Seminário de Troca de Conhencimentos
Geração Solar Fotovoltaica

Florianôpolis – SC – Brasil • 09 de Novembro de 2018

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Florianôpolis – SC – Brasil • 09 de Novembro de 2018

Photovoltaics: Technology and Progress

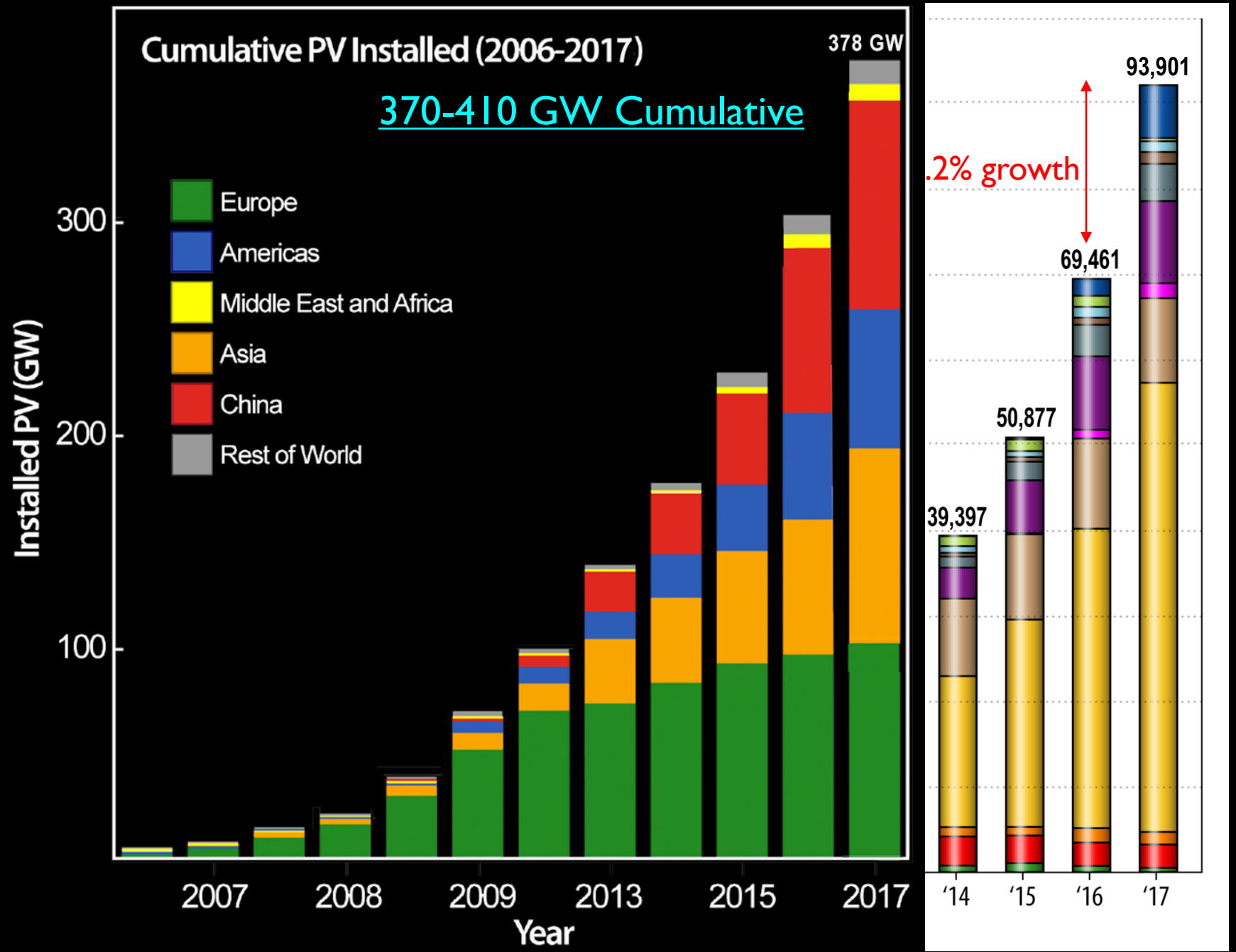
Amanhã é Hoje!

Lawrence L. Kazmerski
NREL and University of Colorado Boulder
Colorado, USA

Objectives

- Explore the history of this PV technology
- Establish where we are today (markets, technology)
- Examine where we expect to be in the future

World PV Shipments 2006-2017: *Where we are*



94 Gigawatts
in 1-year!

Power?

How many homes in US?

1,310,000 homes

India?

29,500,000 homes

Objectives

- Explore the history of this PV technology
- Establish where we are today
- Examine where we expect to be in the future

Driving force for technology has been, is, and will continue to be ***innovation***

Inovação?

Inovação: aplicação de idéias originais ou novas, que levam a soluções que criam *valor*.

A semente da inovação é a *criatividade*.

Inovação leva a mudanças *significativas* e *positivas.*

A **visão** é a força motriz para a inovação.

"I put my money on the sun and solar energy.
What a source of power!"
Thomas Alva Edison [1903]

"The sun . . .
our greatest energy source!"
Charles Proteus Steinmetz [1908]

"The sun is the spring that drives all . . .
A better way to obtain power would be to avail ourselves of the sun's rays."
Nikola Tesla [1900]

Os inovadores e visionários

"I put my money on the sun and solar energy.
What a source of power!"
Thomas Alva Edison [1903]

"The sun . . .
our greatest energy source!"
Charles Proteus Steinmetz [1908]

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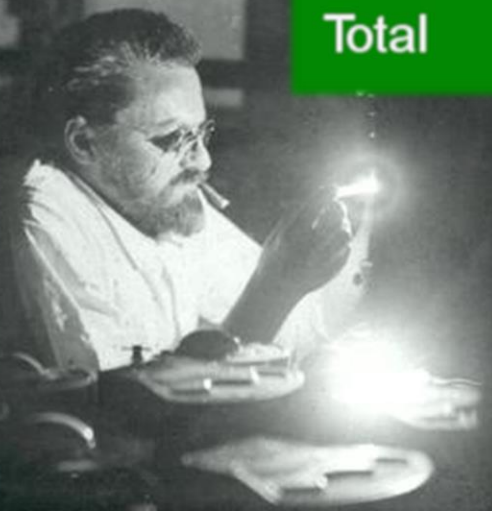
1. 2 hours labor	$ 10.
2. Knowing where to mark	$ 9,990.
Total	$10,000.



"The sun is the spring that drives all . . .
A better way to obtain power would be to avail ourselves of the sun's rays."
Nikola Tesla [1900]

Os inovadores e visionários

I'd put my money on the sun and solar energy.
What a source of power!
I hope we don't have to wait until oil and coal run out
before we tackle that.

Os inovadores e visionários

"In every walk with nature one receives far more than he seeks." - John Muir

Estamos mudando!

Xcel to Replace 2 Colorado Coal Units With Renewables...

On Monday, Xcel won preliminary approval for its coal plant retirement plan. The Colorado Public Utility Commission voted unanimously to allow for the early closure of coal-fired units 1 and 2 at the Comanche Generating Station in Pueblo County....

Read more

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Chernobyl Goes Solar With New 1 Megawatt Installation At ...

Chernobyl has been reclaimed to some degree this week as a long-awaited plan to install solar at the site of one of the worst nuclear disasters in history has become a reality. The new solar park at the Chernobyl

Many associate energy with oil, and oil with Saudi Arabia . . .

Repower America New 'Solar' Ad From the WE Campaign (Video)

George Spyros
Business / Corporate Responsibility
March 3, 2009

America West is Saudi of Solar

New Ad Calls for Investment in Clean Energy to Help America Transition off Dirty Coal, Foreign Oil

The "We" Campaign is launching a new national TV ad, called "Solar" calling for continued major investment in solar energy. It's the latest in a series of ads that from the org's (we can) "repower America" campaign targeting 100 percent clean energy in 10 years through upgrades in energy efficiency, wind power and plug-in cars. **The shiny new solar ad spot from the WE Campaign**

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America West is Saudi of Solar

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BREAKING: Metro-North lines have resumed normal service. LISTEN LIVE: 1010 WINS | WCBS 880

NEWS

Suffolk County Opens Solar Carport In Hauppauge: The Saudi Arabia of Solar

October 13, 2011 1:57 PM

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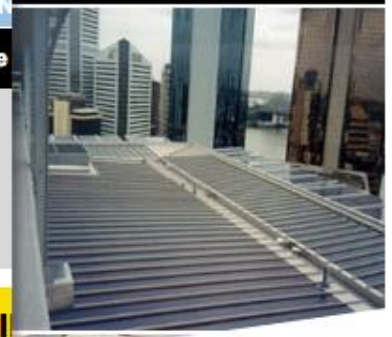

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global warming. New Mexico with one of the greatest solar resources
entire Unites States, has been referred to as the "Saudi Arabia of Solar."

Everguard Solar is a New Mexico based green energy company speci
in the design, engineering and installation of photovoltaic (PV) system
From initial consultation to system completion, Everguard
decades of professional experience in
roofing and electrical
that is a maj
New Mexico.

use of solar energy reduces our dependence on foreign oil, reduc
pollution, and our urgent need to address the issues of climate chang
global warming. New Mexico with one of the greatest solar resources
entire Unites States, has been referred to as the "Saudi Arabia of Solar."

Everguard installs systems that may last 40 years with 25 year performance warranties on your roof top
Building Integrated PhotoVoltaic – BIPV. Your roof is important and an experienced Everguard Roofing c
assure your roof will last as long as your solar system.

The environmental benefits of PV are undeniable and proven. The economics, performance and quality o
systems are proven as well – here in New Mexico.

A number of tax credits, utility incentives and other programs make solar PV a sensible solution.

State-of-the-art high efficiency products produced by leading companies such as General Electric, PV
Powered, Sunny Boy, Schott, Sanyo, Suntech and BP are installed by Everguard.

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Southern California Desert: The Saudi Arabia of Green Power

Exporting solar, wind, biofuel & geothermal power to the counties of LA, Orange & San Diego to meet the RPS 33% by 2020 Climate Change Challenge.

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California Solar Industry Booming: Report Finds State's Solar Capacity Has Doubled Over Past Five Years

First Posted: 11/09/11 02:38 PM ET | Updated: 11/10/11 12:53 PM ET

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According to a new report, California's solar indus is absolutely booming.

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Southern California Desert: The Saudi Arabia of Green Power

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Just another pretty face

Aug 19

Australia, the Saudi Arabia of solar?

Subtitle: Wholly Kangaroo Bangers, BG!

We have another Aussie solar update. According to Sydney TreeHugger Warren McLaren the Australian federal government wants 20% of Australia's total electricity supplied by renewables by 2020. In the same period, Australian power company Worley Parsons, would like to deliver 40% of the country's renewable energy from solar thermal power plants.

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Energia

Energia solar no Brasil pode ser vantjosa a partir de 2013
Brasil - Arábia Saudita da energia solar

Arley Reis - 02/10

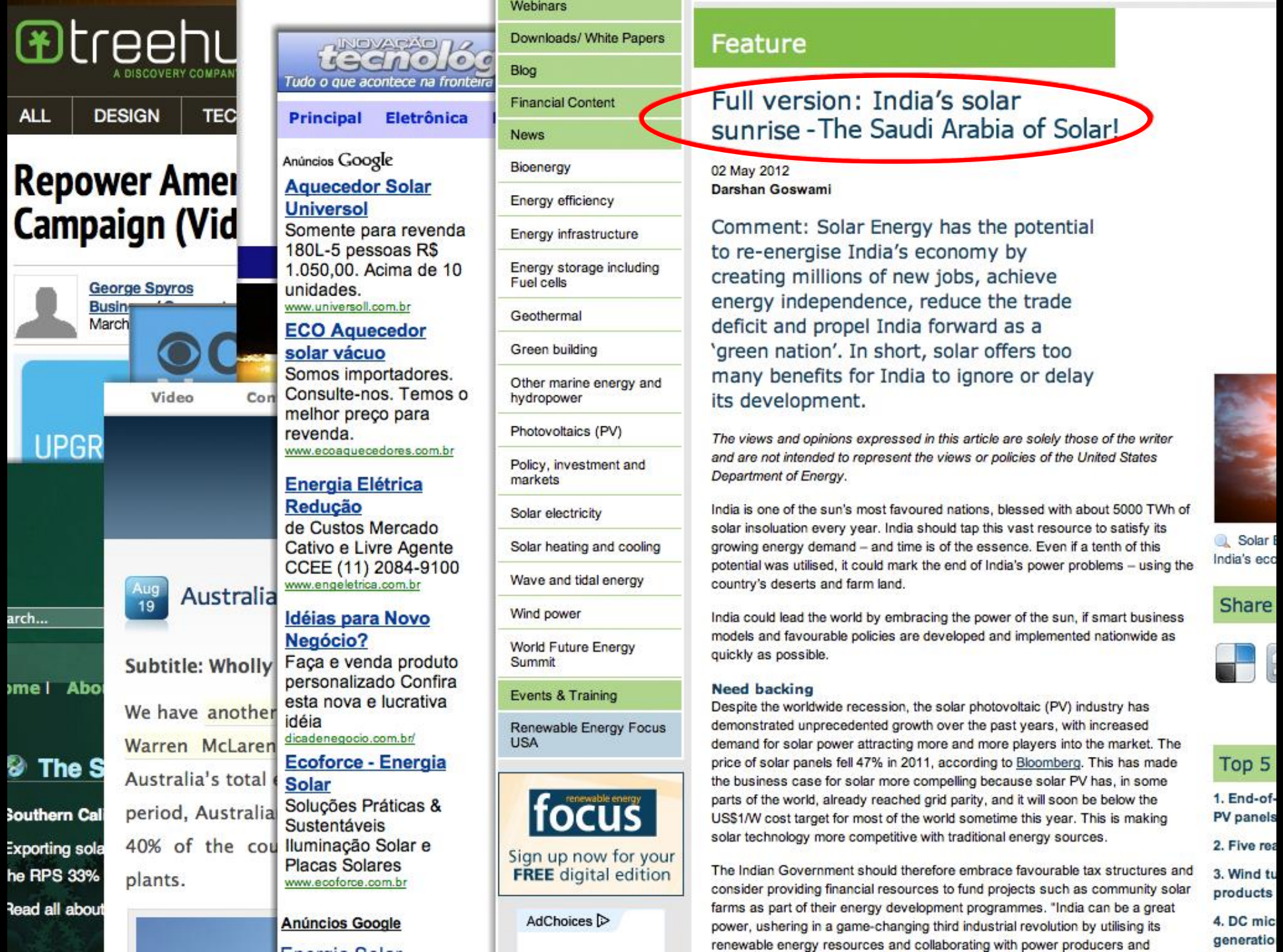
Pesquisadores da Universidade Federal de Santa Catarina mostraram que, entre 2012 e 2013, algumas regiões do Brasil já poderão ter preços equivalentes de energia fotovoltaica e energia convencional.

Programa Solar Brasileiro

Os dados são resultado de simulações de cenários para um eventual Programa Solar Brasileiro. As simulações identificam, entre diversos itens, o custo total do programa, o impacto tarifário que terá através da diluição dos custos aos consumidores finais e o momento em que o preço da energia fotovoltaica e da energia convencional será o mesmo para o usuário final.

De acordo com o coordenador dos trabalhos, o professor Ricardo Rüther, foram realizadas simulações para diferentes portes de programa,

Telhados solares poderão gerar energia elétrica com custo similar ao da energia convencional a partir de 2013. [Imagem: Labsolar/UFSC]



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Full version: India's solar sunrise - The Saudi Arabia of Solar!
02 May 2012
Darshan Goswami
Comment: Solar Energy has the potential to re-energise India's economy by creating millions of new jobs, achieve energy independence, reduce the trade deficit and propel India forward as a 'green nation'. In short, solar offers too many benefits for India to ignore or delay its development.
The views and opinions expressed in this article are solely those of the writer and are not intended to represent the views or policies of the United States Department of Energy.
India is one of the sun's most favoured nations, blessed with about 5000 TWh of solar insoluation every year. India should tap this vast resource to satisfy its growing energy demand – and time is of the essence. Even if a tenth of this potential was utilised, it could mark the end of India's power problems – using the country's deserts and farm land.
India could lead the world by embracing the power of the sun, if smart business models and favourable policies are developed and implemented nationwide as quickly as possible.
Need backing
Despite the worldwide recession, the solar photovoltaic (PV) industry has demonstrated unprecedented growth over the past years, with increased demand for solar power attracting more and more players into the market. The price of solar panels fell 47% in 2011, according to Bloomberg. This has made the business case for solar more compelling because solar PV has, in some parts of the world, already reached grid parity, and it will soon be below the US$1/W cost target for most of the world sometime this year. This is making solar technology more competitive with traditional energy sources.
The Indian Government should therefore embrace favourable tax structures and consider providing financial resources to fund projects such as community solar farms as part of their energy development programmes. "India can be a great power, ushering in a game-changing third industrial revolution by utilising its renewable energy resources and collaborating with power producers and
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Full version: India's solar sunrise - The Saudi Arabia of Solar!

02 May 2012
Darshan Goswami

Comment: Solar Energy has the potential to re-energise India's economy by creating millions of new jobs, achieve nergy independence, reduce the trade eficit and propel India forward as a green nation'. In short, solar offers too hany benefits for India to ignore or delay s development.

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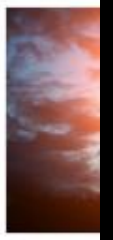

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Himalayas could become the Saudi Arabia of solar

- 17:33 18 October 2011 by **Chelsea Whyte**
- Magazine issue 2835. **Subscribe and save**
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Think of solar arrays and you'll probably picture panels under blistering desert heat – but we may be able to get more energy from solar panels on snow-capped mountains.

Kotaro Kawajiri at the Massachusetts Institute of Technology mapped solar irradiance across the globe in collaboration with colleagues in Japan. They found that some of the highest levels of sunlight can be found in the Himalayas and the Andes: at altitude, less light is lost to the atmosphere.

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Norway to help bring solar energy to Kingdom
Saudi Gazette
JUBAIL – Swicorp Joussour Company, a Saudi joint stock company capitalized at SR2.67 billion ($712 million) launched by Swicorp, announced that it has partnered with Chemical Development Company (CDC) of Saudi Arabia, and NorSun of Norway to invest in the construction of a polysilicon plant in the industrial city of Jubail.
NorSun will initially own 50 percent of the shareholding in the company, with Swicorp Joussour and CDC holding the balance. The transaction is aligned with Swicorp Joussour Company's focus on energy and energy-intensive industries that leverage the competitive advantages of the region.
This project has attracted two top tier companies to the region, NorSun and SunPower, both of which will be off-takers of the project. Commercial production is planned to commence in 2010 with an initial capacity of 3,000 metric tons per year.
"Jubail is an excellent location for this polysilicon plant allowing Swicorp Joussour and its partners to benefit from the world class infrastructure and competitive energy costs in the Kingdom," said Faysal Hamza, executive director, Private Equity, Swicorp Joussour.
"In addition, this project is a very compelling investment for our shareholders with the solar industry's projected growth of more than 30 percent across the value chain and its contribution towards developing alternative energy in the region."
In the Middle East, alternative energy is a new area of interest, which has gained recent attention due to the pressing need for economies to look toward diversified energy sources for future generations.
Ibrahim Al-Humaidan, president of CDC, said: "Harnessing diversified sources of energy is critical to the development of tomorrow's

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ECONOMY

Norway to help bring solar energy to Kingdom

Saudi Gazette

JUBAIL – Swicorp Joussour Company, a Saudi announced that it has partnered with Chemica construction of a polysilicon plant in the industr

NorSun will initially own 50 percent of the st transaction is aligned with Swicorp Joussour C advantages of the region.

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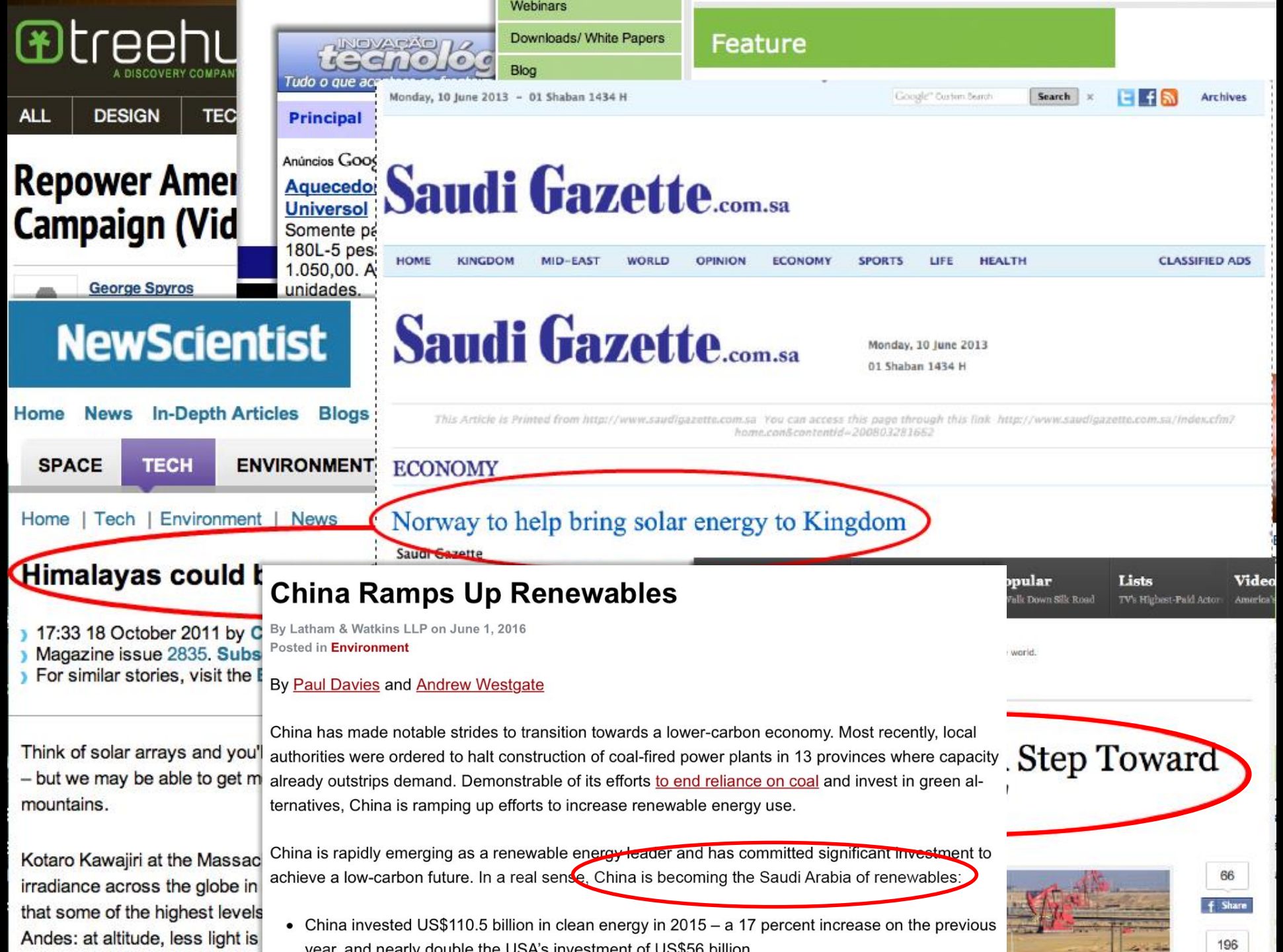

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China Ramps Up Renewables

By Latham & Watkins LLP on June 1, 2016
Posted in Environment

By Paul Davies and Andrew Westgate

China has made notable strides to transition towards a lower-carbon economy. Most recently, local authorities were ordered to halt construction of coal-fired power plants in 13 provinces where capacity already outstrips demand. Demonstrable of its efforts to end reliance on coal and invest in green alternatives, China is ramping up efforts to increase renewable energy use.

China is rapidly emerging as a renewable energy leader and has committed significant investment to achieve a low-carbon future. In a real sense, China is becoming the Saudi Arabia of renewables:

- China invested US$110.5 billion in clean energy in 2015 – a 17 percent increase on the previous year, and nearly double the USA's investment of US$56 billion

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ECONOMY

Norway to help bring solar energy to King

Saudi Gazette

NewScientist

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SPACE | TECH | ENVIRONMENT

Home | Tech | Environment | News

Himalayas could b

17:33 18 October 2011 by C
Magazine issue 2835. Subs
For similar stories, visit the E

Think of solar arrays and you'
– but we may be able to get m
mountains.

Kotaro Kawajiri at the Massac
irradiance across the globe in
that some of the highest levels
Andes: at altitude, less light is

China Ramps Up Renewables

By Latham & Watkins LLP on June 1, 2016
Posted in Environment

By Paul Davies and Andrew Westgate

China has made notable strides to transition towards a lower-carbon economy. M
authorities were ordered to halt construction of coal-fired power plants in 13 provi
already outstrips demand. Demonstrable of its efforts to end reliance on coal and
ternatives, China is ramping up efforts to increase renewable energy use.

China is rapidly emerging as a renewable energy leader and has committed signi
achieve a low-carbon future. In a real sense, China is becoming the Saudi Arabia

- China invested US$110.5 billion in clean energy in 2015 – a 17 percent incre
year, and nearly double the USA's investment of US$56 billion

SANTA FE NEW MEXICAN

Chile aims to become 'solar Saudi Arabia'

By Nick Miroff
The Washington Post Mar 31, 2017 (...)

A tractor is used to clean the photovoltaic panels at Finis Terrae solar park near Calama. Strong desert winds stir up dust that coats the panels, reducing their energy output. Tamara Merino/The Washington Post.

MARIA ELENA, Chile - On the solar farms of the Atacama Desert, the workers dress like astronauts. They wear bodysuits and wraparound sunglasses, with thick canvas headscarves to shield them from the radiation.

The sun is so intense and the air so dry that seemingly nothing survives. Across vast, rocky wastes blanched of color, there are no cactuses or other visible signs of life. It is Mars, with better cellphone reception.

It is also the world's best place to produce solar energy, with the most potent sun power on the

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Your guide to Renewable Energy

SOLAR | WIND | BIOMASS | SMALL HYDRO POWER | MISCELLANEOUS | COVER STORIES | INTE

Solar | April 4, 2012 3:33 pm

Saudi Arabia plans to generate 10 per cent of its energy from solar power by 2020

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Riding on huge investments and aggressive renewable energy plans, the Kingdom of Saudi Arabia aims to derive 10 per cent of its electrical supply from solar power by 2020. The Arab kingdom has announced ambitious energy project which may see it become world's largest source of solar energy.

The kingdom announced that so far it has secured $3 billion in funding for developing PV and CSP power plant in the future. Such an achievement will see Saudi Arabia emerge as the world's largest source of solar energy.

A statement by the Saudi government said that the country hopes to be able to generate 5 GW of solar energy by 2020 in order to meet this target. The move also aims to create more job opportunities, as the Saudi government said the Kingdom's budding solar industry could create over 15,000 jobs.

The statement further said that the government was encouraging the development of solar farms, plants for processing of raw materials and assembly, and other related facilities. As a result, various investors have already pledged more than $3 billion for various solar ventures.

One of the most talked about projects is a $380 million polysilicon plant, slated to be built along the Gulf Coast. The development of the Saudi Arabia's solar power sector will be at the heart of Saudi Energy 2012

SANTA FE NEW MEXICAN

Chile aims to become 'solar Saudi Arabia'

By Nick Miroff
The Washington Post Mar 31, 2017 (...)

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Solar | April 4, 2012 3:33 pm

Saudi Arabia plans to generate 10 per c solar power by 2020

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Riding on huge invest
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see it become world's

The kingdom announc
funding for developing
Such an achievemen
world's largest source

A statement by the S
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processing of raw materials and assembly, and other related facili
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One of the most talked about projects is a $380 million polysilico
Coast. The development of the Saudi Arabia's solar power sector

Saudi Arabia to Become the Saudi Arabia of Solar Electricity

By Garvin Jabbusch, Green Alpha Advisors, LLC

June 10, 2011 | 15 Comments

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Tweet 43 | Share 143 | Share 30 | +1 1

A couple days ago Bloomberg reported the following: "Saudi Arabia plans to generate solar electricity equaling the amount of its energy from crude exports, Oil Minister Ali Al-Naimi said." Wait, what?

That sounds like a ridiculous quantity of solar electricity. The article doesn't say quantitatively how much energy that is, so I did a quick check. Saudi Arabia exports about 2.7 billion barrels of oil per year, each containing the equivalent of 1,700 Kilowatt hours of electricity for a total of 4.59×10^{12} kWh per year, or the equal of about one quarter or the world's annual electricity demand.

Okay, so obviously solar electricity equal to the energy in all of Saudi Arabia's crude exports is far more than the Saudis could ever use, so maybe I'm misunderstanding the Oil Minister's meaning. Except, Bloomberg goes on to report that "Saudi Arabia, the world's largest oil exporter, has the potential by 2020 to produce enough solar power to meet more than four times global demand for electricity, al-Naimi said." Okay, so it appears they really are planning to ramp up huge. World leading huge. Region-or-more powering huge. A development plan this ambitious can only mean that Saudi Arabia intends to become a huge source of exportable electricity.

Why would the world's largest oil producer wish to so quickly become the world's largest

CAN

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ark near Calama.
ergy output. Tamara

VIDEO N

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orkers dress like
canvas headscarves to

Across vast, rocky
life. It is Mars, with

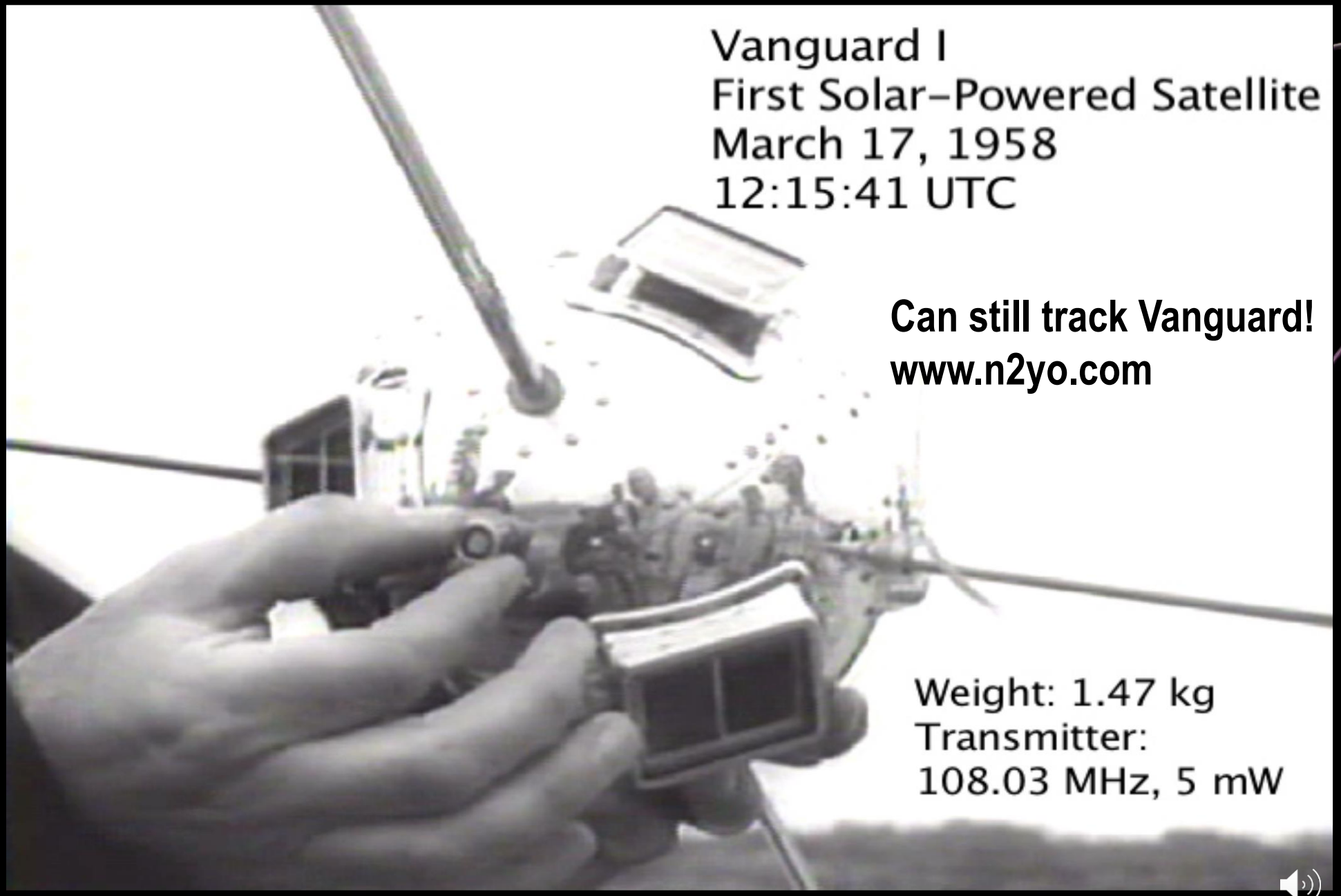
otent sun power on the

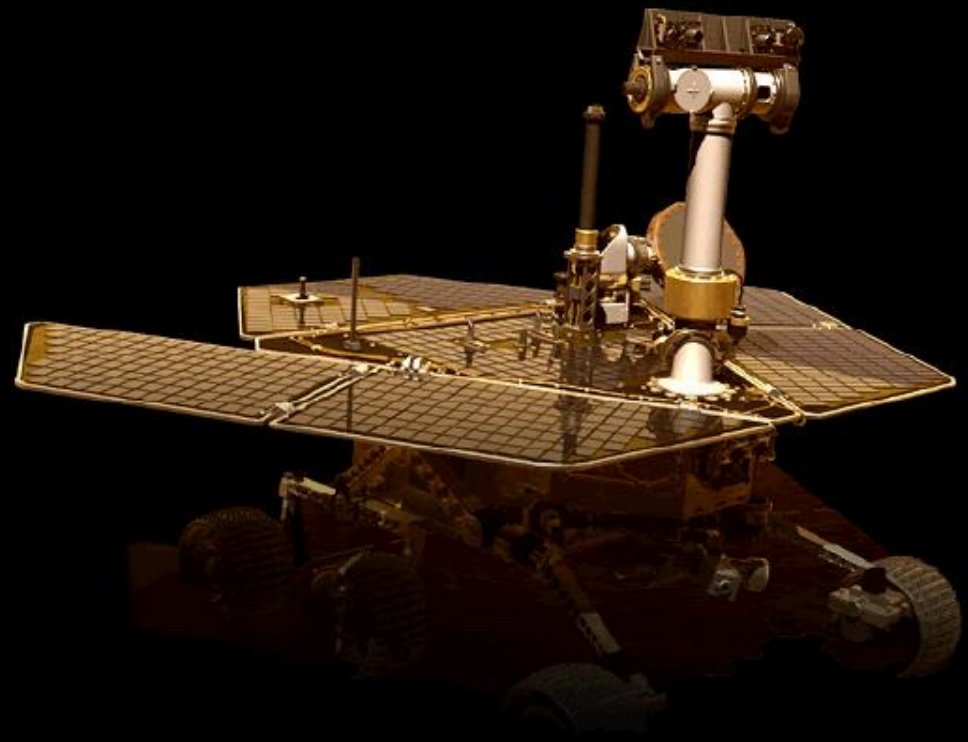
60 anos atrás . . .

60 anos atrás . . .

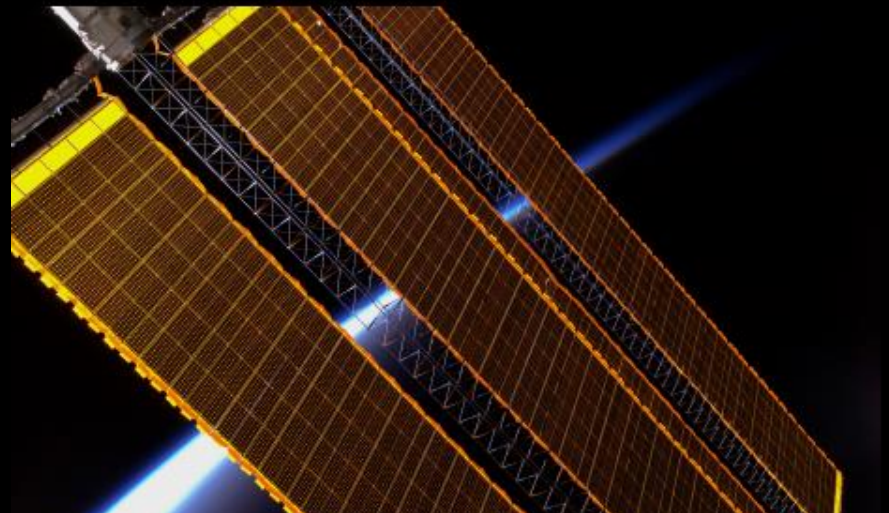
How did this all begin?

