

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

and/or

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

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## 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, 2nd ed., 2003
- Bowden et al, PV CD ROM [[pvcdrom.pveducation.org](http://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
- Photon international magazine

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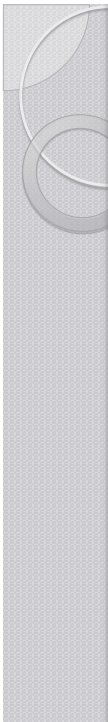


# INTRODUCTION

## TODAY

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

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# 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.

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# INTRODUCTION

## Brief history of photovoltaics

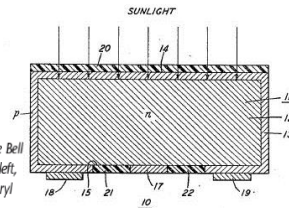
Feb. 5, 1957

D. M. CHAPIN ET AL  
SOLAR ENERGY CONVERTING APPARATUS  
Filed March 5, 1954

2,780,765



FIG. 1

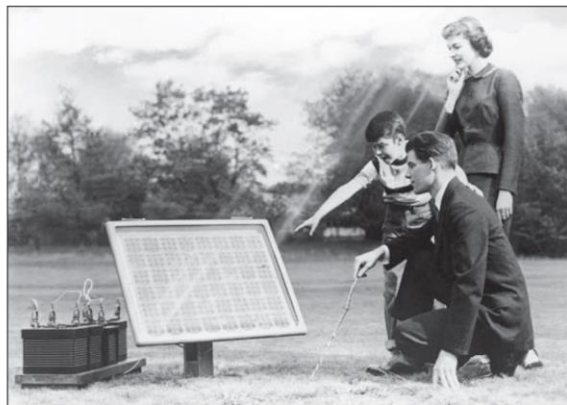


The inventors of the Bell Solar Battery, from left, Gerald Pearson, Daryl Chapin, and Calvin Fuller, check devices for the amount of solar electricity derived from sunlight, here simulated by a lamp.

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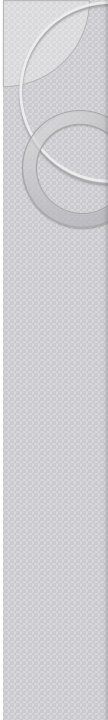
# INTRODUCTION

## Brief history of photovoltaics



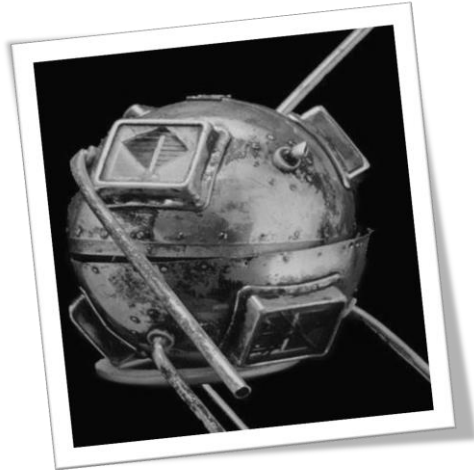
Advertisement photos, such as this one that appeared in the 1956 issue of Look Magazine, show off the "Bell Solar Battery" to the American public.

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# INTRODUCTION

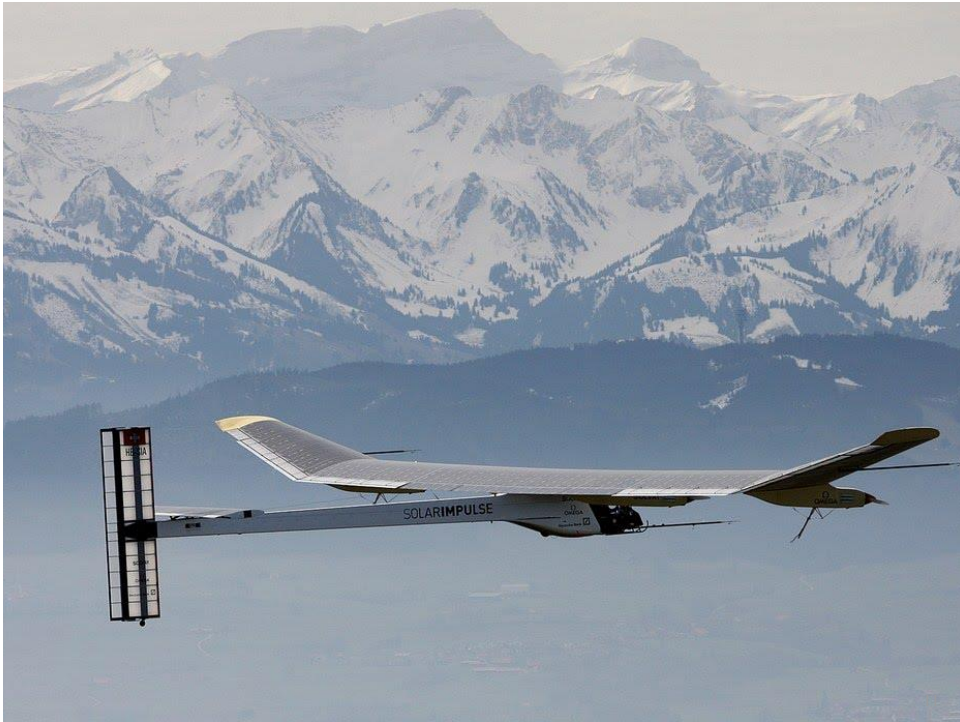
Brief history of photovoltaics



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# 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**

