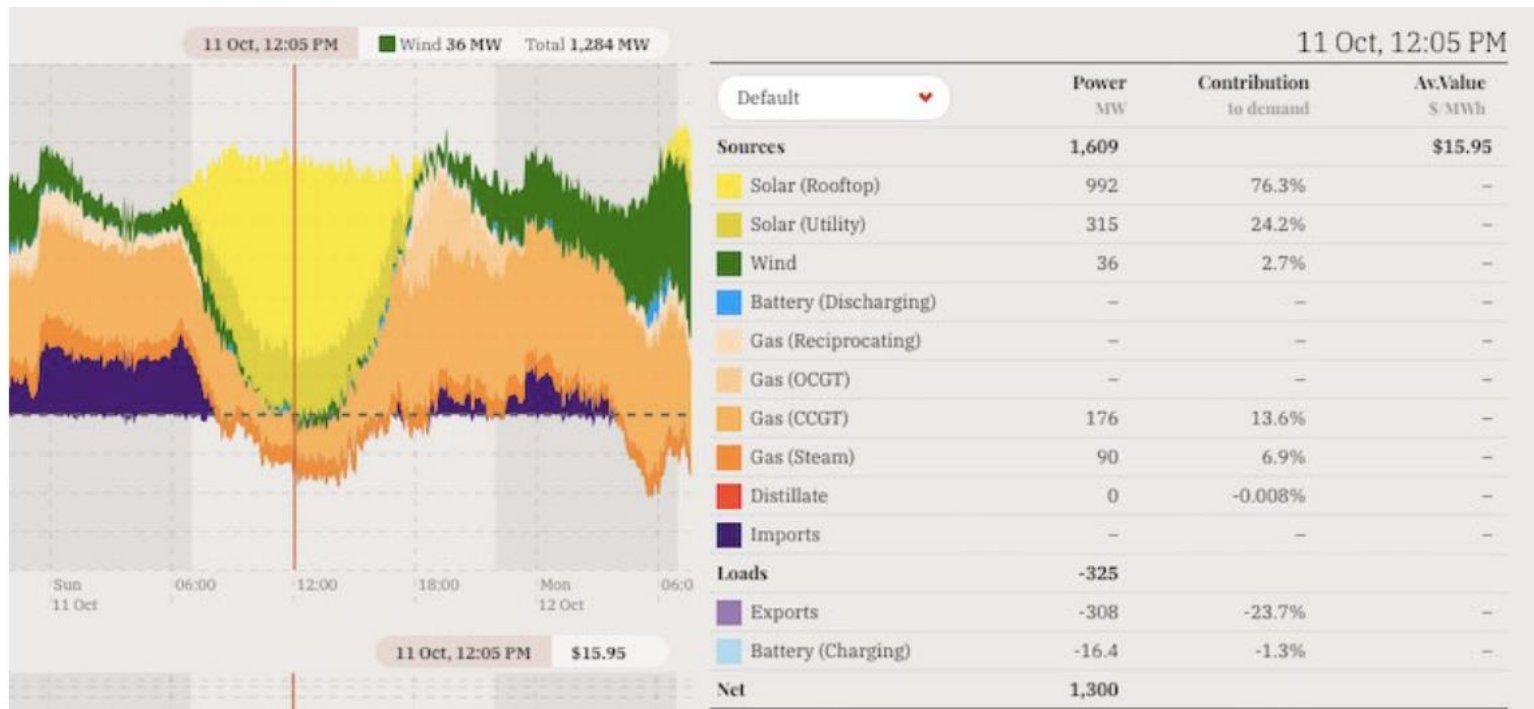
Giles Parkinson 12 October 2020

46

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Tweet

in 0



# Brief history (2): markets

1990's – Japan

Subsidies to installation

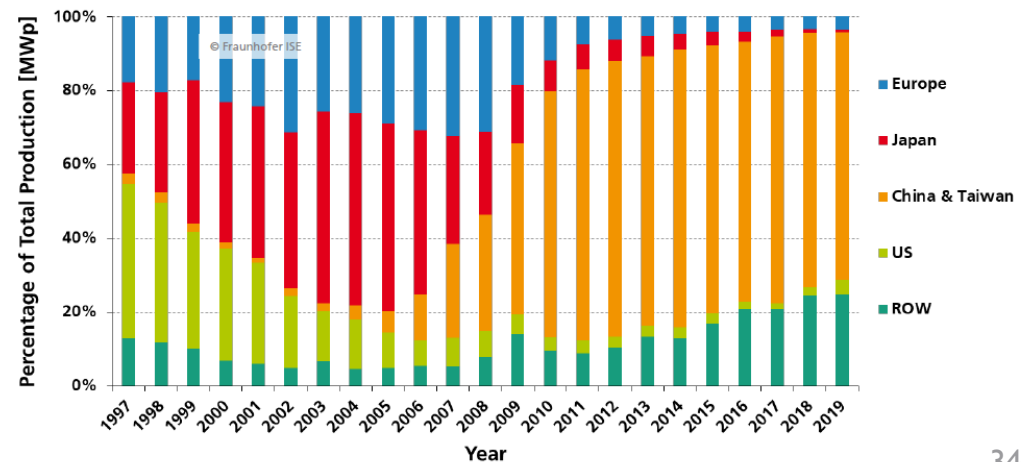
2000's – Germany (and the rest of EU)

Feedin tariff

2010's – China

Industrial support

**PV Module Production by Region 1997-2019**  
Percentage of Total MWp Produced





# Brief history (2): markets

1990's – Japan

Subsidies to installation

2000's – Germany (and the rest of EU)