First market for PV . . . space

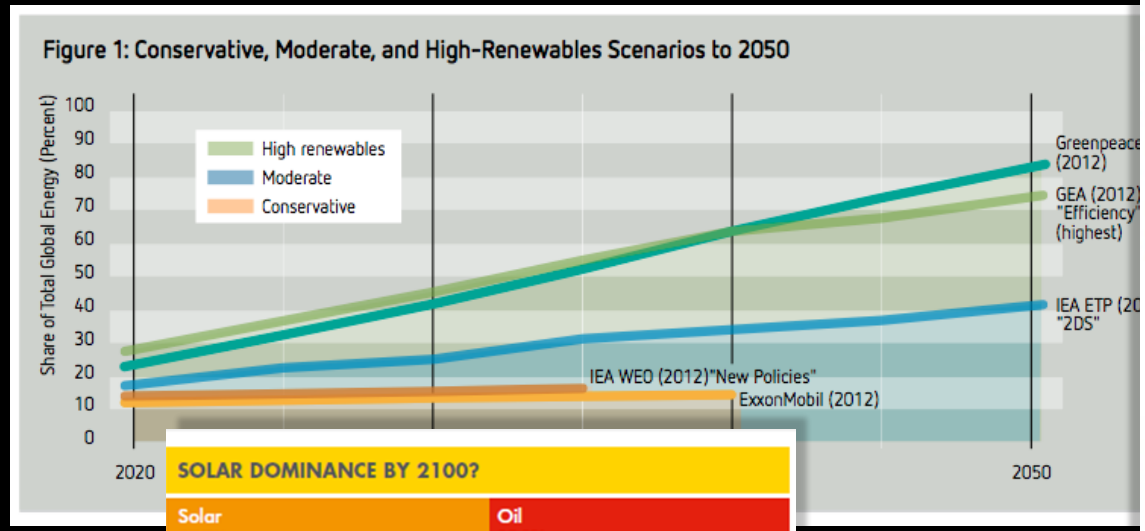


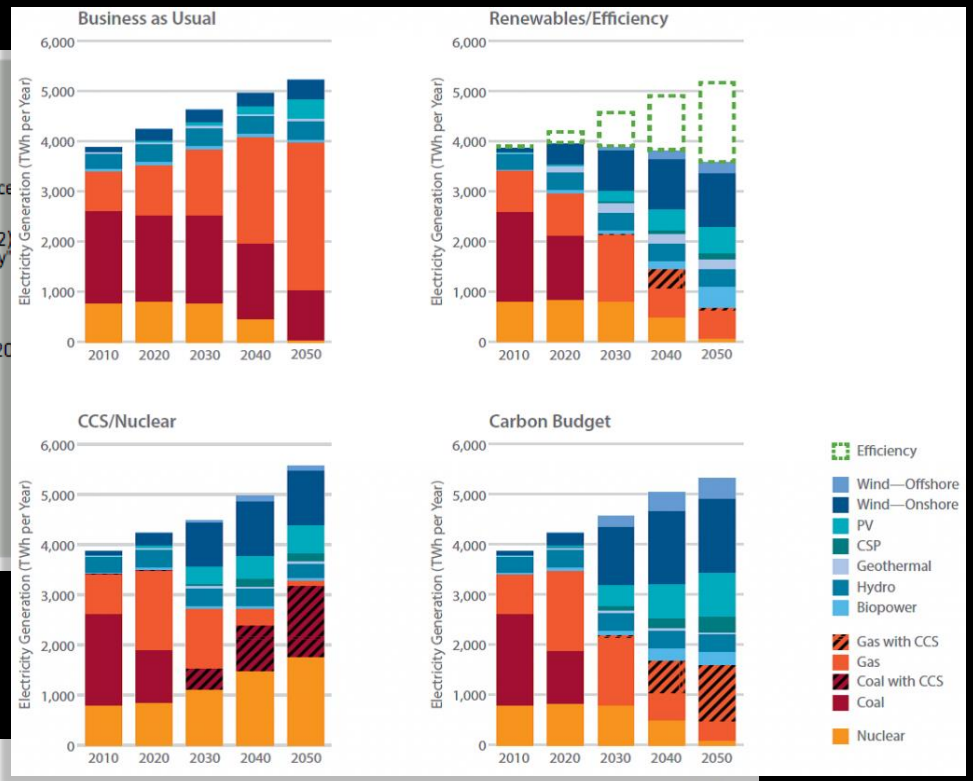


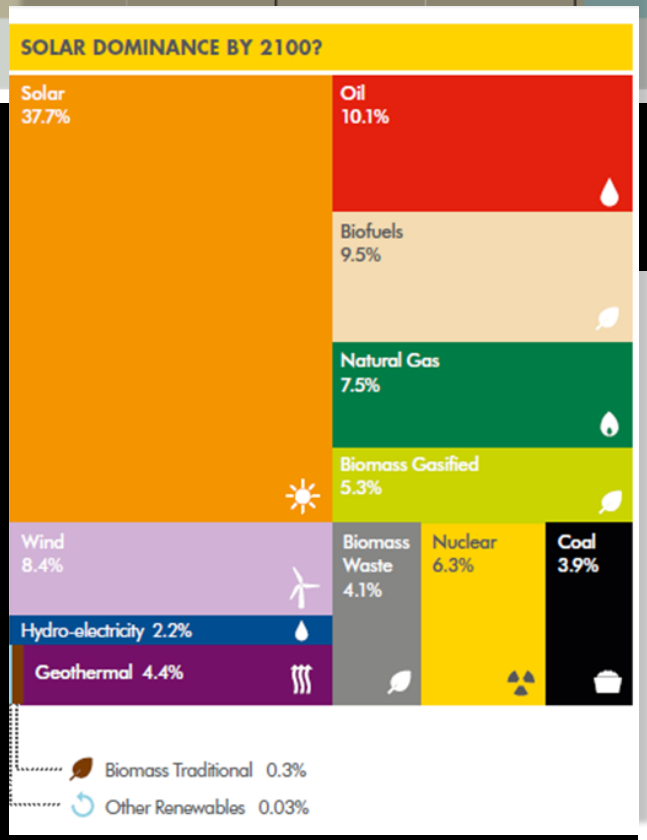
Currently:
>1400 active satellites in earth orbit

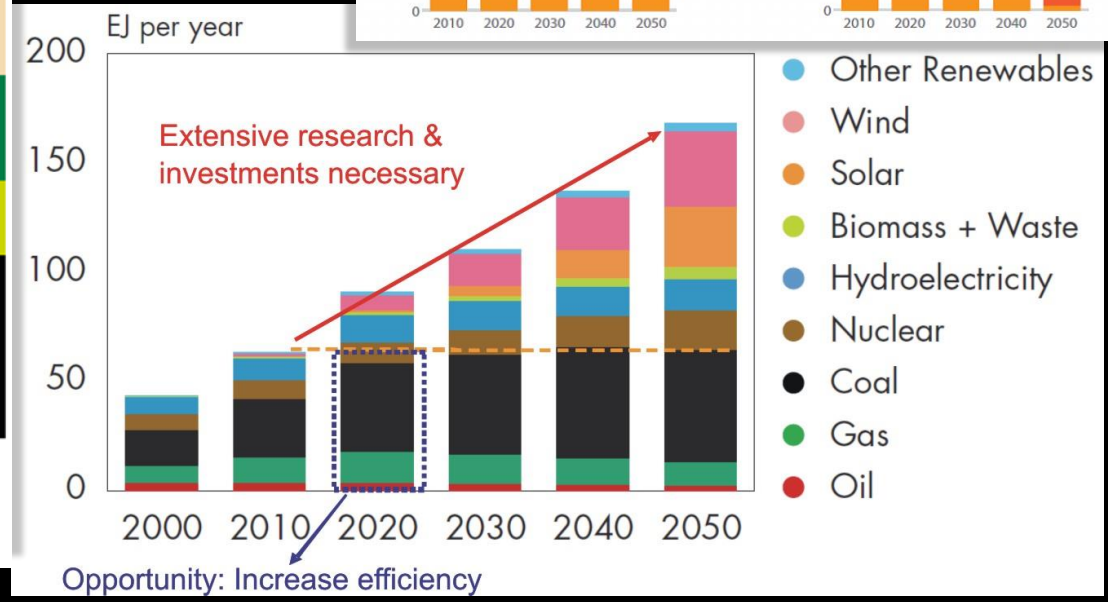


The future . . . scenarios







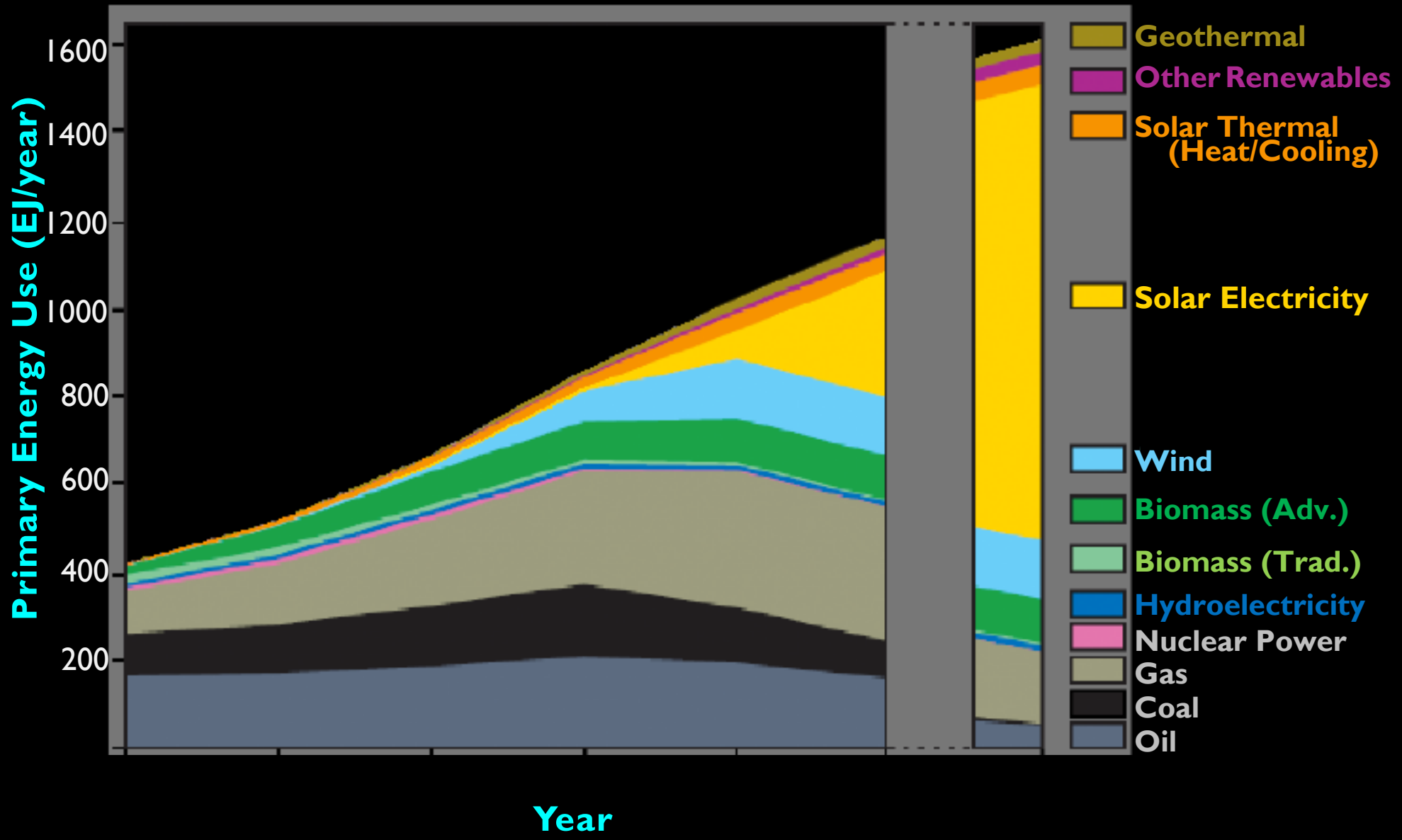


The future . . . scenarios

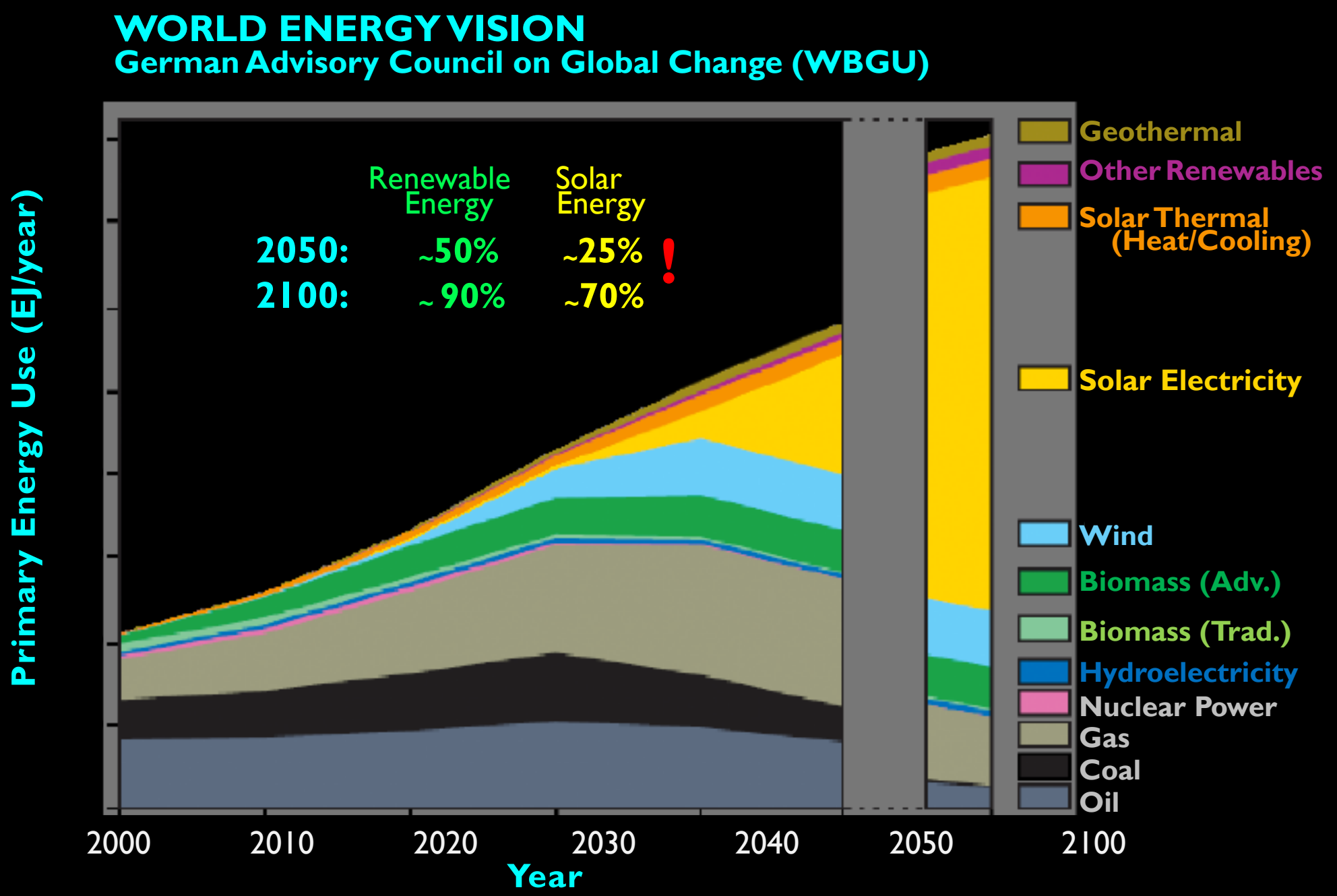
WORLD ENERGY VISION

German Advisory Council on Global Change (WBGU)

WorldEnergy.org



The future . . . scenarios



Expanding Markets

Solar Power
Jordan

Modi government sets revised solar mission target at 100 GW

100 GW by 2022

India

Aruna Kumarankandath @CSE_Aruna | Thursday 18 June 2015

The revised capacity has been divided into 40 GW for rooftop solar electricity generation and 60 GW for large and medium-scale grid-connected projects

The Centre had announced the Jawaharlal Nehru National Solar Mission in 2010 (Credit: Jonas Hamberg)

Prime Minister Narendra Modi has given his approval for increasing the national solar mission capacity from the current 22 gigawatt (GW) to 100 GW by 2022.

In a bid to reduce the use of fossil fuels and increase the capacity of renewables, the Centre had announced the Jawaharlal Nehru National Solar Mission (JNNSM) in 2010 for developing 20-GW capacity solar grids and 2-GW

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Home » News » China aims for 150 GW of solar PV by 2020

China

150 GW by 2020

China aims for 150 GW of solar PV by 2020

14. OCTOBER 2015 | GLOBAL PV MARKETS, FINANCIAL & LEGAL AFFAIRS | BY: CHRISTIAN ROSELUND

The nation has again raised its targets for PV deployment, with a goal to install 20 GW annually from 2016 through 2020.

NEA will push for more distributed solar in densely populated Eastern and Central China.

On Tuesday, China's National Energy Administration (NEA) told state news agency Xinhua that China will increase deployment of solar PV to 20 GW annually through 2020, to reach a capacity of 150 GW.

NEA estimates that the nation had installed 35.8 GW of solar PV by the end of June 2015, with 7.7 GW installed in the first half of 2015 alone. This is the second increase of goals made this month, following the increase of China's 2015 installation target to 23.1 GW.

NEA New Energy Office Director Dong Xiufen says that future work will focus on distributed PV in Central and Eastern China as well as Western China, which has seen the bulk of development to date.

Egypt's Ministry of Electricity to receive bid
first ever solar PV plant

07. OCTOBER 2013 | APPLICATIONS & INSTALLATIONS, GLOBAL PV MARKETS, MARKET
BY: IAN CLOVER

The 200 MW plant is being offered on a build-own-operate scheme, with 23 Egyptian and international companies expe lodge bids in the tender.

Algeria Takes Solar Steps with Tender and Grand Plans

Faced with a potentially toxic mix of crippling public spending and decreasing oil and gas production, Algeria is looking for ways to expand their energy sector into new directions, including a substantial 20 year solar plan. The North African nation took a step towards

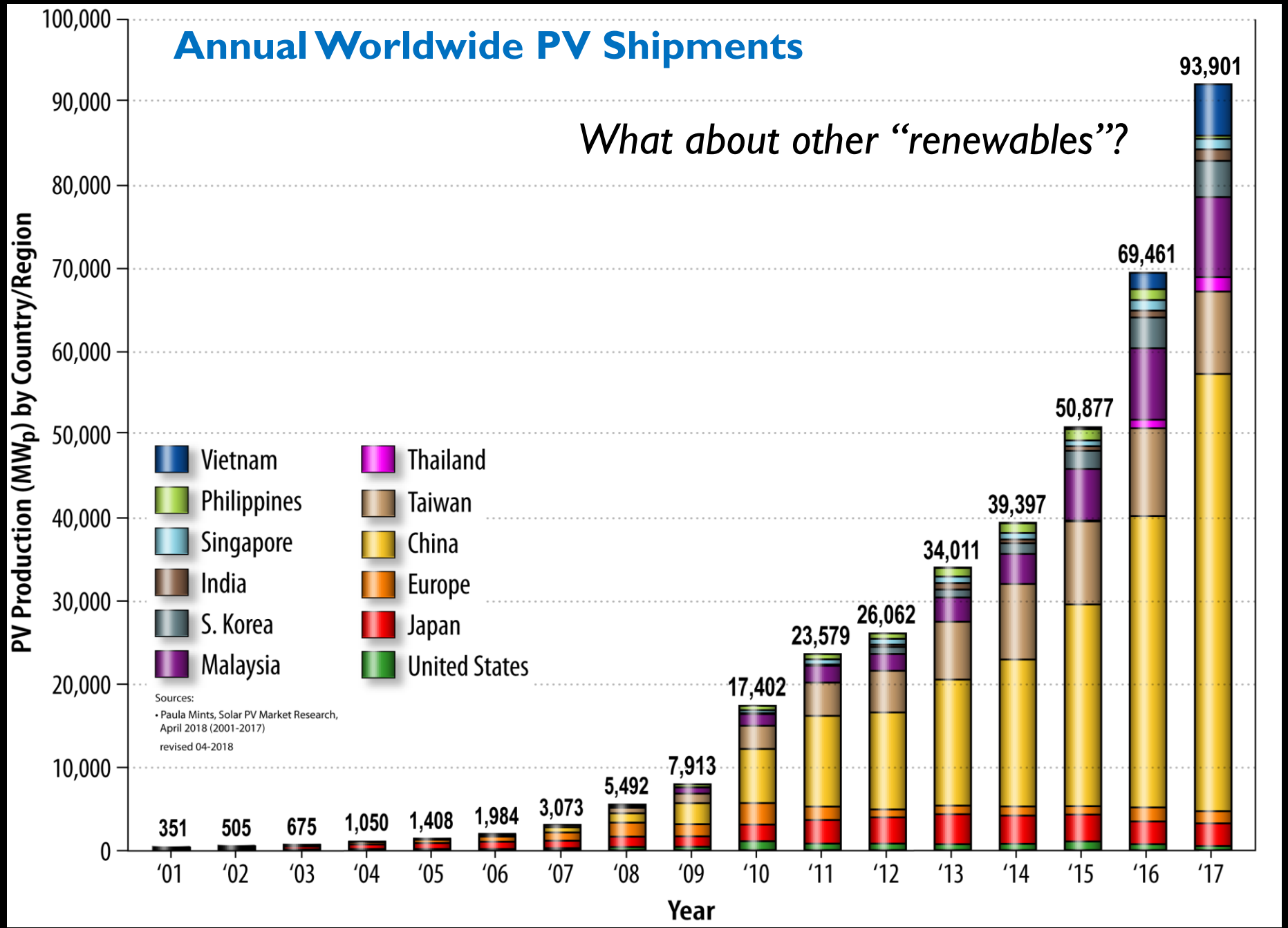
The first phase of the project will be expected to be tendered in the first quarter of 2014. (Image source: Andreas Demmelbauer/Flickr)

set to be tendered in Q1 2014

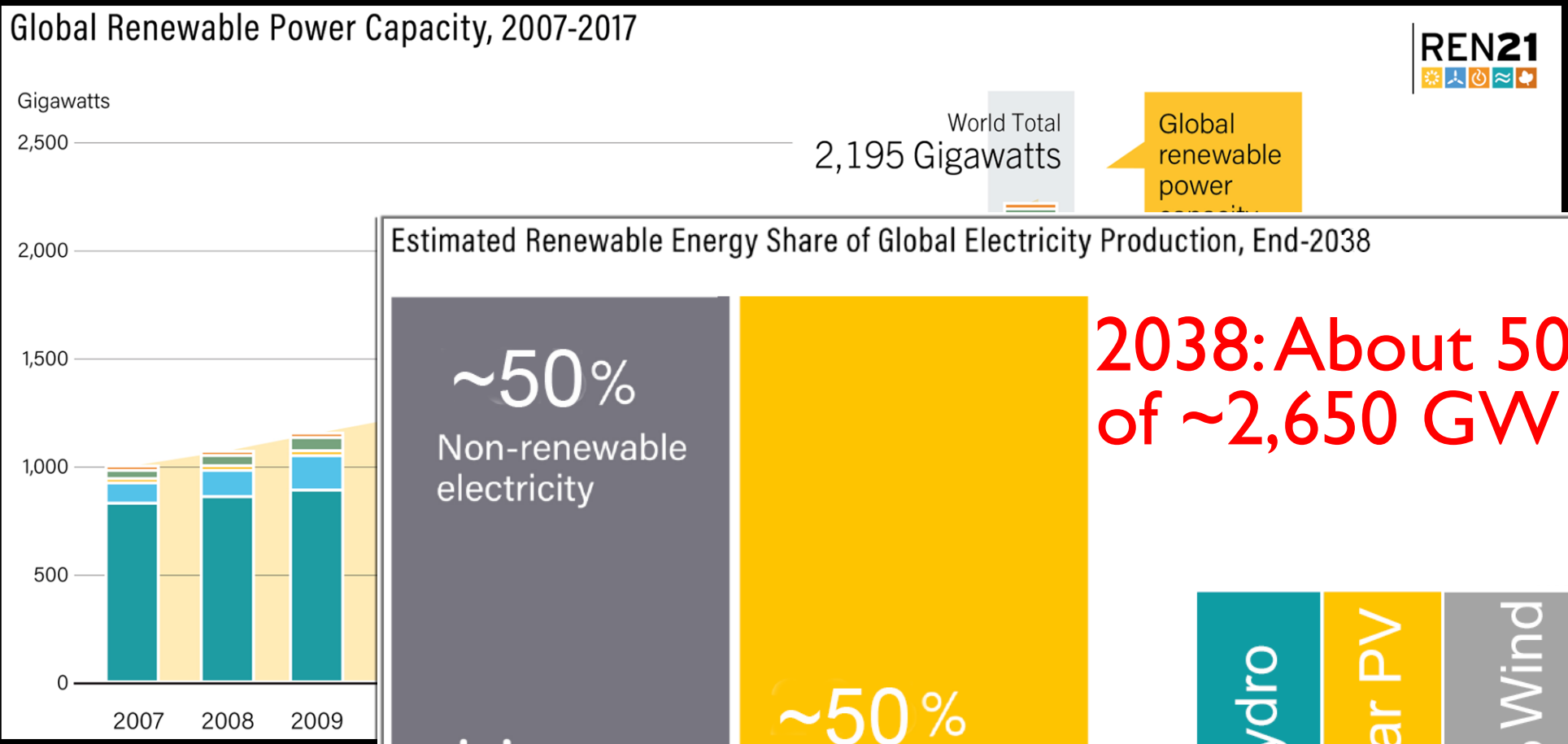
Qatar General Electricity and Water Corporation (Kahramaa) h been charged with the task of delivering the 200MW solar ener plant project by 2020.

Kahramaa renewable energy technologies section head Saleh Hamad al Marri will soon be providing a detailed update on the strategy and technology requirements for the upcoming solar project at the Solar Qatar Summit 2013, to be held i mid-November this year.

World PV Shipments 2001-2017: *Where we are*

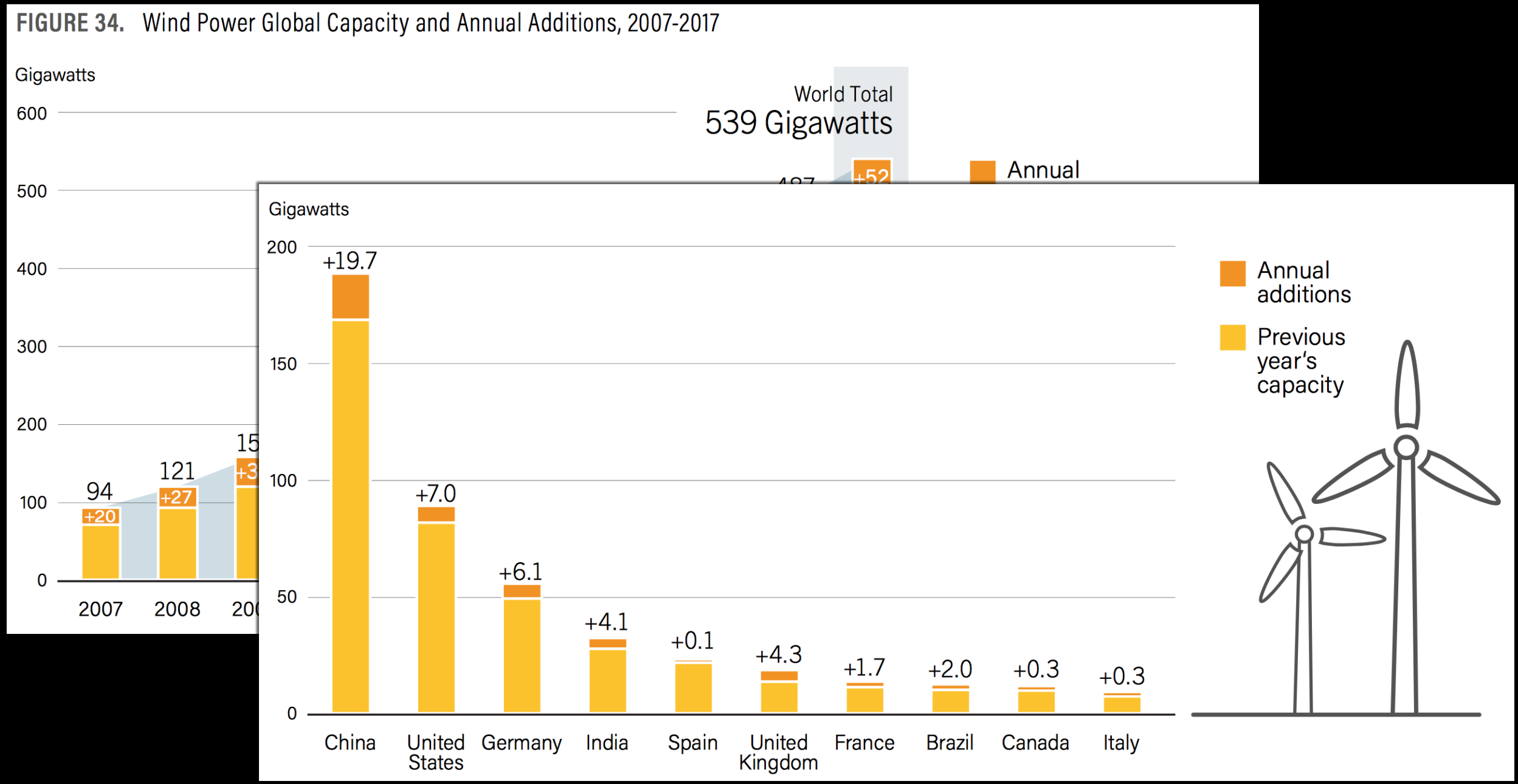


Global Renewable Energy Portfolio



Wind Energy

FIGURE 34. Wind Power Global Capacity and Annual Additions, 2007-2017

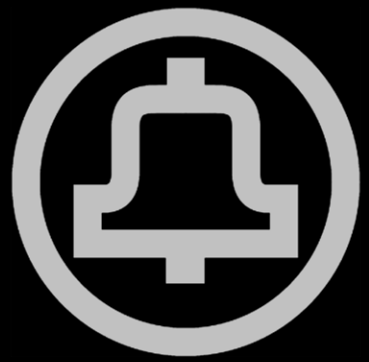


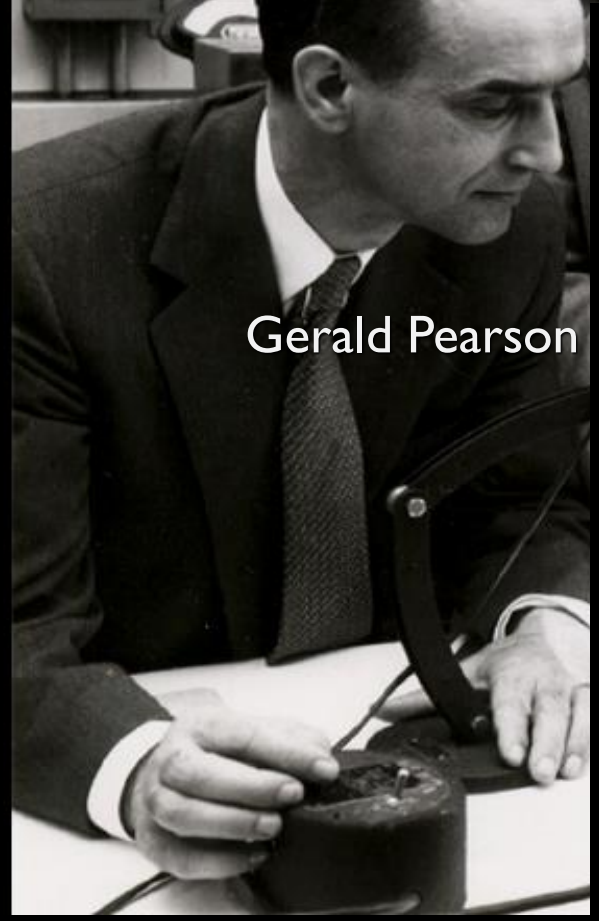
The PV beginnings . . .

64 years ago !

The PV beginnings . . .

It started in 1954 at Bell Telephone Laboratories



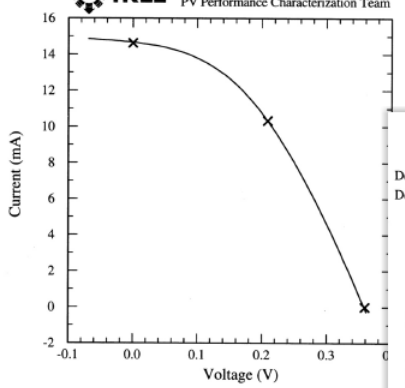


Bell Labs
mono-Si Cell

Device ID: 1
Dec 03, 2002 12:06
Reporting Spectrum: AM1.5 Global

Device Temperature: 25.0 ± 1.0 °C
Device Area: 1.400 cm²
Irradiance: 1000.0 W/m²

NREL
X25 IV System
PV Performance Characterization Team



V_{oc} = 0.3589 V
I_{sc} = 14.620 mA
J_{sc} = 10.443 mA/cm²
Fill Factor = 41.12 %

I_{max} = 10.334 mA
V_{max} = 0.2088 V
P_{max} = 2.1578 mW
Efficiency = 1.54 %

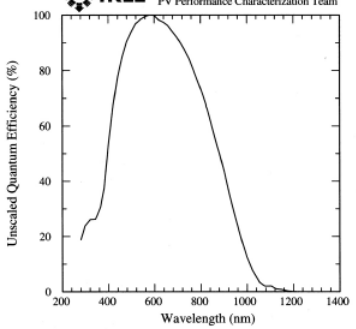
Apertured to 1.4 SQ cm. Made in 1954
AT&T archives.

Bell Labs
mono-Si Cell

Device ID: 1
Dec 3, 2002 9:43 AM

Device Temperature: 25.0 ± 1 °C
Device Area: 1.400 cm²

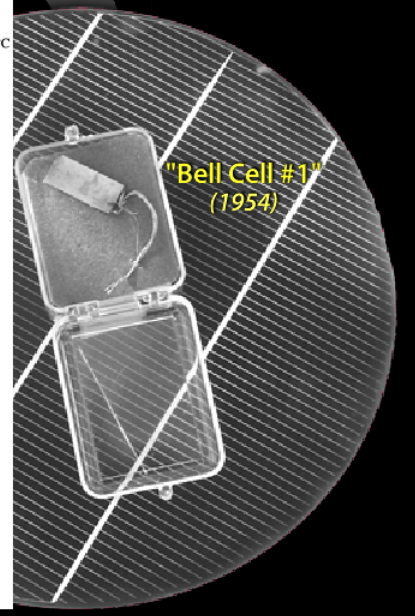
NREL
Filter QE System
PV Performance Characterization Team



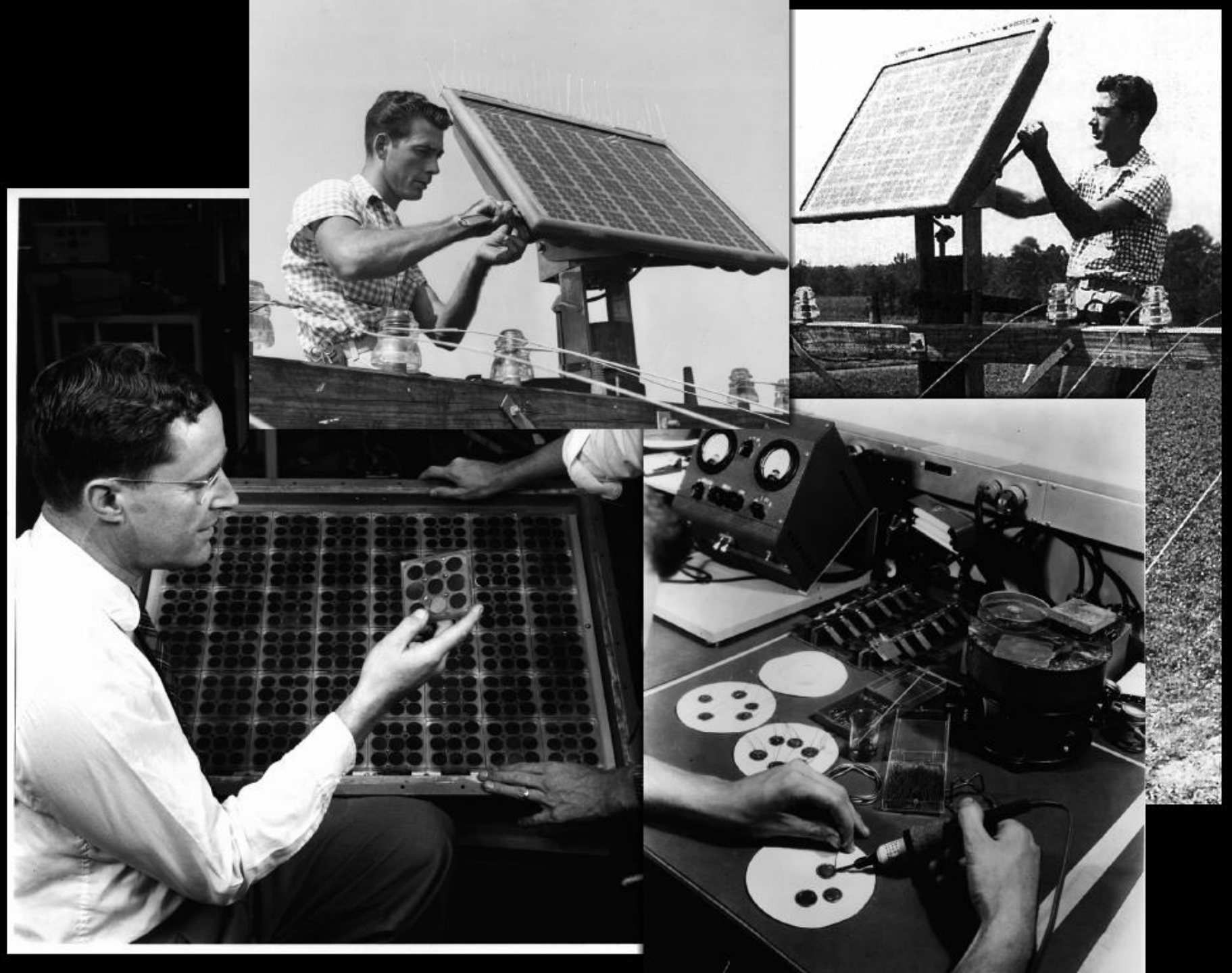
Voltage Bias: 0.0 V
Light bias for 10.9 mA
Light Bias region area: 1.400 cm²
Light Bias Density: 7.757 mA/cm²

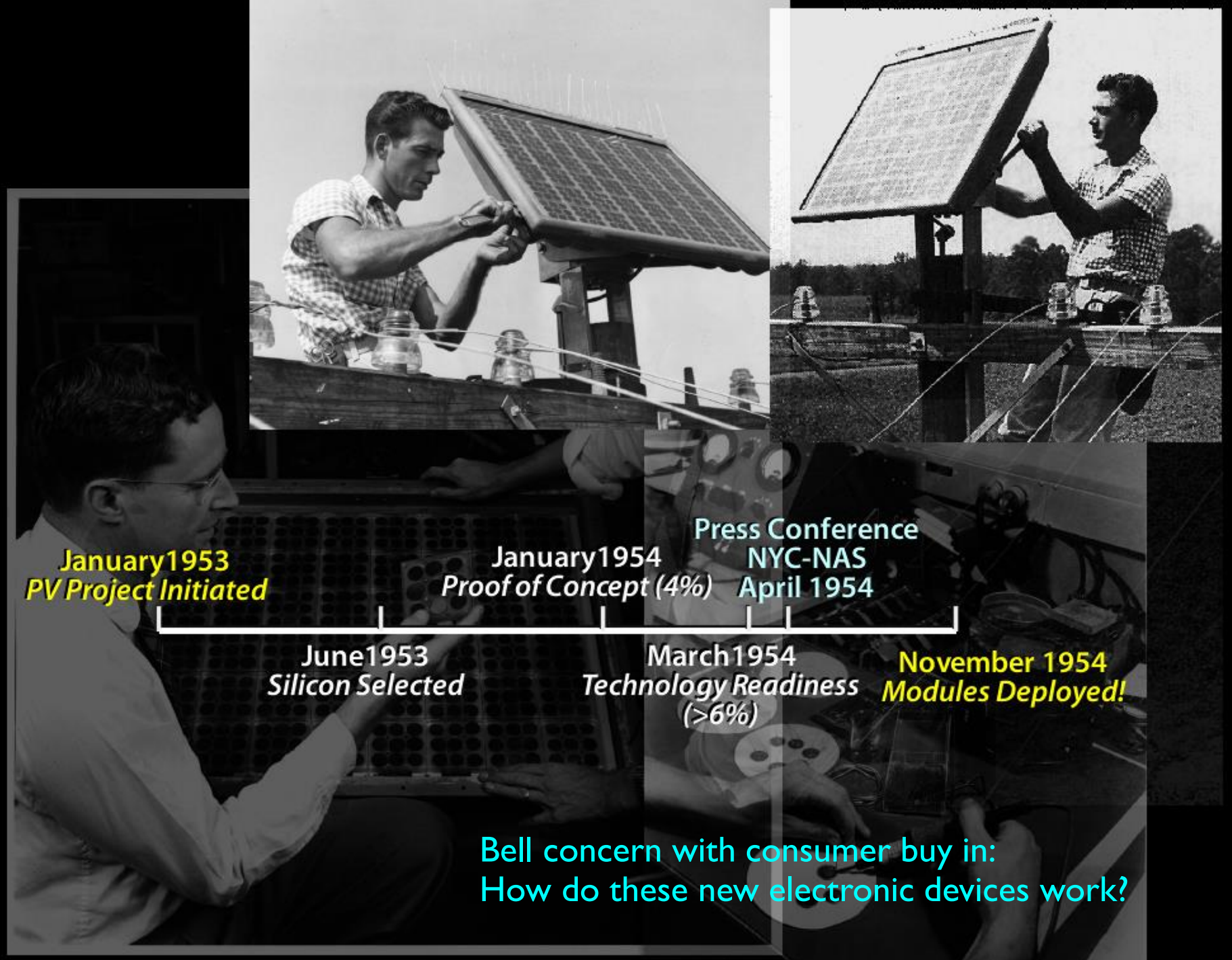
J_{sc} Estimate:
J_{sc} (Global) = 29.0 mA/cm²

Apertured to 1.4
AT&T Archives



"Bell Cell #1"
(1954)



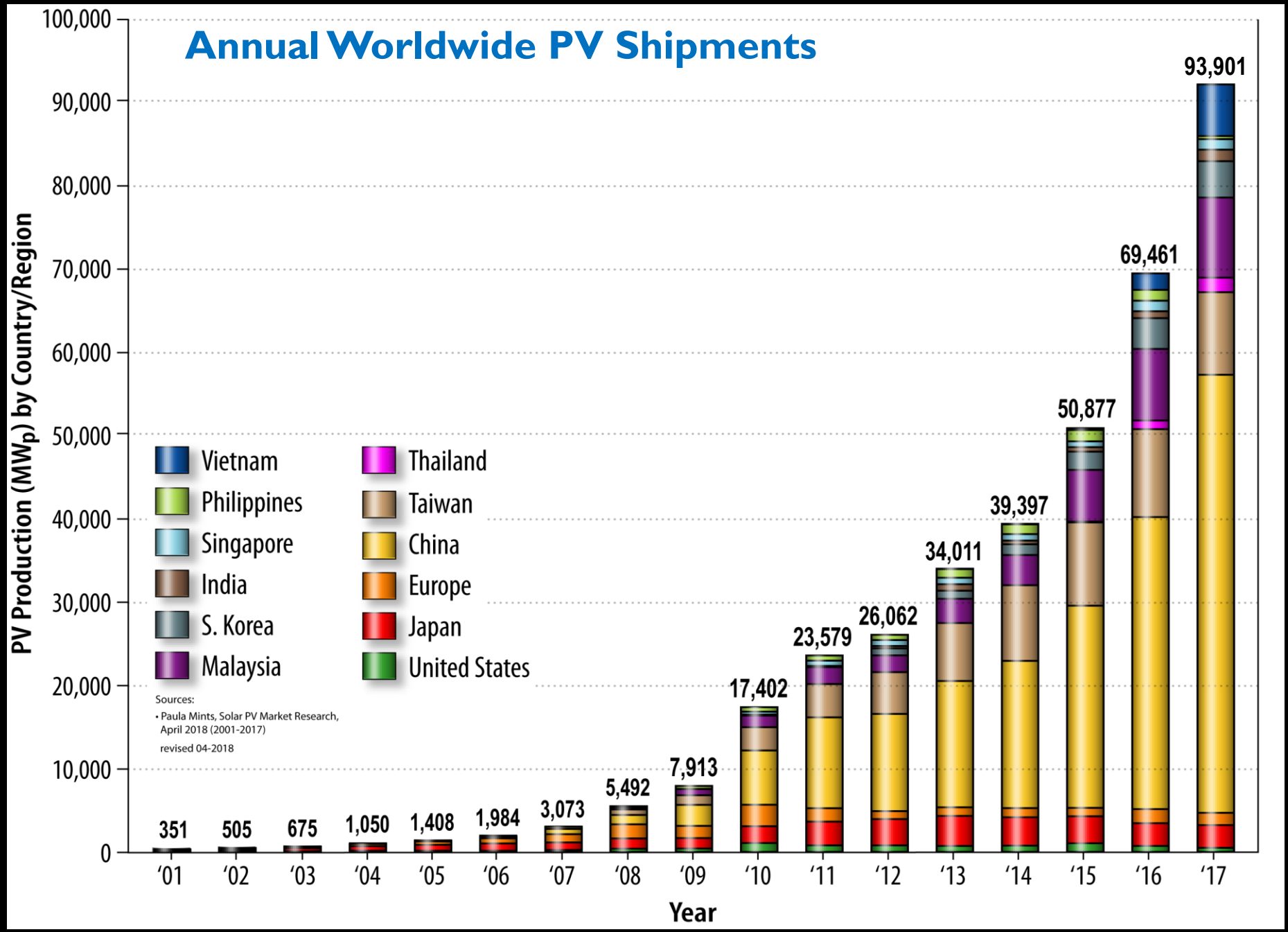

January1953
PV Project Initiated
June1953
Silicon Selected
January1954
Proof of Concept (4%)
March1954
Technology Readiness
(>6%)
Press Conference
NYC-NAS
April 1954
November 1954
Modules Deployed!
Bell concern with consumer buy in:
How do these new electronic devices work?

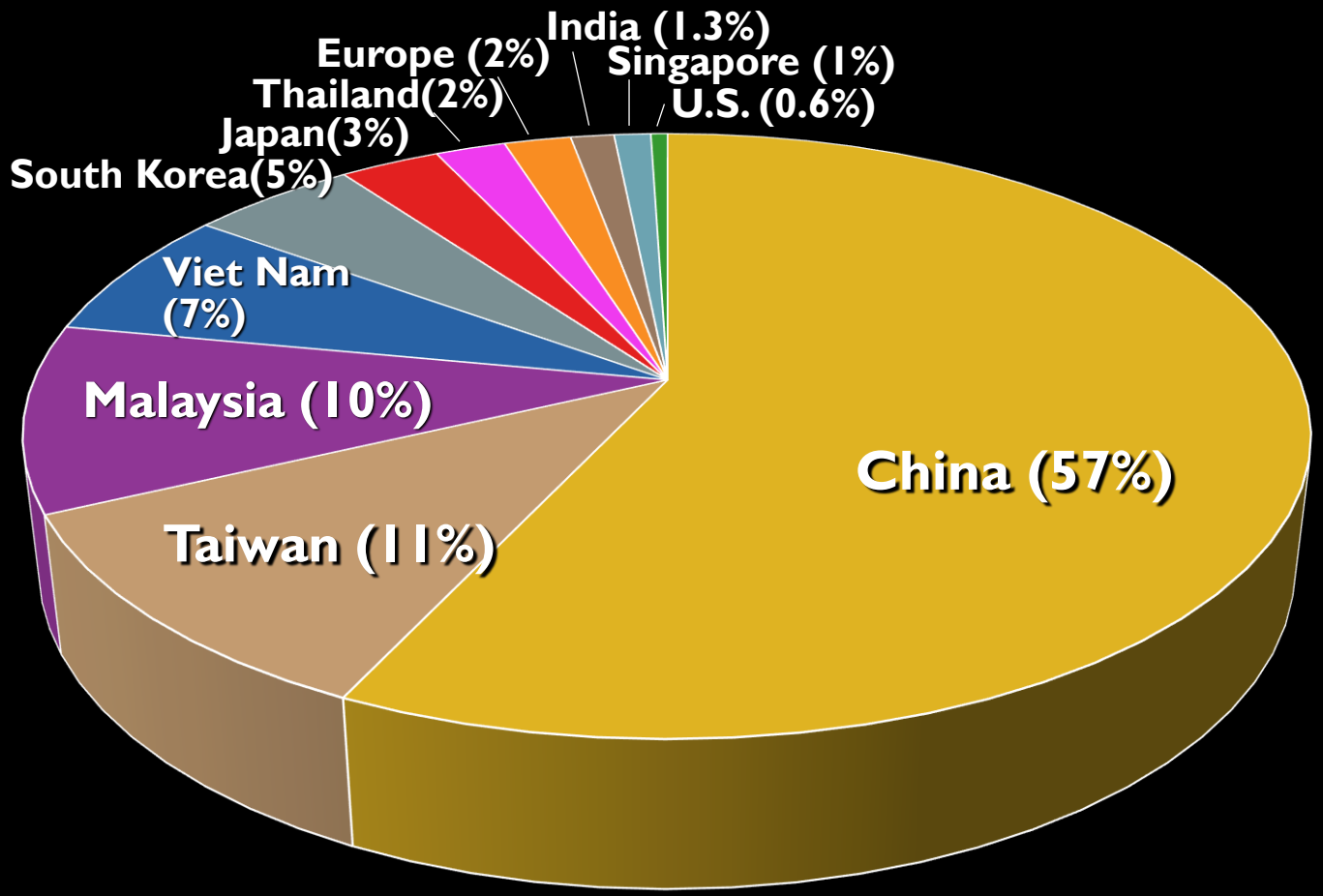

OUR
MR. SUN
The 1956 Spectacular
Production Frank Capria's
Television Series for
Bell Telephone Laboratories
OUR
MR. SUN

In 1958, the annual production of photovoltaic cells was ~50 W from Hoffman Electronics!!!