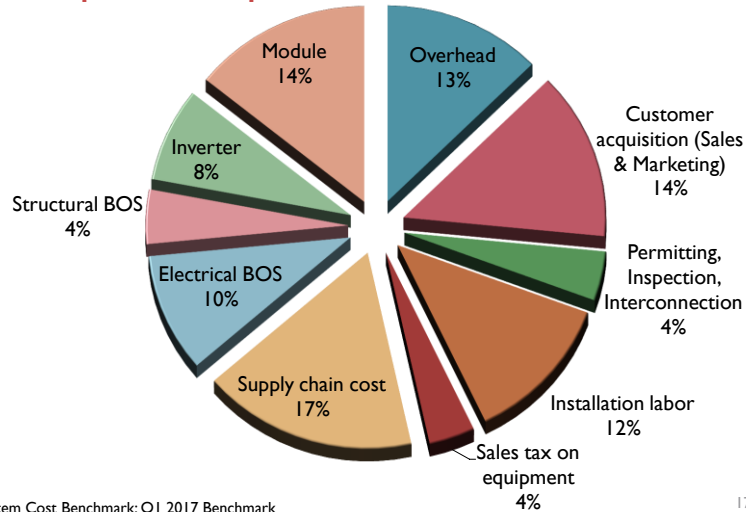
**Simple** and objective to determine, usually refers to module cost (Spot market? Factory gate? End user?) and thus it does not represent **full installation** system cost.

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

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# 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)

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# 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.

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# INTRODUCTION

## Grid parity

Electricity prices will increase

PV costs will decrease

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

When?

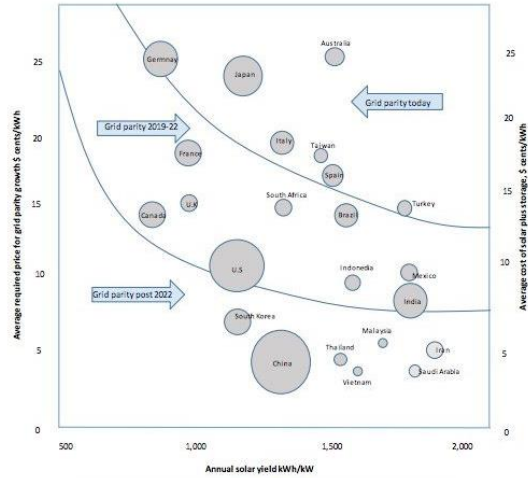
Where?

At what time of the day/year?

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# INTRODUCTION

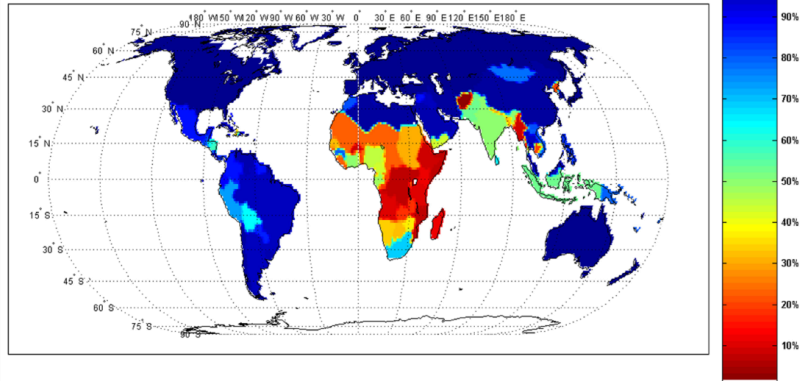
## Grid parity



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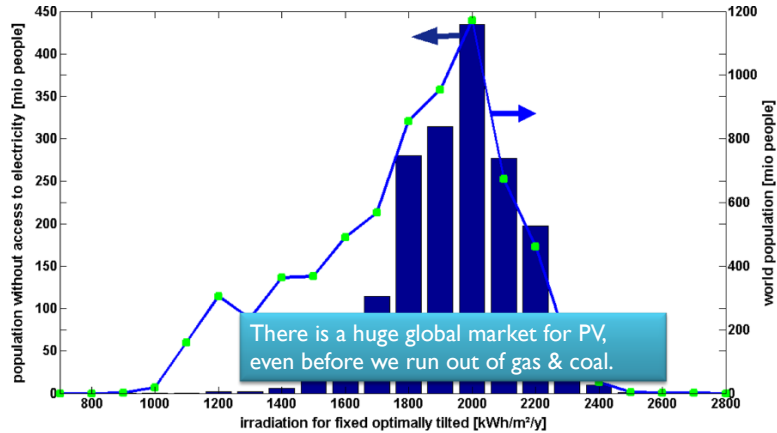
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## Global access to electricity in percent of local population



# INTRODUCTION

Population without access to electricity and local irradiation

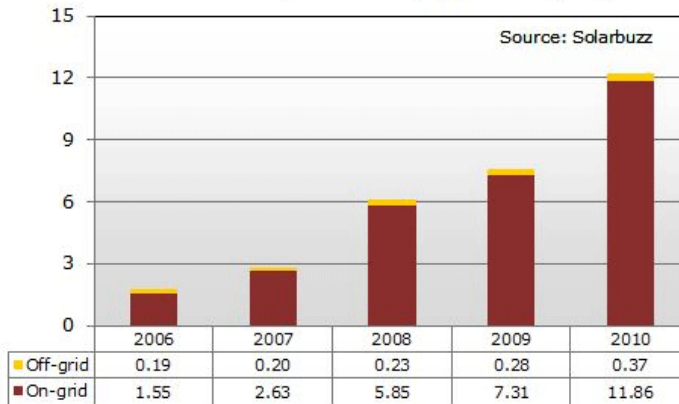


Christian Breyer and Alexander Gerlach, *Global overview on grid-parity*, Prog. Photovolt: Res. Appl. (2012) DOI: 10.1002/PIP.1254