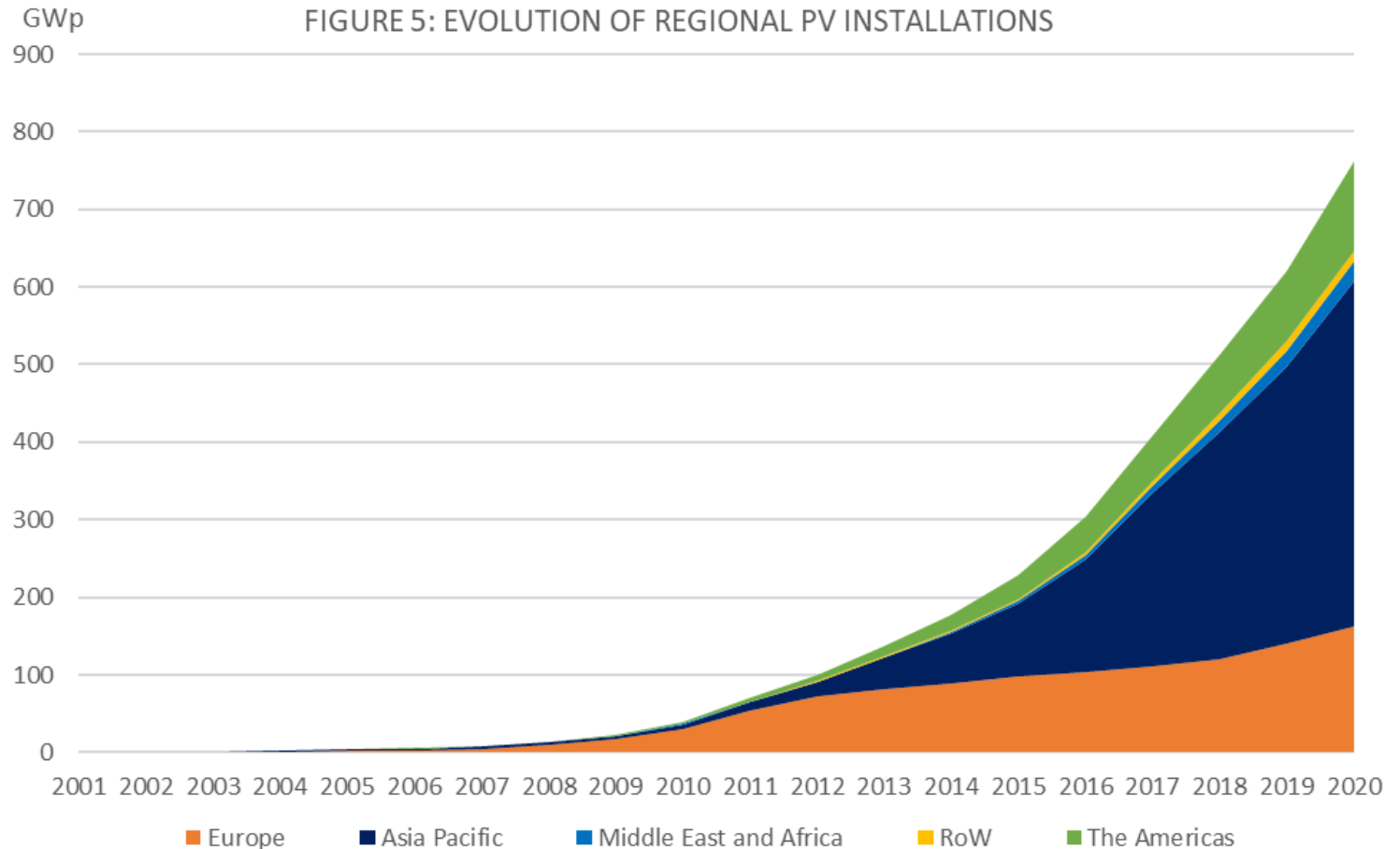
Feedin tariff

2010's – China

Industrial support

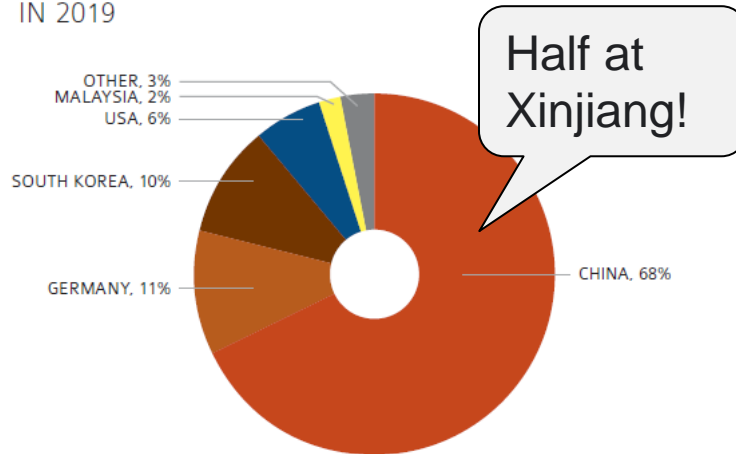
- Very large industrial scale
- Local supply chain
- Adoption of green standards
- High quality products (strong innovation)
- Largest world market

# China is largest market

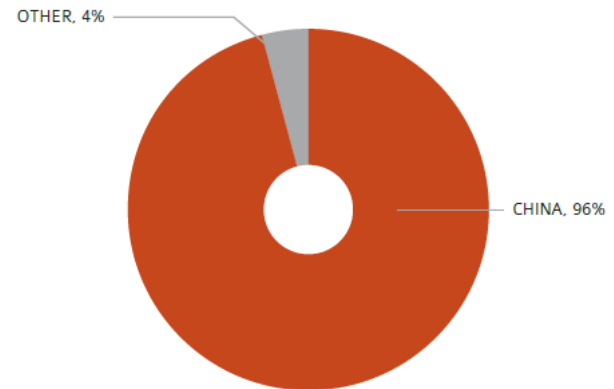


# China is largest producer

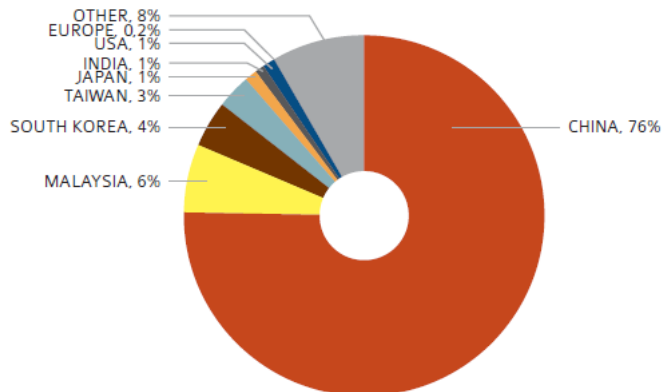
**FIGURE 4.2:** SHARE OF PV POLYSILICON PRODUCTION IN 2019



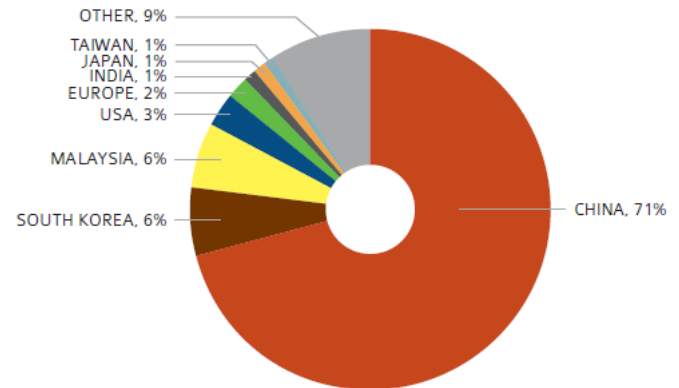
**FIGURE 4.3:** SHARE OF PV WAFERS PRODUCTION IN 2019