Now . . .

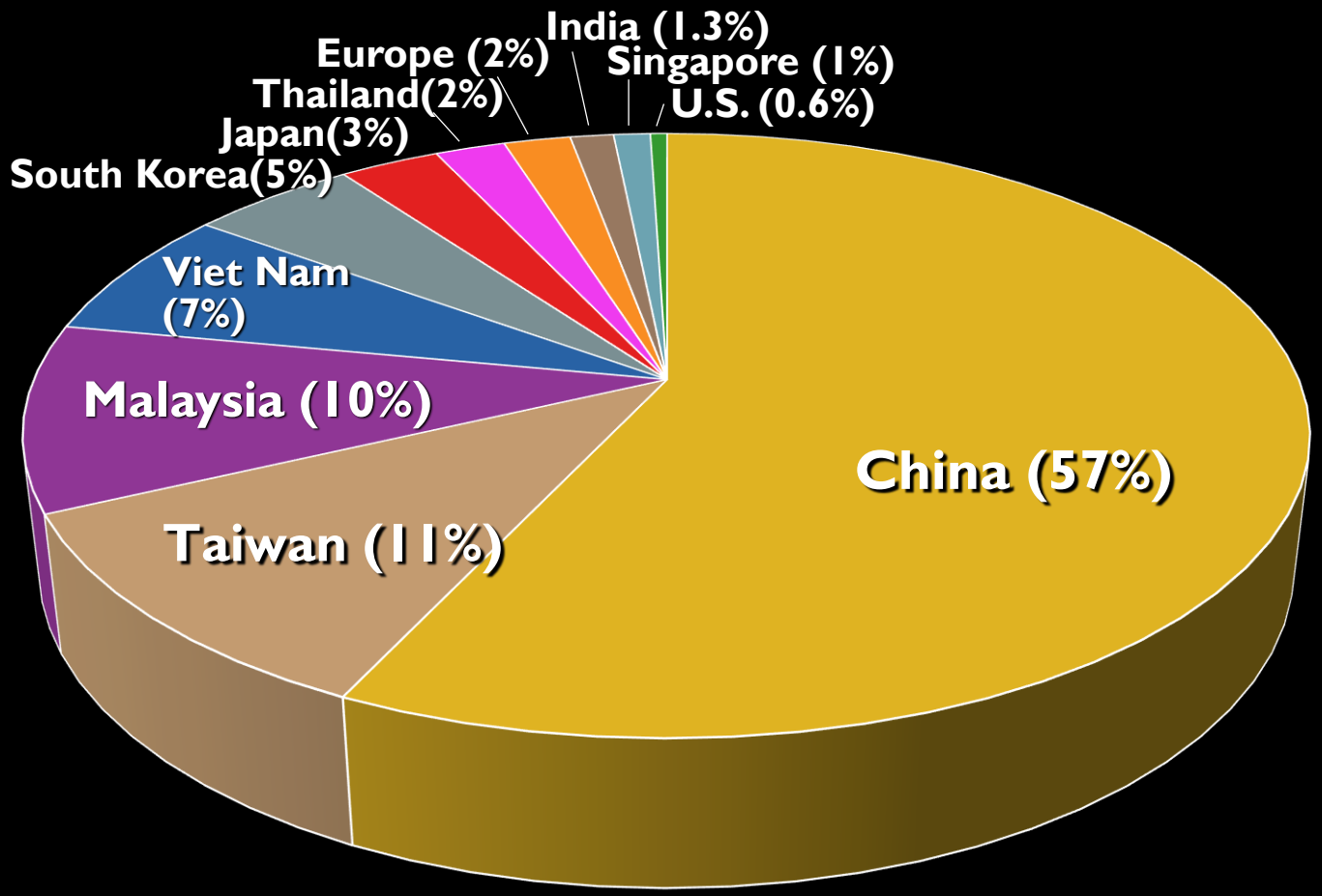
Where is all this PV coming from?





PV Shipped (2017)

Country of Origin – 93.9 GW

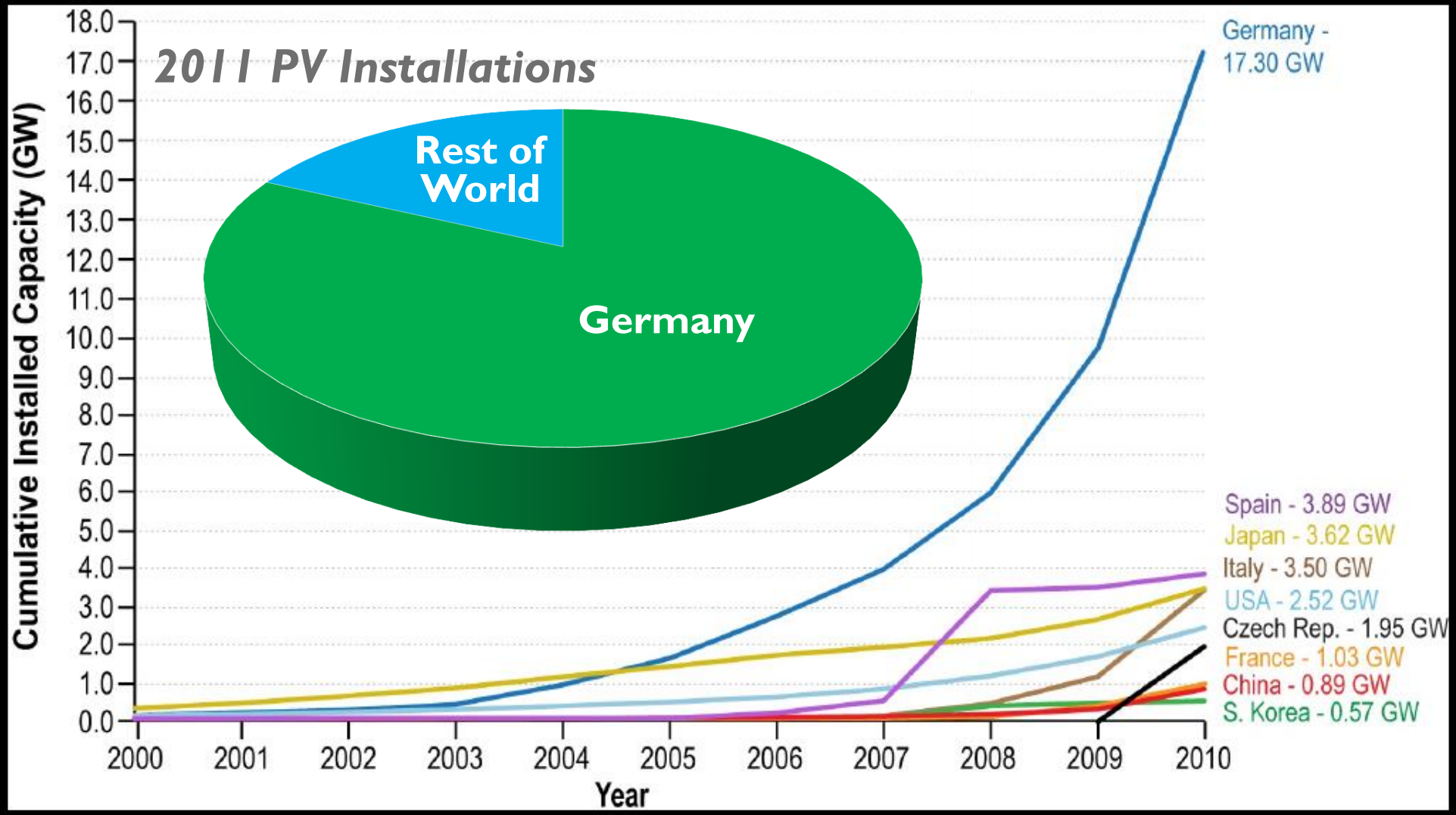


PV Shipped (2017)
Country of Origin – 93.9 GW

Top PV Manufacturers in 2017

1. Jinko Solar (9.7 GW)
2. Trina Sollar (9.1 GW)
3. JA Solar (7.5 GW)
4. Canadian Solar(6.85 GW)
5. Hanwha Q cells (5.4 GW)
6. GCL (4.6 GW)
7. Lerri Solar Tech (4.40 GW)
8. Yingli Green (2.65 GW)
9. First Solar (2.60 GW)
10. Risen Energy (2.5 GW)

Where is all this PV going?



SAUDI'S ELECTRICITY MARKET: A BRIGHTER FUTURE?

Saudi Arabia has enough sunlight to meet the world's electricity needs four times over. The kingdom should not only expand its solar energy sector but help initiate a region-wide energy grid to help its neighbours meet their growing energy demands.

BY BEN AINSLEY & LEWIS MACKINNON

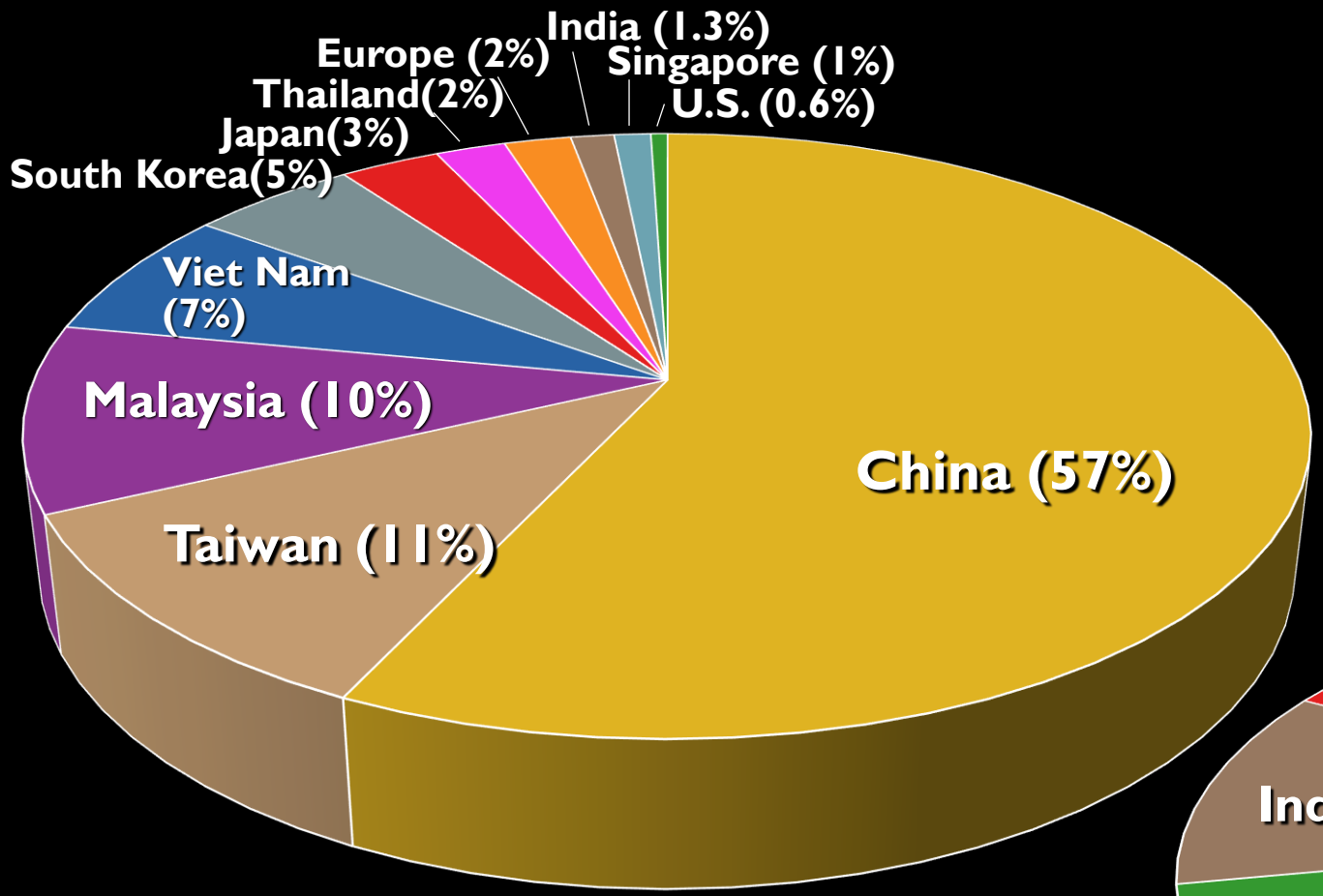
THE NAME SAUDI ARABIA IS SYNONYMOUS with oil. With 267 billion barrels of reserves and a production level of over 11.6 million barrels per day, Saudi Arabia dominates OPEC and plays a central role in setting global oil supply and price. Nonetheless, Saudi Arabia also has the potential to be a key player in another energy market: solar power. According to NASA data, Saudi Arabia is the 'second sunniest place on earth'— behind Chile's Atacama Desert — with solar irradiation levels along The Red Sea coastline north of Jeddah as high as 8.66kWh per square metre per day. Theoretically, Saudi Arabia has enough sunlight to meet the world's electricity needs four times over.

In February 2013 a White Paper was realised by the Saudi government laying out plans for the solar power industry. For numerous political, economic and demographic reasons, Saudi Arabia should not only expand its solar energy sector but go further than the White Paper proposes and help initiate a region-wide energy grid to help its neighbours meet their growing energy needs.

Saudi Arabia's desire to move into solar power is an idea still in its infant stages. In 2011 the country did not have a single renewable energy target and at present solar energy accounts for just ten megawatts (MW) of a total state capacity of 41,924MW. Most recently the kingdom completed a 3.5MW plant that will be used to power desalinisation plants.

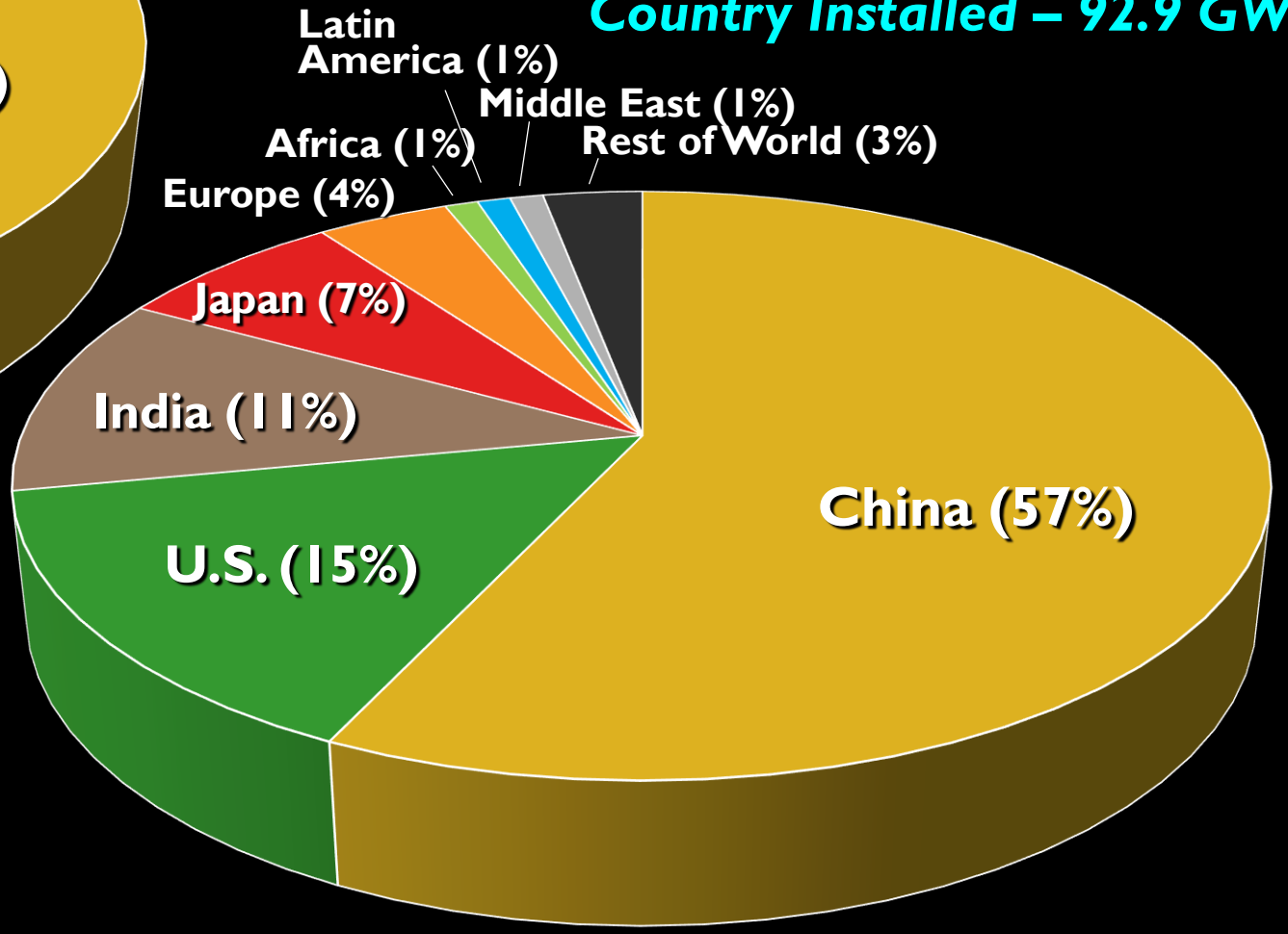
In February 2013 the King Abdullah City for Atomic and Renewable Energy released a much anticipated White Paper outlining a tender process for solar energy projects and the goals it wishes to achieve. The document outlines a $109bn investment plan in solar power infrastructure that would total 41,000MW of solar power (by 2030). The 41,000MW would be split between two different varieties of solar power: photovoltaic (16,000MW) and solar thermal (25,000MW). This shift to solar would save the country the equivalent of 523,000 barrels of oil a day. This investment is huge; in 2011 total global solar investment was just $136bn. Nonetheless, given the changing global market and Saudi Arabia's insatiable energy demand the country should go further and begin

- Average module Prices decreased by 8% from 2016 ($ 0.53/W) to 2017 ($ 0.49/W)
- Lowest price in 2017: $ 0.29/W
- Modules with ≥72 cell/module dominate

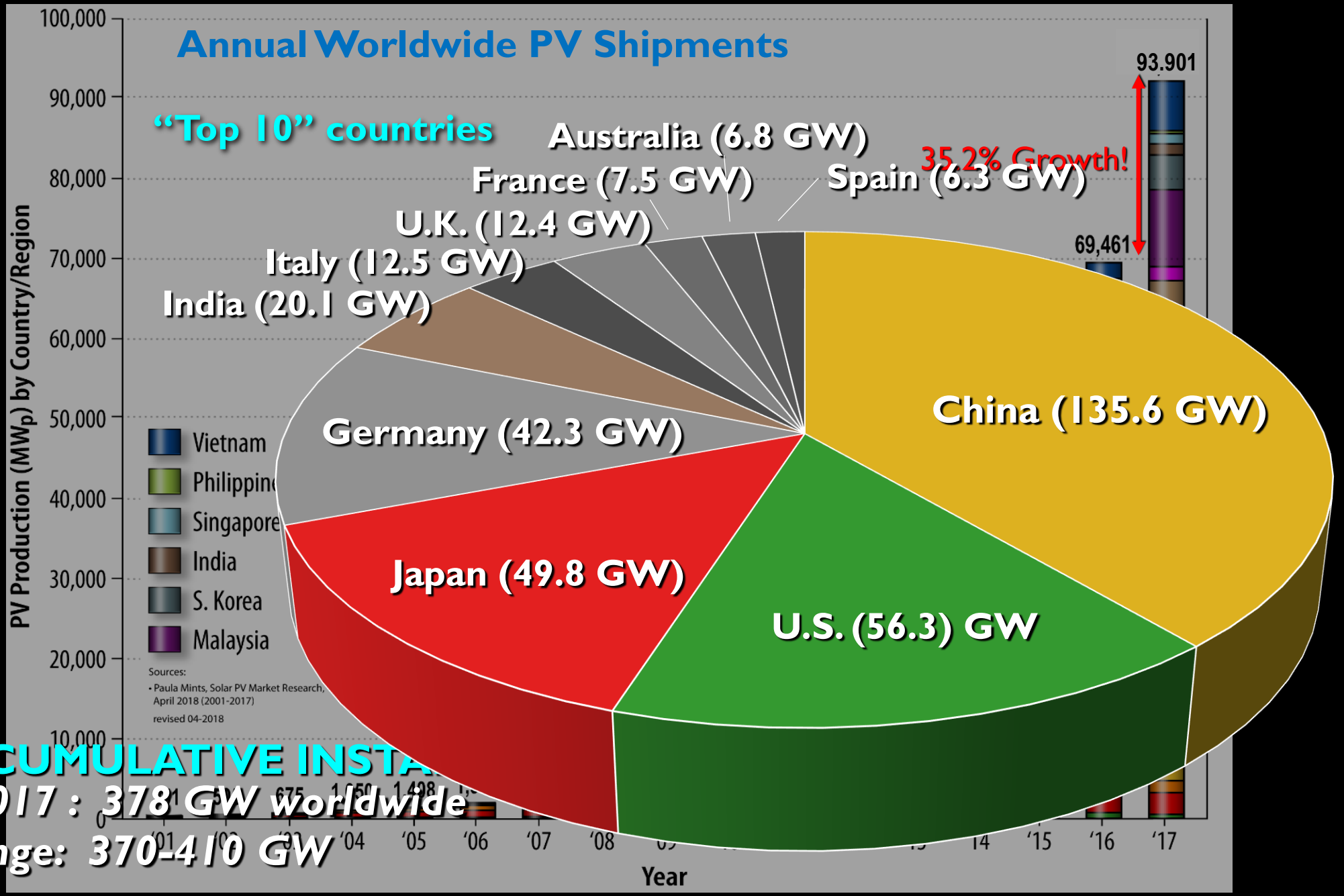


PV Shipped (2017)
Country of Origin – 93.9 GW

PV Installed (2017)
Country Installed – 92.9 GW



TOTAL CUMULATIVE?

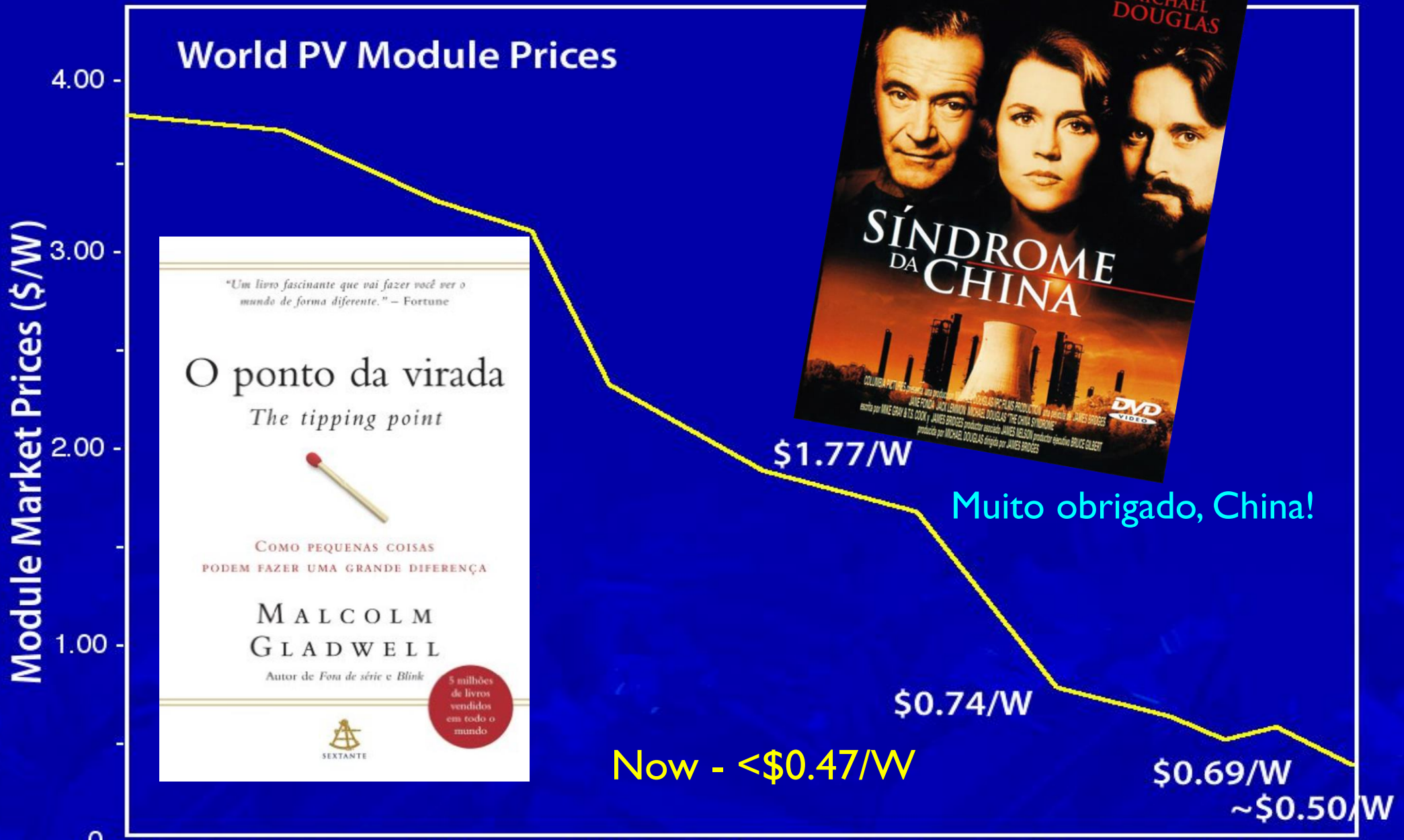


TOTAL CUMULATIVE INSTA

1975 – 2017 : 378 GW worldwide

Range: 370-410 GW

The Effect?



Muito obrigado, China!

Thin-Film PV Manufacturing Companies (USA)

2012

a-Si and Thin-Si

Uni-Solar – MI
Applied Materials – CA
Signet Solar – CA
EPOD Solar – CA
PowerFilm Solar – IA
EPV Solar – NJ
Solar Thin Films – NJ
Xunlight – OH
MWOE Solar – OH
MV Systems – CO
Nano PV – NY
Sencera – NC
Helianthos – ID
Solasta – MA
Lightwave Power – MA
ProtoFlex – CO
New Solar Ventures – NM
Innovalight – CA
NanoGram – CA
CrystalSolar – CO
Ampulse – CO
Solexel – CA
SiGen – CA
SierraSolar – CA
AstroWatt – TX
Parachete Energy – SC

CdTe

First Solar – OH
Abound Solar – CO
GE Primestar Solar – CO
Nuvo Solar Energy – CO
Calyxo – OH
Sunlight 26 – OH
Canrom – NY
Ascentool – CA
Solexant – CA
Bloo Solar – CA
SunPrint – CA
Zia Watt Solar – TX
Evolucia – FL
W&K Solar – OH
EPIR – IL
Natcore – MA

Organic

Konarka – MA
Plextronics _ PA
Solarmer Energy – CA
PowerFilm Solar – IA
GPEC – NY
LumoFlex – GA
MicroFab – TX
Luna Innovations –VA
SolarAmp – NC

CIGS

Global Solar – AZ
Ascent Solar – CO
Miasolé – CA
Nanosolar – CA
Heliovolt – TX
Solyndra - CA
SoloPower – CA
JNL Solar – CA
Telio Solar – CA
AQT – CA
Stion – CA
NuvoSun – CA
Sun King Solar – CA
EPV Solar – NJ
Amelio Solar – NJ
ISET – CA
Daystar -NY
IBM – NY
RESI – NJ
First Solar - US
Light Solar – NV
XSunX - OR
Crystalsol – US
Suntricity - NY

Thin-Film PV Manufacturing Companies (USA)

2012 ➡ 2014

a-Si and Thin-Si

~~Uni-Solar – MI~~
~~Applied Materials – CA~~
~~Signet Solar – CA~~
~~EPOD Solar – CA~~
PowerFilm Solar – IA
EPV Solar – NJ

CdTe

First Solar – OH
~~Abound Solar – CO~~
~~GE Primestar Solar – CO~~
~~Nuvo Solar Energy – CO~~
Calyxo – OH
~~Sunlight 26 – OH~~

CIGS

~~Global Solar – AZ~~
Ascent Solar – CO
Miasolé – CA
~~Nanosolar – CA~~
~~Heliovolt – TX~~
~~Solyndra – CA~~

Bankability

The capacity or capability to manufacture or produce a product competitively (e.g., with an acceptable profit, reliability, etc.)

Lightwave Power – MA
~~ProtoFlex – CO~~
~~New Solar Ventures – NM~~
Innovalight – CA
~~NanoGram – CA~~
~~CrystalSolar – CO~~
~~Ampulse – CO~~
~~Solexel – CA~~
~~SiGen – CA~~
~~SierraSolar – CA~~
~~AstroWatt – TX~~
~~Parachete Energy – SC~~

~~EPIR – IL~~
~~Natcore – MA~~

Organic

~~Konarka – MA~~
Plextronics _ PA
~~Solarmer Energy – CA~~
PowerFilm Solar – IA
~~GPEC – NY~~
~~LumoFlex – GA~~
MicroFab – TX
~~Luna Innovations – VA~~
~~SolarAmp – NC~~

~~Ametto Solar – NJ~~
~~ISET – CA~~
~~Daystar – NY~~
IBM – NY
~~RESI – NJ~~
~~First Solar – US~~
~~Light Solar – NV~~
~~XSunX – OR~~
~~Crystalsol – US~~
Suntricity - NY

Longyangxia Dam Solar Park
Qinghai, China
Phase I: 320 MW (2013)
Phase II: 850 MW (2015)

Solar Star Facility
California, USA
579 MW (2015)

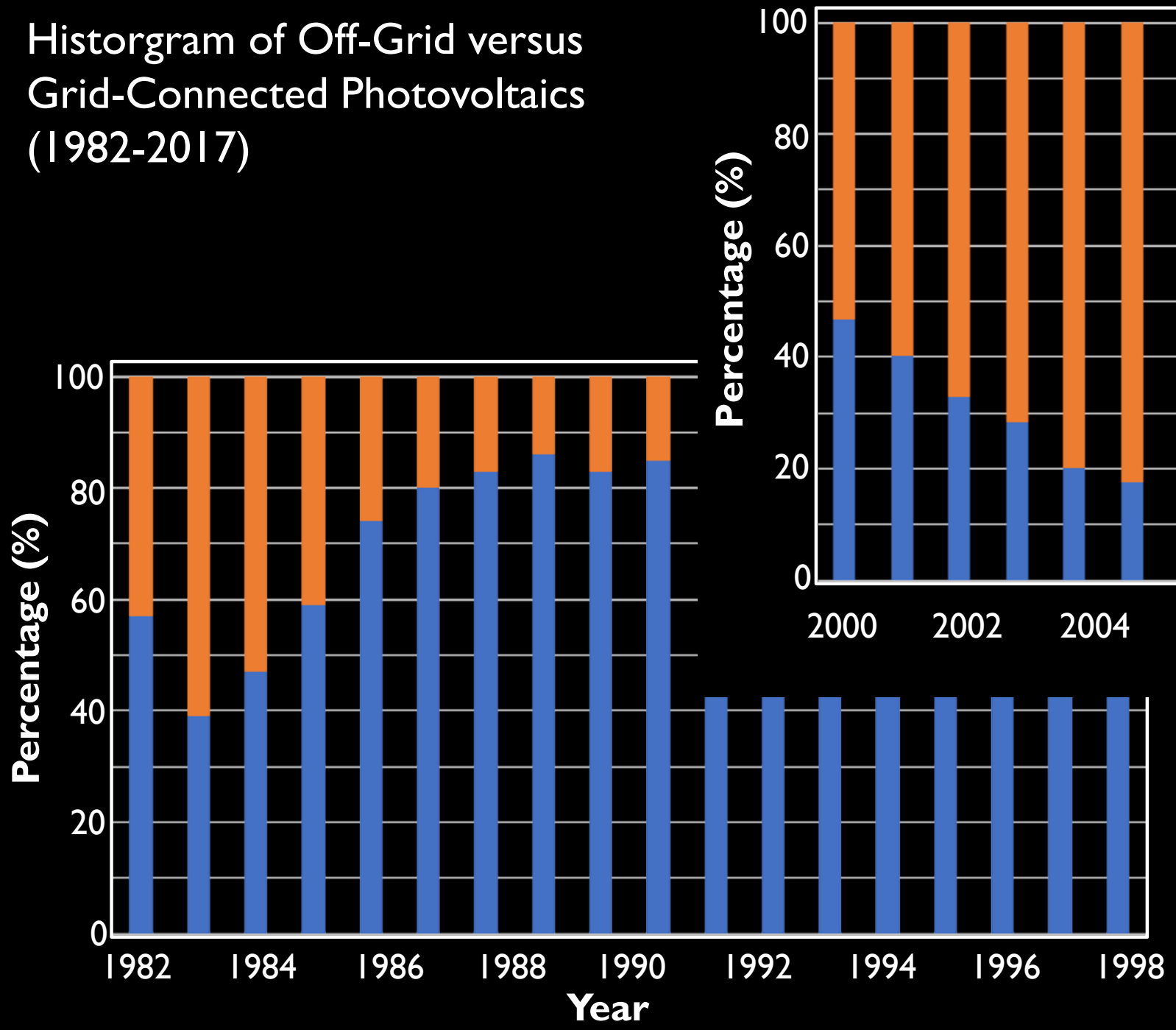
Gurjarat Solar Park Facility
India (Several Locations)
857 MW (2015)

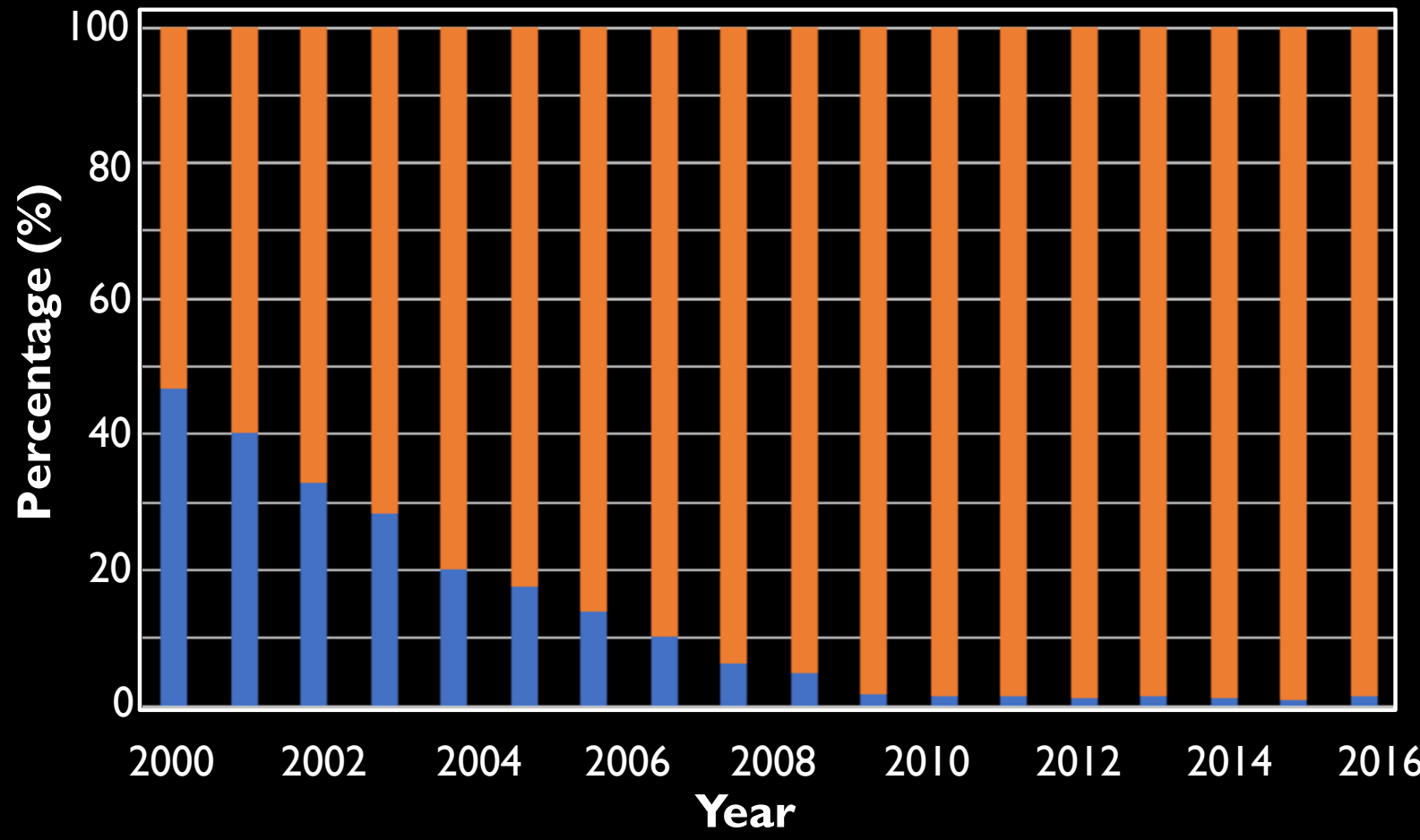
Topaz Solar Farm
California, USA
550 MW (2014)

Name	Country	Location	Capacity MW_p	Generation GW·h p.a.	Size km^2	Year	Remarks
Tengger Desert Solar Park	China	37°33′00″N 105°03′14″E	1,500		43	2016	1547MW solar power was installed in Zhongwei, Ningxia by 2015.
Copper Mountain Solar Facility	United States						d in December mpleted in ase 3 completed struction of mpleted in 2016.
Desert Sunlight Solar Farm	United States						MW completed in n of phase II to 0 MW completed
Huanghe Hydropower Golmud Solar Park	China	36°24′00″N 95°07′30″E	500		23	2014	in October 2011, II and III. 60 MW phase IV under construction. Within a group of 1,000 MW of co-located plants

Off-Grid versus Grid-Connected?