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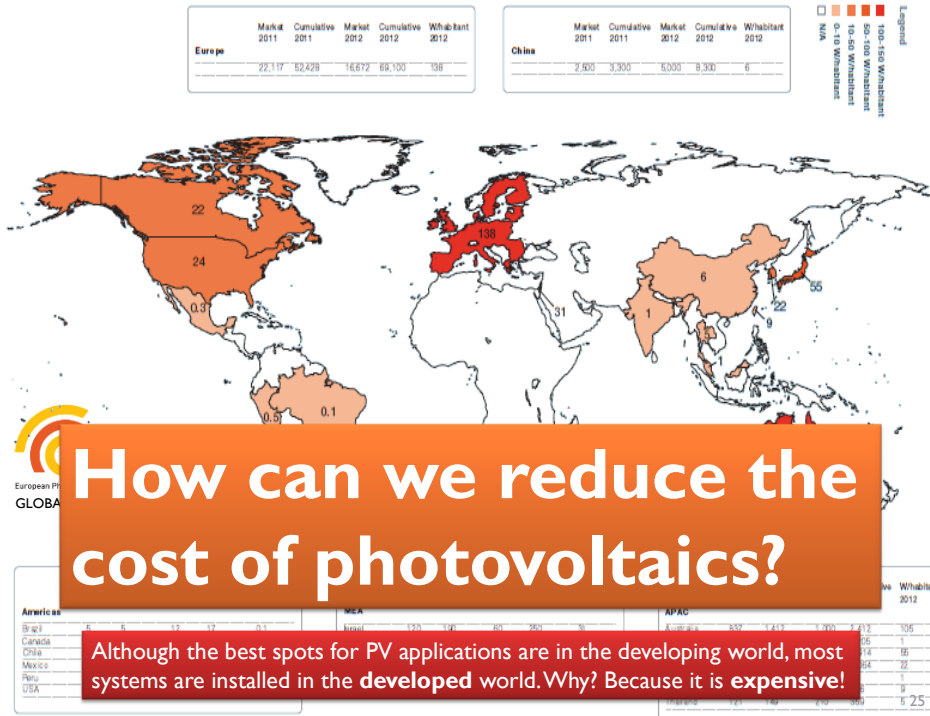
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PV Market Size: Segmentation By Application (GW)

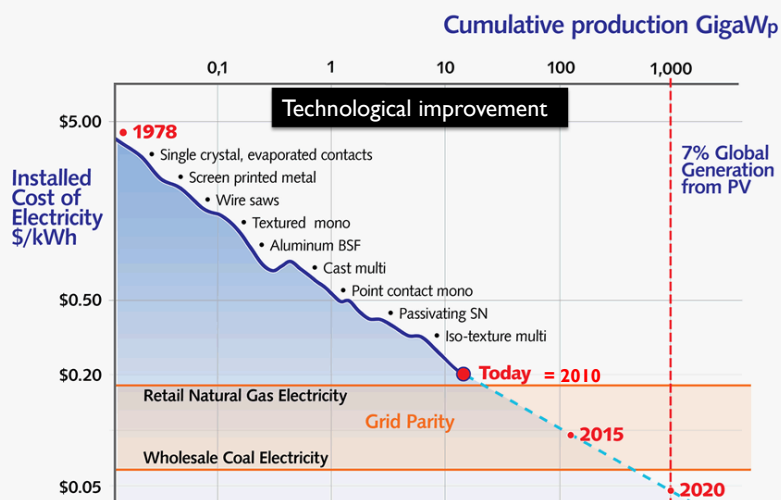


Although the best spots for PV applications are in the developing world, most systems are installed in the **developed** world. Why? Because it is **expensive**!

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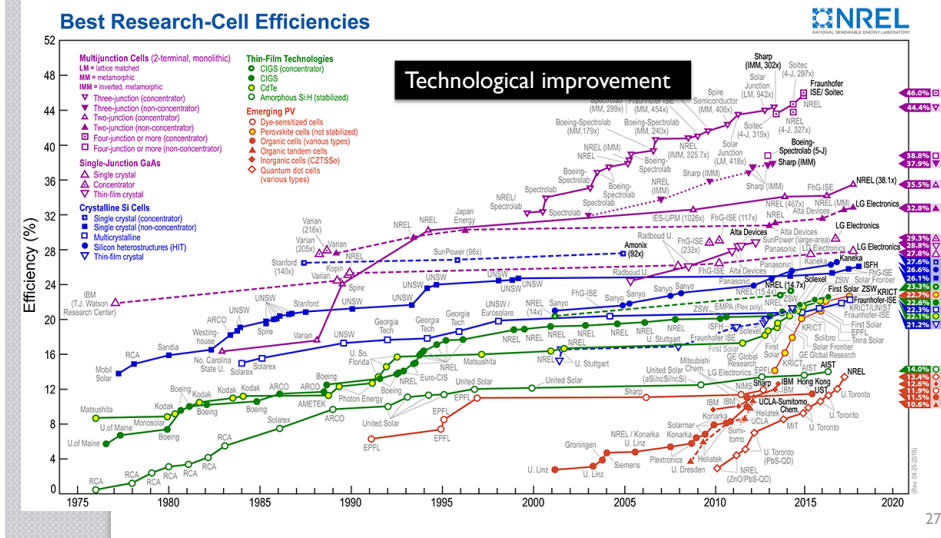


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Source: Professor Emanuel Sachs, Massachusetts Institute of Technology.  
 \* Assumes annual production growth of 35% and an 18% learning curve. PV costs based on 18% capacity factor and 7% discount rate.