**FIGURE 4.4:** SHARE OF PV CELLS PRODUCTION IN 2019

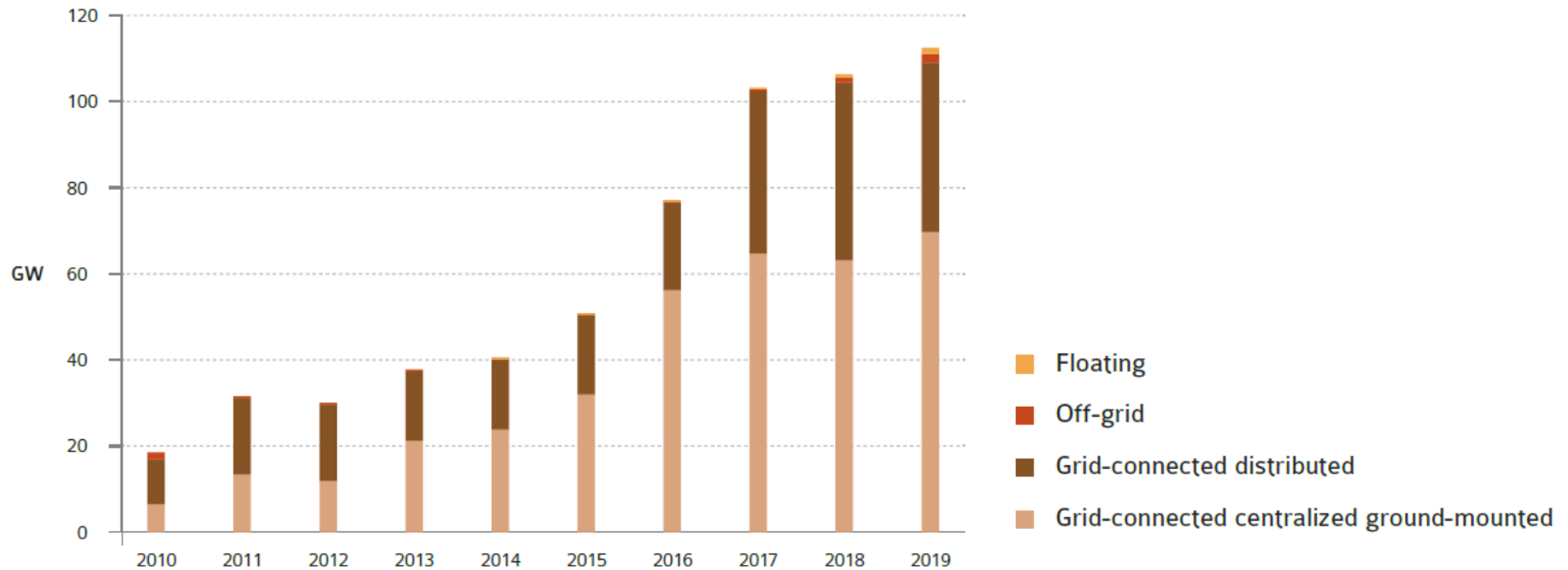


**FIGURE 4.5:** SHARE OF PV MODULES PRODUCTION IN 2019



# PV market today

FIGURE 2.9: ANNUAL SHARE OF CENTRALIZED, DISTRIBUTED, OFF-GRID AND FLOATING INSTALLATIONS

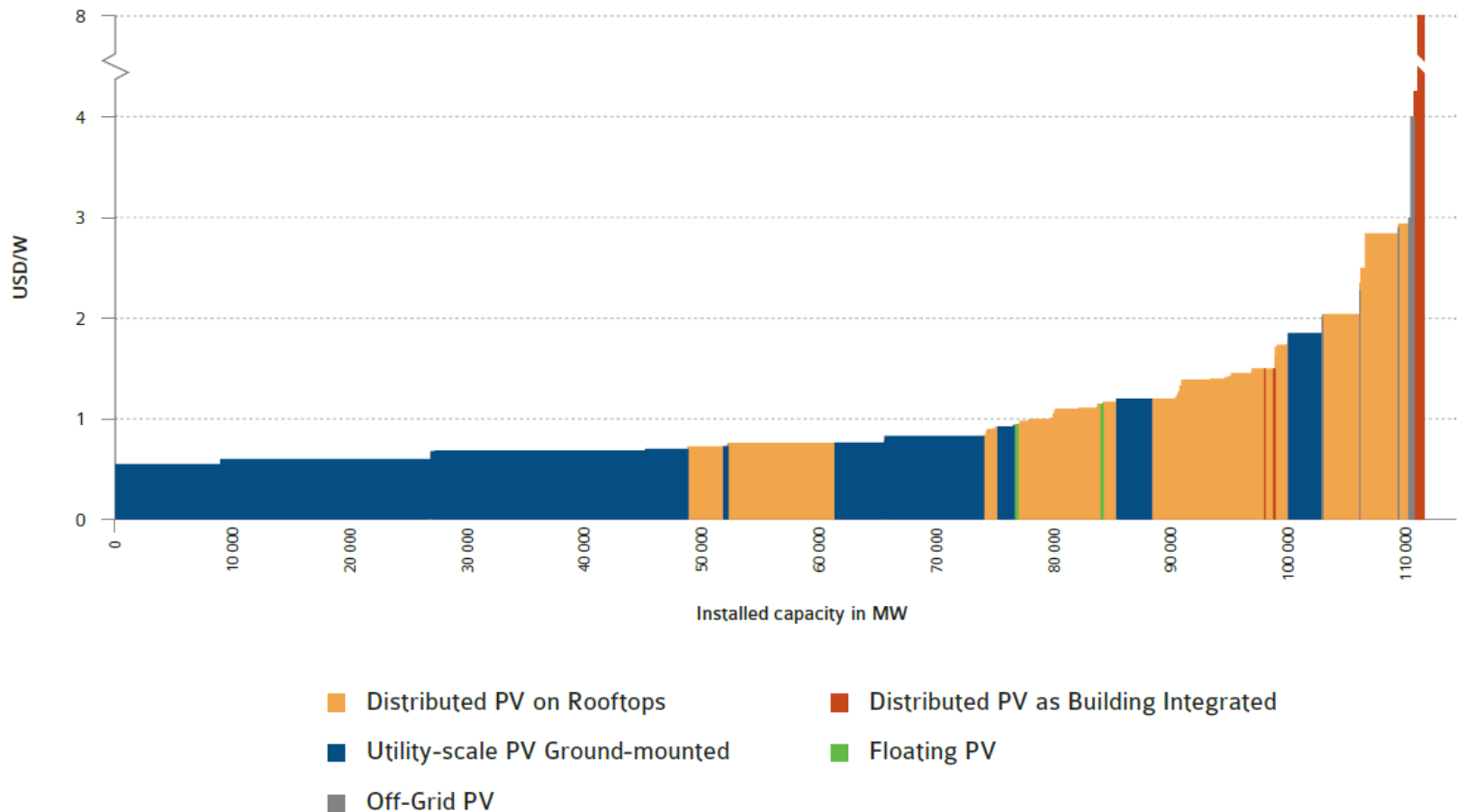


All sectors growing but  
Utility scale PV is the largest segment  
Off grid solar is almost negligible