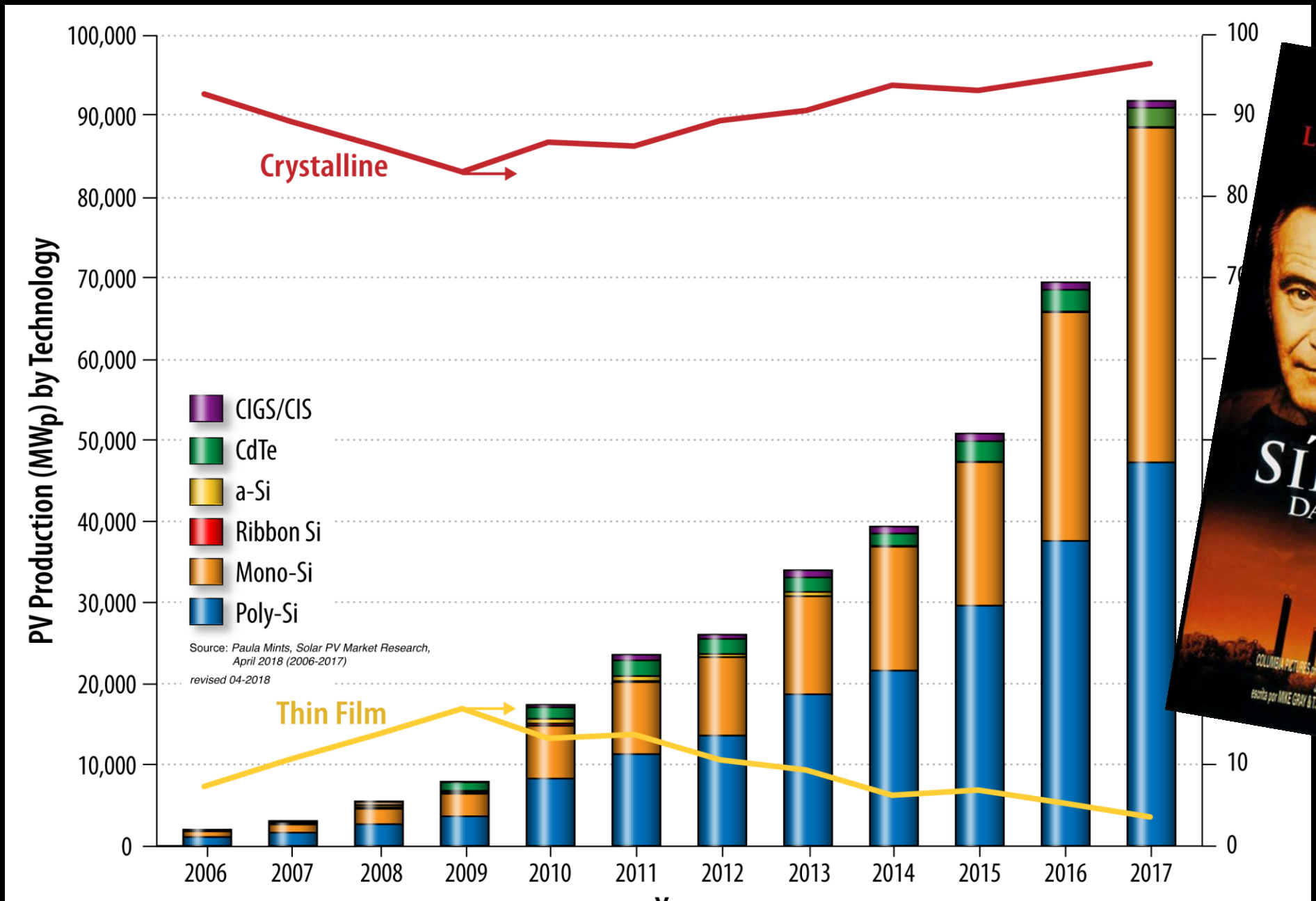
Historgram of Off-Grid versus Grid-Connected Photovoltaics (1982-2017)



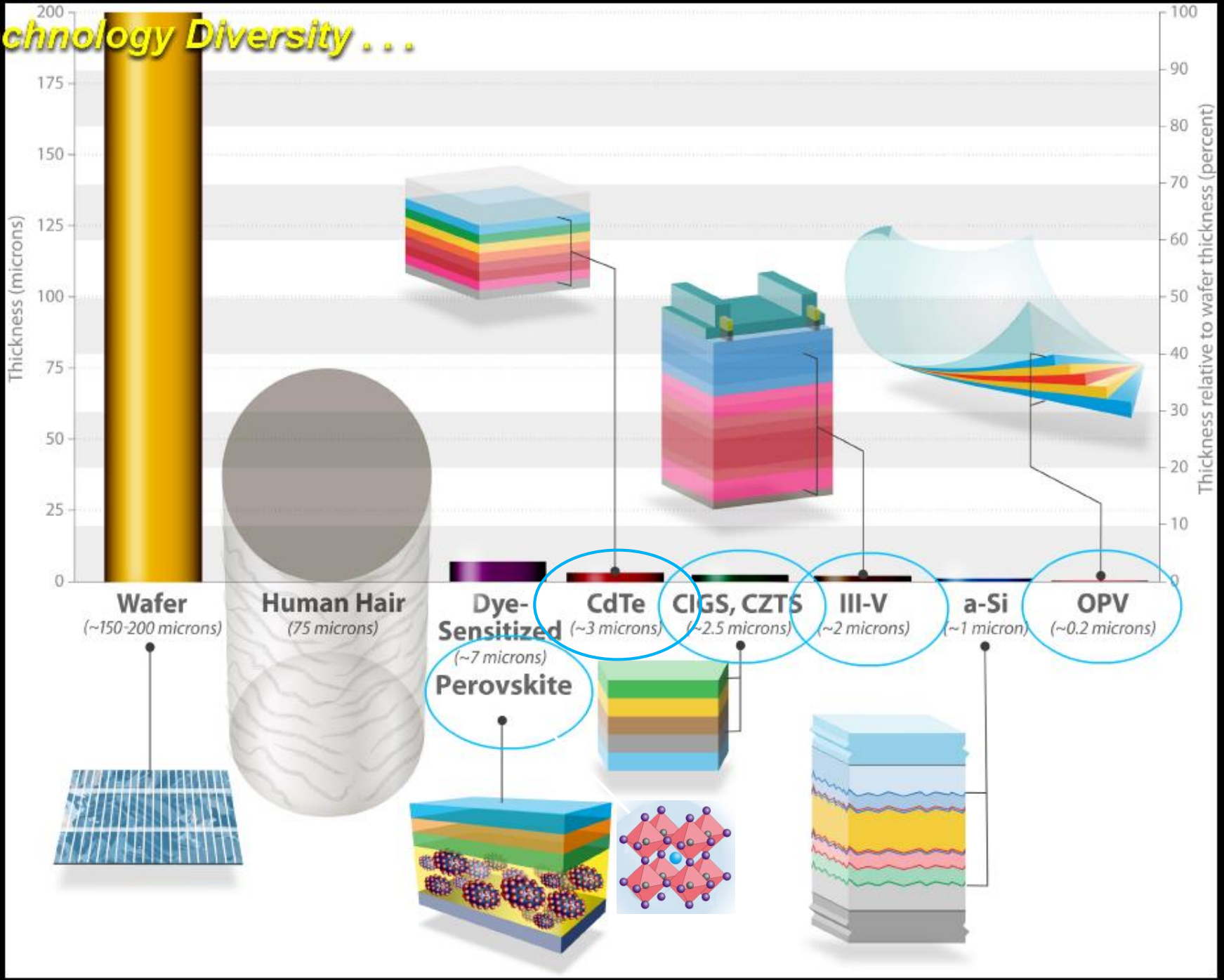


Grid-Connected
Off-Grid

Technology Diversity

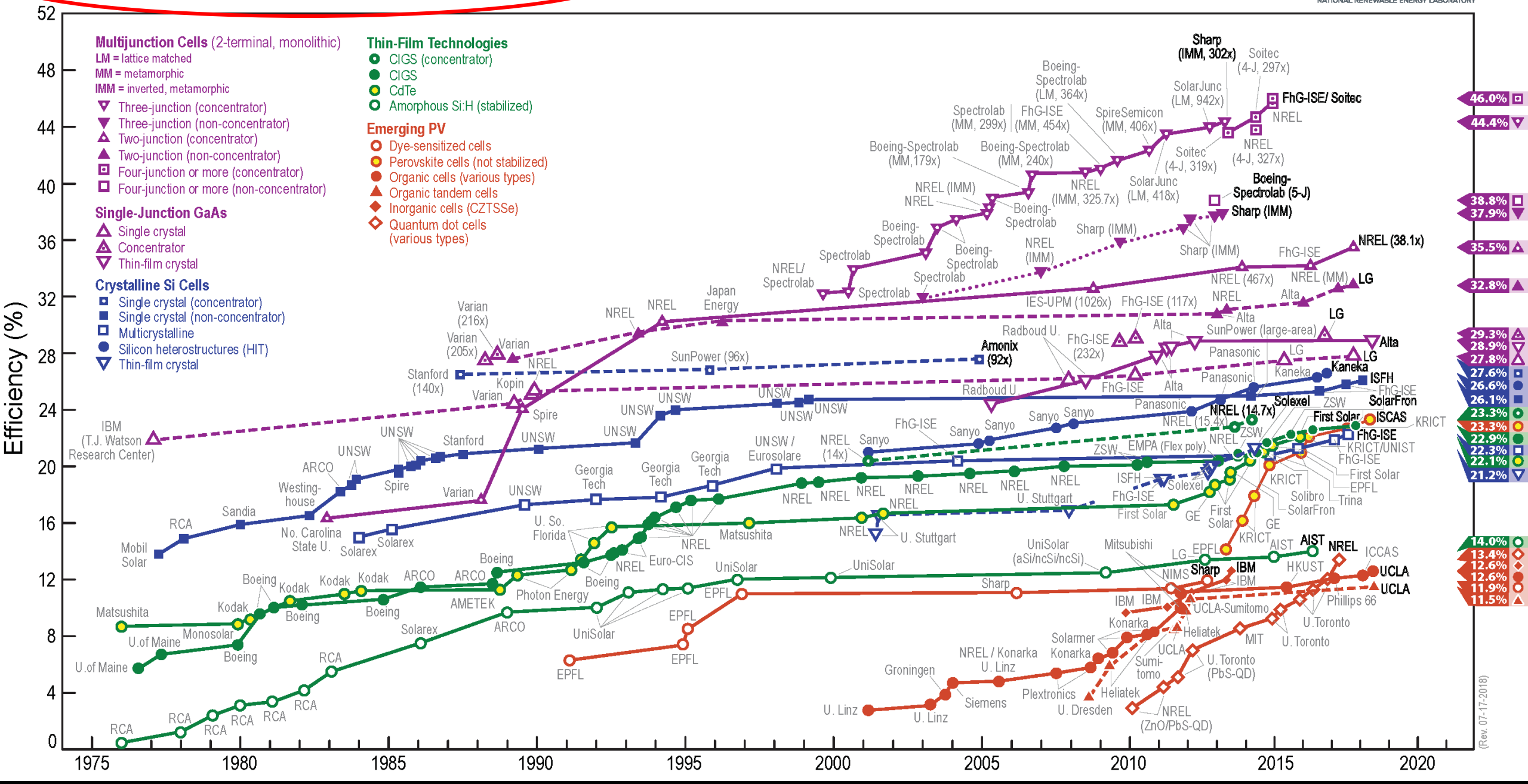


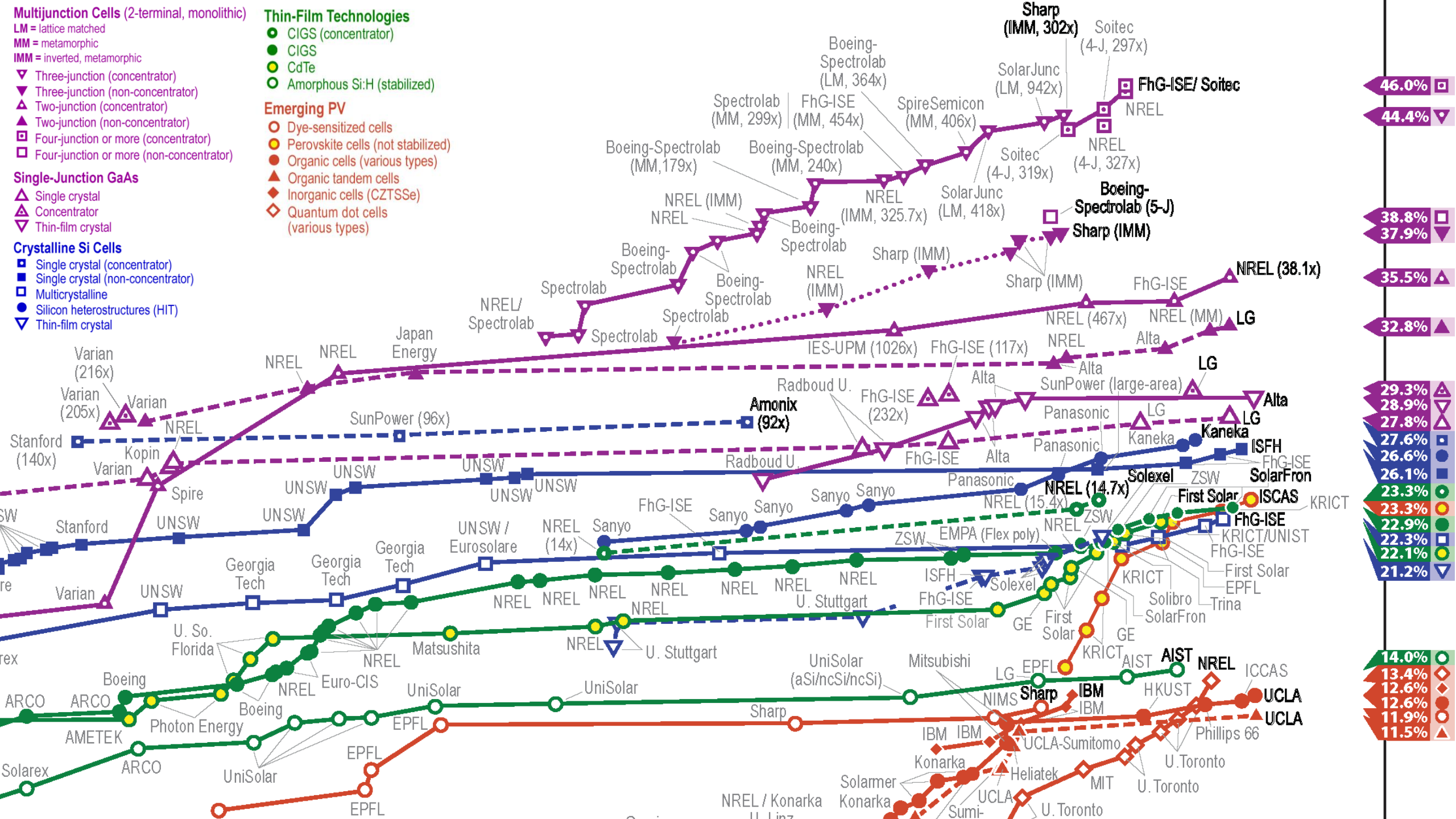
Technology Diversity . . .



Best Research-Cell Efficiencies

NREL
NATIONAL RENEWABLE ENERGY LABORATORY




Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Emerging PV
Dye-sensitized cells
Perovskite cells (not stabilized)
Organic cells (various types)
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells (various types)
Sharp (IMM, 302x)
Soitec (4-J, 297x)
Boeing-Spectrolab (LM, 364x)
SolarJunc (LM, 942x)
FhG-ISE/ Soitec
NREL
Spectrolab (MM, 299x)
FhG-ISE (MM, 454x)
SpireSemicon (MM, 406x)
NREL (4-J, 327x)
Soitec (4-J, 319x)
Boeing-Spectrolab (MM,179x)
Boeing-Spectrolab (MM, 240x)
NREL (IMM, 325.7x)
SolarJunc (LM, 418x)
Boeing-Spectrolab (5-J)
Sharp (IMM)
NREL (IMM)
NREL
Boeing-Spectrolab
Sharp (IMM)
NREL (38.1x)
FhG-ISE
NREL/ Spectrolab
Spectrolab
Boeing-Spectrolab
NREL (IMM)
Spectrolab
NREL (467x)
NREL (MM)
LG
IES-UPM (1026x)
FhG-ISE (117x)
NREL
Alta
Varian (216x)
Varian (205x)
Varian
NREL
NREL
Japan Energy
Radboud U.
Alta
LG
Amonix (92x)
SunPower (large-area)
Alta
SunPower (96x)
FhG-ISE (232x)
Panasonic
LG
Stanford (140x)
NREL
Kopin
Varian
Spire
Radboud U.
FhG-ISE
Alta
Kaneka
LG
Kaneka
ISFH
Panasonic
FhG-ISE
UNSW
UNSW
UNSW
UNSW
UNSW
UNSW
Panasonic
NREL (14.7x)
Solexel
ZSW
SolarFron
FhG-ISE
Sanyo
Sanyo
Sanyo
Sanyo
NREL (15.4x)
First Solar
ISCAS
KRICT
Stanford
UNSW
UNSW
UNSW / Eurosolare
NREL (14x)
Sanyo
ZSW
EMPA (Flex poly)
NREL
FhG-ISE
KRICT/UNIST
FhG-ISE
Georgia Tech
Georgia Tech
Georgia Tech
Varian
UNSW
NREL
NREL
NREL
NREL
NREL
NREL
NREL
ISFH
Solexel
First Solar
EPFL
KRICT
Solibro
Trina
SolarFron
U. Stuttgart
FhG-ISE
First Solar
GE
First Solar
GE
U. So. Florida
NREL
Matsushita
NREL
U. Stuttgart
Boeing
NREL
Euro-CIS
UniSolar
UniSolar
UniSolar (aSi/ncSi/ncSi)
Mitsubishi
LG
EPFL
KRICT
AIST
AIST
NREL
ICCAS
ARCO
ARCO
Boeing
Photon Energy
AMETEK
EPFL
Sharp
NIMS
Sharp
IBM
IBM
HKUST
UCLA
UCLA
IBM
IBM
UCLA-Sumitomo
Phillips 66
Solarex
ARCO
UniSolar
EPFL
EPFL
Konarka
Heliatek
U.Toronto
Solarmer
Konarka
UCLA
MIT
U. Toronto
NREL / Konarka
Sumi-
U. Toronto
46.0%
44.4%
38.8%
37.9%
35.5%
32.8%
29.3%
28.9%
27.8%
27.6%
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22.3%
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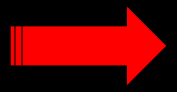
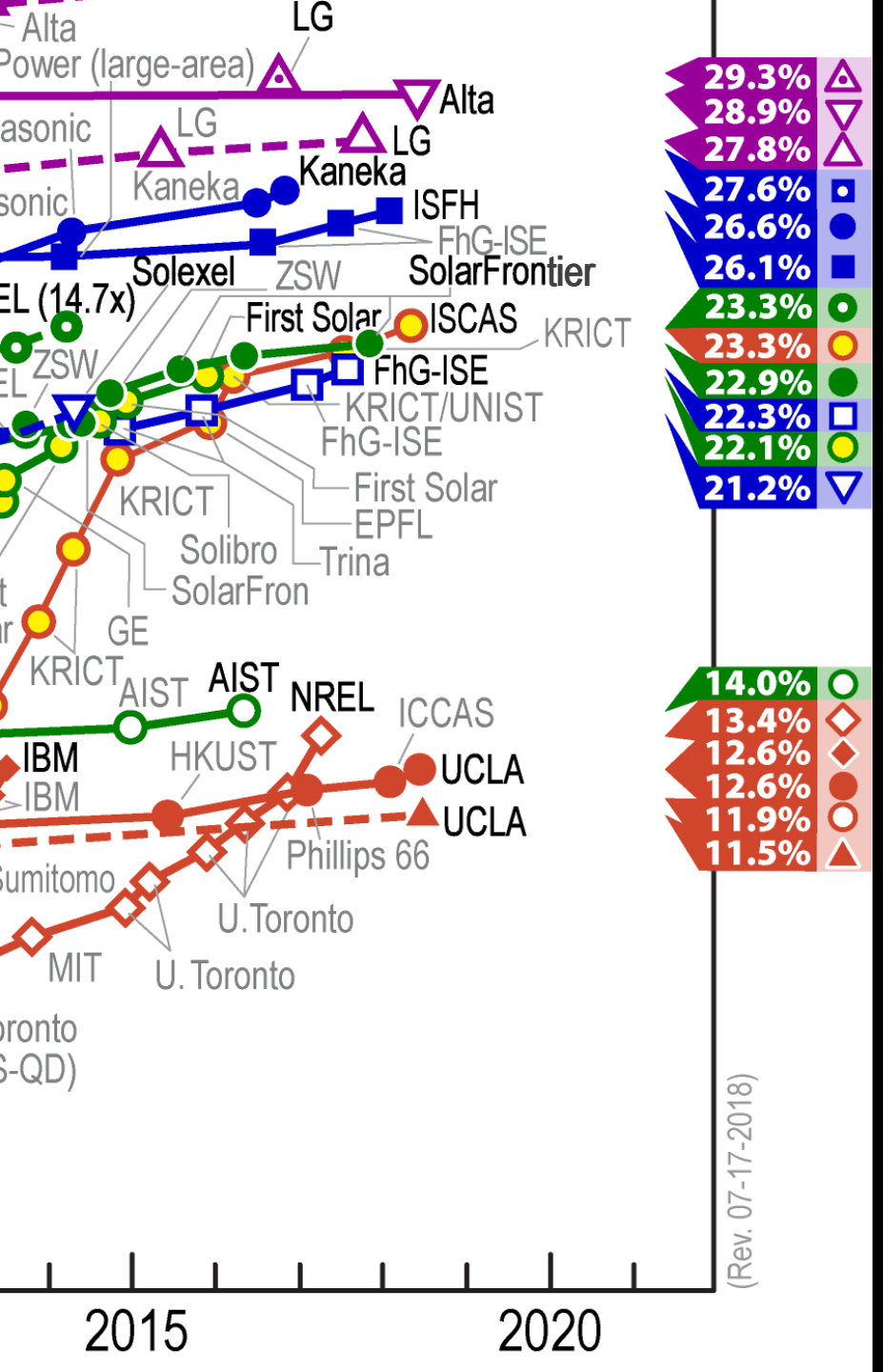
11.5%

Current R&D Priorities



- Materials and Devices
- Manufacturing
- Reliability


Alta
LG
Power (large-area)
Alta
asonic
LG
LG
Kaneka
Kaneka
sonic
ISFH
FhG-ISE
Solexel
ZSW
SolarFrontier
EL (14.7x)
First Solar
ISCAS
KRICT
ZSW
FhG-ISE
KRICT/UNIST
FhG-ISE
First Solar
KRICT
EPFL
Solibro
Trina
SolarFron
GE
KRICT
AIST
AIST
NREL
ICCAS
IBM
HKUST
UCLA
IBM
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Phillips 66
Sumitomo
U.Toronto
MIT
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oronto
S-QD)
29.3%
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22.3%
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21.2%
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13.4%
12.6%
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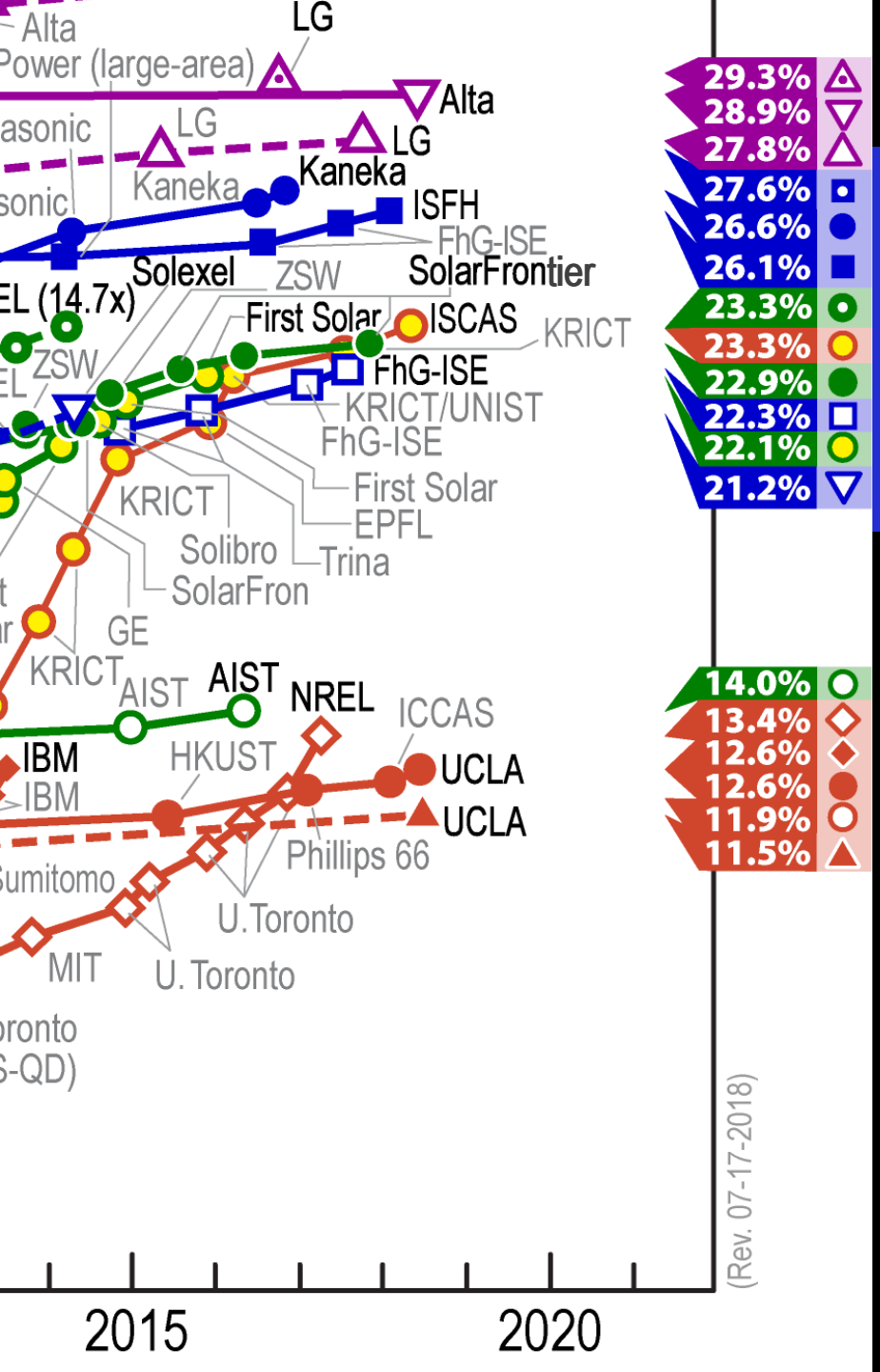
(Rev. 07-17-2018)
2015
2020



29.3%
28.9%
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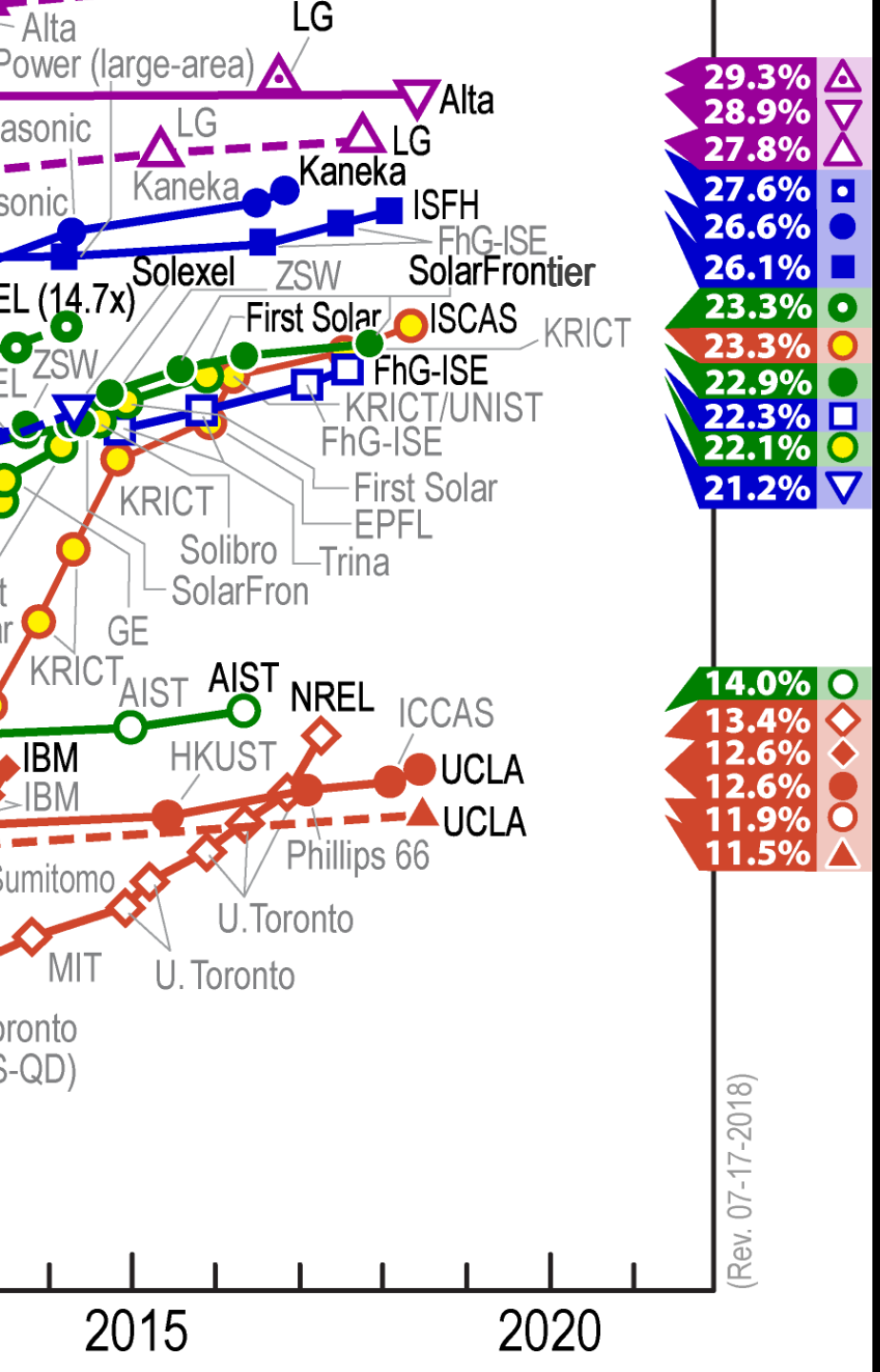
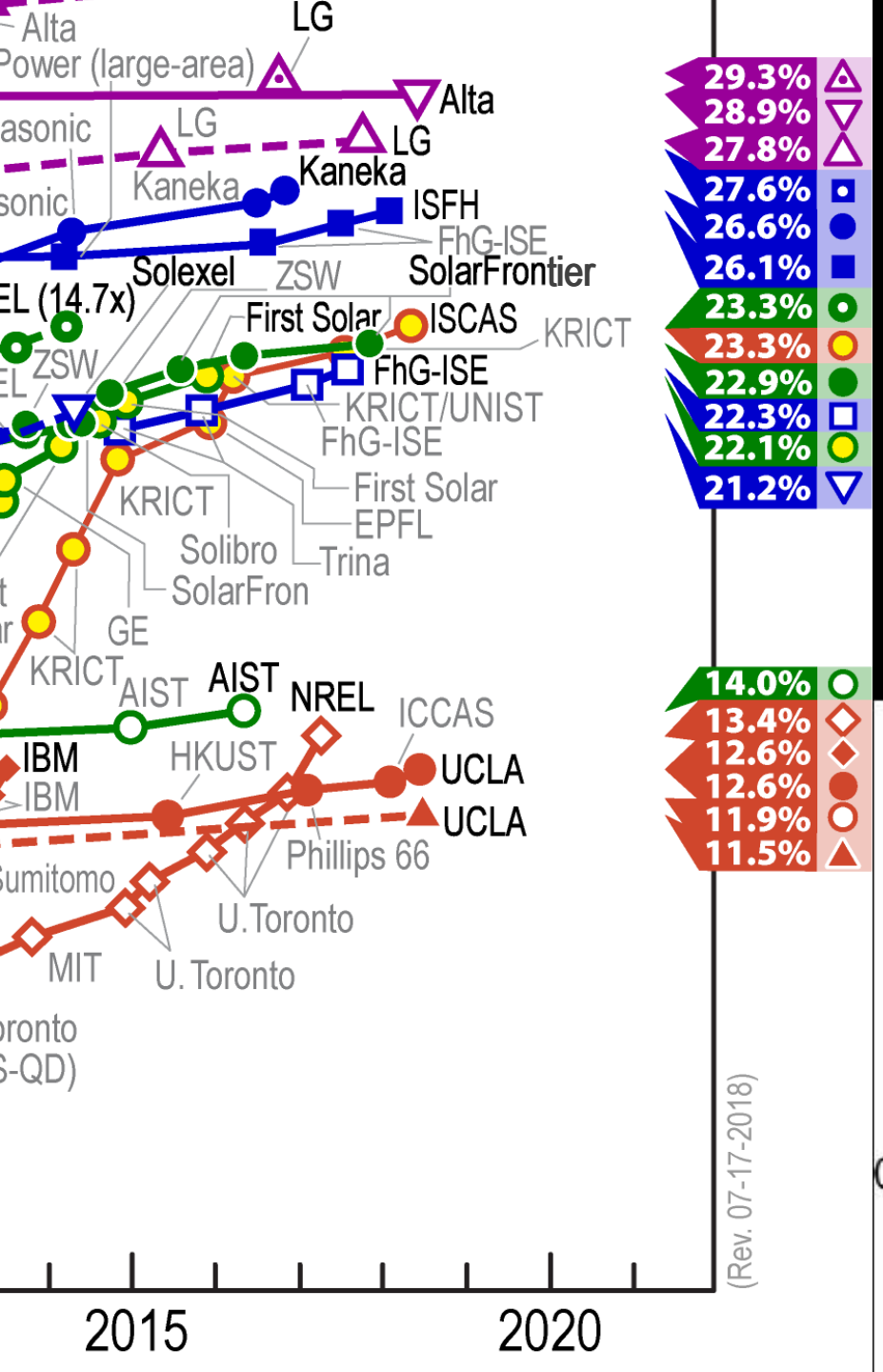
26.1%
23.3%
23.3%
22.9%
22.3%
22.1%
21.2%

Crystalline Silicon

14.0%
13.4%
12.6%
12.6%
11.9%
11.5%



Si Heterojunction
Interdigitated Back Contact



29.3%
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22.3%
22.1%
21.2%

Si Heterojunction

14.0%
13.4%
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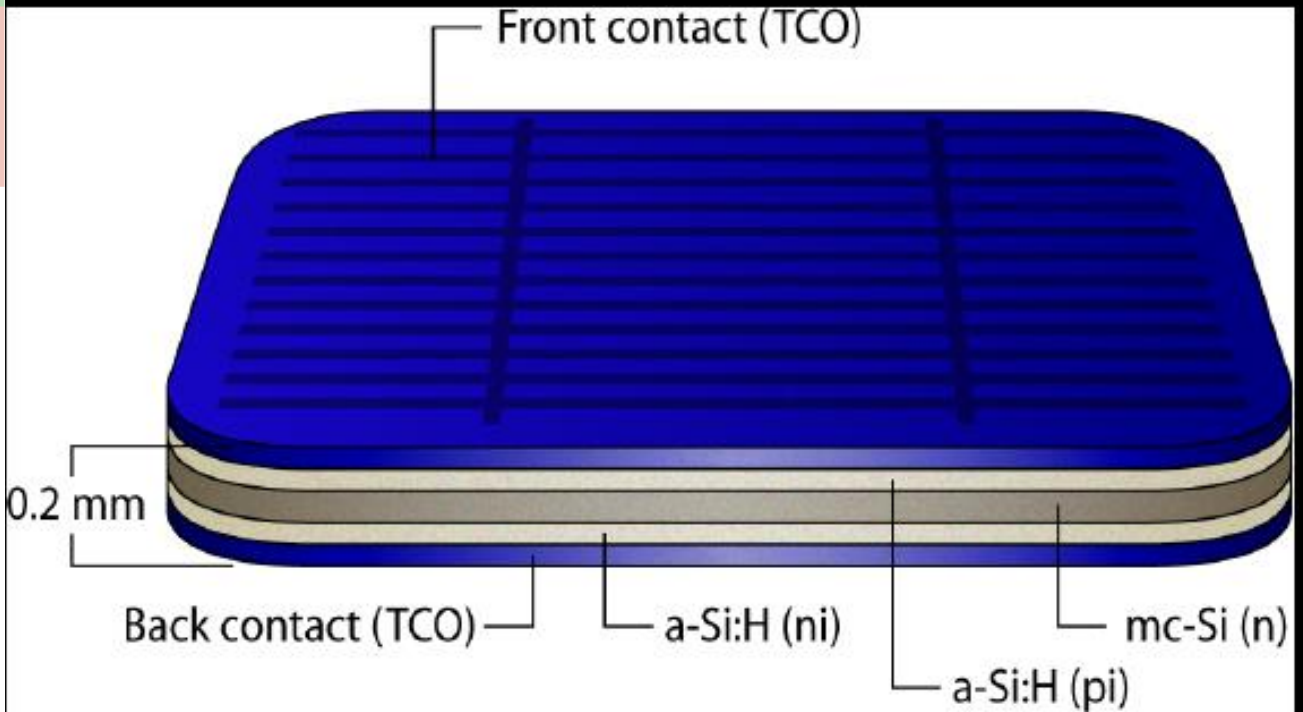
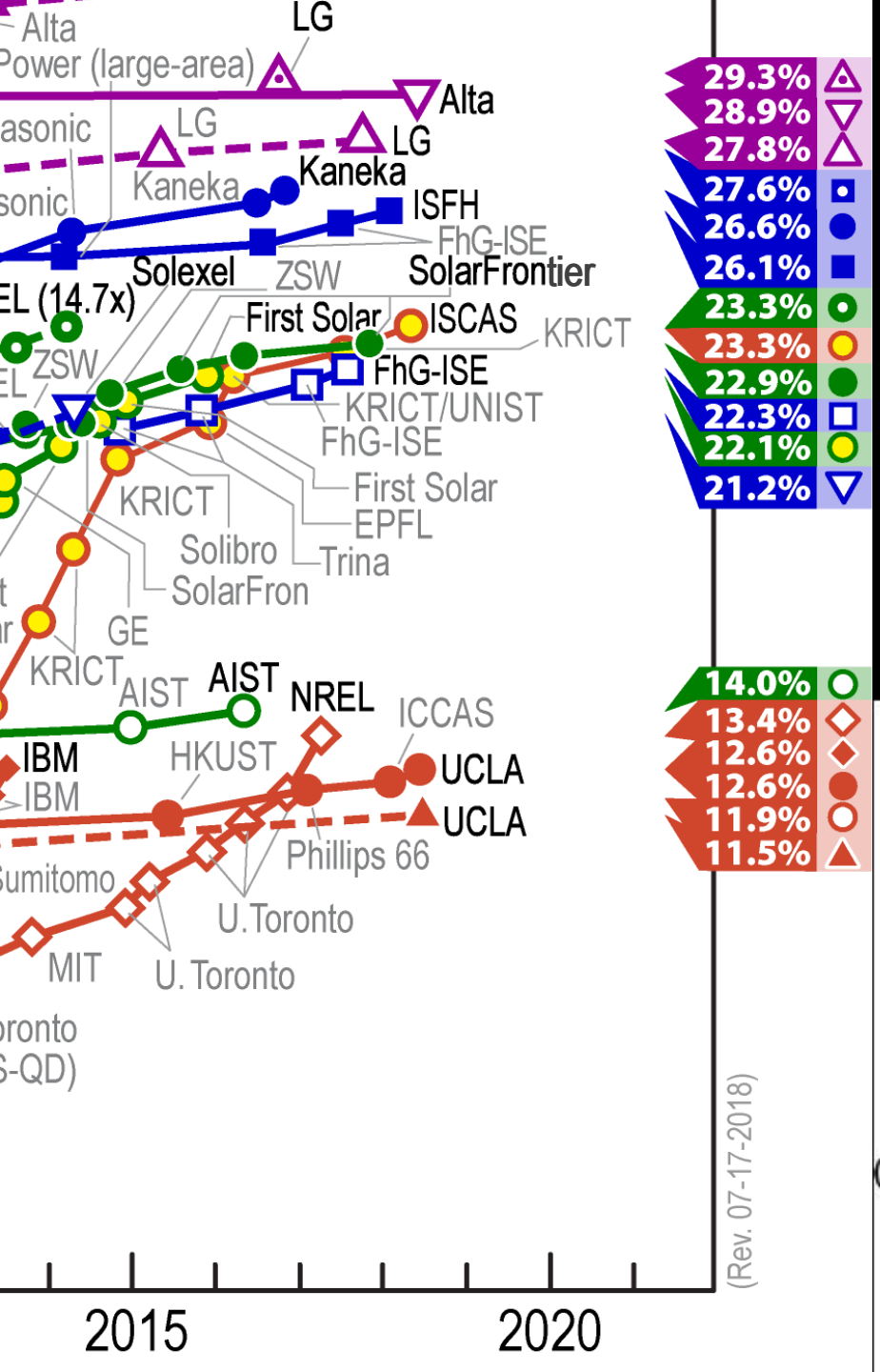
11.5%



Panasonic
~~Sanyo~~
HIT Cell



29.3%
28.9%
27.8%
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21.2%

14.0%
13.4%
12.6%
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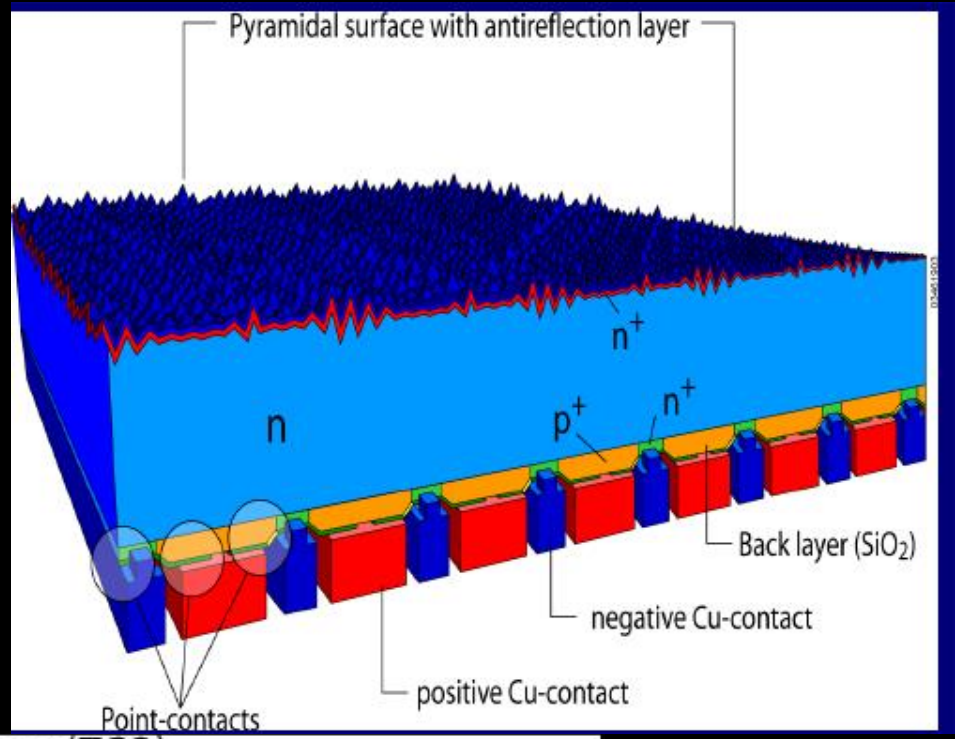
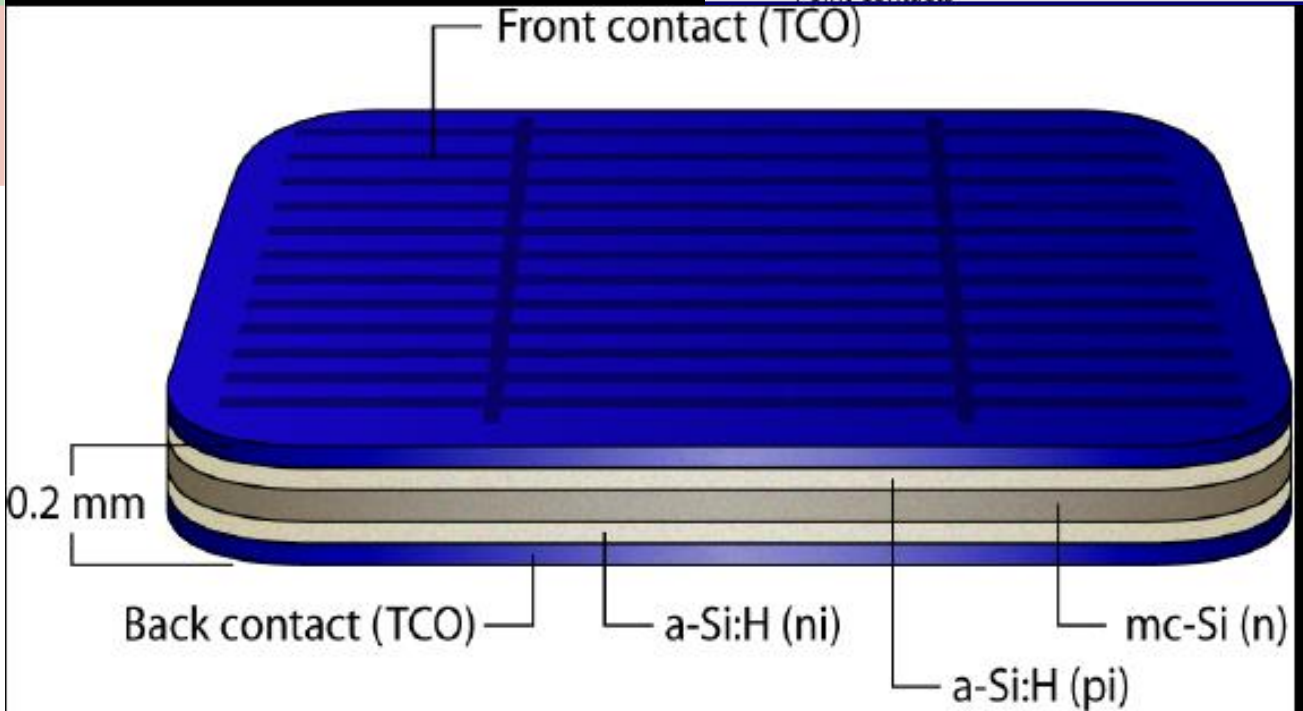
11.5%