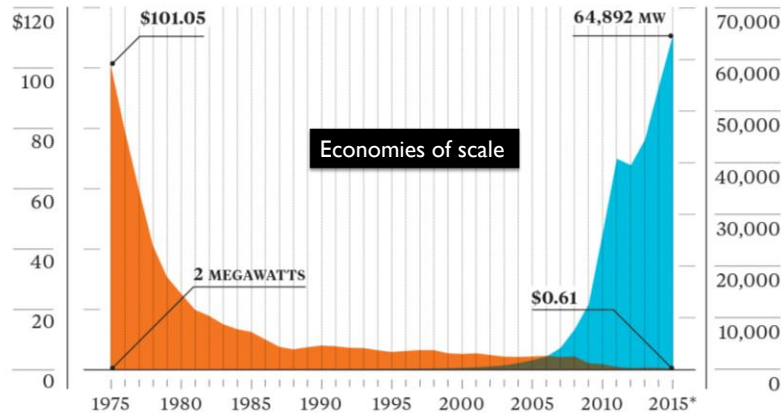
# INTRODUCTION



# INTRODUCTION

Price of a solar panel per watt

Global solar panel installations



That is why there have been incentives to the deployment of PV worldwide... 28

# 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

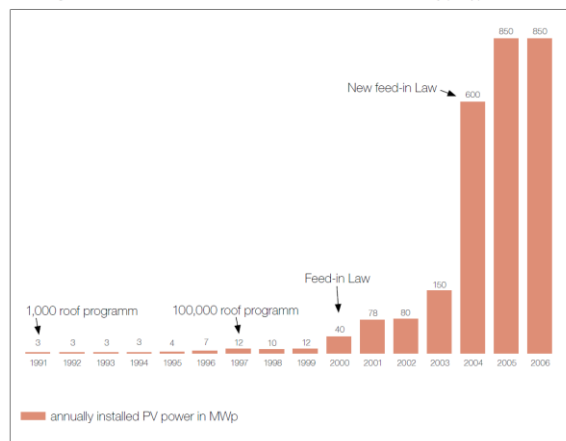
M.G. Rogol, *Why did the solar power sector develop quickly in Japan?*, MSc Thesis, MIT 2007

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# INTRODUCTION

## PV market – German market in 2000s

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

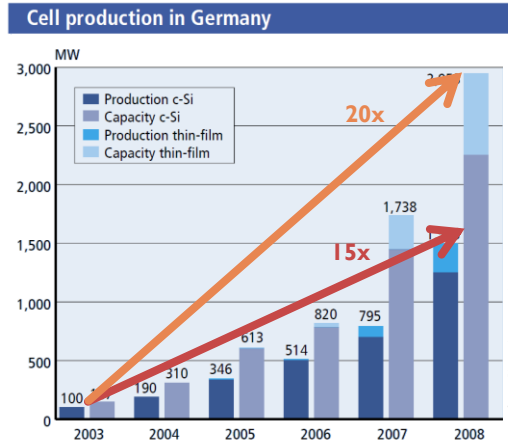


EPIA Brochure: *Supporting Solar Photovoltaic Electricity - An Argument for Feed-in Tariffs*, January 2008

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# INTRODUCTION

## PV market – German market in 2000s



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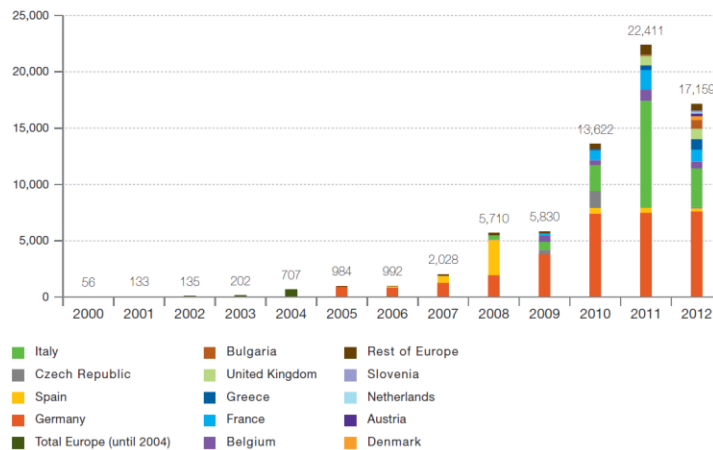
# INTRODUCTION



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)



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## INTRODUCTION

### PV market – German market in 2000s

- PV electricity production **today** not relevant for German electricity: <0.5% (2007)
- **CO<sub>2</sub>** 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

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## 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/supply for PV industry

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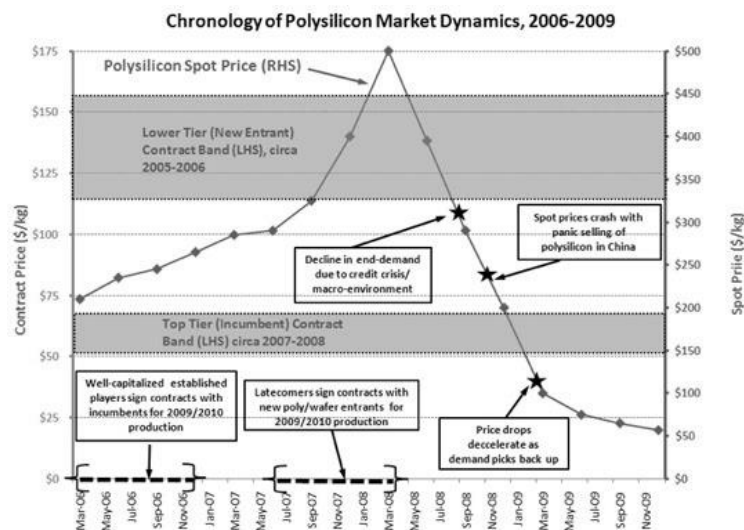
# INTRODUCTION

## 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 **skyrocketed** (spot market: 500\$/kg)
- New **players**, large **investments**
- New polisilicon **technologies** window opportunity
- Huge capacity **expansion**
- **Falling** prices
- Companies **bankrupting**.