# PV market today

FIGURE 6.3: 2019 PV MARKET COSTS RANGES



# PV market today

FIGURE 6.8: UTILITY-SCALE SYSTEM HARDWARE COST BREAKDOWN

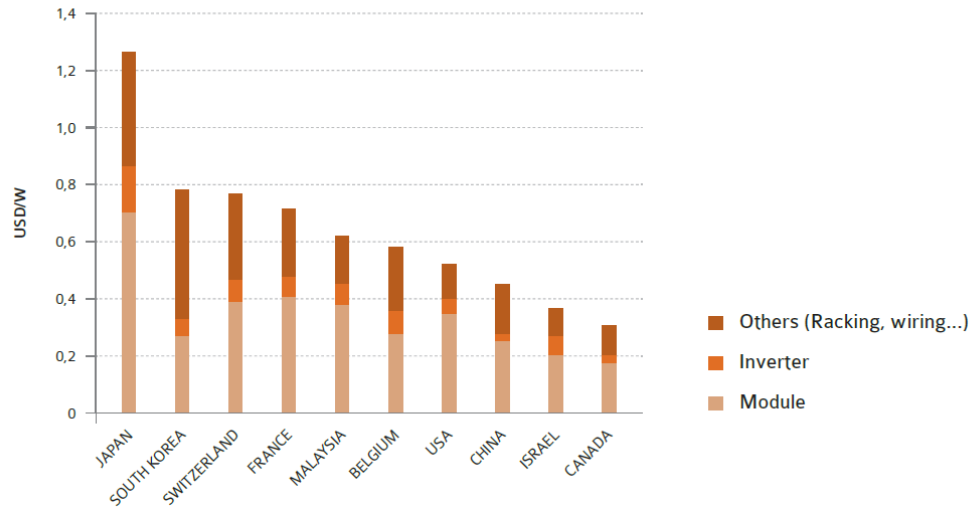
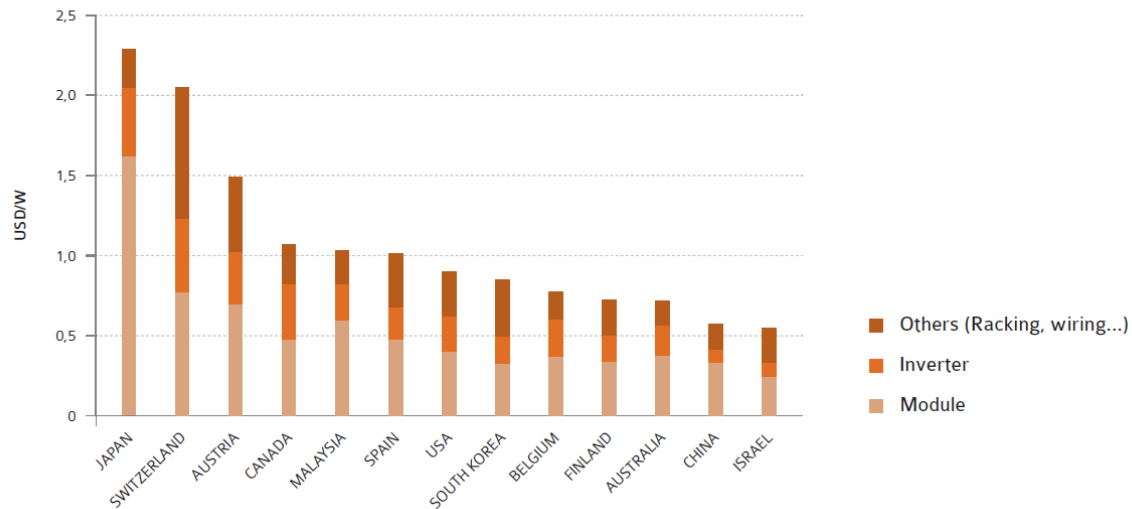
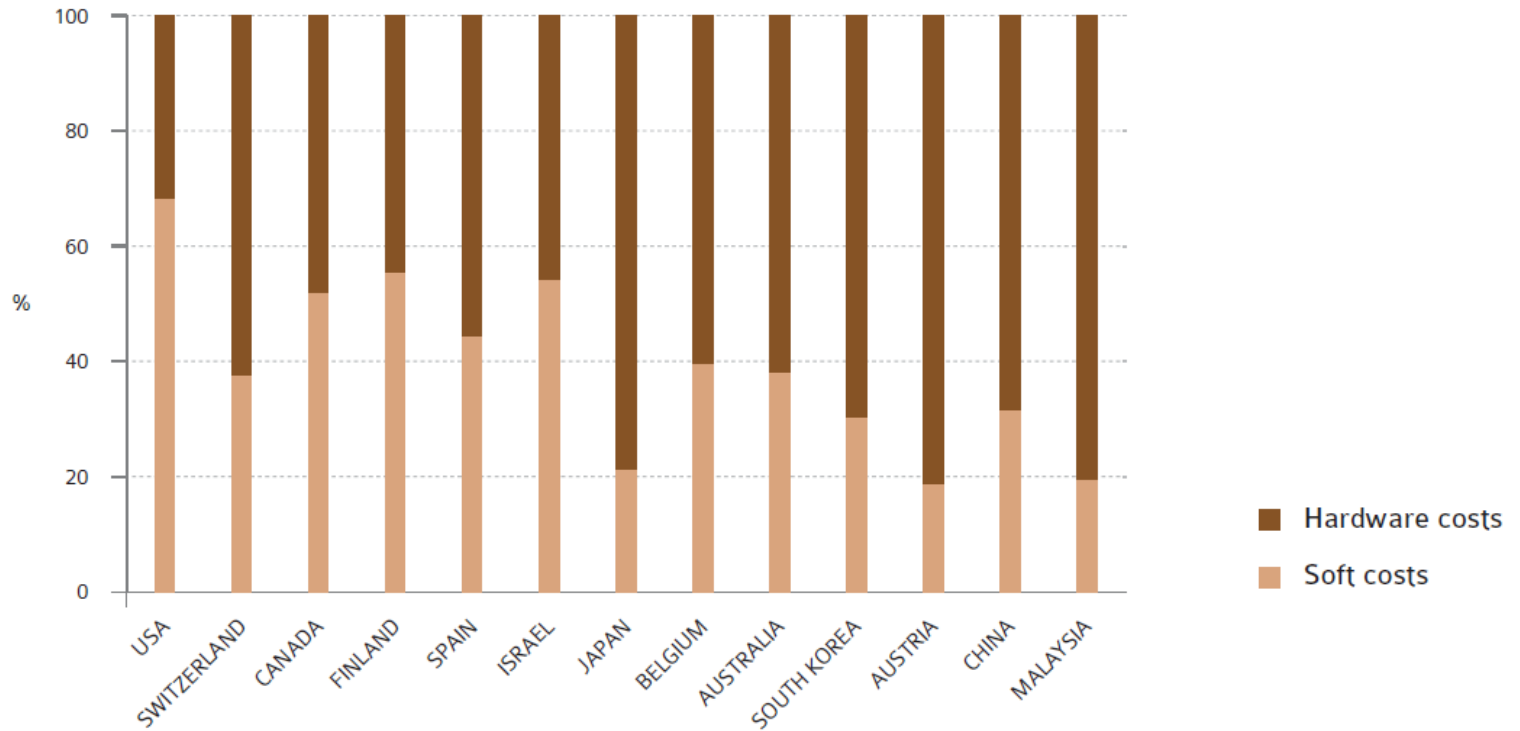