Interdigitated Back Contact

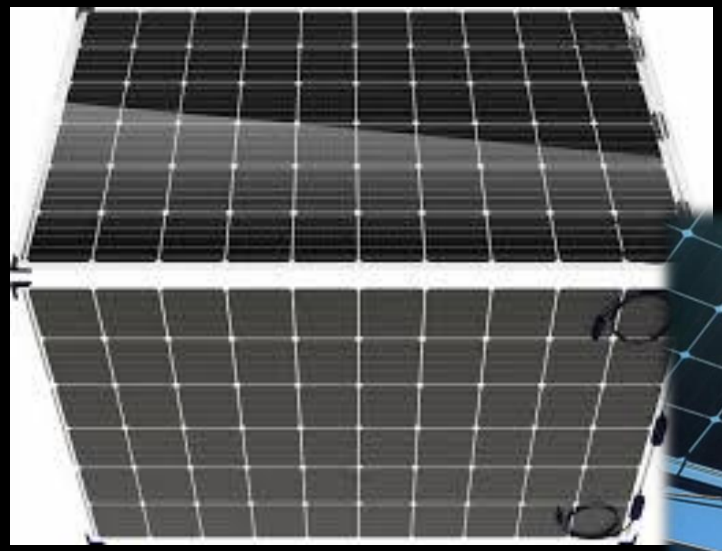


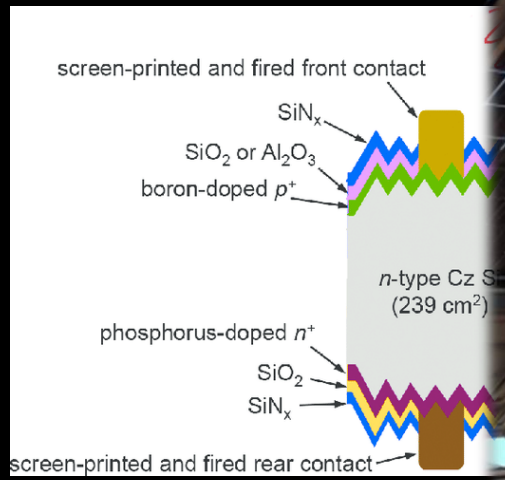


SunPower Cell

Panasonic
~~**Sanyo**~~
HIT Cell

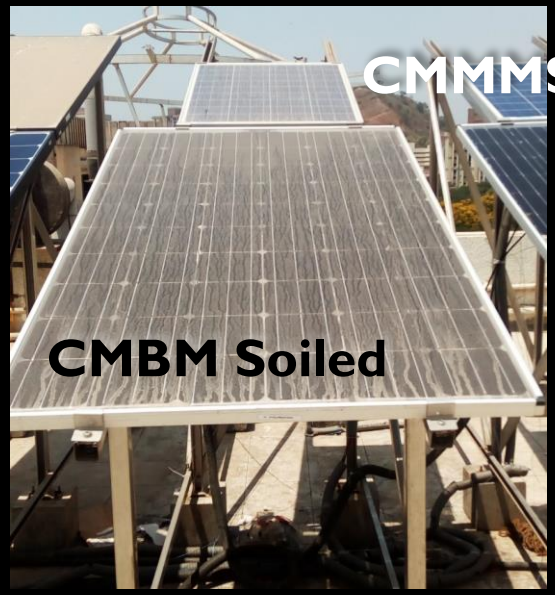
The Fast-Evolving World of Bi-Facial Solar Cells/Modules





Benefit Example: Soiling after 27 days in India

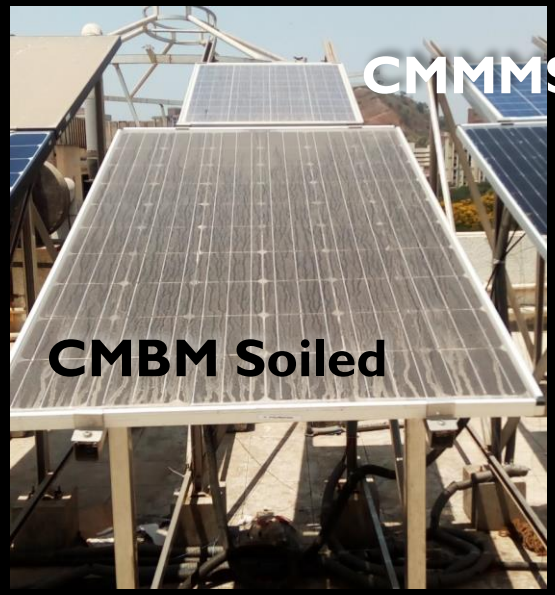
— Vertically Mounted



— Conventionally Mounted

Benefit Example: Soiling after 27 days in India

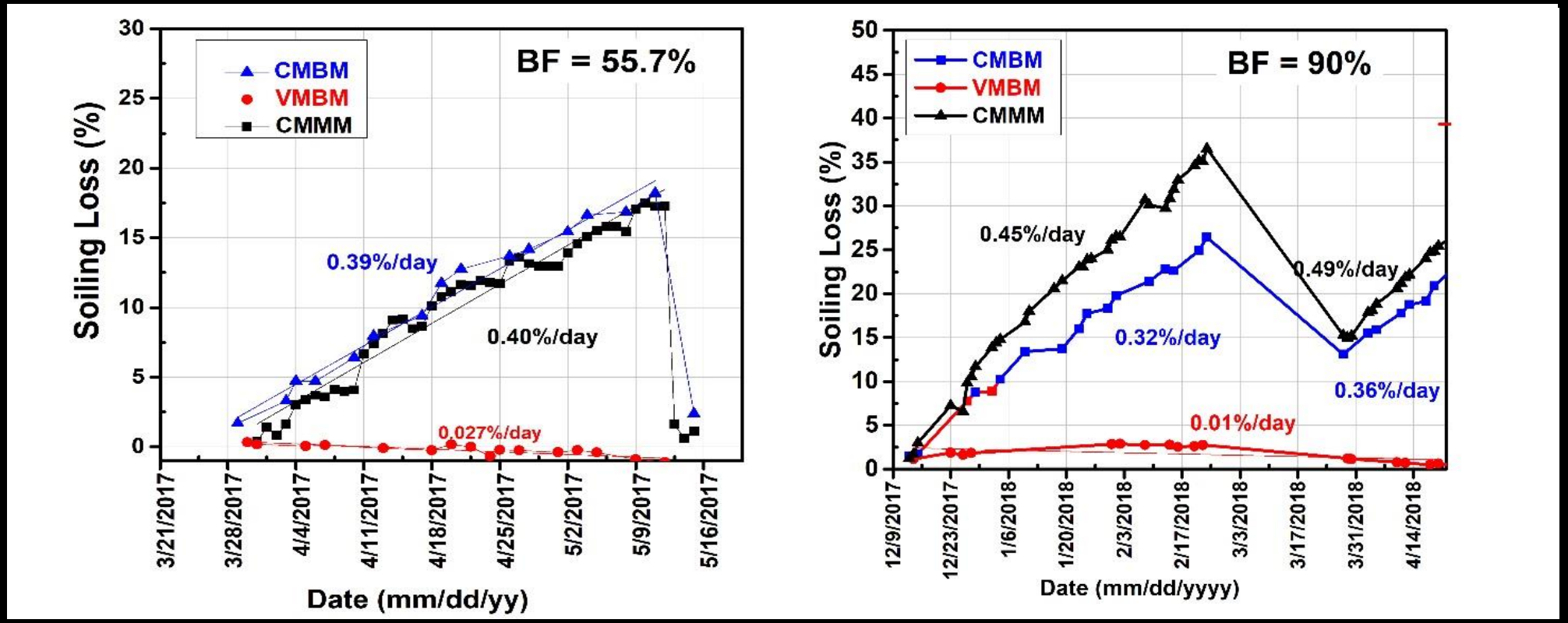
— Vertically Mounted

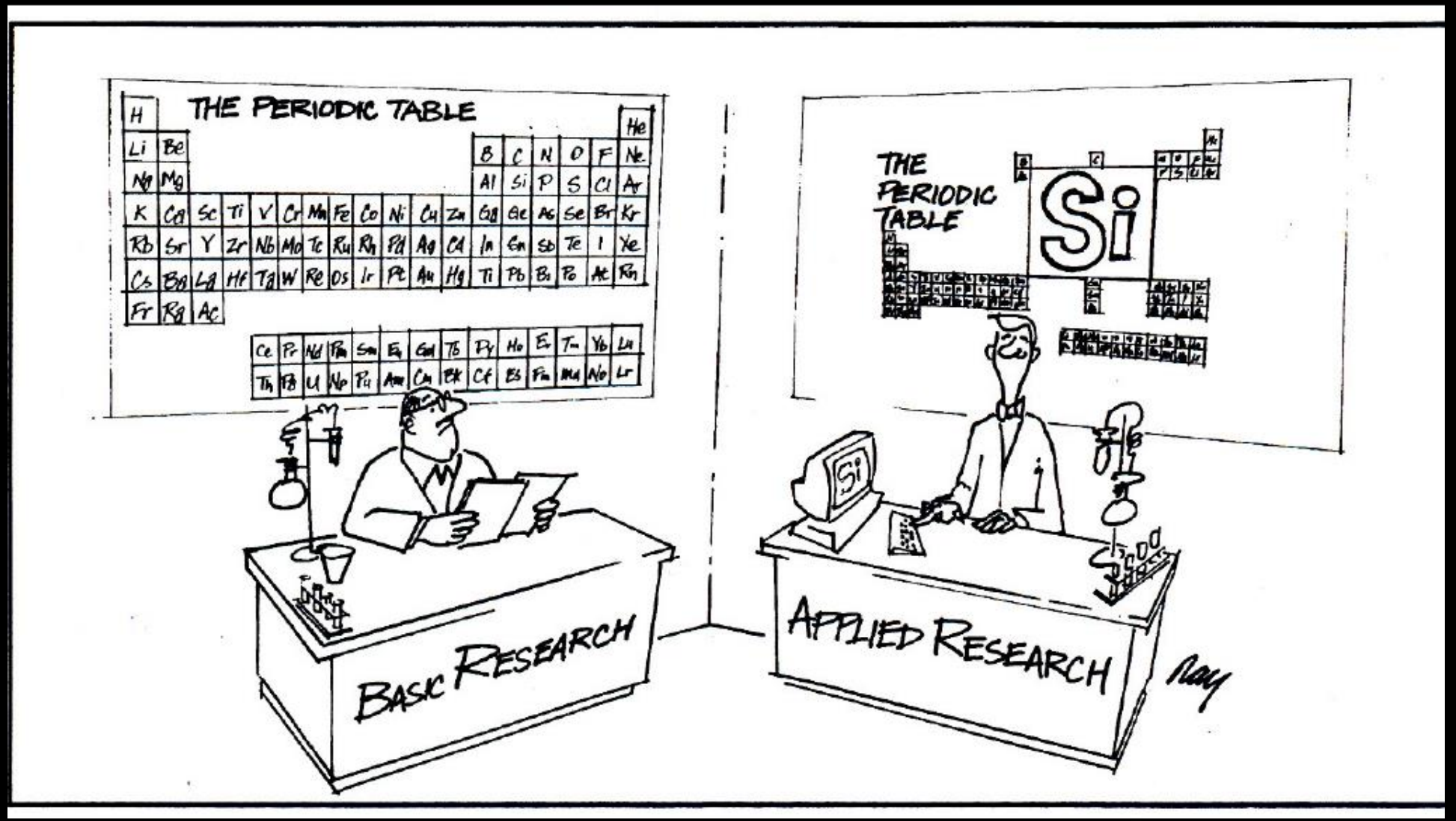


— Conventionally Mounted

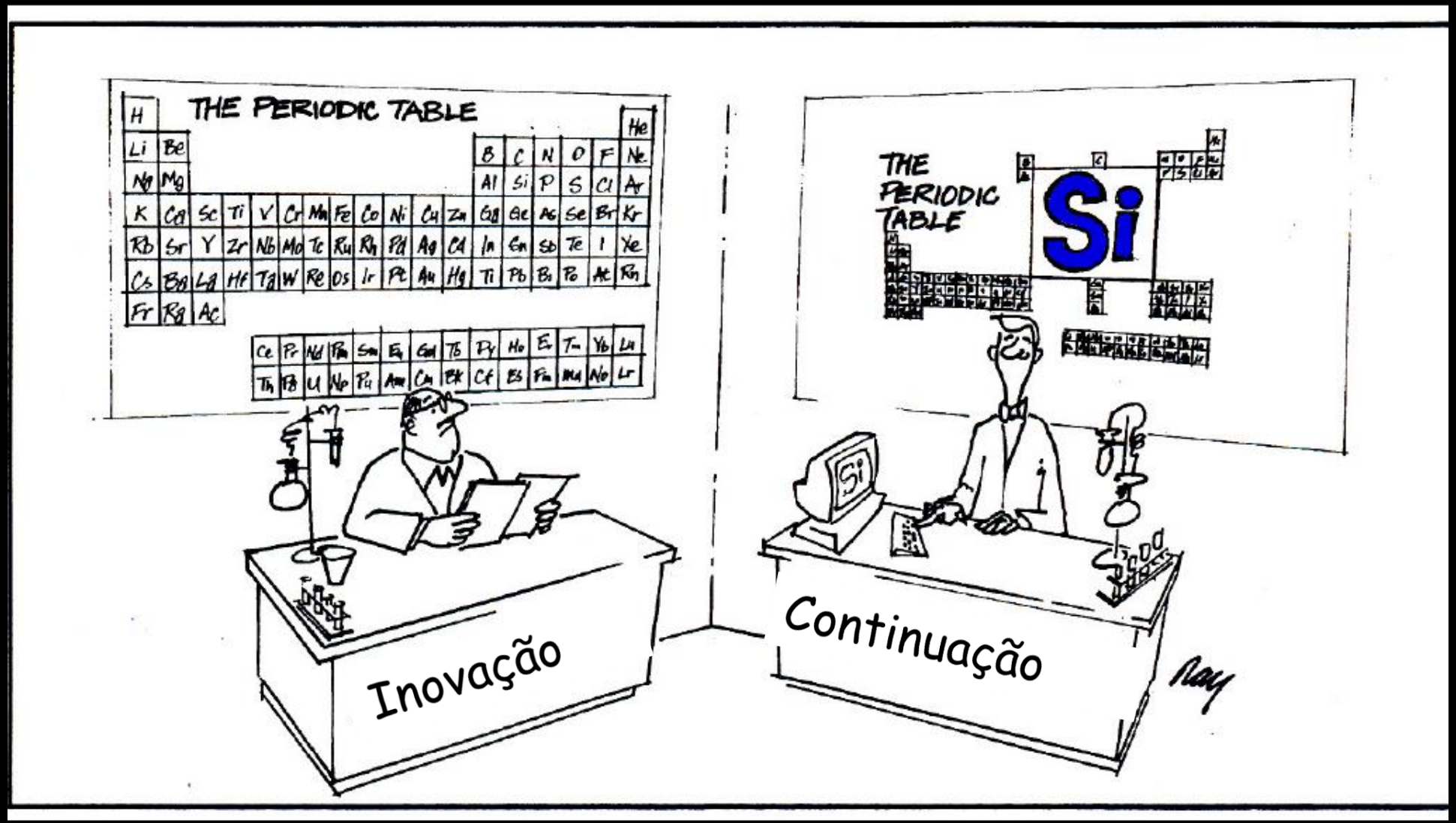
Soiling Loss Result

$$\text{Soiling Loss (\%)} = 1 - \frac{Energy_{\text{soiled}}}{Energy_{\text{cleaned}}}$$

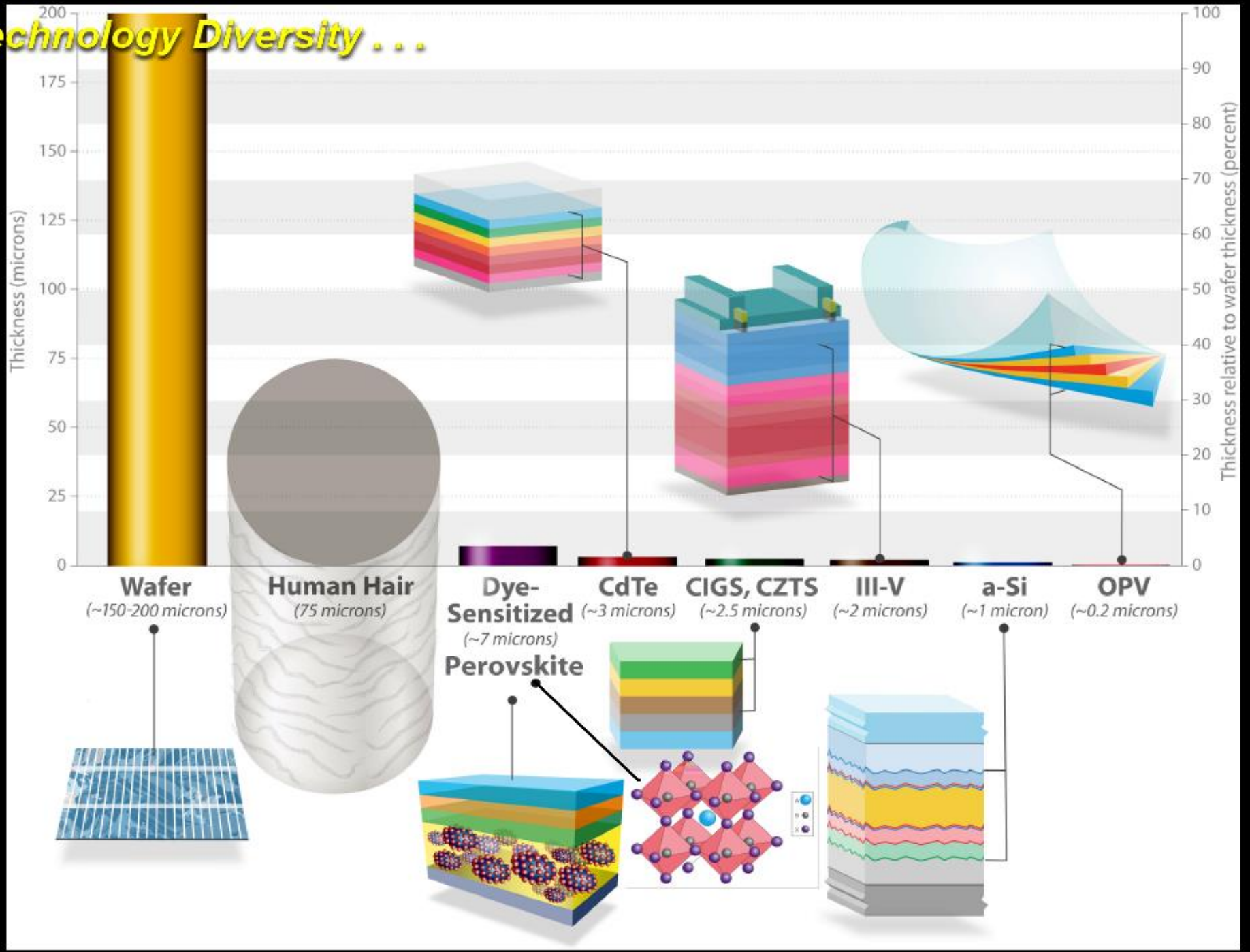



THE PERIODIC TABLE
BASIC RESEARCH
THE PERIODIC TABLE
Si
APPLIED RESEARCH

Silicon

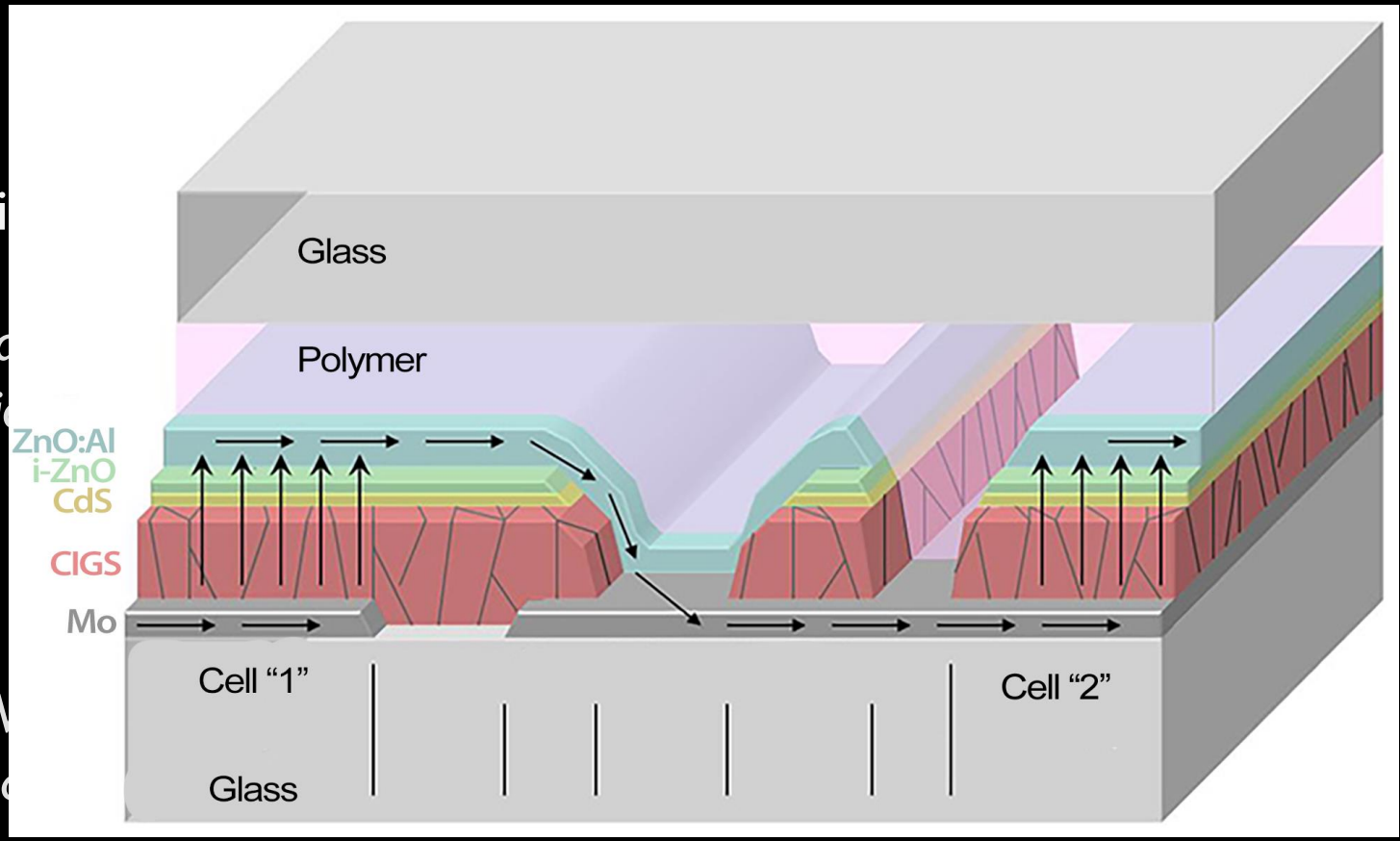

THE PERIODIC TABLE
THE PERIODIC TABLE
Si
Si
Inovação
Continuação

Technology Diversity . . .



Arguments for Thin-Film PV

- Semiconductors
  - *Direct bandgap: more-efficient light absorbers*
  - *Thinner layers required to absorb sunlight–better materials utilization*
  - *Semiconductor bandgaps well-matched to solar spectrum and some tunability*
  - *Diversity of semiconductors*
  - *Diversity of device structures*
- Fewer Processing Steps
- Processing well-suited to Automati
  - *Monolithic integration*
  - *Substrate diversity: flexible, rigid, semi-tra*
  - *"Glass in –Module out": Roll-to-roll fabri*
  - *Large-area modules*
- Performance
  - *Better energy output - kWhr/kW*
  - *Perform better at lower light levels – kW*
  - *Perform better in diffuse and as well in*



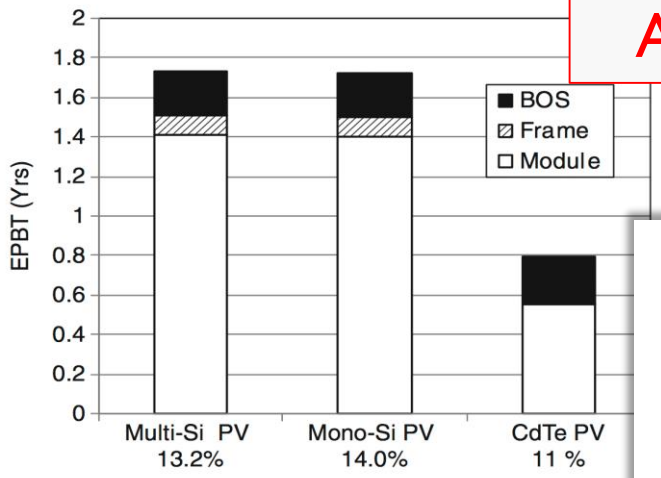
Challenges

- Higher module efficiency
- Gaps in efficiency: *Between cells and modules; Between best cells and attainable levels*
- Thinner absorber layers (<1.0 μm?)
- Alternative absorber production (processes)
- Faster absorber processing
- Stability and encapsulation *(water/water vapor ingress)*
- Materials availability/cost
- Uniformity and stoichiometry *(manufacturing issues)*
- Standardization of equipment
- Environmental/materials concerns
- Recycling, "Insurance"
- Substrates (glass, plastics)
- Engineering of V_{oc} . . .

"Bankability"

Technology Diversity . . .

ALL PV: Very good "energy payback" times



Solar Cells: Energy Payback Times and Environmental Issues. Figure 3

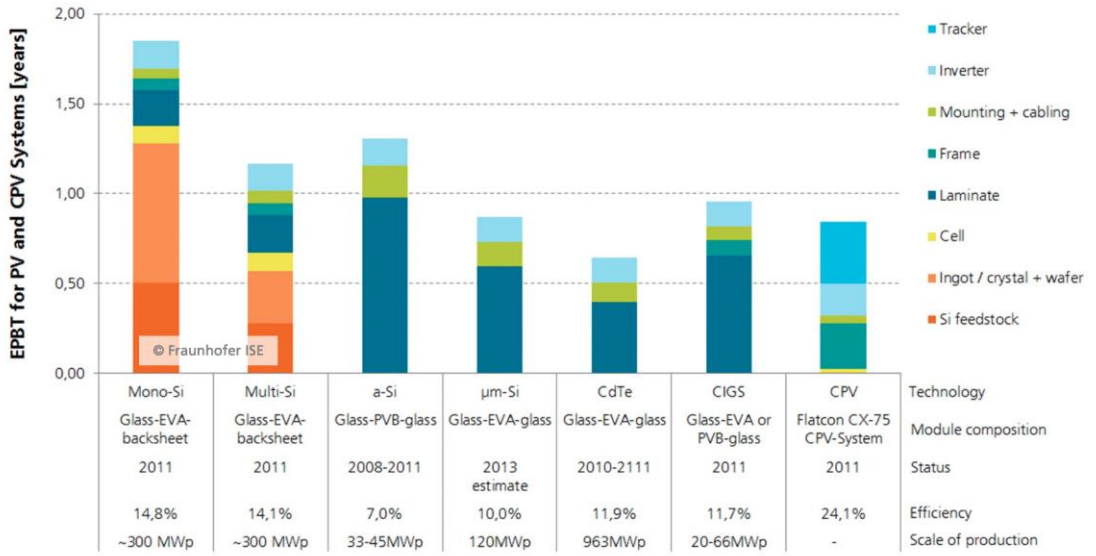
EPBT of PV systems: Rooftop installed module with insolation =1,700 kWh/m^2/year and performance ratio = 0.75; European production

V. Fthenakis, in Encyclopedia of Sustainability Science and Technology, Springer, 341-357 (2016)

Energy Pay-Back Time for PV and CPV Systems

Different Technologies located in Catania, Sicily, Italy

Global Irrad.: 1925 kWh/m²/yr, Direct Normal Irrad.: 1794 kWh/m²/yr

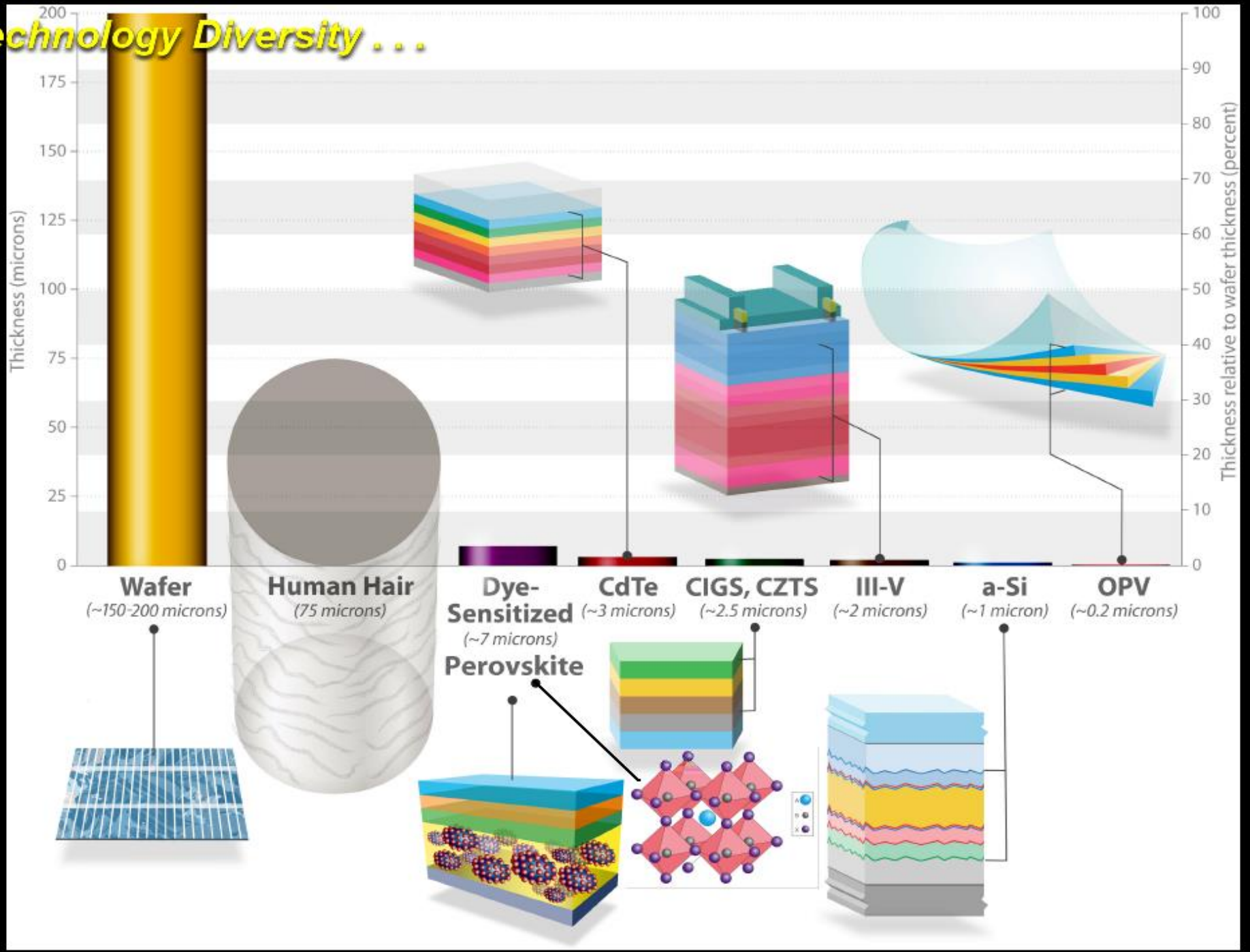


	Mono-Si	Multi-Si	a-Si	µm-Si	CdTe	CIGS	CPV	
Technology								
Module composition	Glass-EVA-backsheet	Glass-EVA-backsheet	Glass-PVB-glass	Glass-EVA-glass	Glass-EVA-glass	Glass-EVA or PVB-glass	Flatcon CX-75 CPV-System	
Status	2011	2011	2008-2011	2013 estimate	2010-2111	2011	2011	
Efficiency	14,8%	14,1%	7,0%	10,0%	11,9%	11,7%	24,1%	
Scale of production	~300 MWp	~300 MWp	33-45MWp	120MWp	963MWp	20-66MWp	-	

Data: M.J. de Wild-Scholten 2013; CPV data: "Environmental Sustainability of Concentrator PV Systems: Preliminary LCA Results of the Apollon Project" 5th World Conference on PV Energy Conversion. Valencia, Spain, 6-10 September 2010. Graph: PSE AG 2014

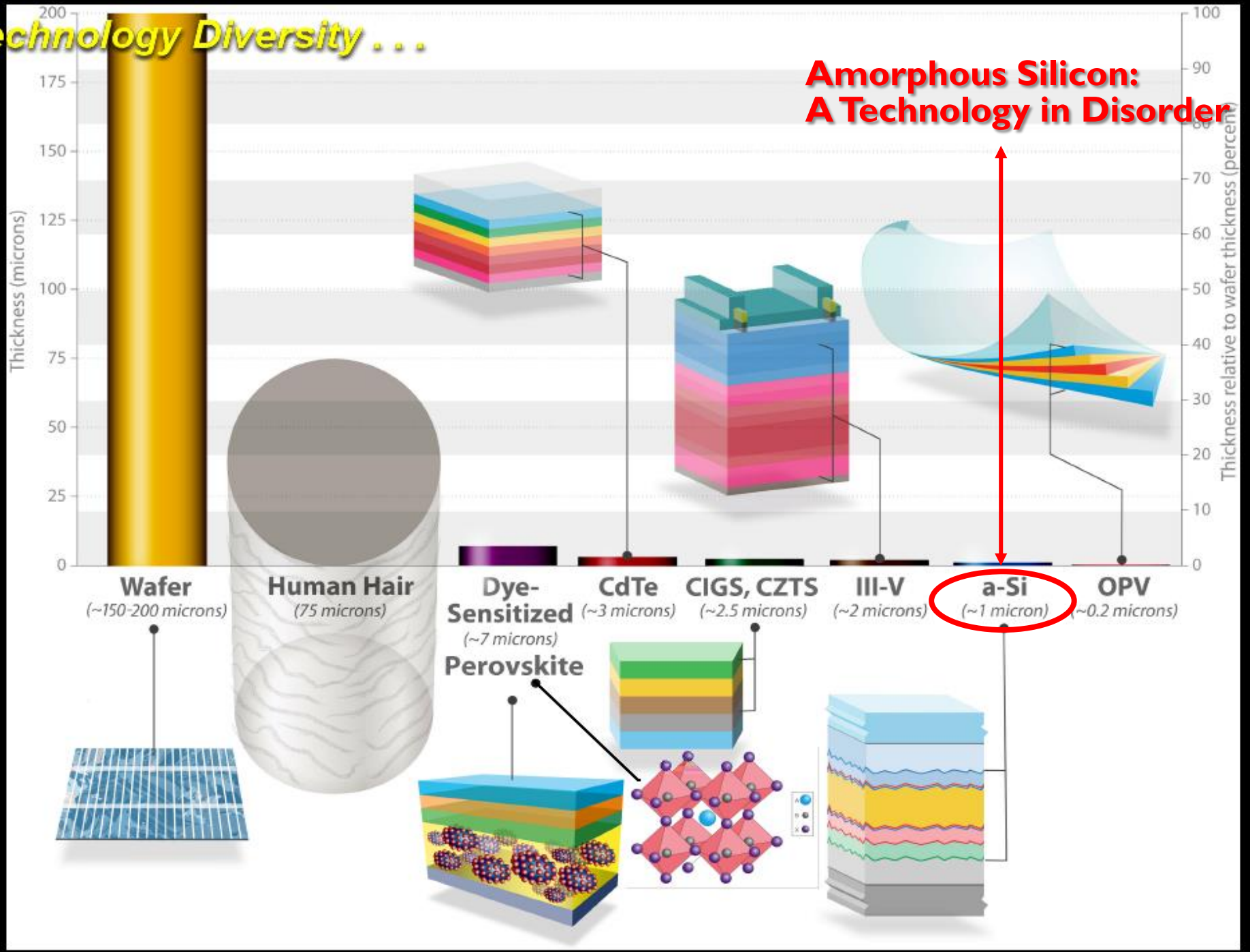
Fraunhofer ISE

Technology Diversity . . .

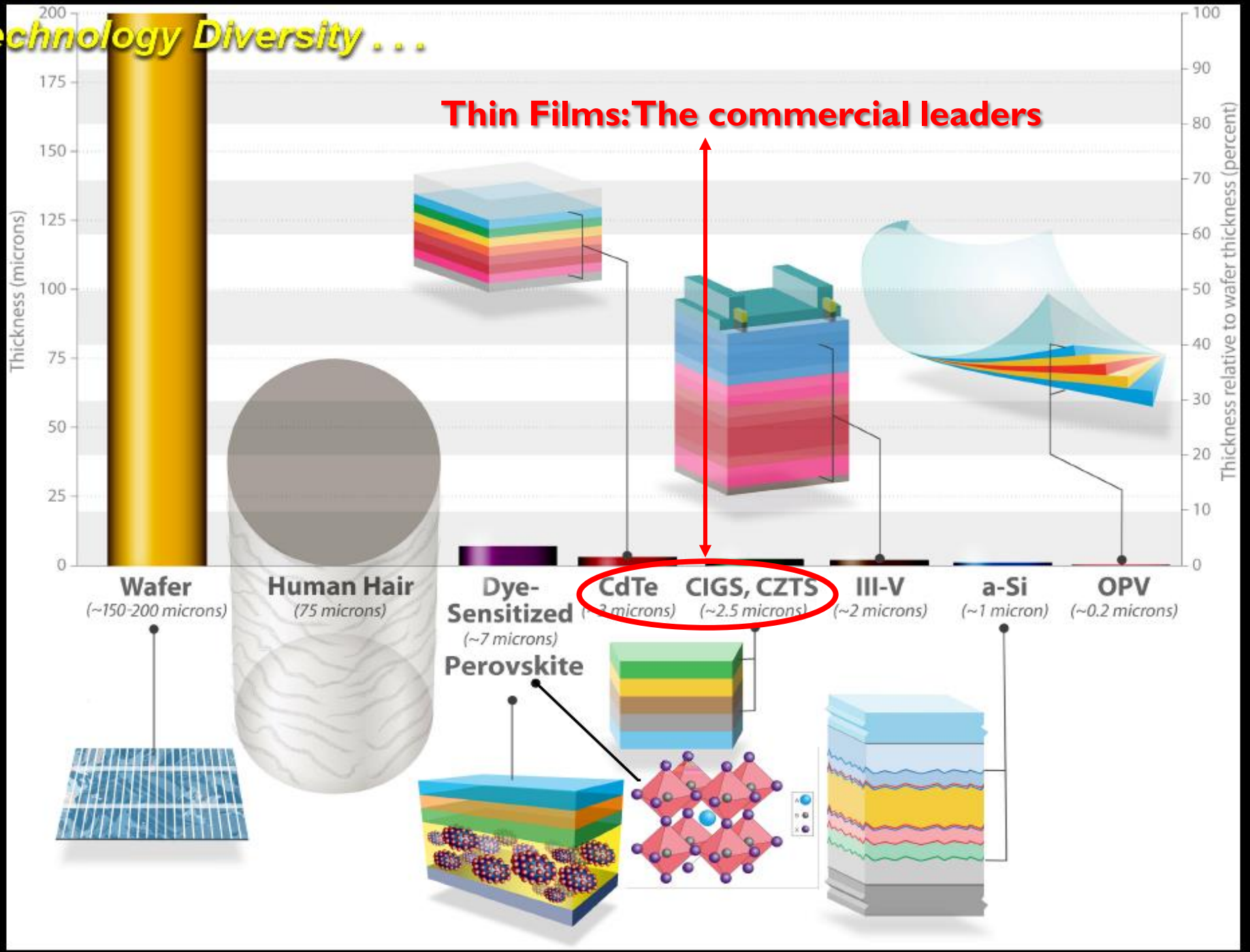


Technology Diversity . . .

Amorphous Silicon: A Technology in Disorder



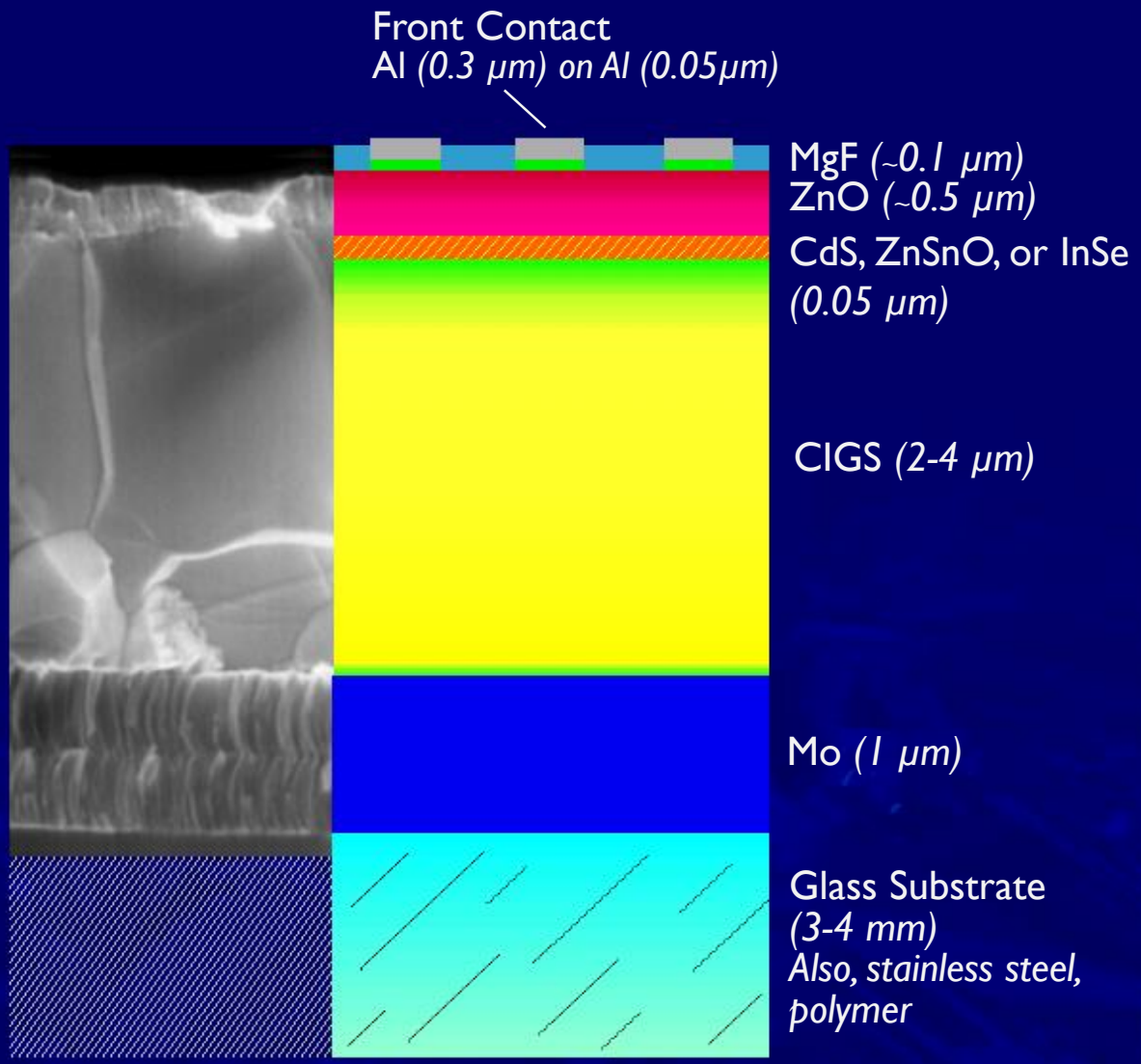
Technology Diversity . . .