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# INTRODUCTION



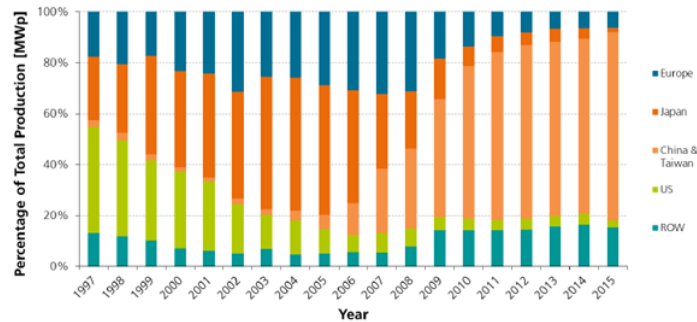
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# INTRODUCTION

## Emergence of PV industry in China



**PV Module Production by Region 1997-2015**  
Percentage of Total MWp Produced



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# INTRODUCTION

## Emergence of PV industry in China



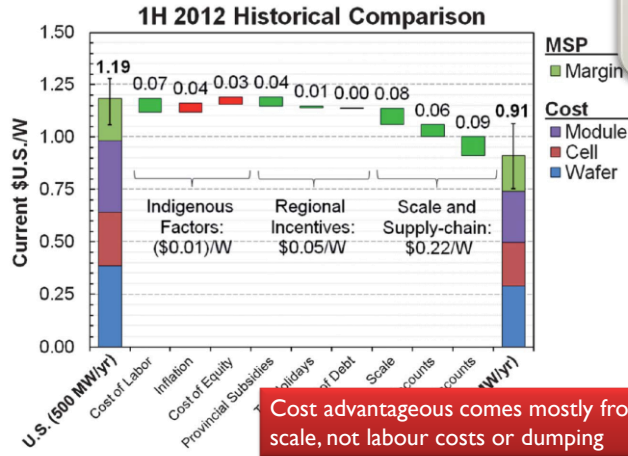
### *Timeline of PV development in China*

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**

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# INTRODUCTION

## Emergence of PV industry in China



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# 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.

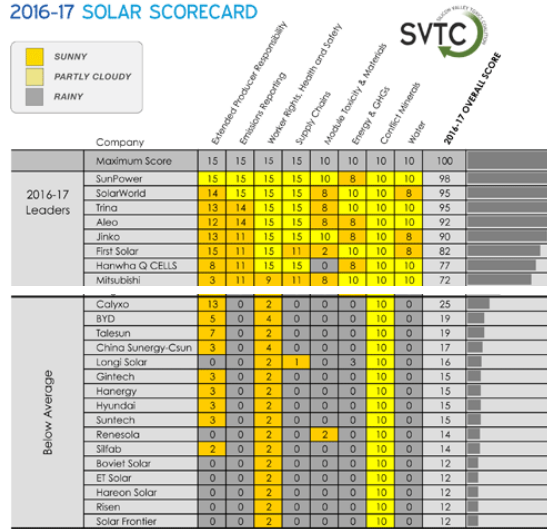


But has been blamed on **environmental** record!

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# INTRODUCTION

## 2016-17 SOLAR SCORECARD

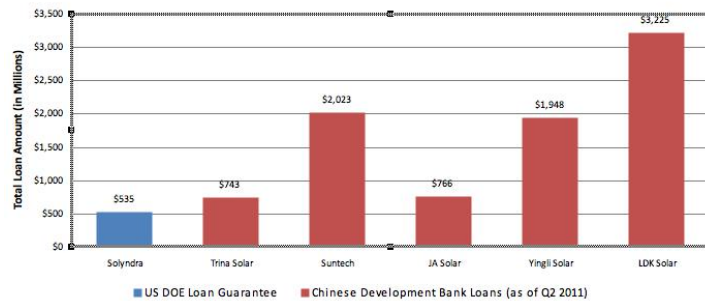


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# INTRODUCTION

And has been blamed on dumping...

## Government Loans to Solar Manufacturers



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# INTRODUCTION

SOLAR

UCILIA WANG: AUGUST 19, 2009

Share Tweet 0

## 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.

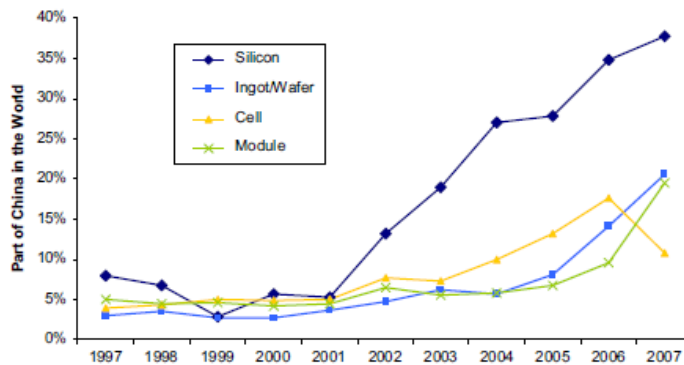
The new record will be included by the science journal **Progress in Photovoltaics** (PIP) that periodically publishes a list of record-holding efficiency for different types of solar cells and panels.

Yet, the answer is also innovation!