FIGURE 6.6: RESIDENTIAL SYSTEM HARDWARE COST BREAKDOWN



# PV market today

FIGURE 6.5: AVERAGE COST BREAKDOWN FOR A RESIDENTIAL PV SYSTEM < 10kW



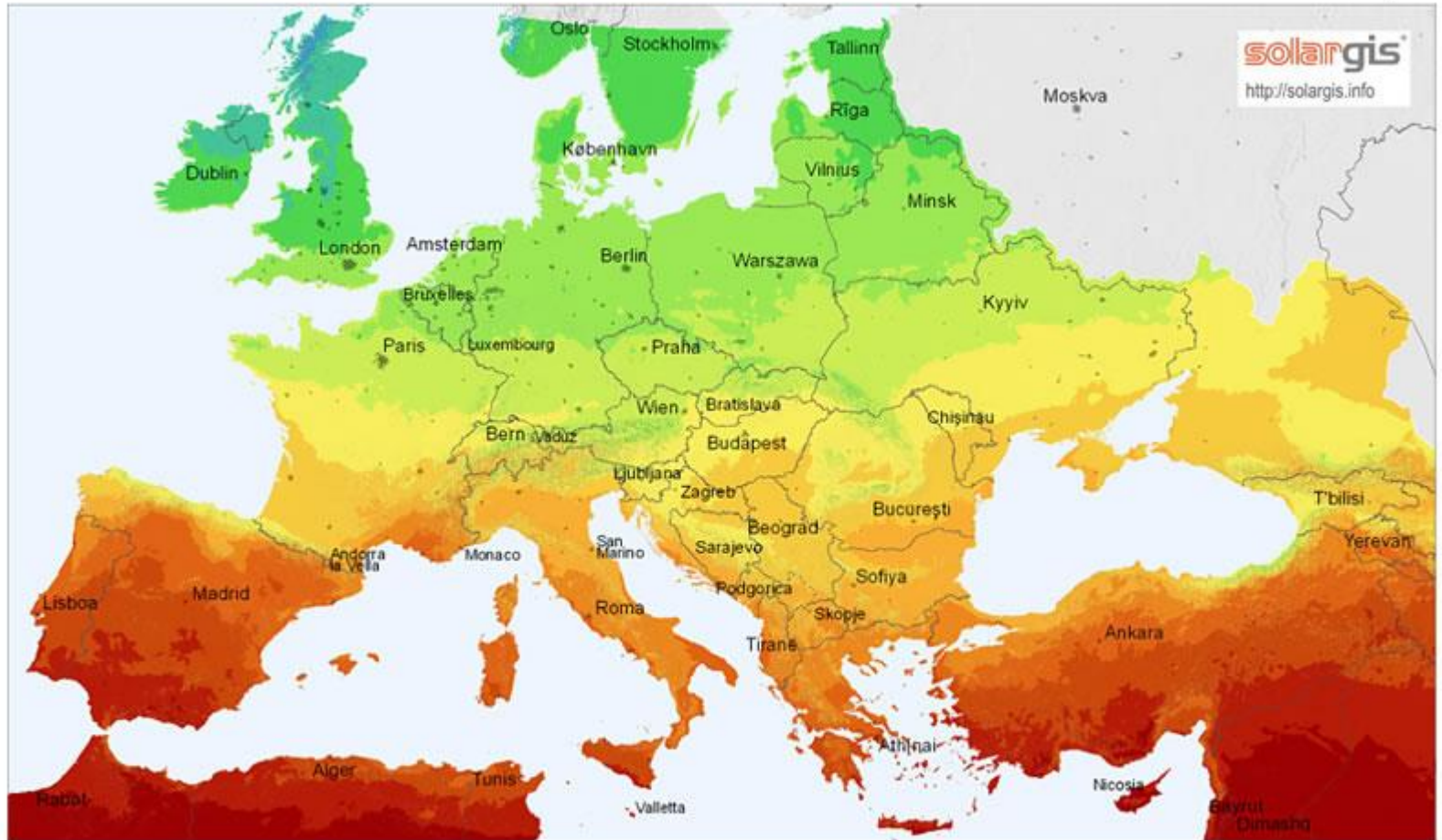
# PV in Portugal



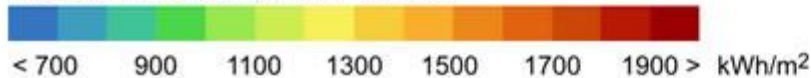
# High resource

Global horizontal irradiation

Europe



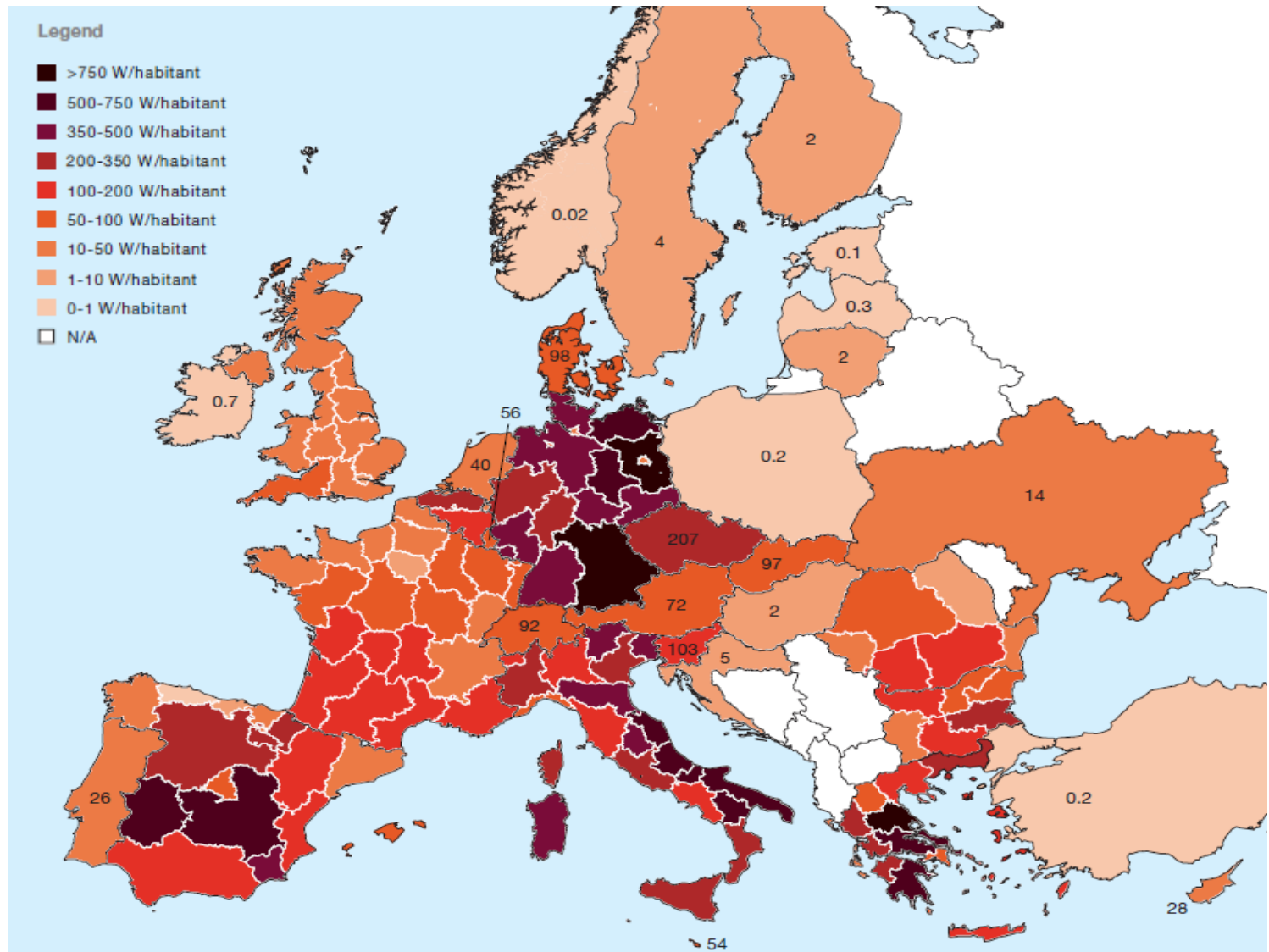
Average annual sum (4/2004 - 3/2010)