Thin Films: The commercial leaders

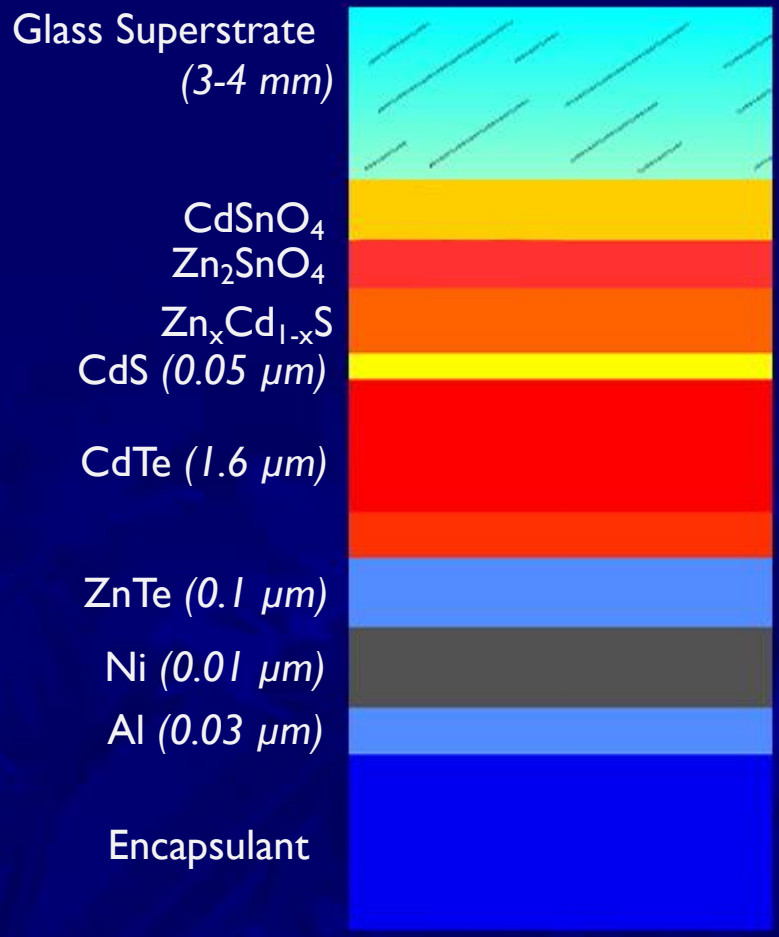
$Cu(InGa)(S,Se)_2$ Thin Film Cell

Best Research: 22.9% - Solar Frontier



CdTe Thin Film Cell

Best Research: 21.1% - First Solar



Thin Films: The commercial leaders

First Solar®

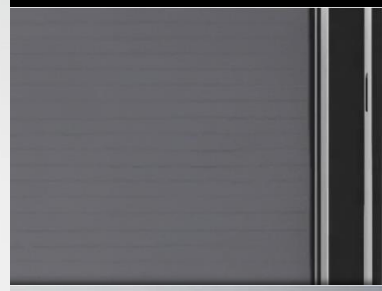
Series 6 Module Technology

INDUSTRY-LEADING MODULE WARRANTY

98% WARRANTED POWER IN THE FIRST YEAR

25-YEAR 0.5% LINEAR PERFORMANCE WARRANTY

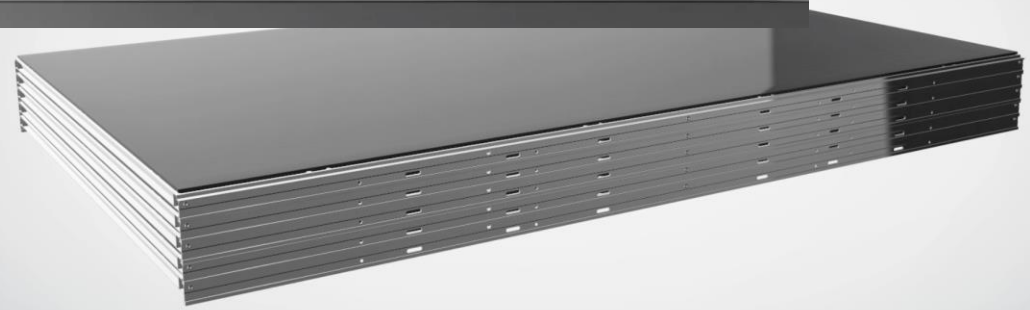
10-YEAR LIMITED PRODUCT WARRANTY



FRAME ON FRAME STACKING

HIGHLY ROBUST

LESS WASTE



INNOVATIVE UNDER-MOUNT FRAME

SOLAR FRONTIER

SOLAR FINANCE & VC

Solar Frontier's CEO Aims for 40-Cents-Per-Watt CIGS Modules

Company

Company > P

Miyaz

Capacity: 60
Site Area: 50
Investment:
On line: 2009

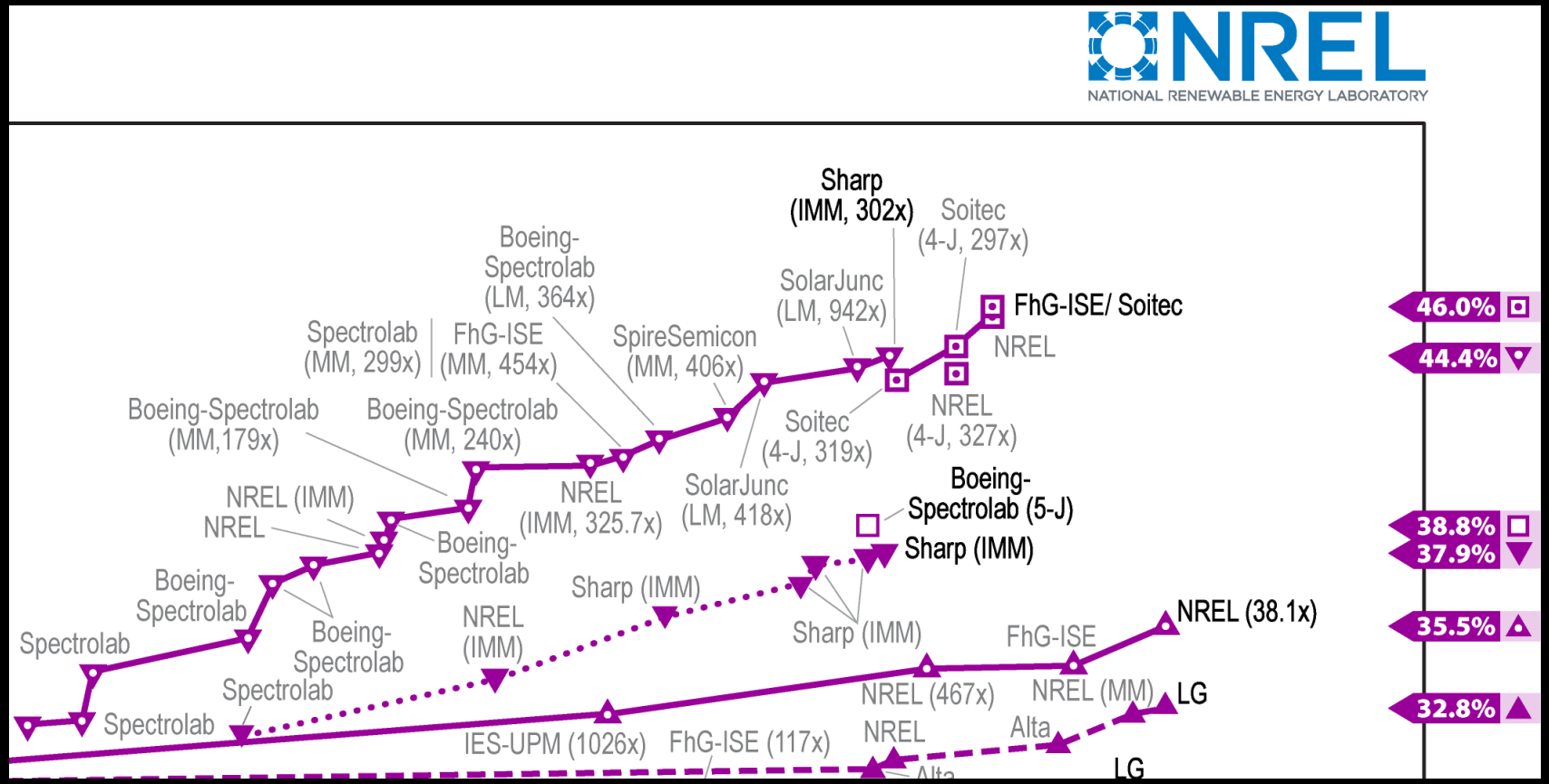
Solar Frontier is
Kunitomi Plant is
wattages availab
commercializatio
will enable the m
class cost levels,

Solar Frontier has continued to push CIGS efficiency, with its latest record

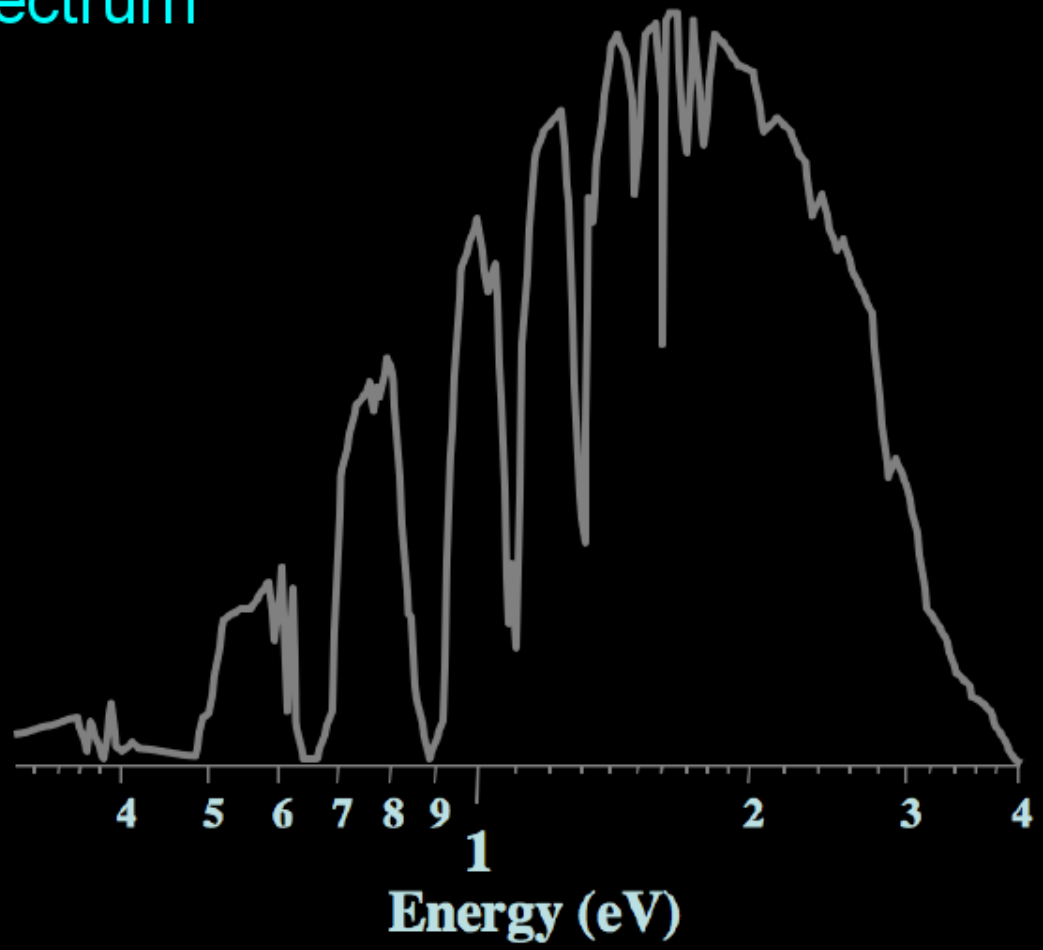
producing a 22.3% CIGS cell, in partnership with the Japan's New Energy and Industrial Technology Development Organization.

Sivapower

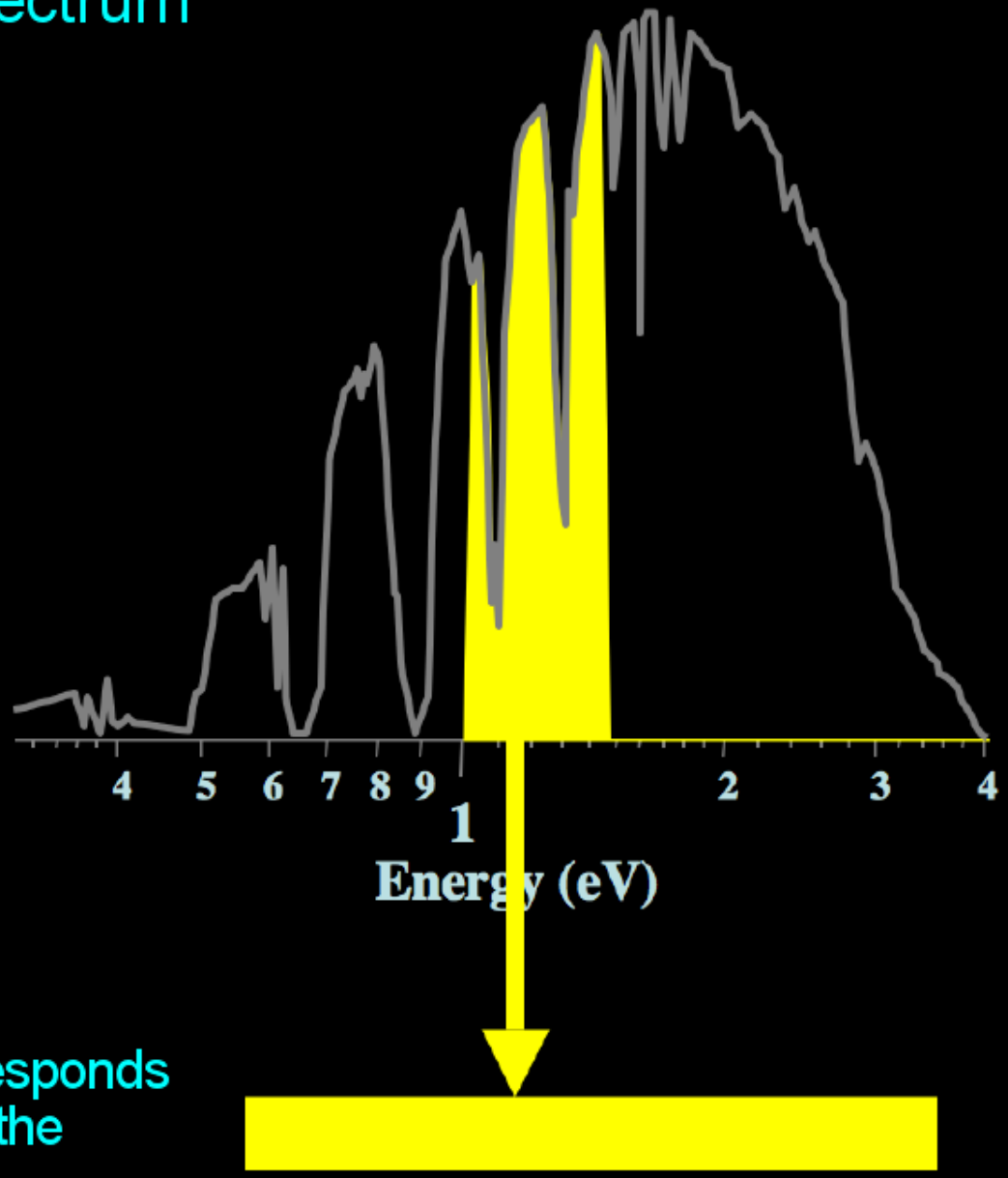
Solar For The Terawatt Era


NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Sharp
(IMM, 302x)
Soitec
(4-J, 297x)
Boeing-
Spectrolab
(LM, 364x)
SolarJunc
(LM, 942x)
FhG-ISE/ Soitec
46.0%
Spectrolab
(MM, 299x)
FhG-ISE
(MM, 454x)
SpireSemicon
(MM, 406x)
NREL
44.4%
Boeing-Spectrolab
(MM,179x)
Boeing-Spectrolab
(MM, 240x)
Soitec
(4-J, 319x)
NREL
(4-J, 327x)
NREL (IMM)
NREL
NREL
(IMM, 325.7x)
SolarJunc
(LM, 418x)
Boeing-
Spectrolab (5-J)
38.8%
Sharp (IMM)
37.9%
Boeing-
Spectrolab
Sharp (IMM)
Spectrolab
Boeing-
Spectrolab
NREL
(IMM)
Sharp (IMM)
NREL (38.1x)
35.5%
FhG-ISE
Spectrolab
NREL (467x)
NREL (MM)
LG
32.8%
Spectrolab
IES-UPM (1026x)
FhG-ISE (117x)
NREL
Alta
LG

Terrestrial Solar Spectrum

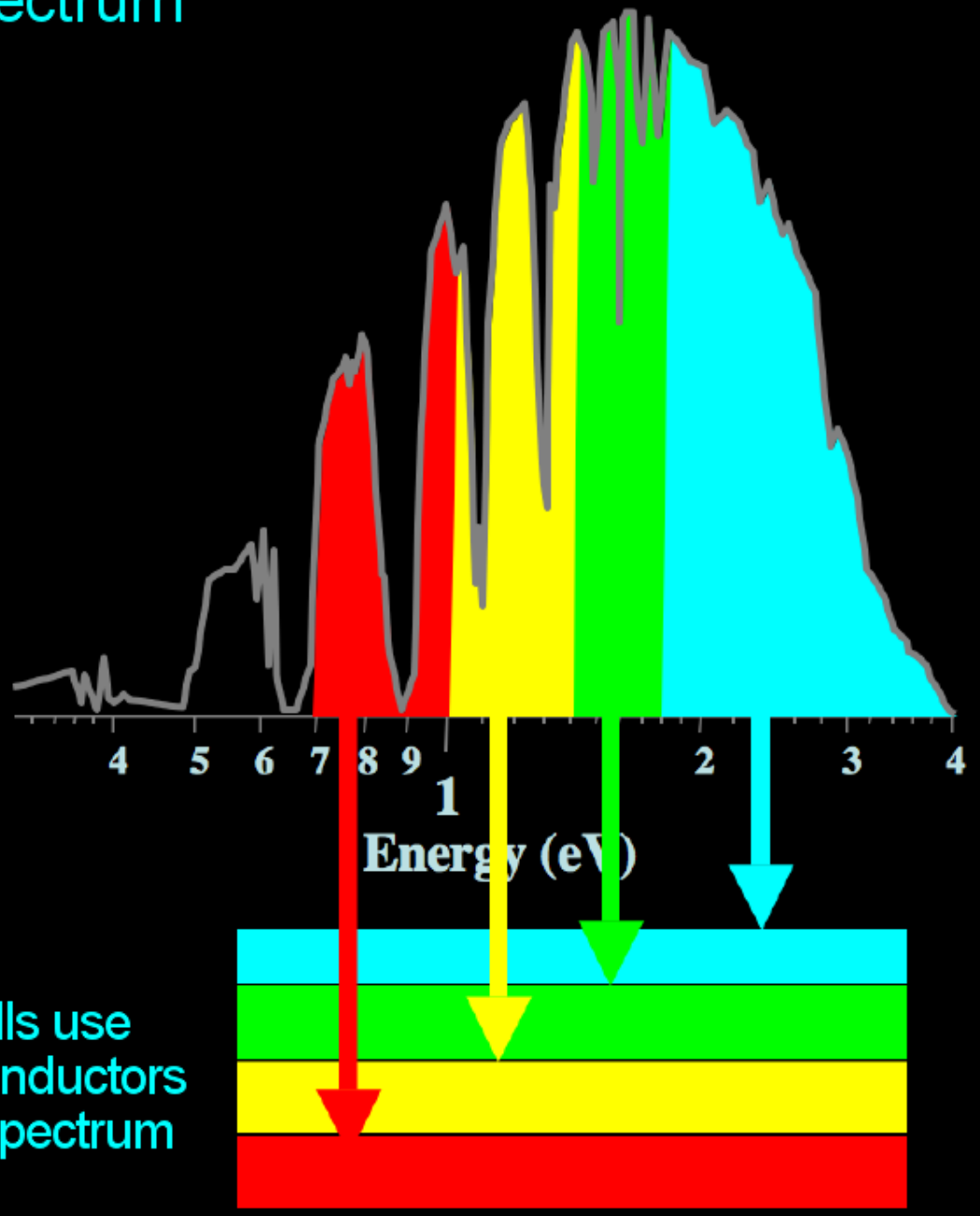


Terrestrial Solar Spectrum



Conventional solar cell responds to one specific portion of the solar spectrum

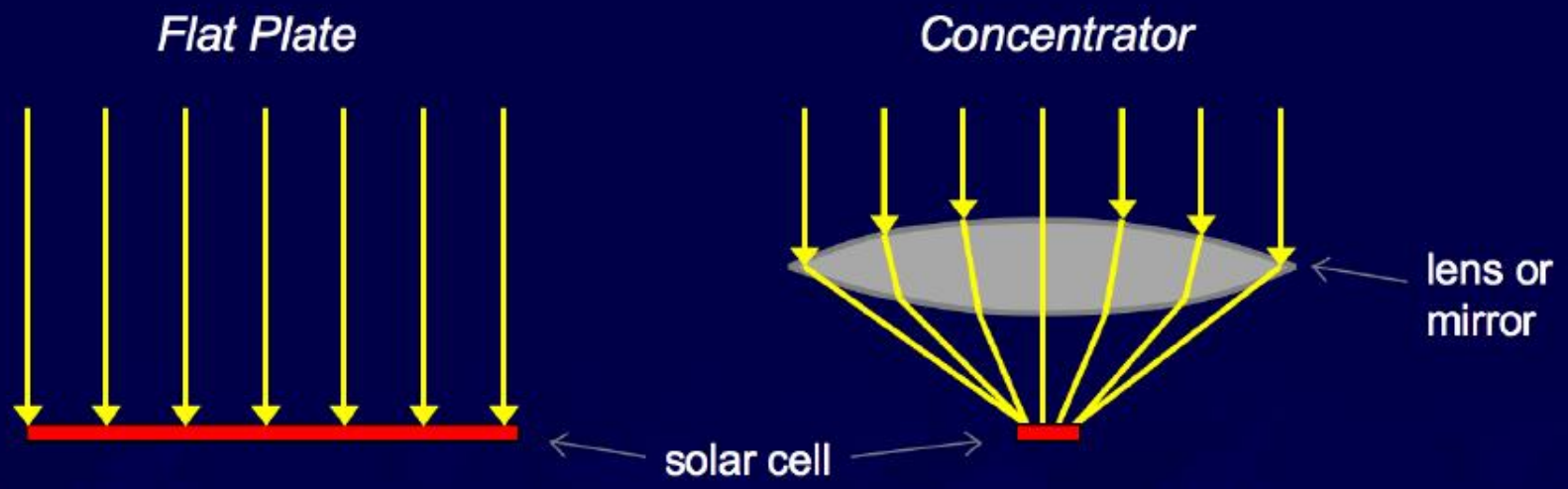
Terrestrial Solar Spectrum



Multiple-junction solar cells use stacks of different semiconductors to use more of the solar spectrum

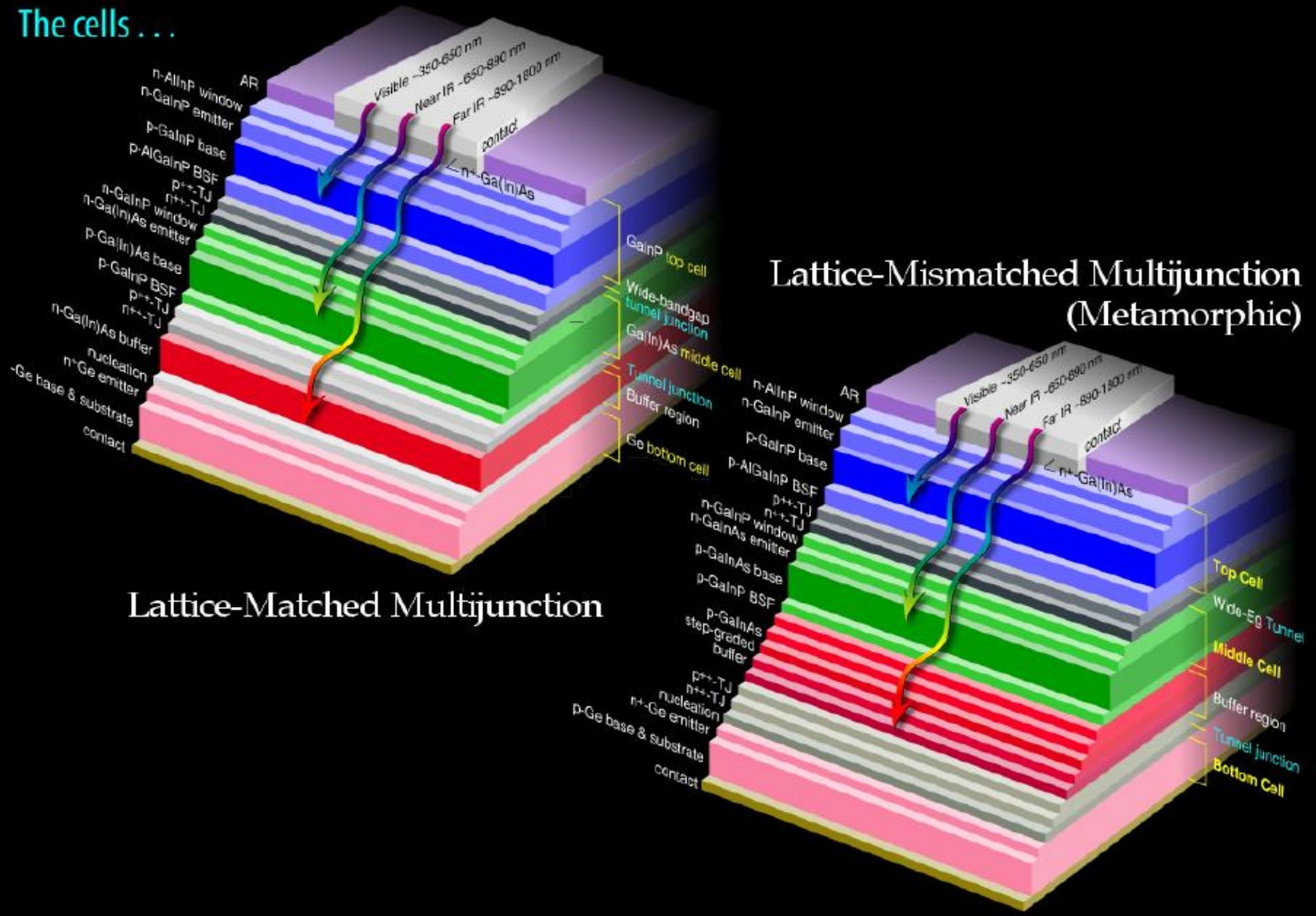
Concentrator Photovoltaics (CPV)

Use optics to reduce the cell area *(from 2 to more than 1000 times)*



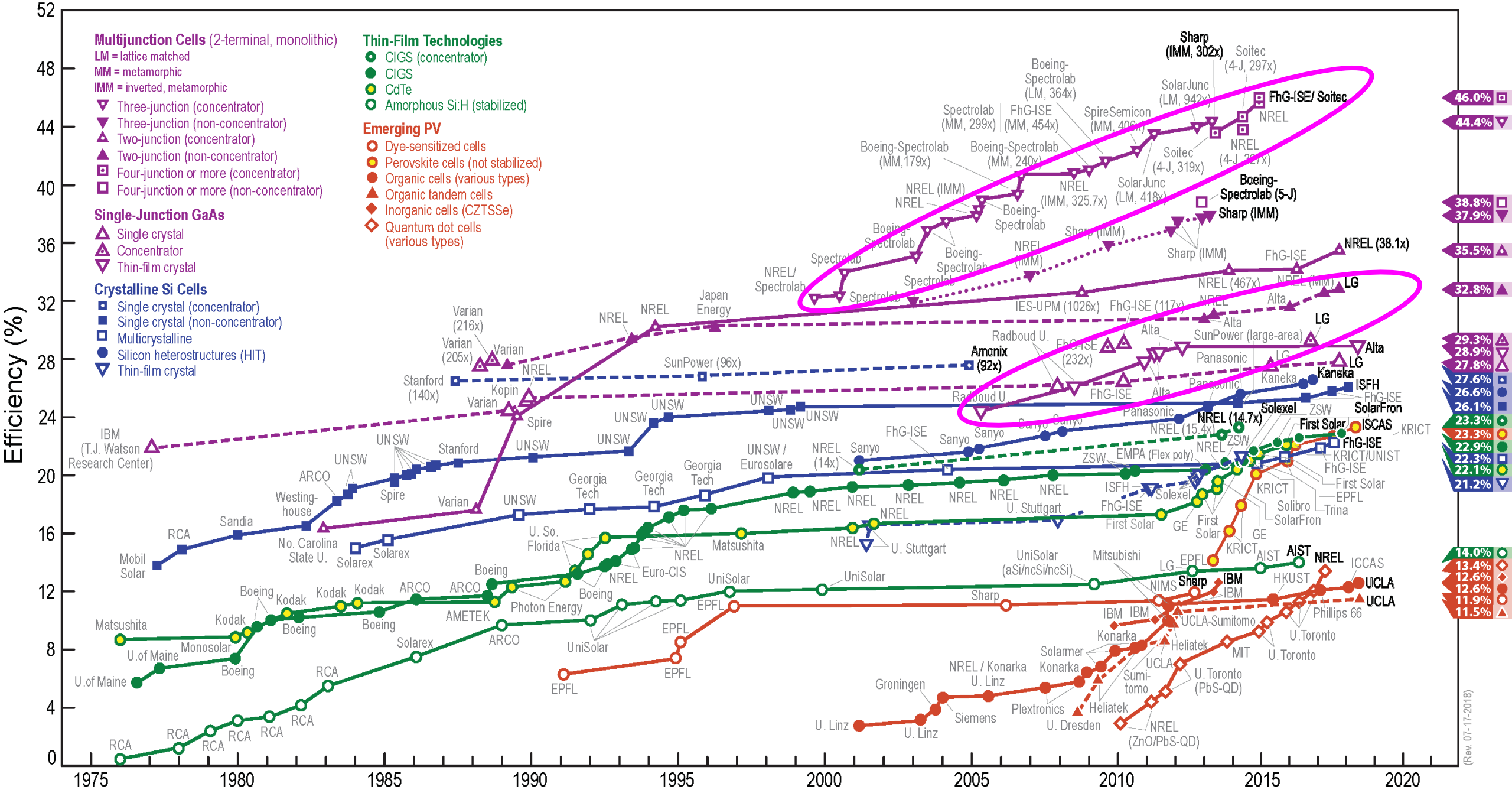
Shifts the major system cost from the cell to the optics
Can afford more efficient, expensive cells

The cells . . .

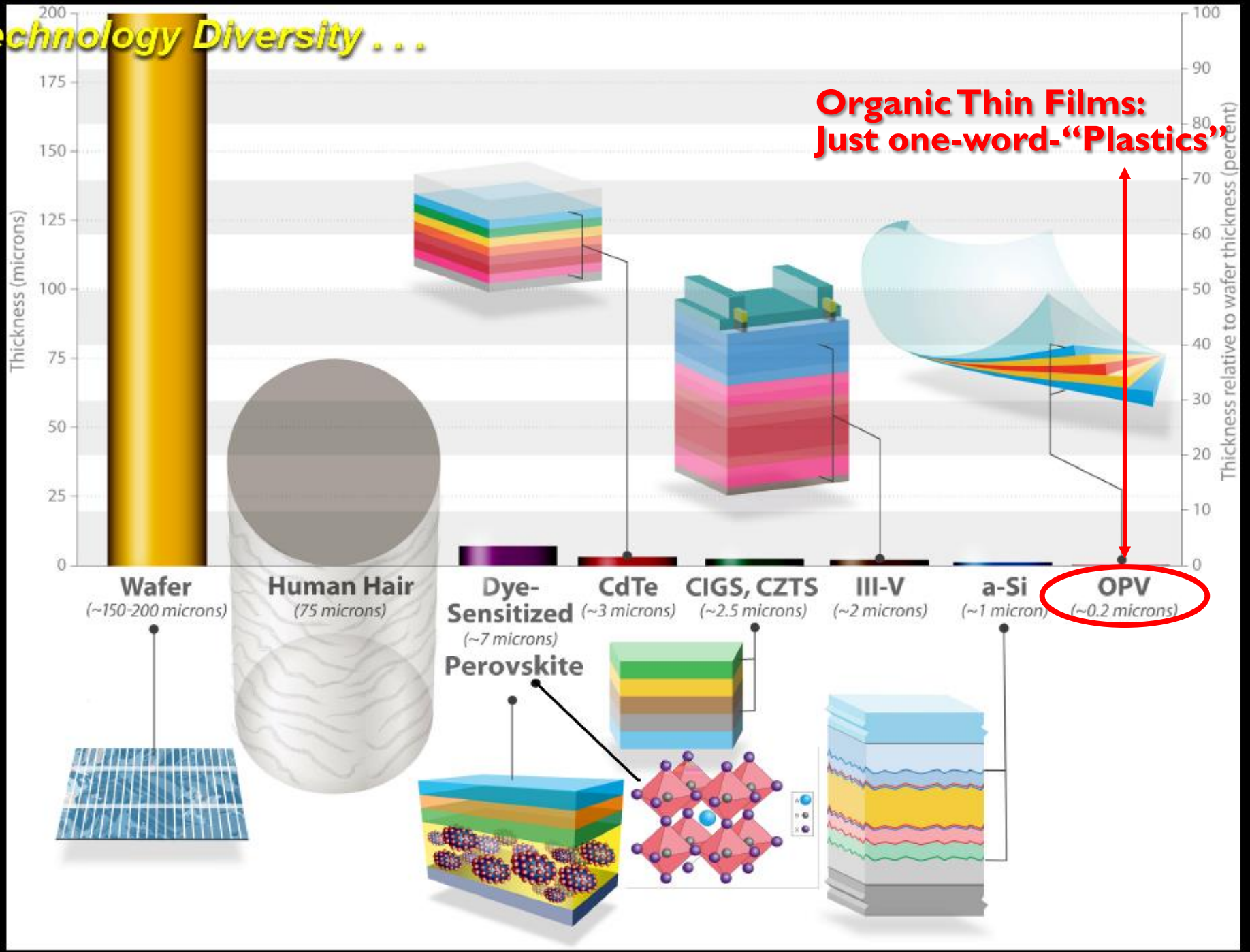

AR
n-AlInP window
n-GaInP emitter
p-GaInP base
p-AlGaInP BSF
p++-TJ
n++-TJ
n-GaInP window
n-Ga(In)As emitter
p-Ga(In)As base
p-GaInP BSF
p++-TJ
n++-TJ
n-Ga(In)As buffer
nucleation
n+-Ge emitter
p-Ge base & substrate
contact
Visible ~350-650 nm
Near IR ~650-890 nm
Far IR ~890-1800 nm
contact
n+-Ga(In)As
GaInP top cell
Wide-bandgap tunnel junction
Ga(In)As middle cell
Tunnel junction
Buffer region
Ge bottom cell
Lattice-Matched Multijunction
Lattice-Mismatched Multijunction (Metamorphic)
AR
n-AlInP window
n-GaInP emitter
p-GaInP base
p-AlGaInP BSF
p++-TJ
n++-TJ
n-GaInP window
n-GaInAs emitter
p-GaInAs base
p-GaInP BSF
p-GaInAs step-graded buffer
p++-TJ
n++-TJ
nucleation
n+-Ge emitter
p-Ge base & substrate
contact
Visible ~350-650 nm
Near IR ~650-890 nm
Far IR ~890-1800 nm
contact
n+-Ga(In)As
Top Cell
Wide-Eg Tunnel
Middle Cell
Buffer region
Tunnel junction
Bottom Cell

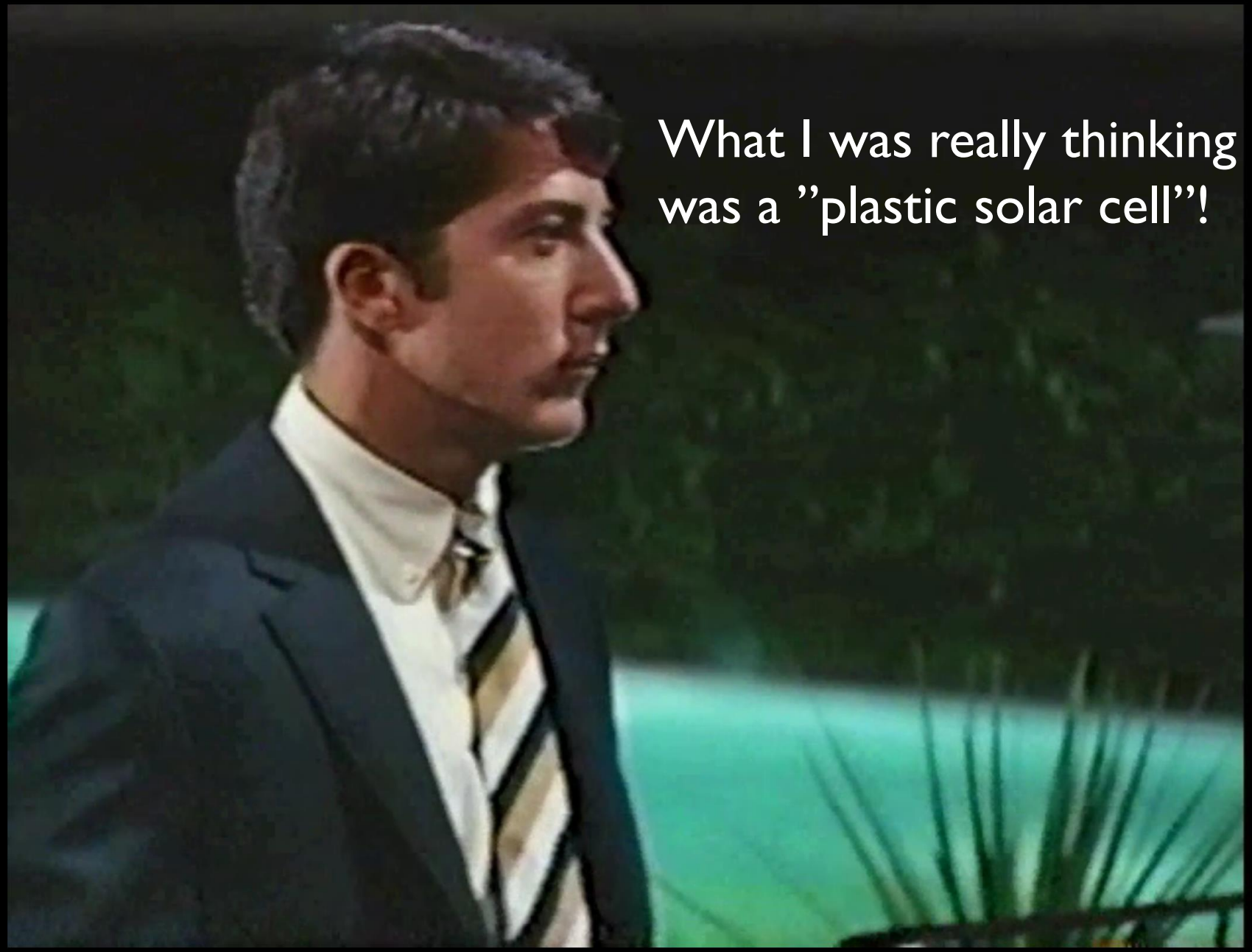
Best Research-Cell Efficiencies

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

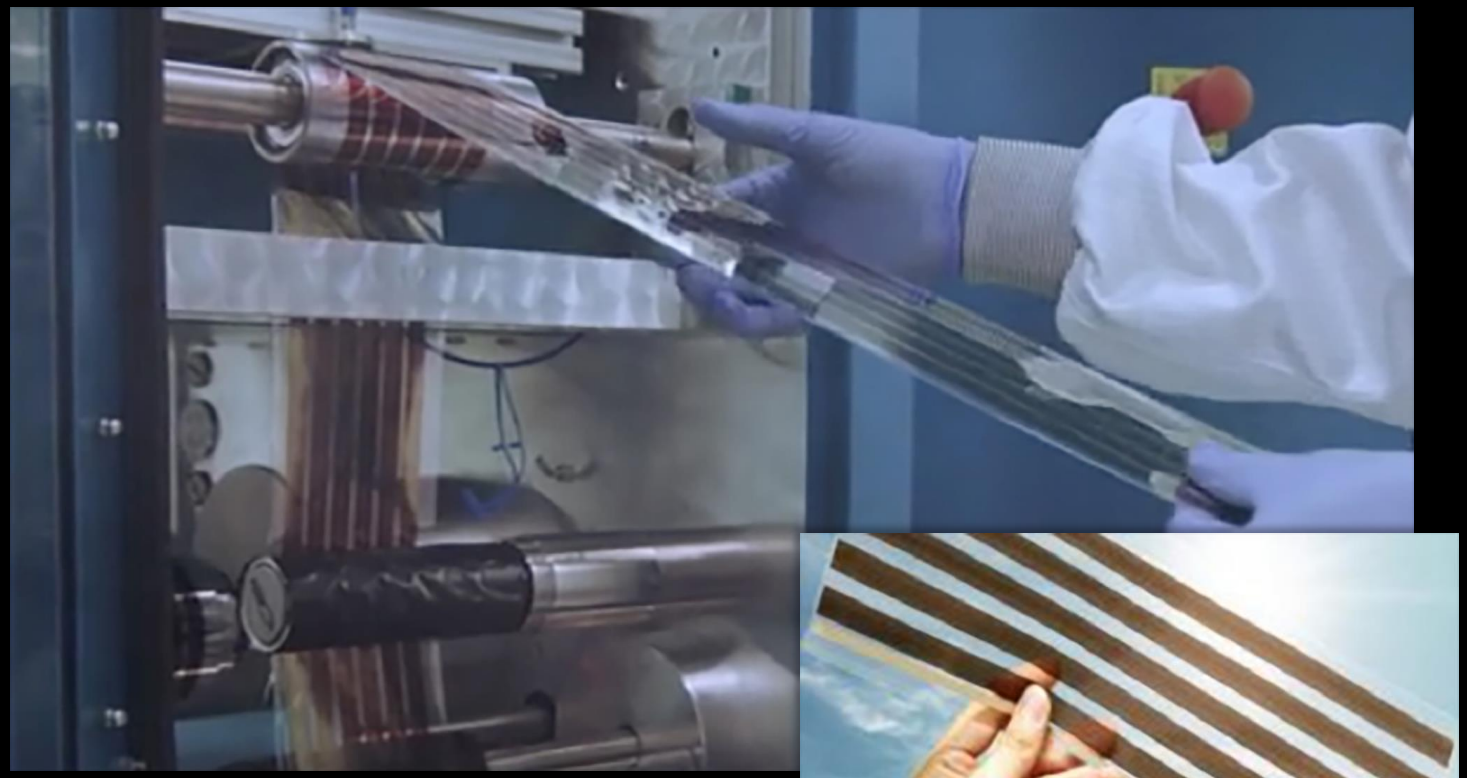


Technology Diversity . . .