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# 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]

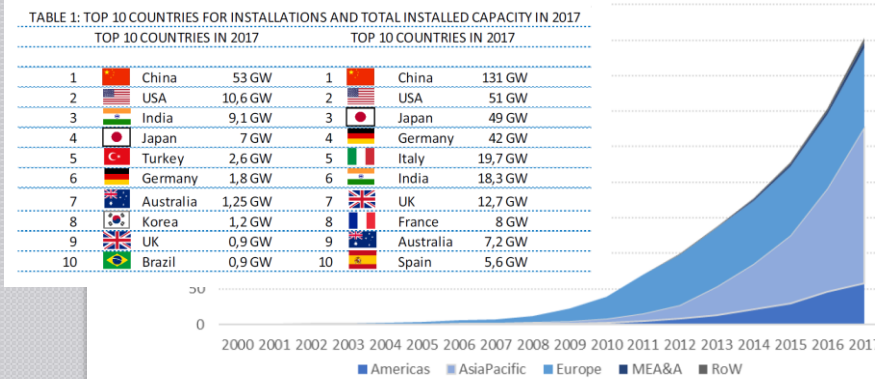
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# INTRODUCTION

## Emergence of PV industry in China

### The fastest increasing PV market

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

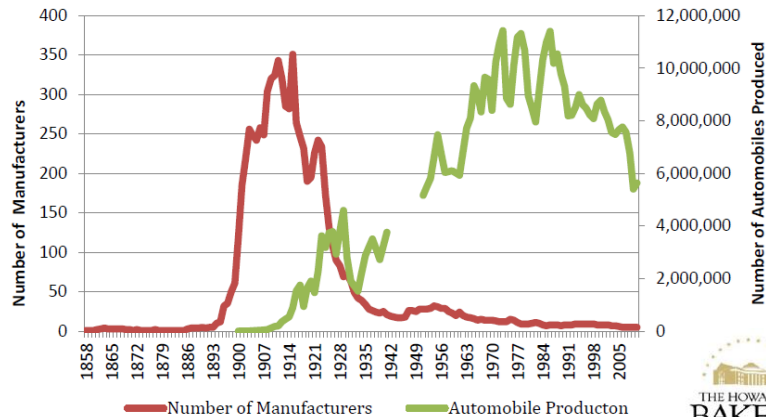


2018 SNAPSHOT OF GLOBAL PHOTOVOLTAIC MARKETS, Report IEA PVPS T1-33:2018

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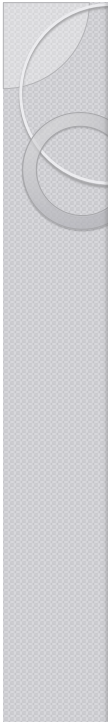
# INTRODUCTION

## Consolidation of the global PV industry



Assessment of Incentives and Employment Impacts of Solar Industry Deployment, 2012

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# INTRODUCTION

## PV market today

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

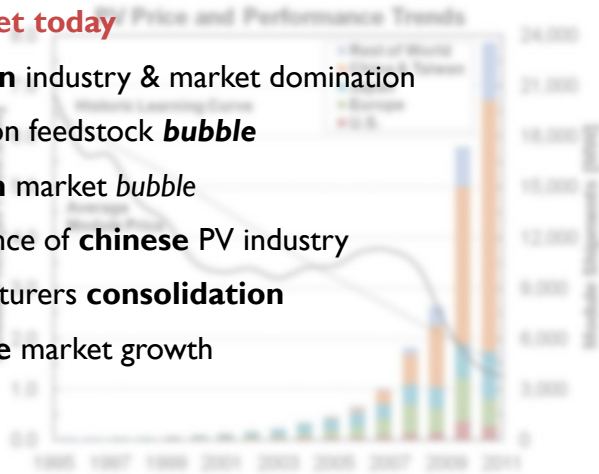
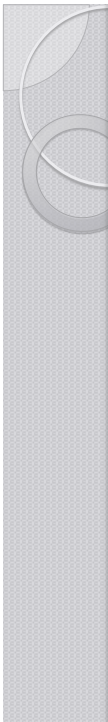


Fig. 1 From 2008 to 2011, reductions in the average global prices of a 60 PV modules have been in line with experience, but the rise of module manufacturing in China and Taiwan has been striking\*