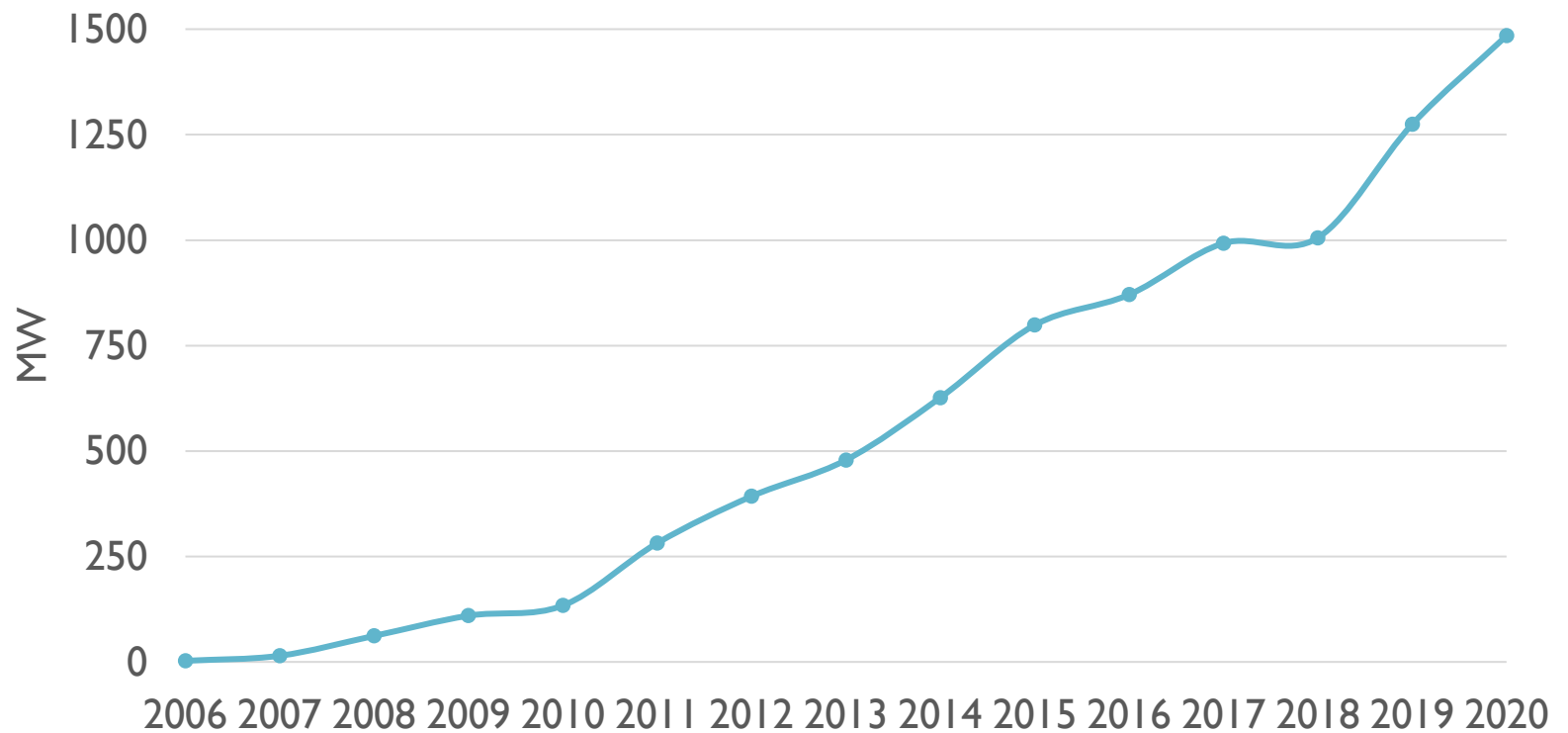
0 250 500 km

© 2011 GeoModel Solar s.r.o.