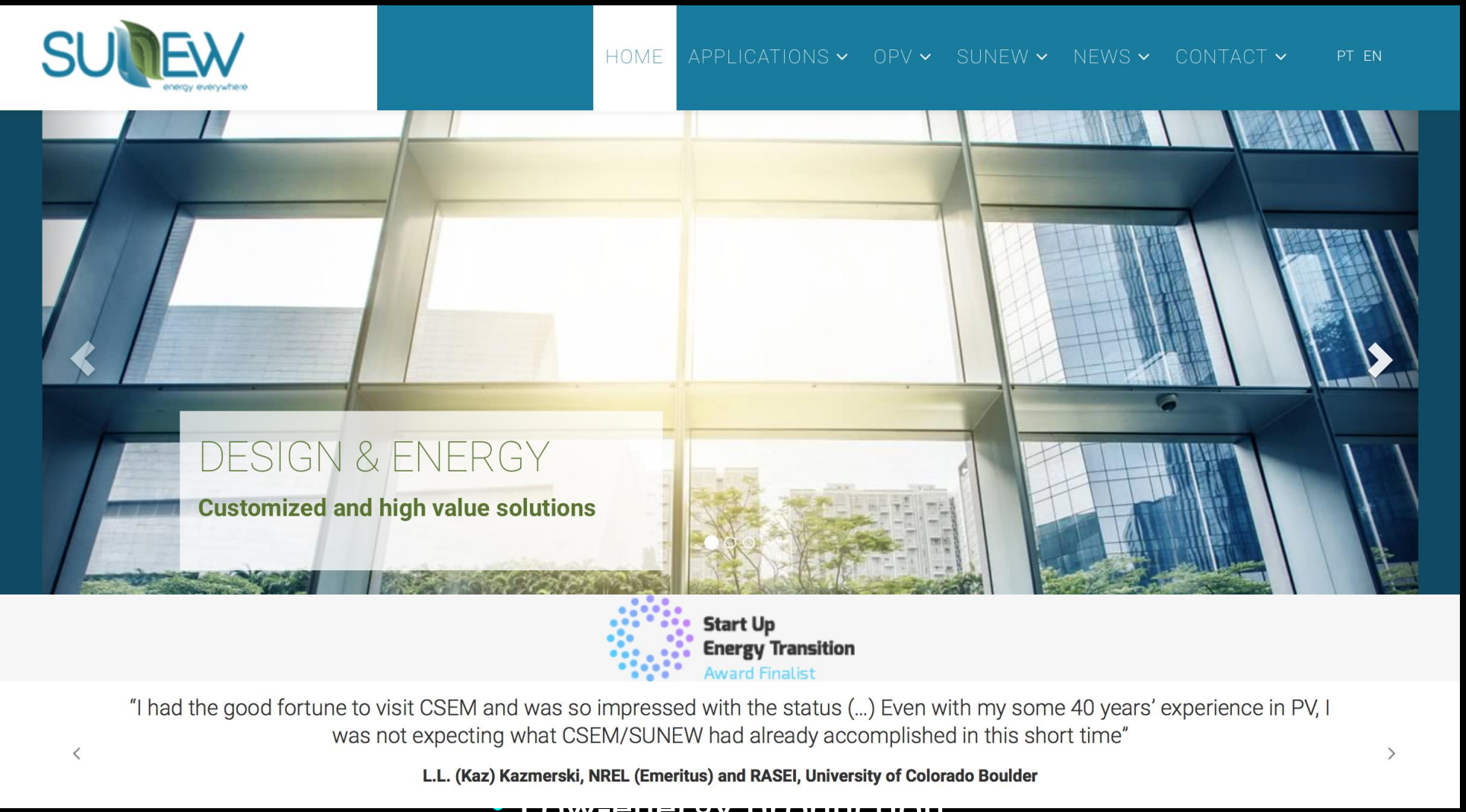

What I was really thinking
was a ”plastic solar cell”!

Organic Photovoltaics (OPV)



- "Flexible"
- Roll-to-roll processing
- Low-energy production
- Inexpensive

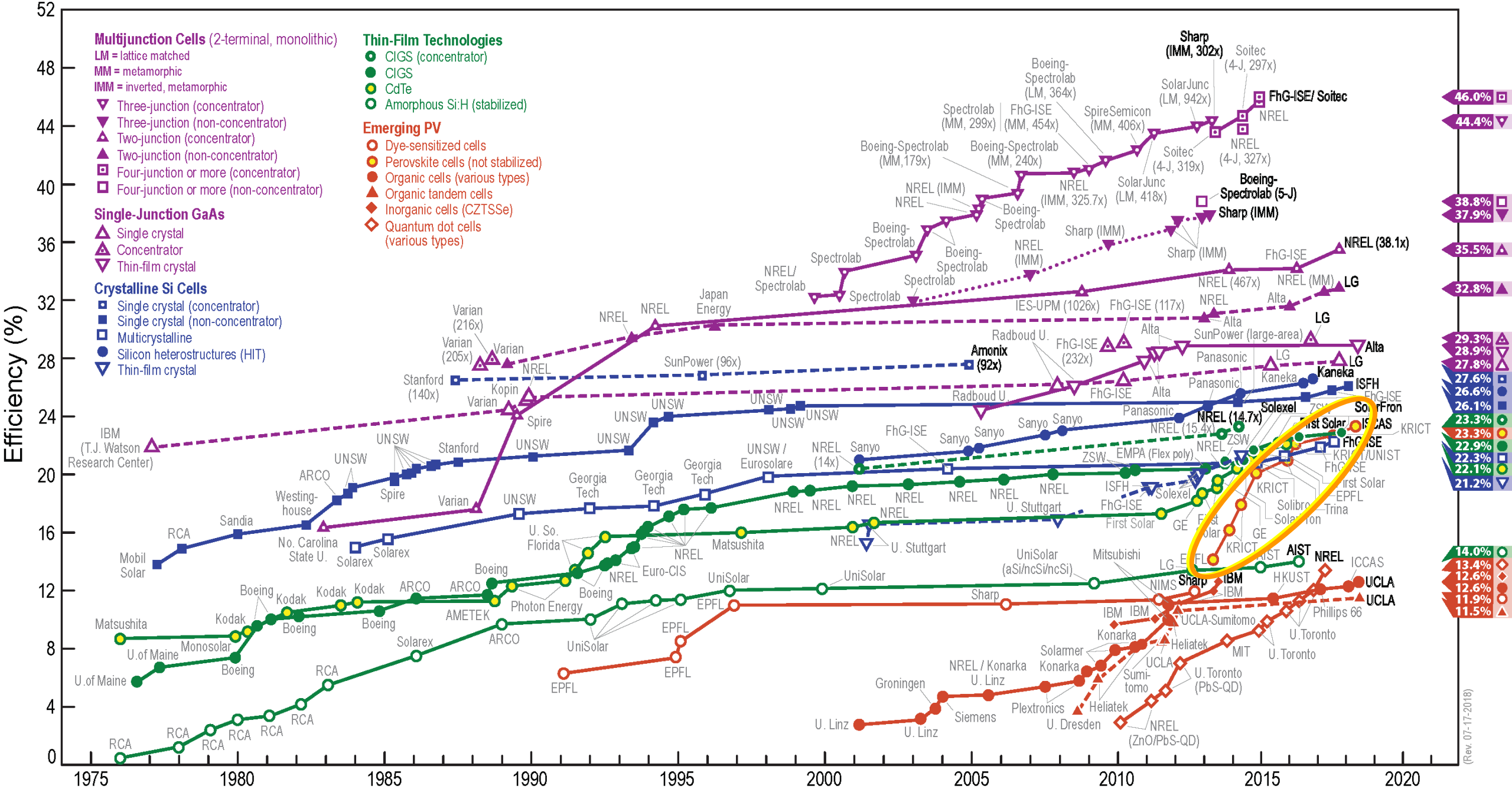
Organic Photovoltaics (OPV)



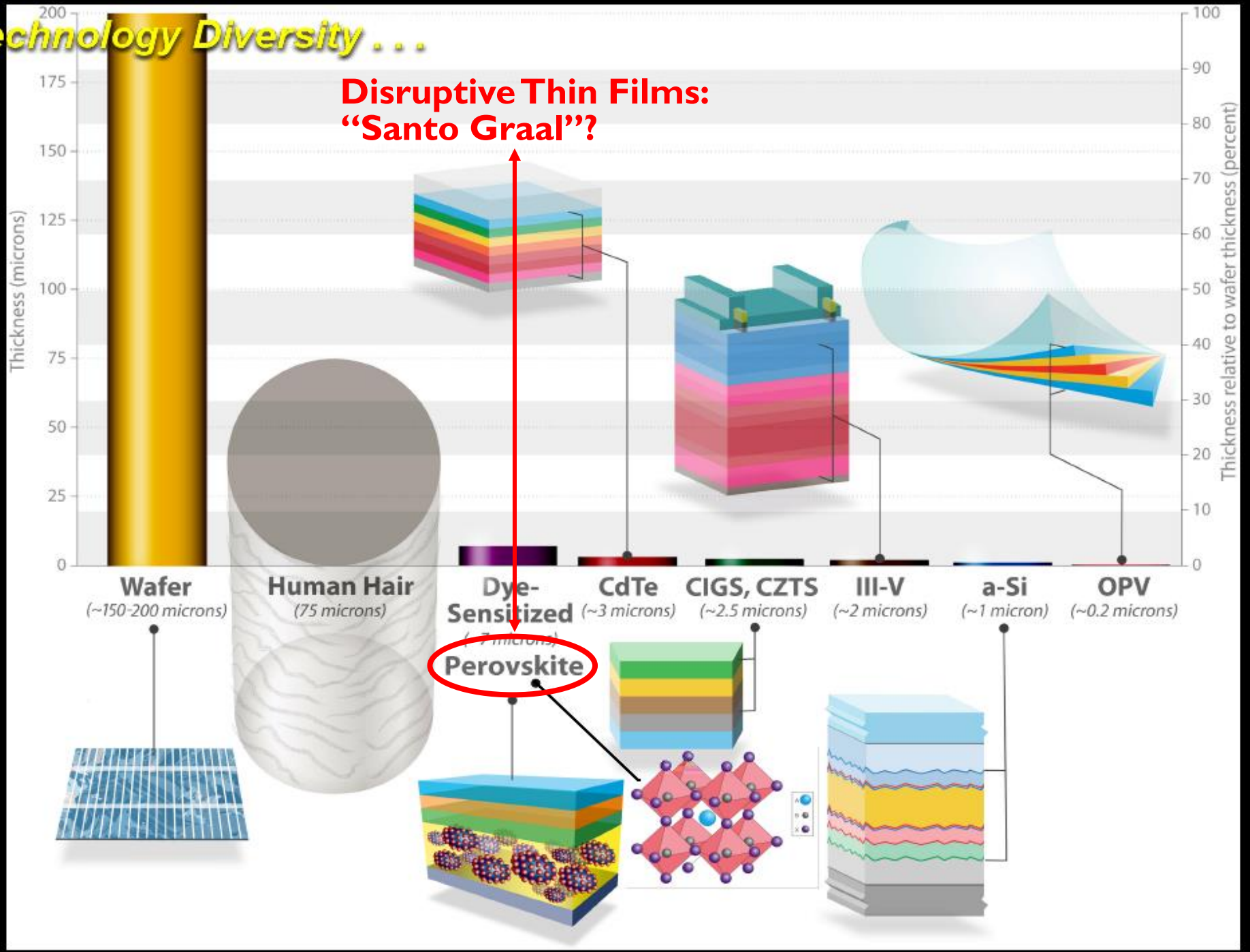
- Low-energy production
- Inexpensive

Best Research-Cell Efficiencies

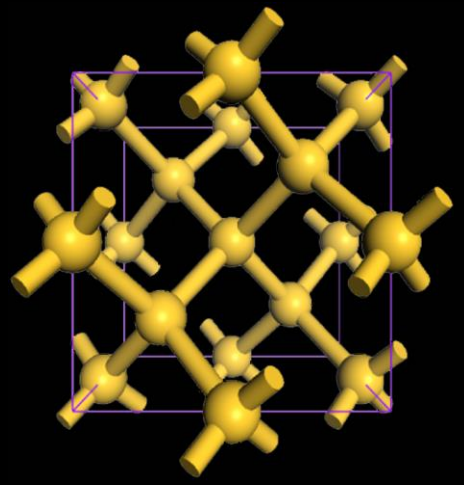
NREL
NATIONAL RENEWABLE ENERGY LABORATORY



Technology Diversity . . .



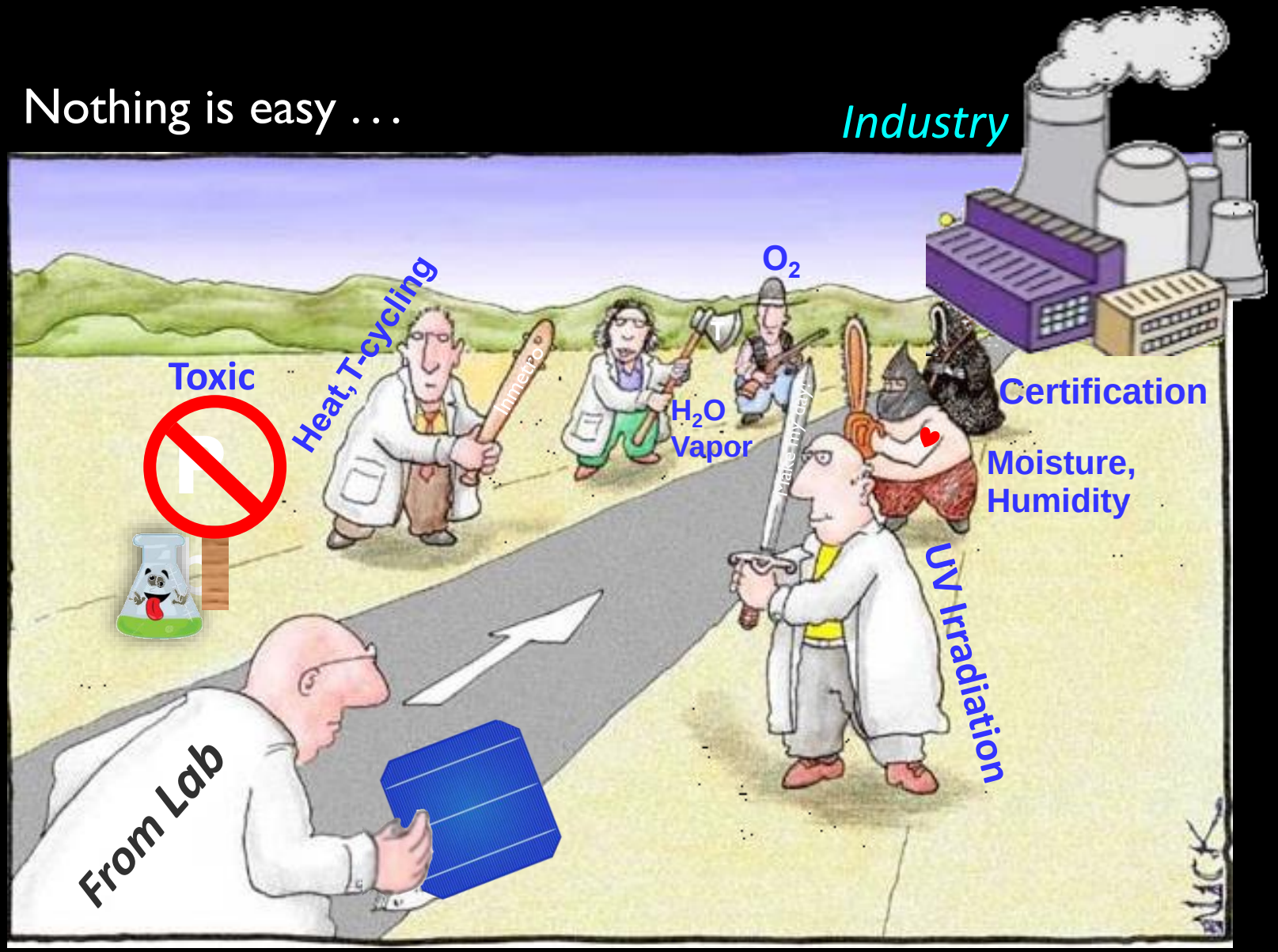
Evolving Complexity of PV Materials Science



Si

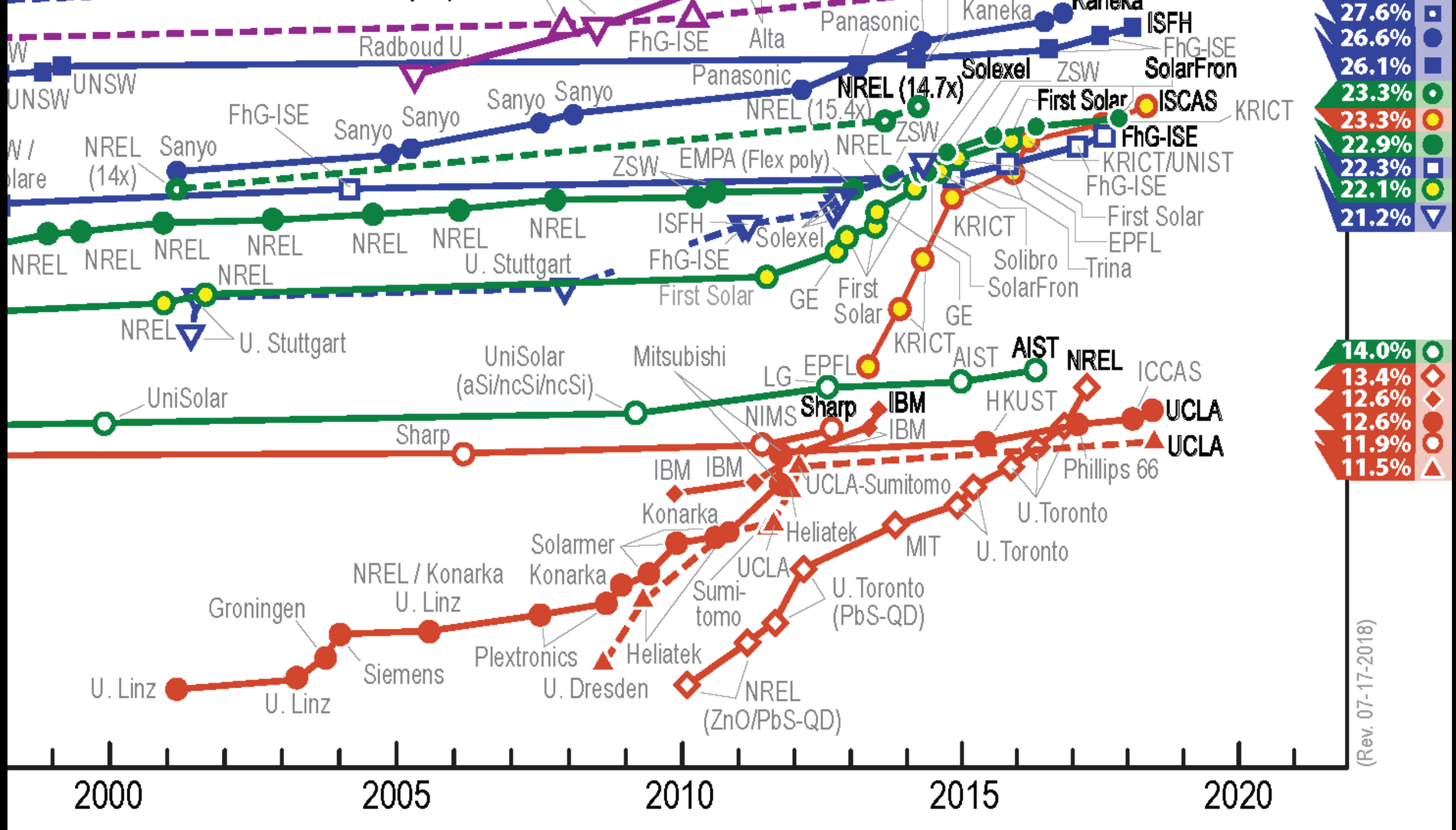
From Lab Bench to Market

Nothing is easy . . .

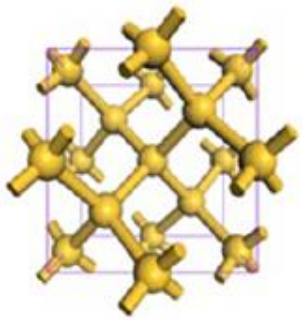


But, what about funding?

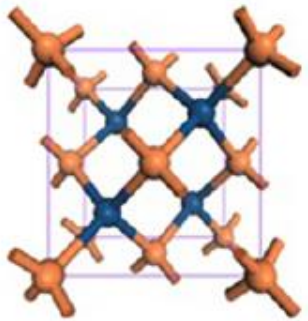
Mas que sobre o financiamento?


27.6%
26.6%
26.1%
23.3%
23.3%
22.9%
22.3%
22.1%
21.2%
14.0%
13.4%
12.6%
12.6%
11.9%
11.5%
ISFH
SolarFron
ISCAS
NREL (14.7x)
Solexel
AIST
NREL
UCLA
UCLA
Sanyo
Panasonic
Kaneka
ZSW
First Solar
KRICT
FhG-ISE
NREL (15.4x)
NREL (14x)
EMPA (Flex poly)
KRICT/UNIST
EPFL
Solibro
Trina
U. Stuttgart
GE
UniSolar
(aSi/ncSi/ncSi)
Mitsubishi
LG
Sharp
IBM
NIMS
HKUST
ICCAS
Phillips 66
UCLA-Sumitomo
Konarka
Heliatek
Solarmer
NREL / Konarka
U. Linz
Groningen
Siemens
Plextronics
U. Dresden
Sumi-
tomo
MIT
U. Toronto
U. Toronto
(PbS-QD)
NREL
(ZnO/PbS-QD)
Radboud U.
Alta
UNSW
2000
2005
2010
2015
2020
(Rev. 07-17-2018)

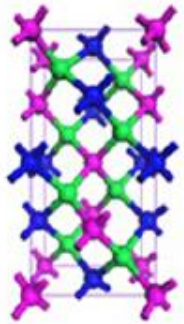
Evolution of Increasingly Complex PV Absorbers



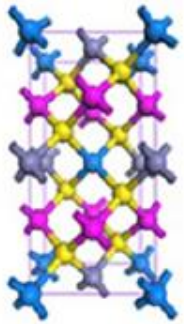
Si



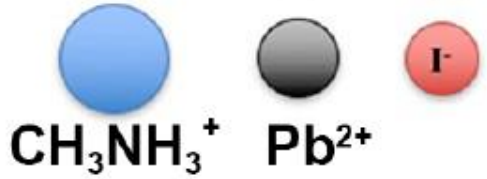
CdTe
GaAs



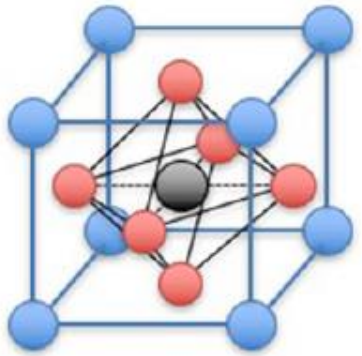
$CuInSe_2$



Cu_2ZnSnS_4

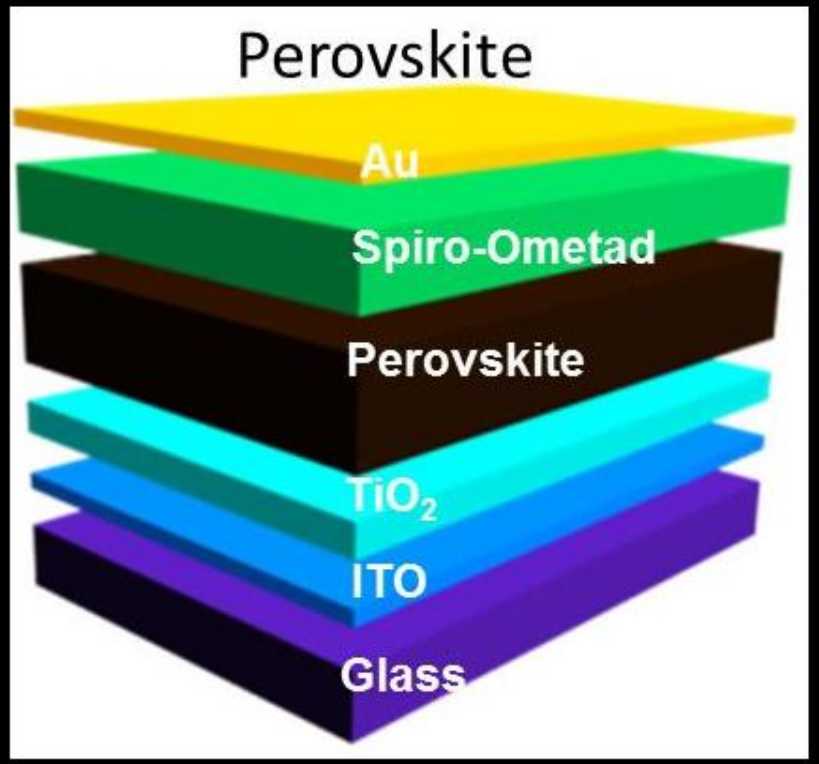


$CH_3NH_3^+$ Pb^{2+}



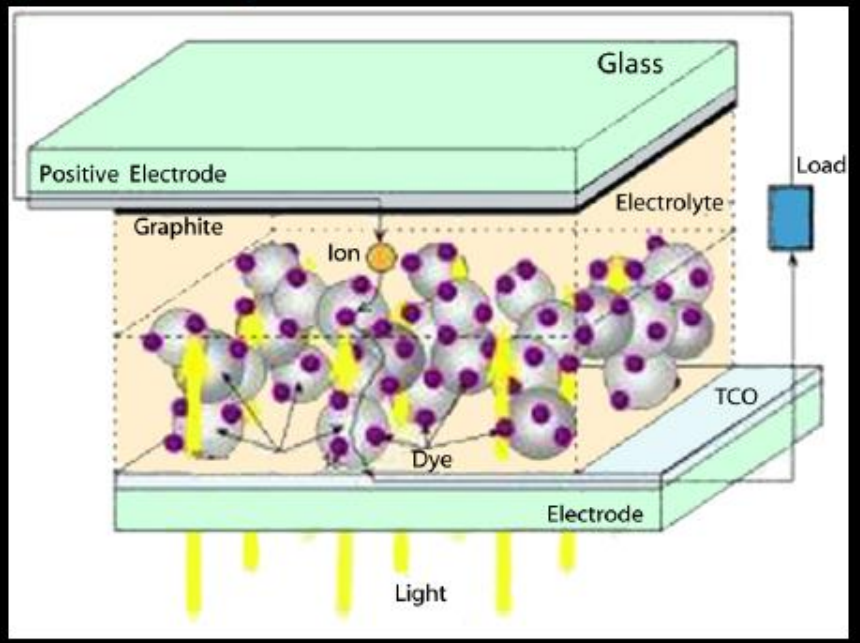
Hybrid organic-inorganic perovskites, with general formula ABX_3

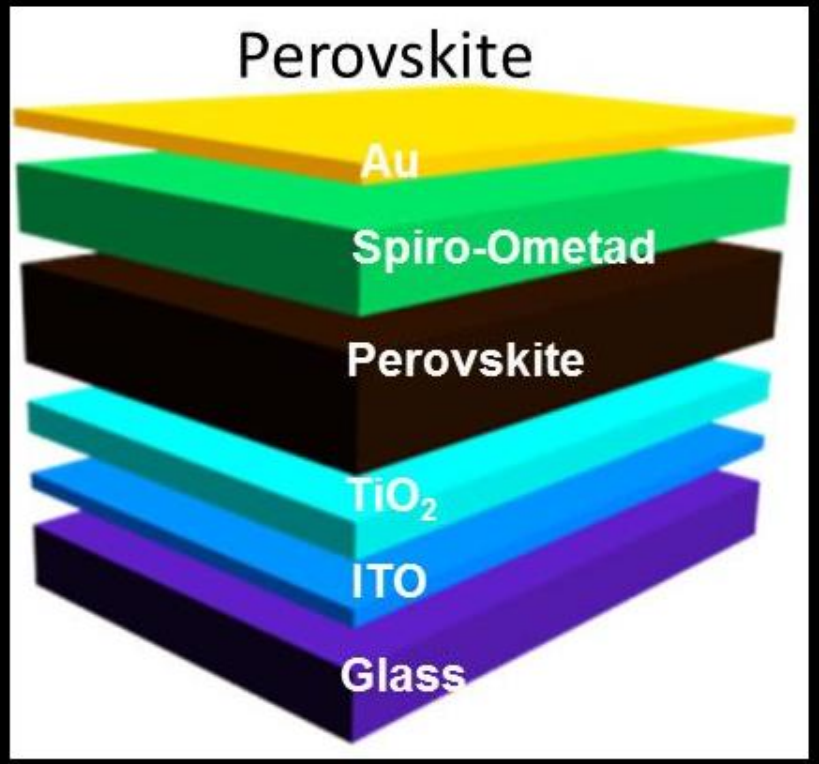
Panasonic
Kaneka
ISFH
FhG-ISE
Solexel
ZSW
SolarFron
NREL (14.7x)
First Solar
SCAS
KRICT
NREL
KRICT/UNIST
Solibro
Sharp
IBM
AIST
NREL
ICCAS
HKUST
UCLA
Heliatek
MIT
U. Toronto
U. Toronto (PbS-QD)
NREL (ZnO/PbS-QD)
Groningen
U. Linz
Siemens
Plextronics
U. Dresden
tomo
27.6%
26.6%
26.1%
23.3%
23.3%
22.9%
22.3%
22.1%
21.2%
Perovskite
14.0%
13.4%
12.6%
12.6%
11.9%
11.5%
CZTSSe
2000
2005
2010
2015
2020
(Rev. 07-17-2018)



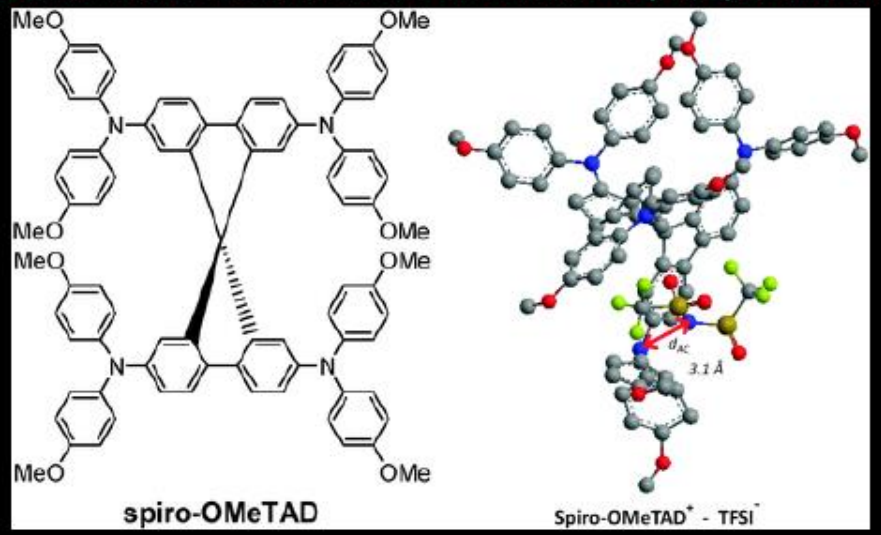
Dye-Sensitized Solar Cell (DSSC)

(Grätzel Cell)

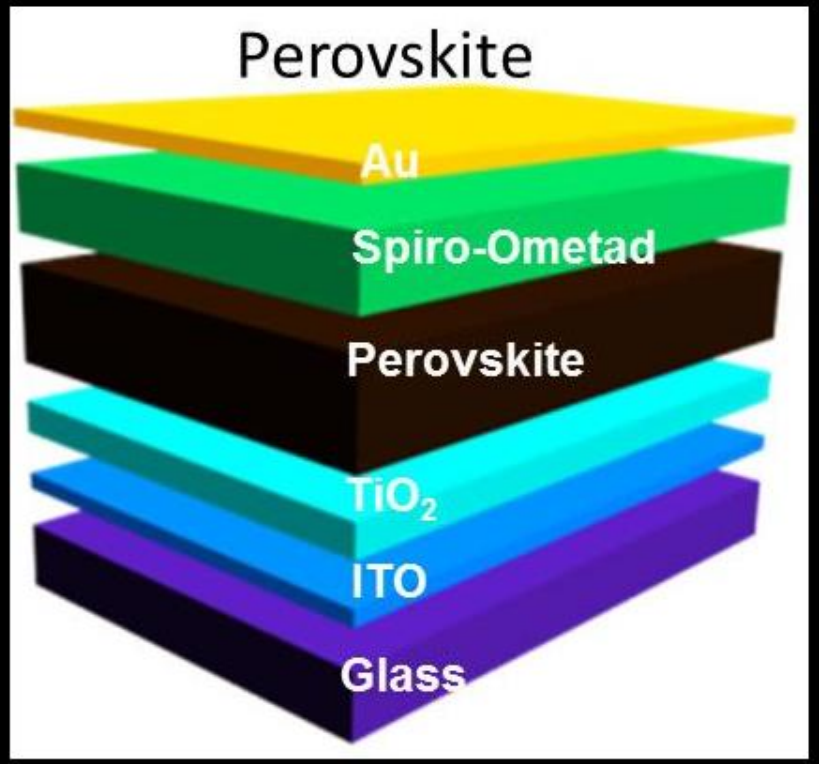


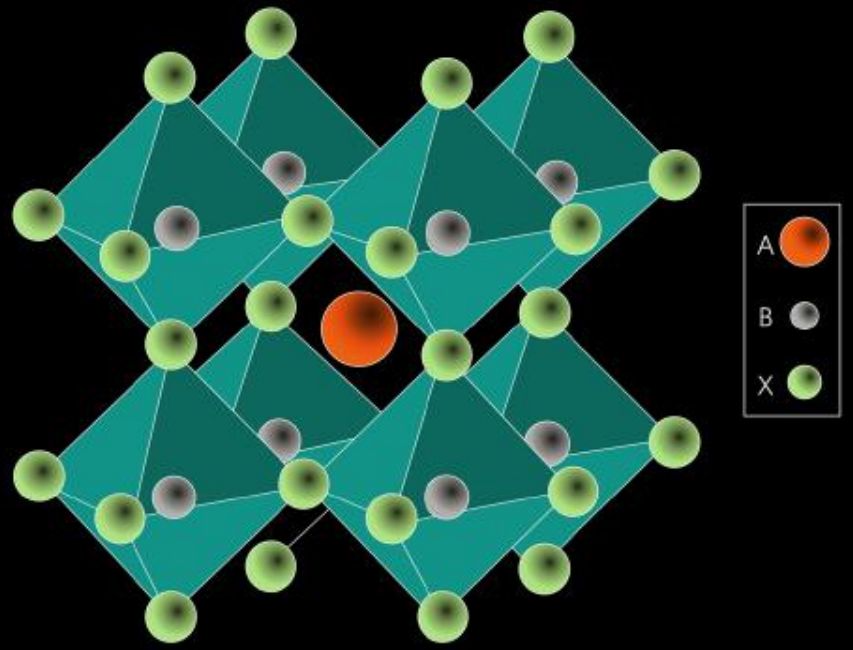


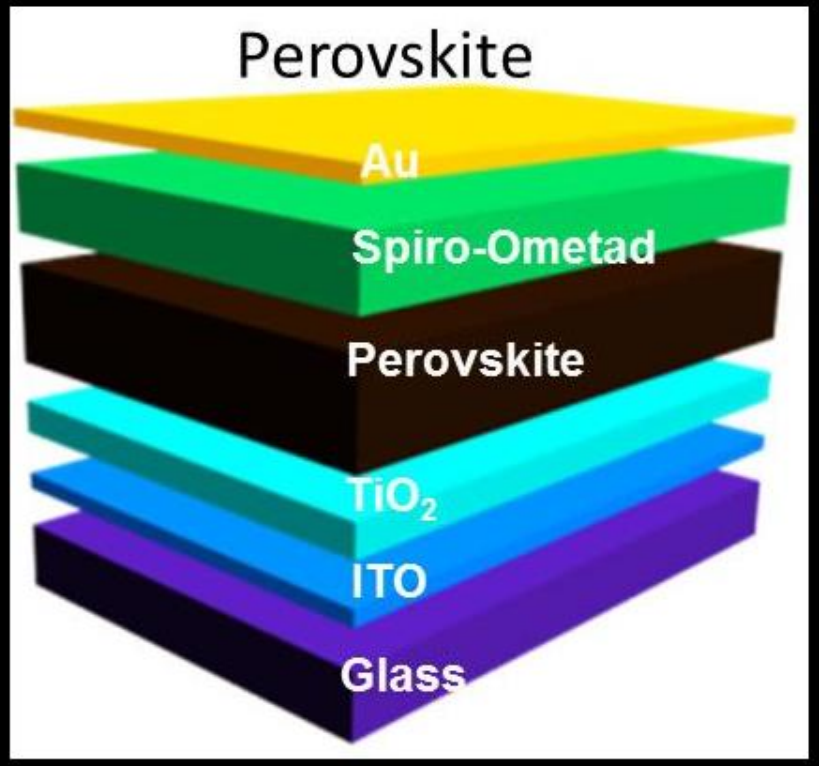
Li-TFSI: Lithium Bis-trifloromethanesulfonimide-doped spiro-MeOTAD



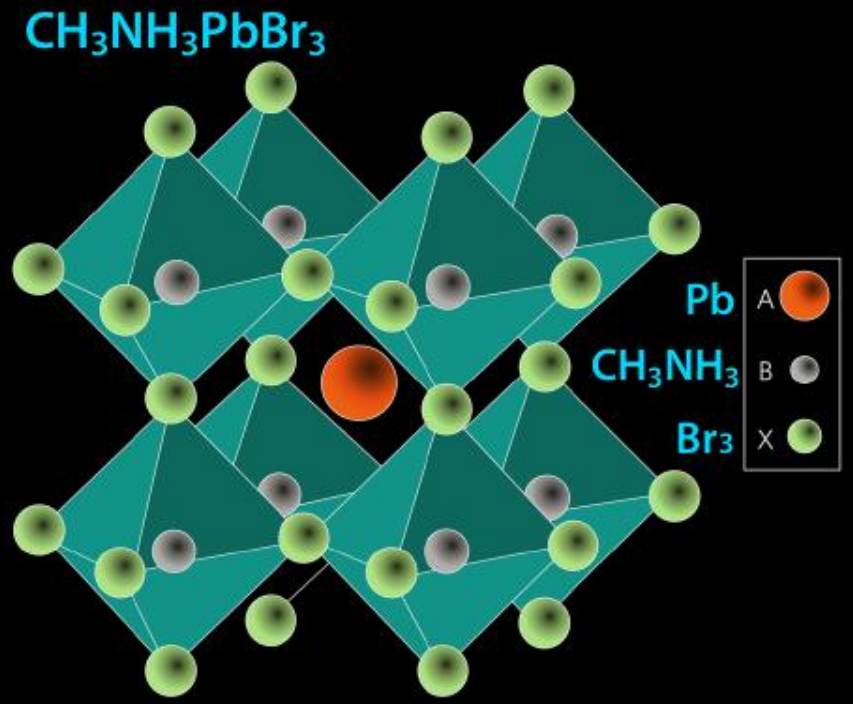
Hole Transporting Layer (Decrease charge recombination and prevent direct contact between perovskite and metal electrode)


Perovskite
Au
Spiro-Ometad
Perovskite
TiO2
ITO
Glass

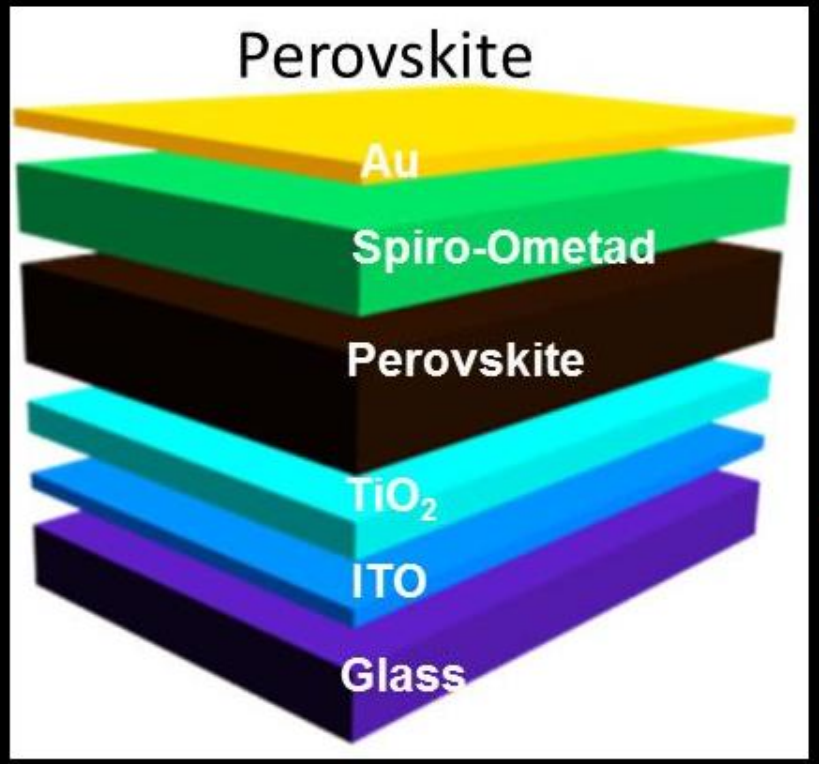

A
B
X

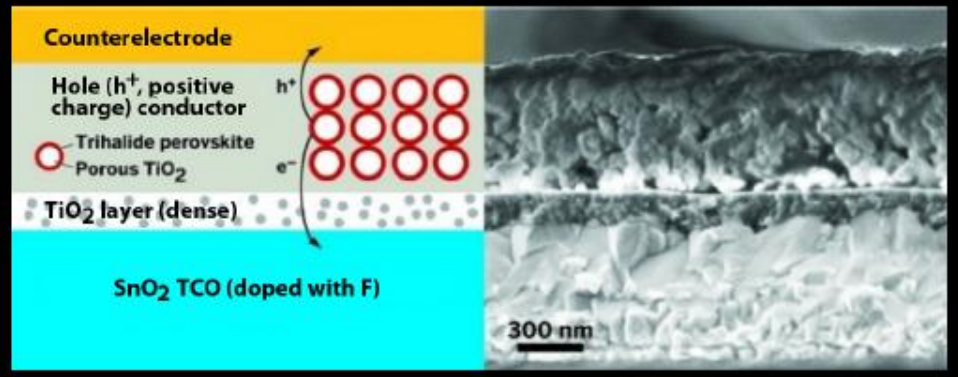


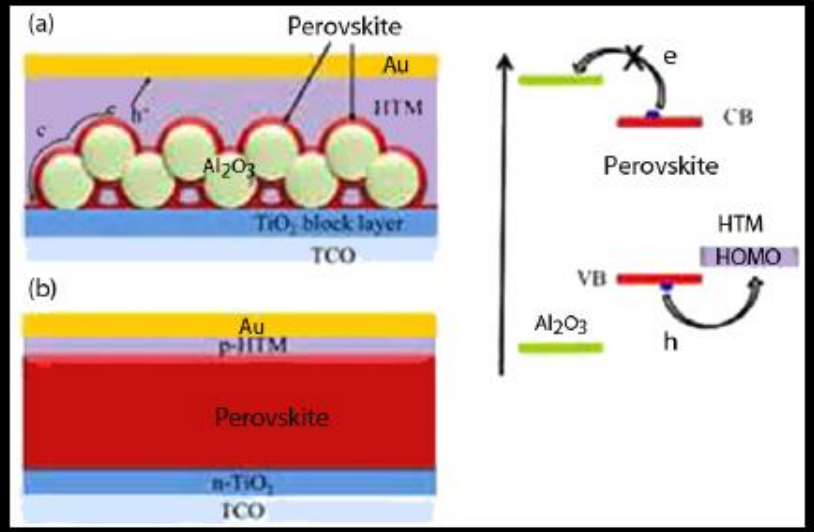
Hybid Perovskite (organic-inorganic)

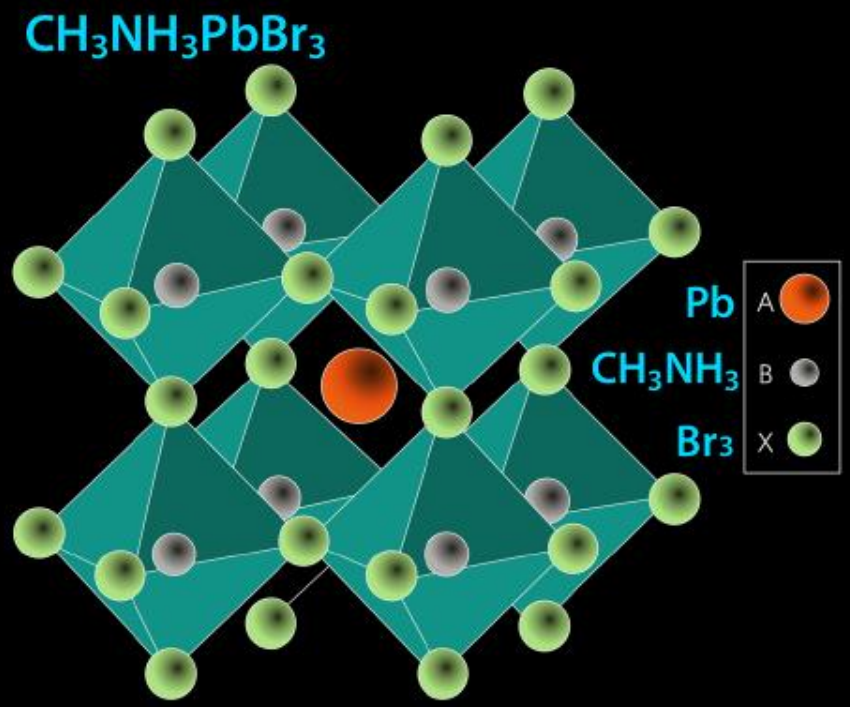


Methyl-ammonium lead halide [$(MA)PbX_3$]


Perovskite
Au
Spiro-Ometad
Perovskite
TiO2
ITO
Glass

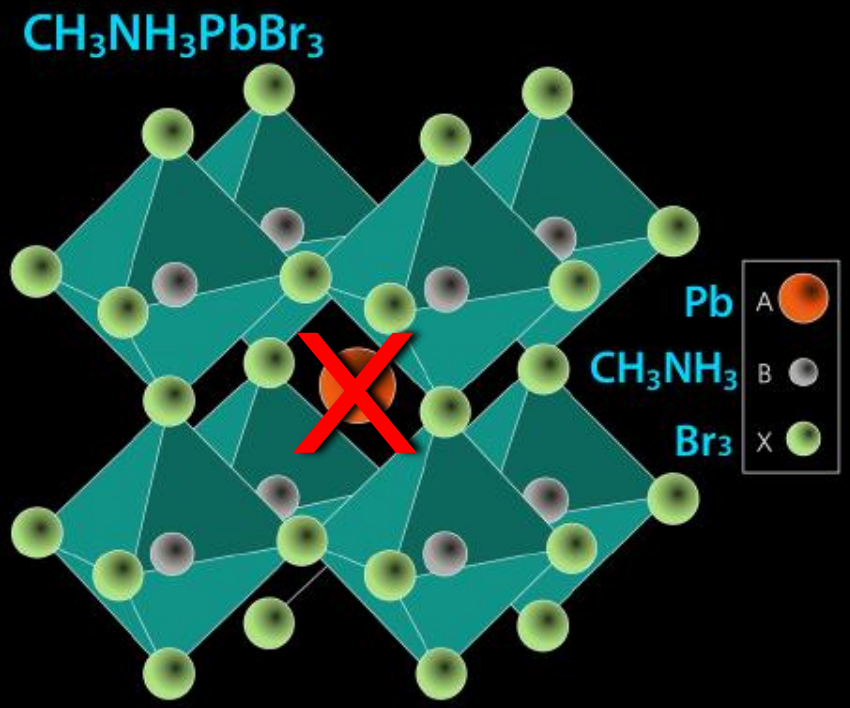

Counterelectrode
Hole (h+, positive charge) conductor
Trihalide perovskite
Porous TiO2
TiO2 layer (dense)
SnO2 TCO (doped with F)
h+
e−
300 nm


(a)
Perovskite
Au
HTM
Al2O3
TiO2 block layer
TCO
(b)
Au
p-HTM
Perovskite
n-TiO2
TCO
e
CB
Perovskite
HTM
HOMO
VB
h
Al2O3


CH3NH3PbBr3
Pb
CH3NH3
Br3
A
B
X

ISSUES *('greater than 20% in lab but . . .')*

- "Get the lead out" (toxicity)
- Stability (performance)
- Manufacturability (large area)



Innovation in Approach:
Materials by Design + Artificial Intelligence

Not your father's materials science anymore!