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# INTRODUCTION

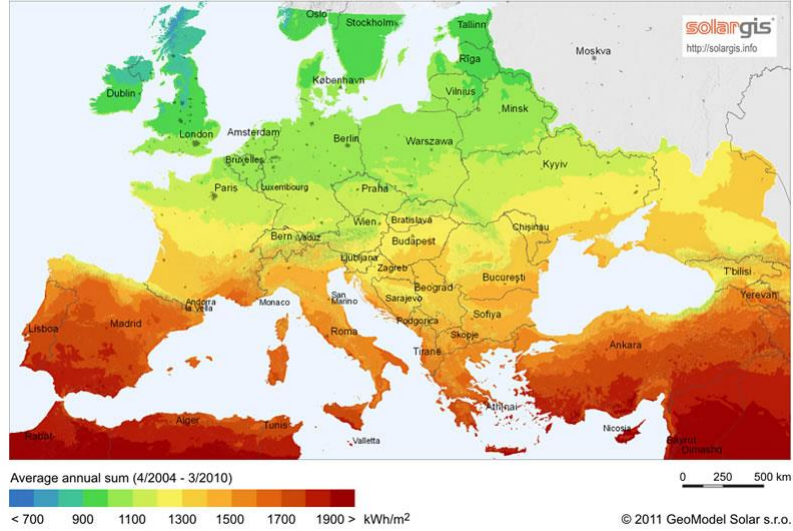
## PV in Portugal

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# INTRODUCTION

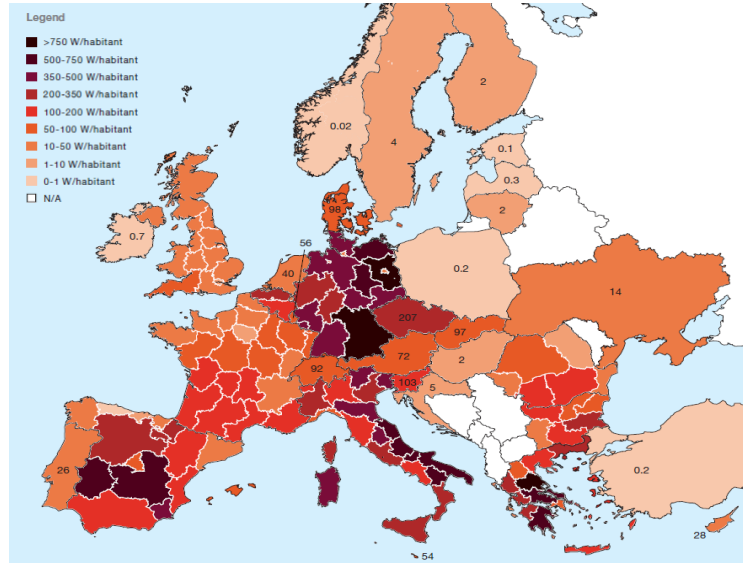
Global horizontal irradiation

Europe



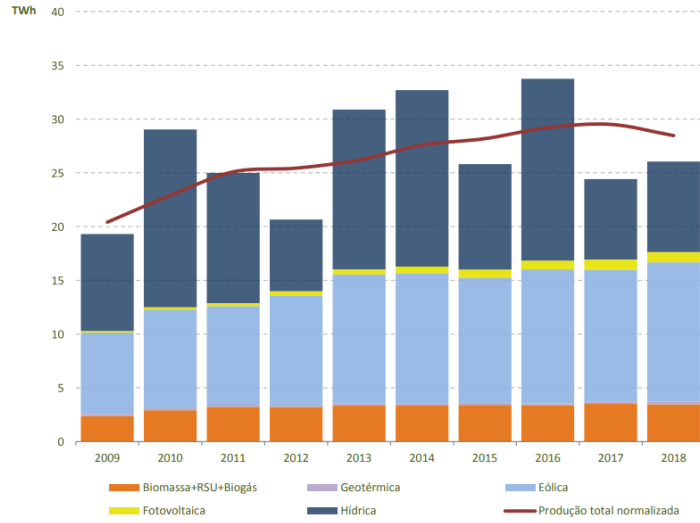
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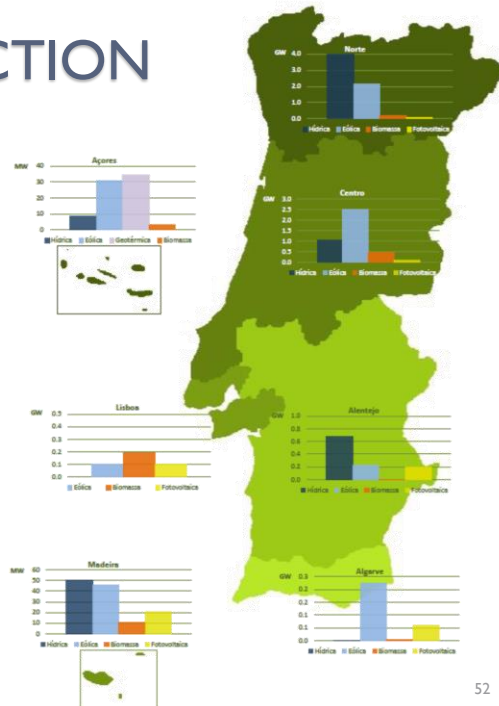
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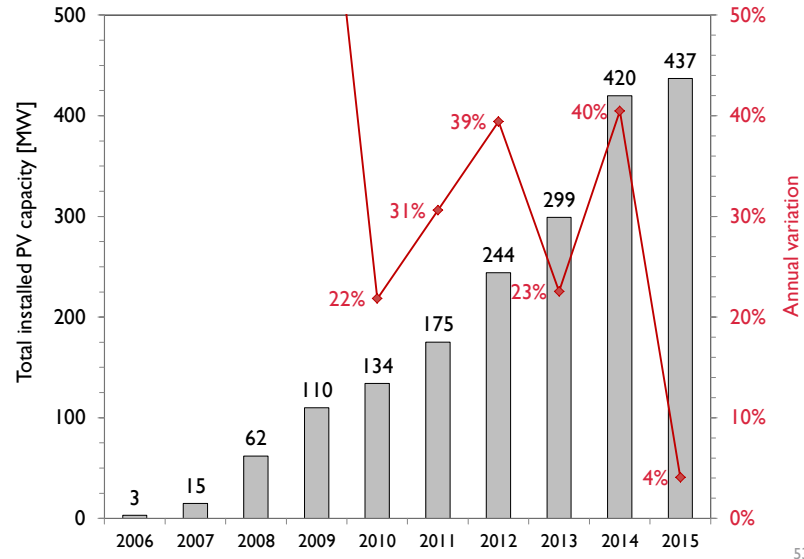
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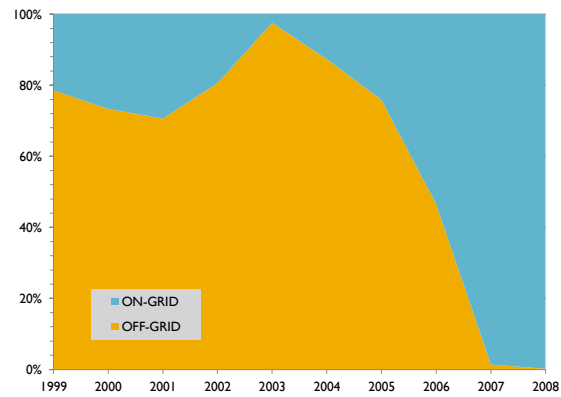
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# INTRODUCTION