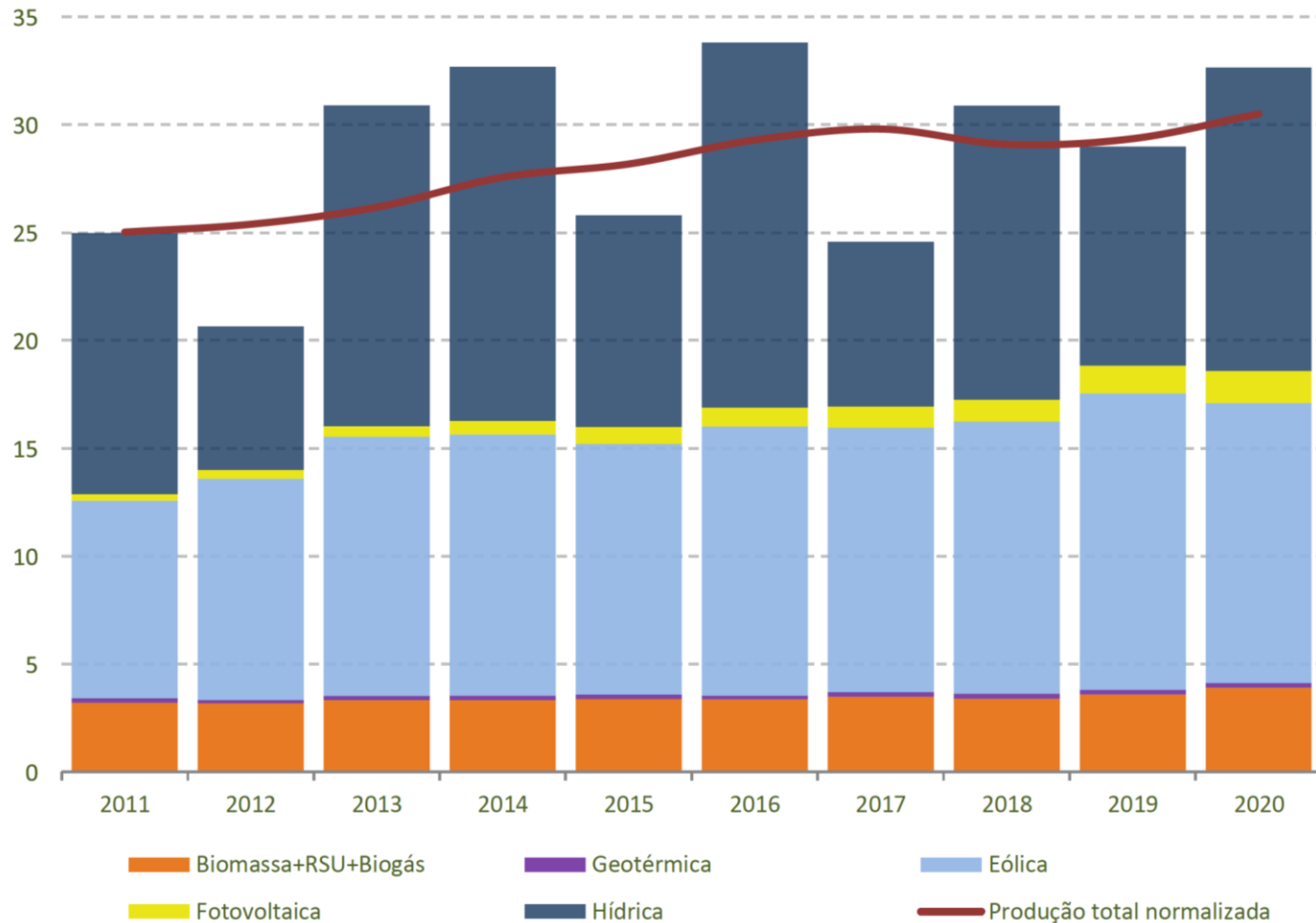
# Low installed capacity



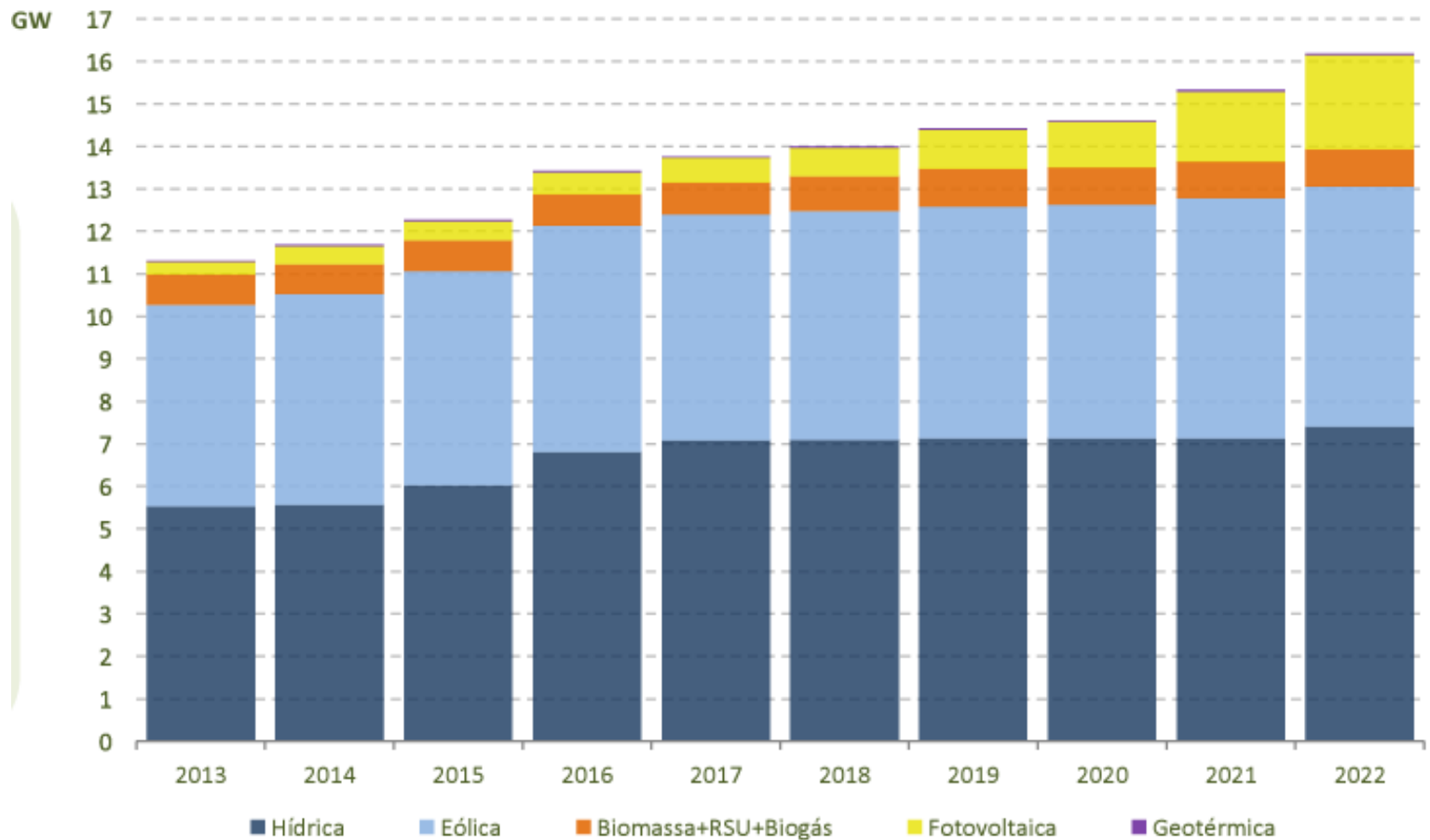
# Increasing capacity



# Only a fraction of the RES fleet



# Only a fraction of the RES fleet





# Legal landscape

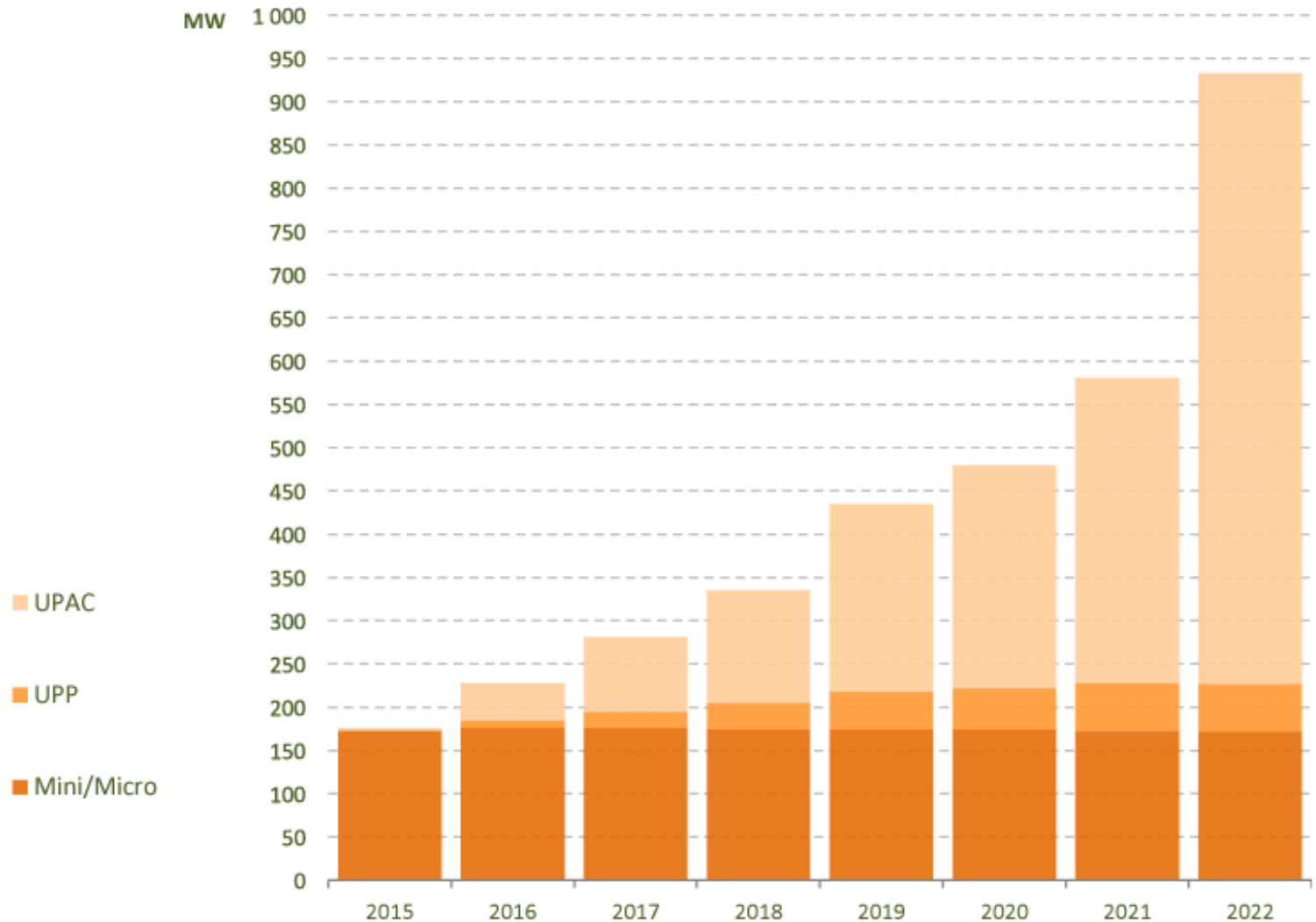
## Roadmaps

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]  
(<20kW: 25c€/kWh; <250kW: auction)
- **Self-demand** [DL 153/2014]
- **Solar auctions** (2019 & 2020)

# Small PV

Total PV: 2.2 GW  
Distributed PV: 0.9 GW



# Big PV

Global Germany Spain France USA Mexico Latin America Australia India China

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## Portuguese auction attracts world record bid of €14.8/MWh for solar

The stunning low tariff is a third world record in five weeks. Solar prices continue to tumble and with a Saudi auction concluding tomorrow, the Iberian benchmark could be short-lived. The official result of the Portuguese tender will be announced August 10.

**JULY 31, 2019** MARIAN WILLUHN

FINANCE HIGHLIGHTS MARKETS UTILITY SCALE PV PORTUGAL

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# Big PV

## Novas centrais solares que vão nascer em Portugal

VALORES EM MEGA VOLT-AMPERES (MVA)

2018 2019 2020 2021

### PORTO

Fabrica Ikea Industry Ikea Industry Portugal 6

### SANTARÉM

Glória (Granho)	Central Solar da Glória	24
Infantado	Central Solar do Infantado	24
Mexeeiro	Power&Sol	28
Alcanhões	Hypericon	21

### ÉVORA

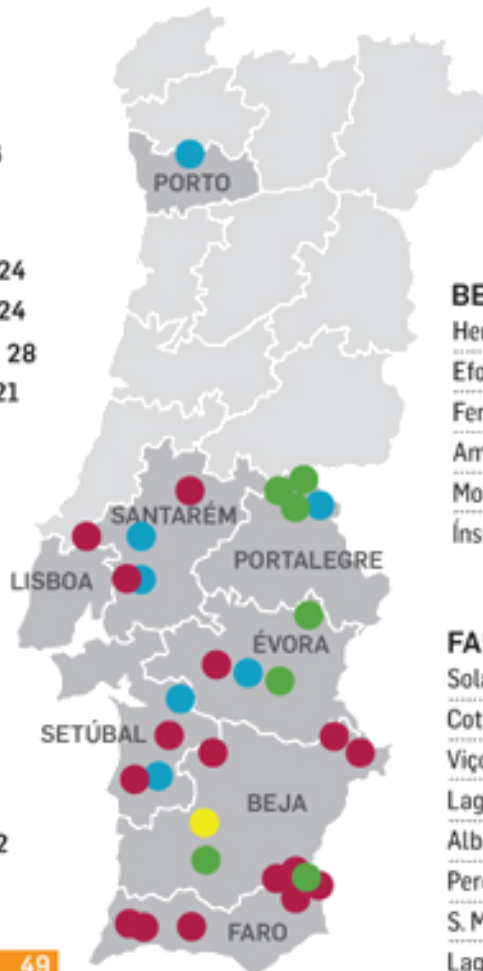
Évora 3	Expoentfokus	29
Montes Novos	Contrate o Sol	3
Vale de Moura	Hyperion	29

### LISBOA

Cadaval Valperal - Soc. Agropecuário 2

### SETÚBAL

Herdade da Casa Nova	C. Solar de Casa Nova	12
Vale Matanças	Warwick Portugal	7
Barros	Teclavertente	5
Morgavel	Solarango	49



### PORTALEGRE

Falagueira I	Expoentfokus	16
Falagueira II	Expoentfokus	15
Falagueira III	Expoentfokus	21
Tendeiros	C. Solar de Tendeiros	24

### BEJA

Herdade dos Murzelos	Morning Chapter	46
Efokus Ourique	Expoentfokus	49