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# INTRODUCTION

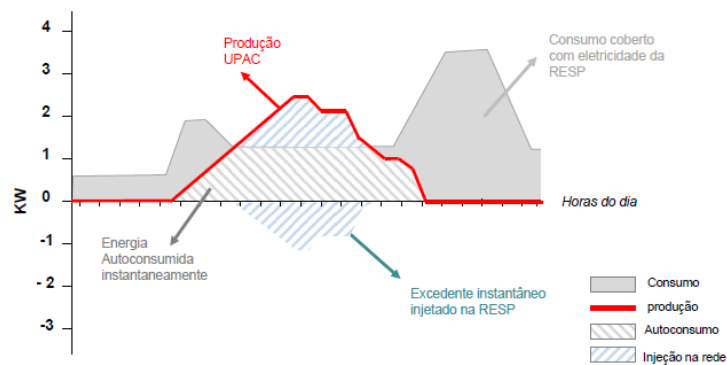
## PV in Portugal – legal framework

- Roadmap: 2020: **1500MW**
- Demonstration R&D projects:  
PV concentration (**28c€/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]

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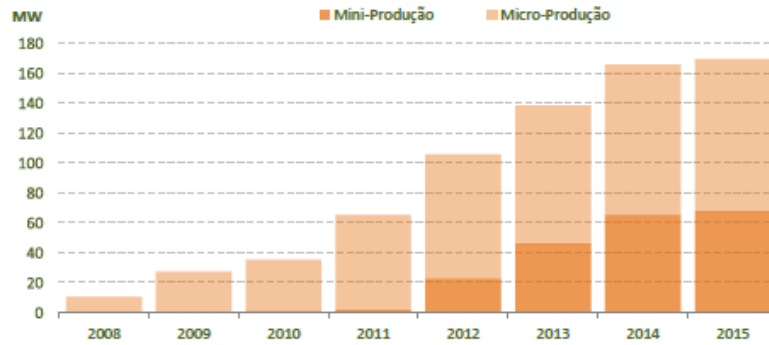
## Self demand in Portugal



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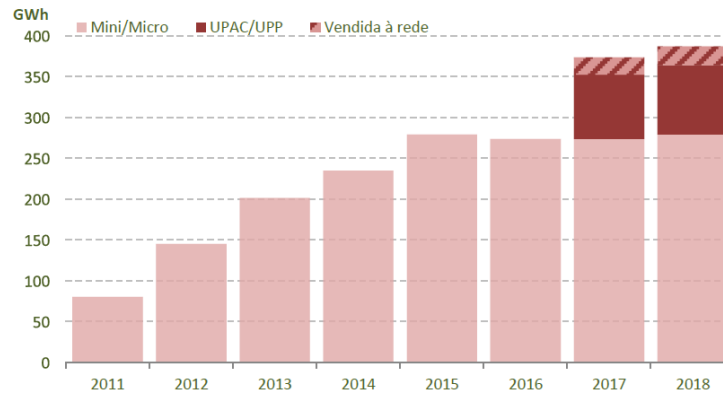
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Micro-generation -  
Mini-generation - Decreto Lei 363/2007



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# INTRODUCTION



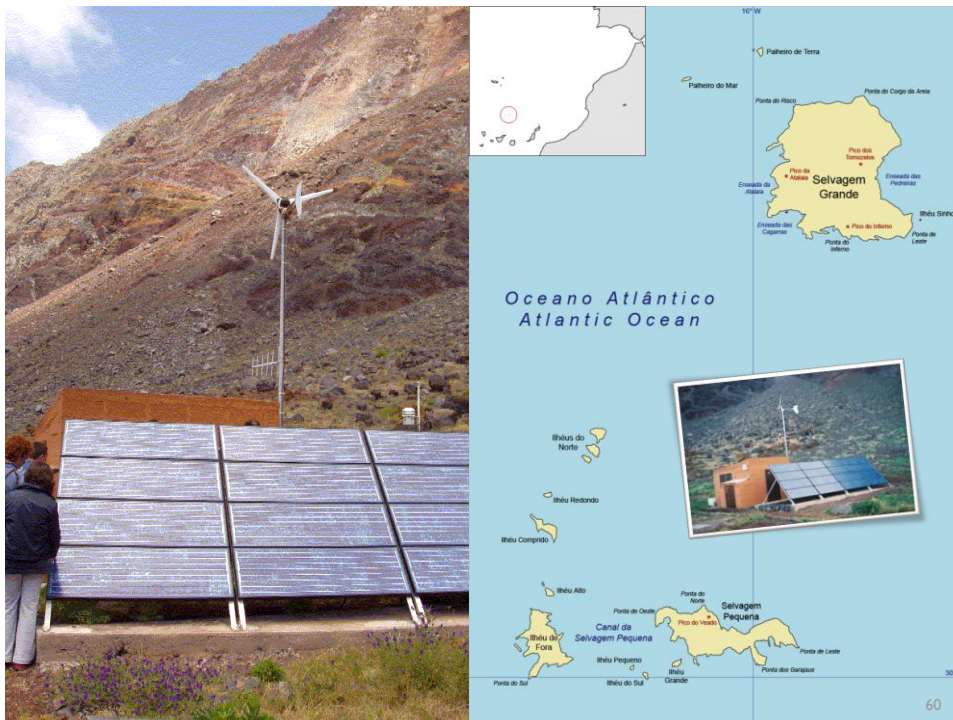
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# INTRODUCTION

## 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)

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## 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
- Untapped huge solar potential

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