Ferreira do Alentejo	Hyperion	42
Amareleja	Hyperion	16
Moura	Hyperion	48
Ínsua	Goldalqueva	49

### FARO

Solara 4	Solara 4	221
Cotovio	Goldiport Solar	49
Viçoso	Goldnalco	48
Lagos	Hyperion	27
Albercas	Muki Solar	28
Pereiro	Muki Solar	29
S. Marcos	Muki Solar	49
Lagos	Lagos Solar Power	21

Está prevista no projeto inicial de uma central solar para a vila de Cercal do Alentejo a instalação de 553 800 módulos fotovoltaicos.

REINALDO RODRIGUES/GLOBAL IMAGES



## O plano de painéis solares em Cercal do Alentejo de que ninguém gosta

**ENERGIA** A instalação de uma central solar está a gerar polémica em Cercal do Alentejo com moradores a contestar a iniciativa. A câmara e a junta de freguesia acompanham as preocupações e esperam que haja uma alteração profunda do projeto.

SOCIEDADE

## Torre Bela. Abate de animais para construção de central fotovoltaica começou há meses



OBSERVADOR

Assinar



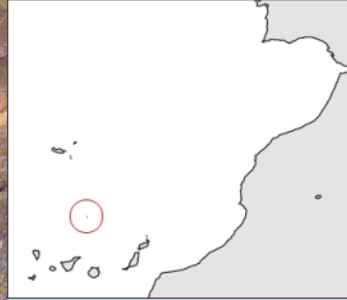
### Zero considera que apenas um em nove projetos de centrais solares é exemplo a seguir

Dos nove projetos, apenas um tem a intenção de instalar a central numa "área concessionada para exploração de recursos geológicos" e alguns exigem áreas contínuas que "ultrapassam os mil hectares".



# Flagship projects

- Selvagem Grande, Madeira (1983, 660W)
- Solar XXI, Lisbon (1989; 2.2kW)+ (2005; 12+6kW)
- Brinches, Serpa (2007; 11MW)
- Amareleja, Moura (2008; 46MW)
- Ourika (2018; 46 MW – sem tarifas)



Oceano Atlântico  
Atlantic Ocean

















# Governo inaugura primeira central solar da Europa sem tarifas garantidas

A central já está a funcionar no concelho de Ourique. As restantes, parte da Central Solar Fotovoltaica Ourika!, devem funcionar em pleno até 2021.

Dinheiro  
Vivo/Lusa

26 Julho, 2018 • 05:22







C1

C4

# INTRODUCTION

## **Remarks - PV in Portugal**

- Almost no manufacturing
- Huge solar potential
- Large scale utility scale PV 'exploding'
- Main limitation: access to grid
- Distributed PV lagging
- Public acceptance decreasing