"Edisonian Approach" - *Conventional trial-by-error science*

"Materials-by-Design" - *Inverse process: Define desired materials functionalities and work backward to computationally define (determine) best-of-class materials*

The Mystery of the Missing Materials

Stay alert, Sherlock Holmes. The Center for Inverse Design is "afoot"!

The Center (CID)—an Office of Science Energy Frontier Research Center—is in hot pursuit of new materials with extraordinary properties. And under CID's magnifying glass is the vast materials space containing the promising A_2BX_4 spinel metal-chalcogenide and ABX half-Heusler tetrahedral compounds, which have great potential for solar-cell and other electronic and optical applications.

Curiously and unexpectedly, when CID researchers turned to the highly respected compilations of documented inorganic compounds, they found that most families of these interesting materials were *missing*!

- Were they not feasible thermodynamically?
- Or were they simply impossible to synthesize?
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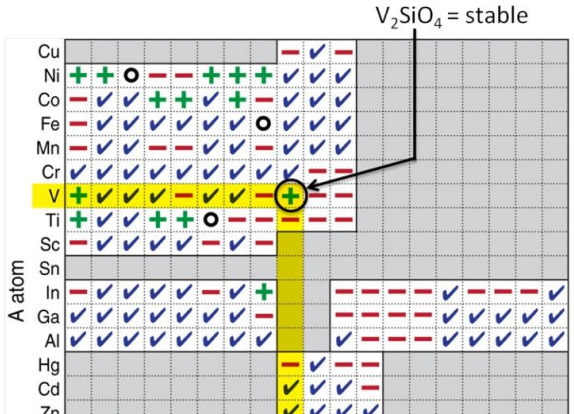
For example, in examining the A_2BX_4 spinel compounds, there are 684

"In solving a problem of this sort, the grand thing is to be able to reason backward." (*A Study in Scarlet*, 1887)

Enter the scientific sleuths—the CID inverse design partners—from the National Renewable Energy Laboratory (NREL), University of Colorado– Boulder, Northwestern University, Oregon State University, and SLAC National Accelerator Laboratory. First, the theory specialists followed the CID-developed inverse design methodology: consider design principles that relate to materials being possible because of their thermodynamic stability. *Can inverse design find some evidence for the existence of these missing materials?*



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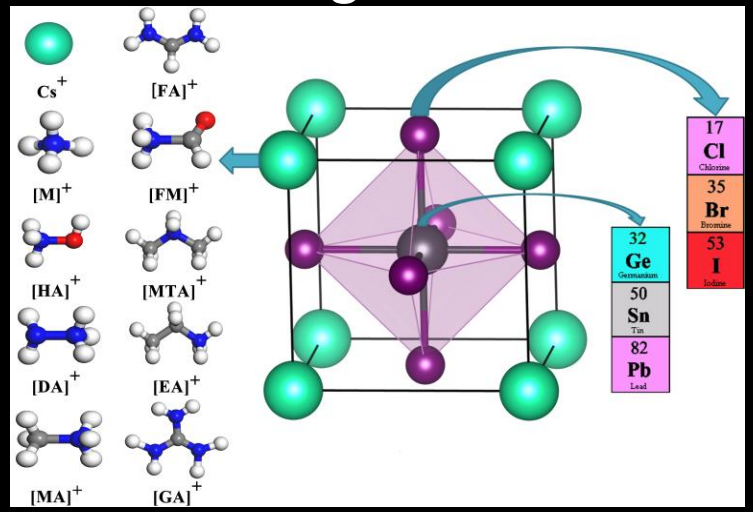
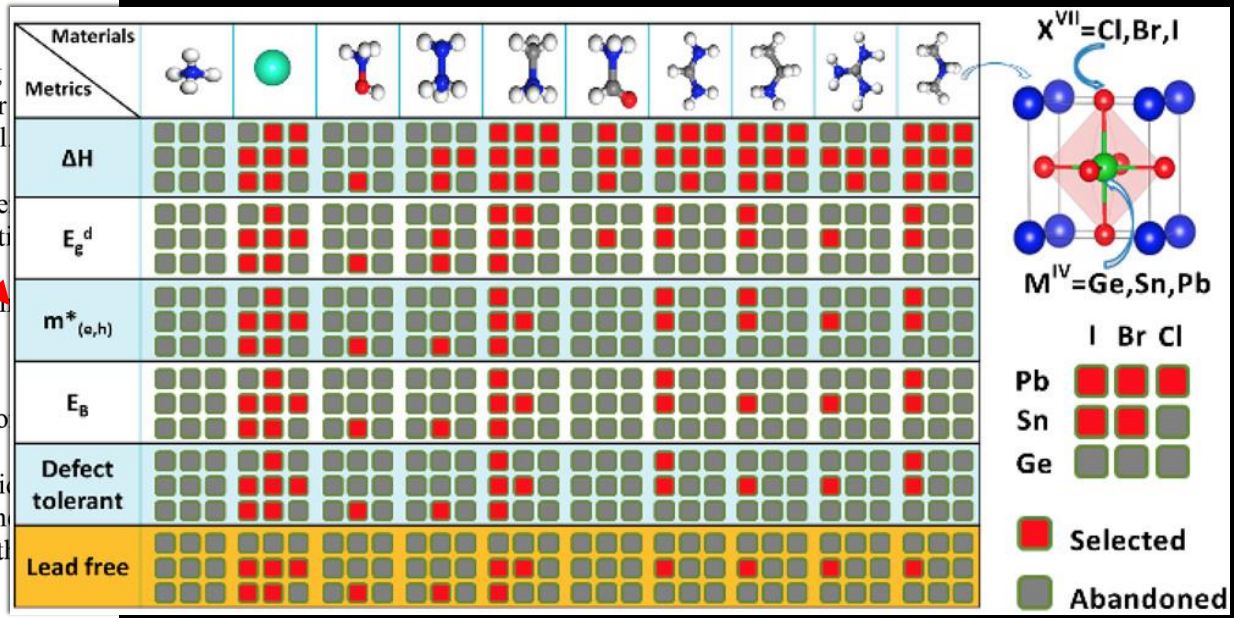
The high-throughput screening these materials is illustrated for case of V_2SiO_4, an oxide spinel. Applying first-principles thermodynamic theory, the scientists calculated the energy of formation each possible combination of elements in the spinel (see the figure below).

Results of chemical potential calculations were also plotted on triangle diagrams for pairs of elements (e.g., see the V-Si oxide triangles on the bottom of the next page). By eliminating all the other non-spinel phases, researchers discovered a "sliver" of

High-throughput inverse-design calculations



The most famous halide perovskite is $MAPbI_3$. Our target is to design other materials with comparable performance & better stability.



The Mystery of the Missing Materials

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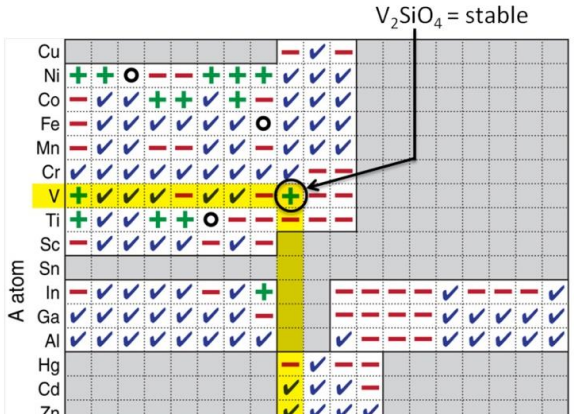

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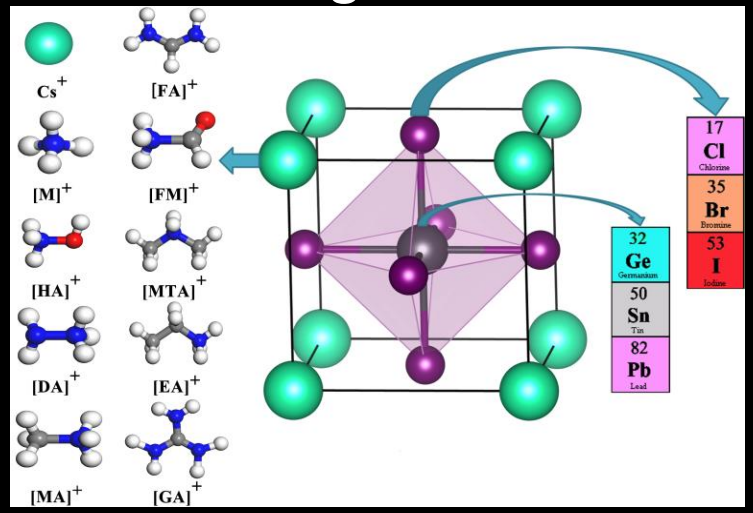

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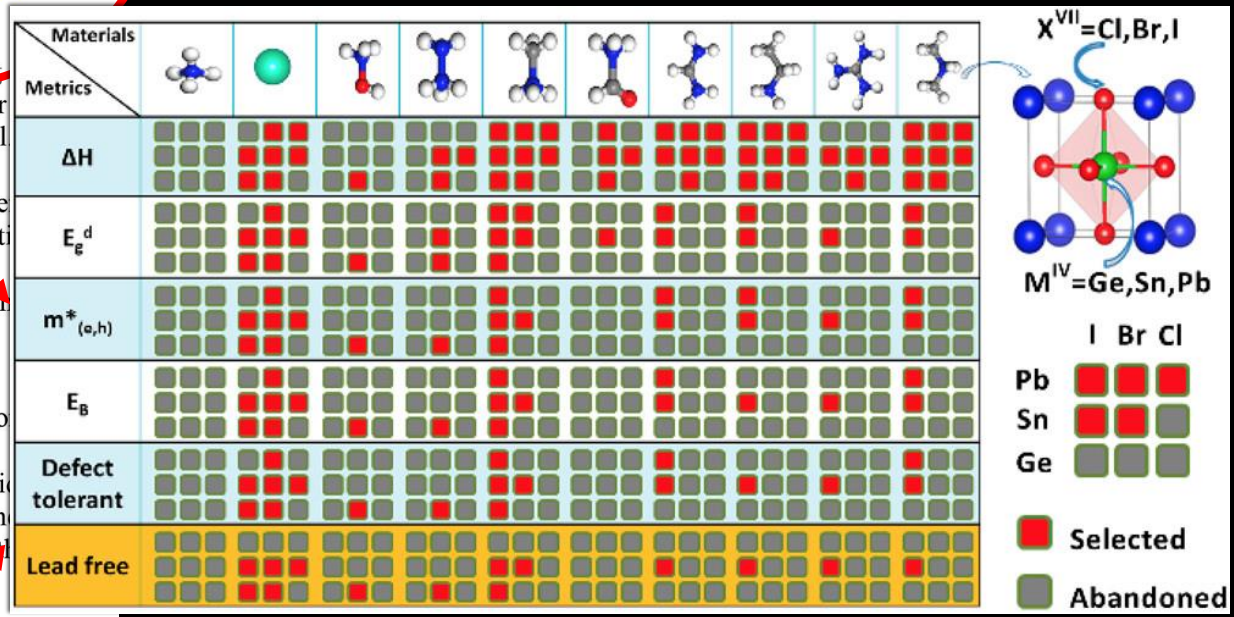
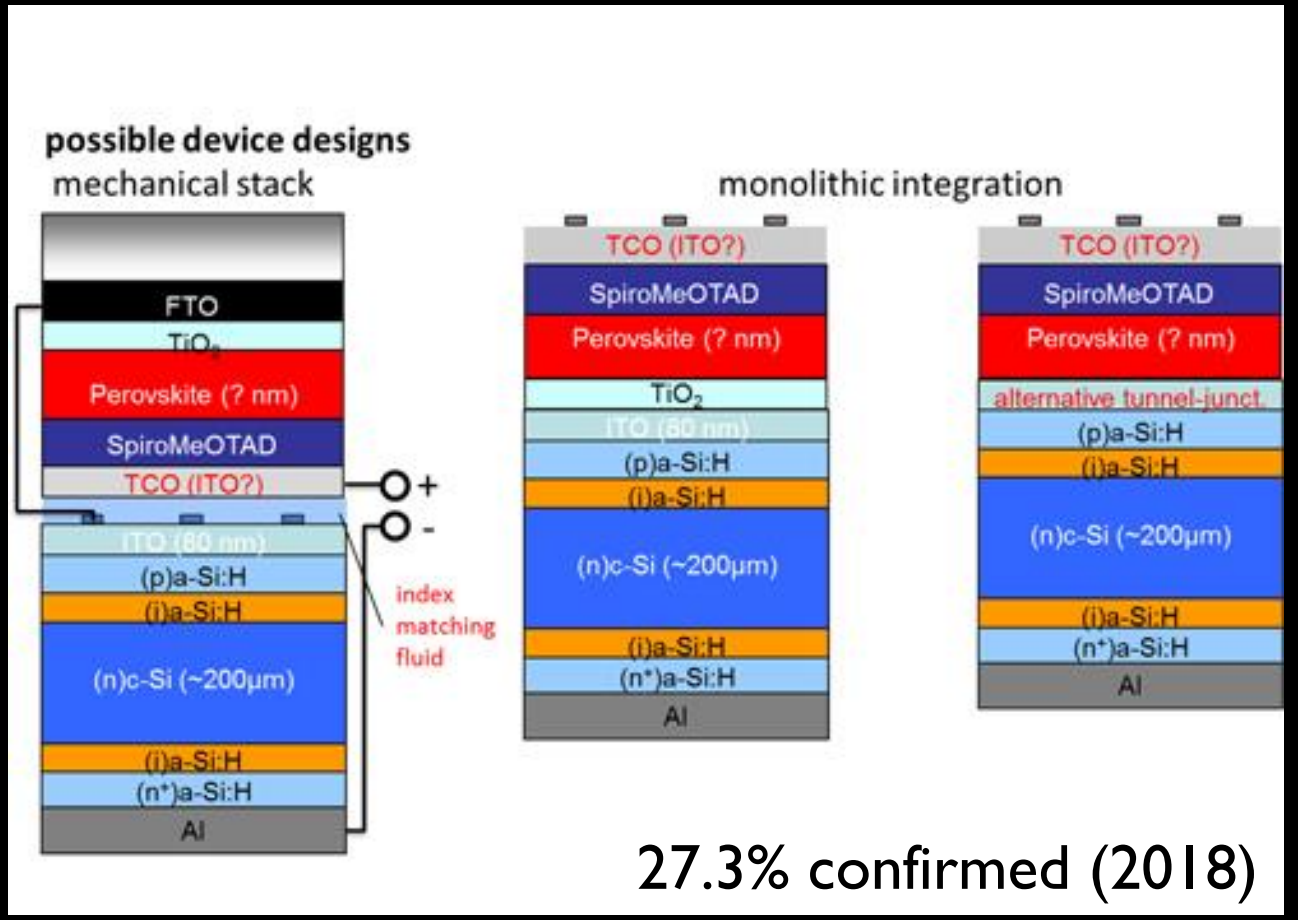


OXFORD PV

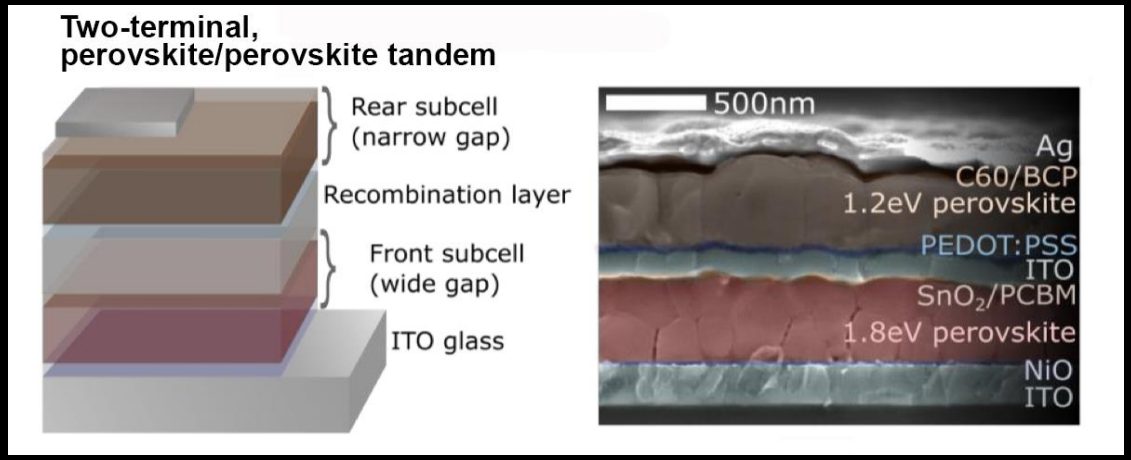
Record tandem
(perovskite on Si)



27.3% confirmed (2018)

NREL

Record tandem
(perovskite-perovskite)



>25%? (2018)


”The only thing about the future
that you couldn’t predict . . .
was the history you didn’t know.”

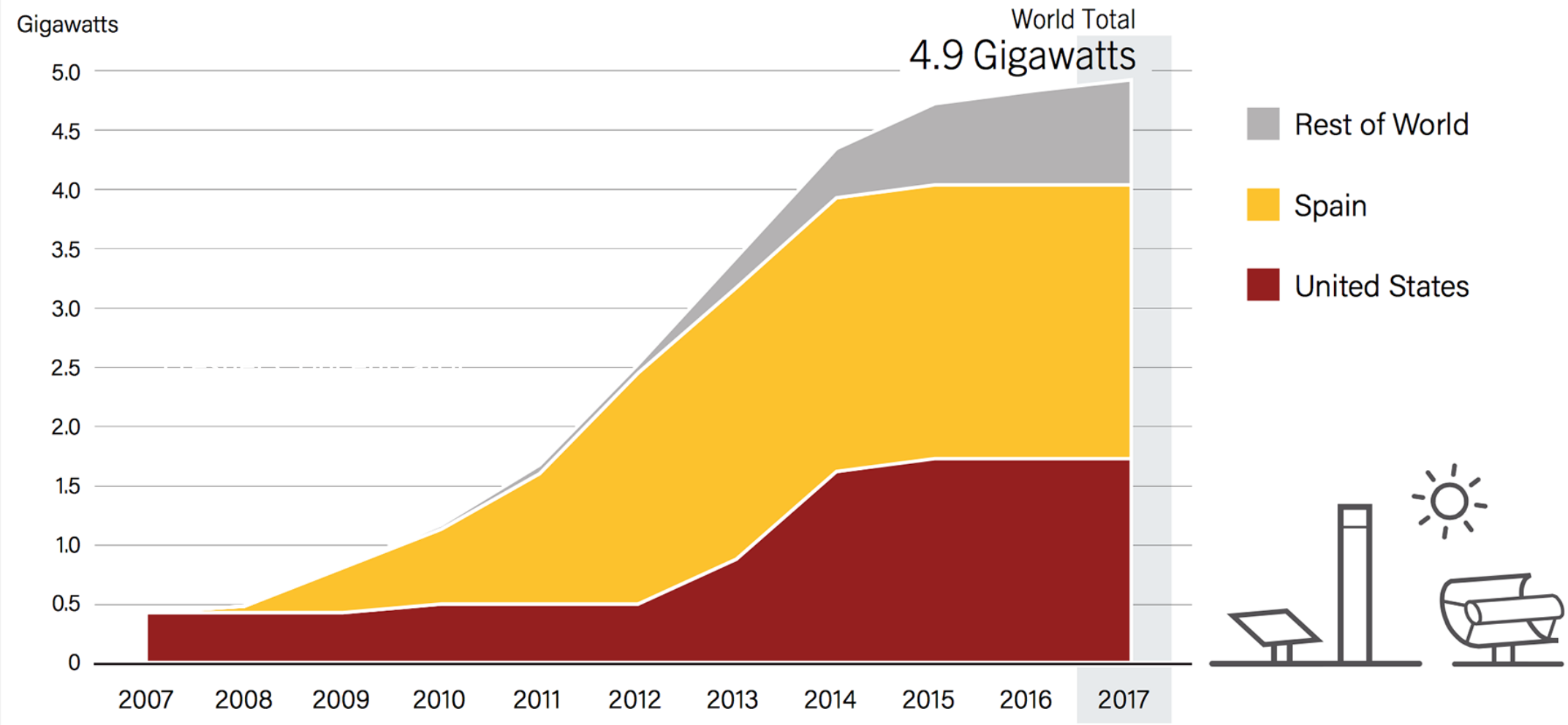

”But, it is easier to grasp the future
if you know what it should look like . . .”

Amanhã é hoje!

Muito Obrigado!

Parabolic Trough

FIGURE 28. Concentrating Solar Thermal Power Global Capacity, by Country and Region, 2007-2017



Parabolic Dish

Conc

Bioenergy
biomass, biofuels, biogas

Geothermal

Solar energy
solar PV, CSP, solar heating/cooling

Wind power

Hydropower
(small-scale)

Hydropower
(large-scale)

= 50,000 jobs

REN21

TABLE 1. Estimated Direct and Indirect Jobs in Renewable Energy, by Country and Technology

	World	China	Brazil	United States	India	Japan	Germany	Total EU[k]
	Thousand jobs							
Solar PV	**3,365**	2,216	10	233	164	272	36	100
Liquid biofuels	**1,931**	51	795[g]	299[h]	35	3	24	200
Wind power	**1,148**	510	34	106	61	5	160	344
Solar thermal heating/cooling	**807**	670	42	13	17	0.7	8.9	34
Solid biomass[a, b]	**780**	180		80[i]	58		41	389
Biogas	**344**	145		7	85		41	71
Hydropower (small-scale)[c]	**290**	95	12	9.3	12		7.3[j]	74[l]
Geothermal energy[a, d]	**93**	1.5		35		2	6.5	25
CSP	**34**	11		5.2			0.6	6
Total	**8,829[f]**	**3,880**	**893**	**786**	**432**	**283**	**332**	**1,268**
Hydropower (large-scale)[e]	**1,514**	312	184	26	289	20	7.3[j]	74[l]
Total (including large-scale hydropower)	**10,343**	**4,192**	**1,076**	**812**	**721**	**303**	**332[j]**	**1,268**

Jobs in Rene

Our technology world in 1998

First megapixel digital camera released

International Space Station:
"Zayra" first module placed in orbit

"Furby" – first domestic robot

1st Blackberry - "950"

USB flash memory (IBM "Disk on Key" 4/8 MB)

India & Pakistan conduct nuclear tests

Google incorporated in California

Nobel Prize in Chemistry to Walter Kohn
for development of Density Functional Theory (DFT)

First MP3 player

Apple iMac introduced
($1299)

wifi (1997-1999)

Windows 98
introduced by Bill Gates at Comdex

Intel Pentium II Xenon Processor introduced
(400 MHz, 512 Cache)

PayPal was founded

Reverses Einstein's "biggest blunder"
Dark energy: Cosmological constant real

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Google

Google!

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First I[illegible]

1998: 10,000 queries/day

Apple iMac introduced ($1299)

wifi (1997-1999)

Windows 98 introduced by [illegible] at Comdex

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Google

2018: 60,000,000 queries/day

Or about 10,000 per 0.25 second!

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First m amera released

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mdex

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PayPal was founded

Reverses
Dark energy:

1998: *1*-Megapixel camera and 32 MB music
0.10 Hollywood movie
~10-20 songs

2018: *12-20* Megapixel camera and 512 GB music
~500 Hollywood movies
~125,000 songs

Our technology world in 1998

First megapixel digital camera released

USB flash memory (IBM "Disk on Key" 4/8 MB)

1st Blackberry - "950"

International Space Station:
"Zayra" first module placed in orbit

"Furby" – first domestic robot

India &

sts

Google

rated in California

1998: 8 MB

First MP3 player

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for d

Kohn
heory (DFT)

wifi (1997-1999)

Windows 98
by Bill Gates at Comdex

2018: 512 MB – 2 TB

Reverses Einstein's "biggest blunder"
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1998: "Furby" –
Simple mechanical movements
Spoke "Furbish" language that evolved to simple English words over time
"Learned"?
Robot value: Entertainment

2018: "Roomba", "China Rose"

Our technology world in 1998

orbit

"Furby" – first domestic robot

1998: Domestic Robot

clear tests

mistry to Walter Kohn
sity Functional Theory (DFT)

Windows 98
iced by Bill Gates at Comdex

2018: Alpha II

PayPal was founded

Reverses Einstein's "biggest blunder"
Dark energy: Cosmological constant real

Other world events in 1998

Tony Blair
Prime Minister of U.K.

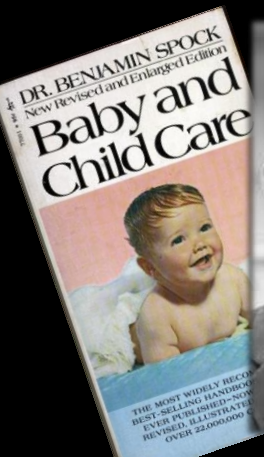
William Clinton
President of U.S.

Oscar for best film:
Titanic

British Pound
1998: 1.61 BP/US$
2018: 1.31 BP/US$

EU agrees to "EURO" currency
1st issue – January 1, 1999

Top song in U.K.:
"No Matter What"



Dr. Benjamin Spock
(1903-1998)

Ferdinand A.E.
Porsche
(1909-1998)

Linda McCartney
(1941-1998)

Sinto *muito* . . .

Copa do Mundo –
France 3 Brasil 0

Wind Energy

FIGURE 34. Wind Power Global C

Gigawatts

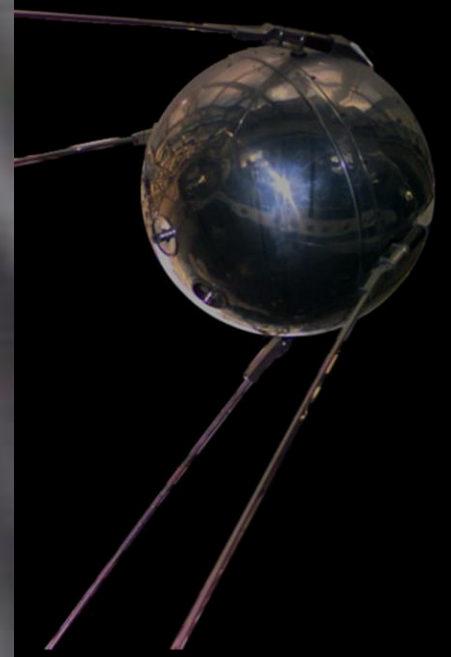
600

UNIVERSAL-INTERNATIONAL NEWS

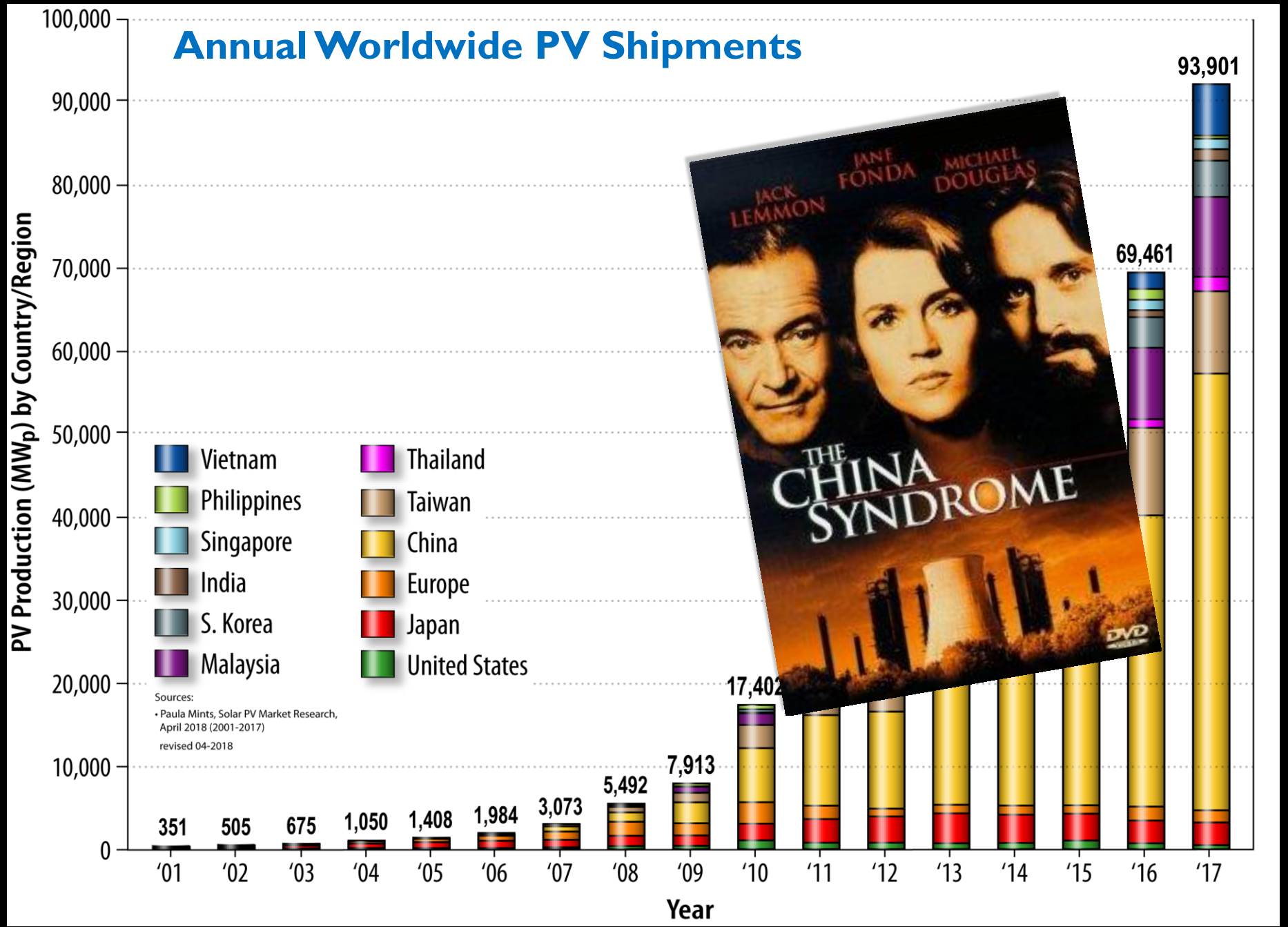
NEW MOON

Reds Launch First Space Satellite

VOICE: ED HERLIHY



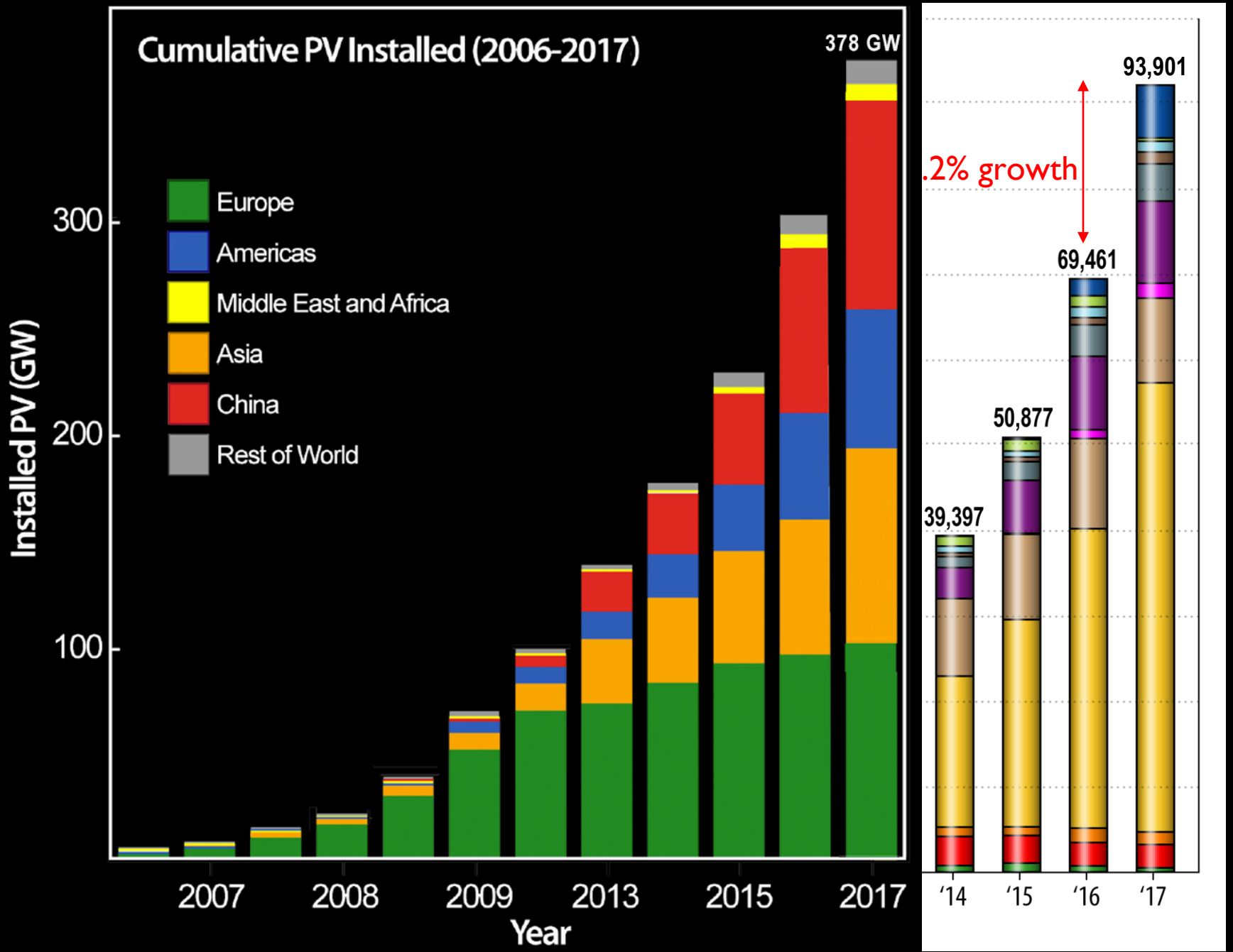
World PV Shipments 2001-2017: *Where we are*



Objectives

- Explore the history of this PV technology
- Establish where we are today
- Examine where we expect to be in the future

World PV Shipments 2006-2017: *Where we are*



94 Gigawatts
in 1-year!

Arguments for Thin-Film PV

- Semiconductors

Direct bandgap: more-efficient light absorbers

Thinner layers required to absorb sunlight–better materials utilization

Semiconductor bandgaps well-matched to solar spectrum
and some tunability

Diversity of semiconductors

Diversity of device structures

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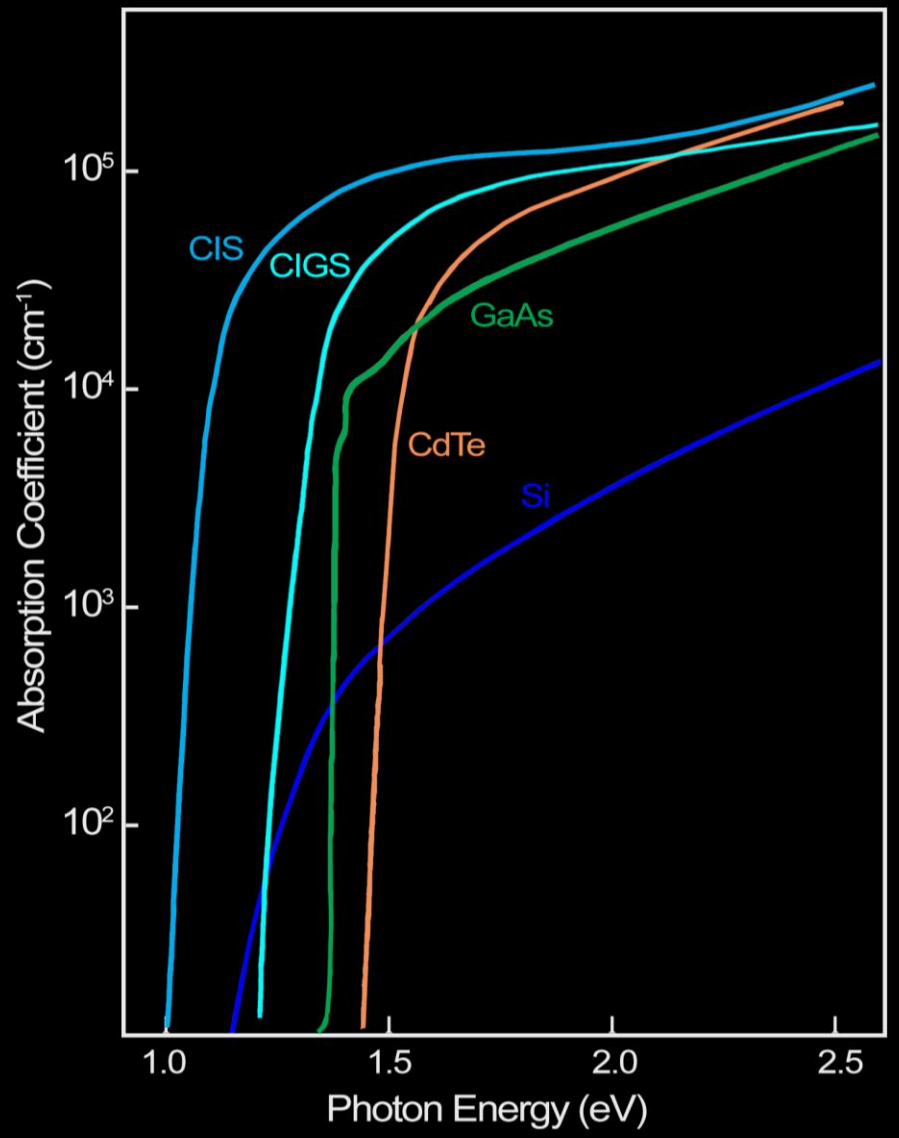
- Semiconductors

  Direct bandgap: more-efficient light absorbers

  -better materials utilization

  solar spectrum



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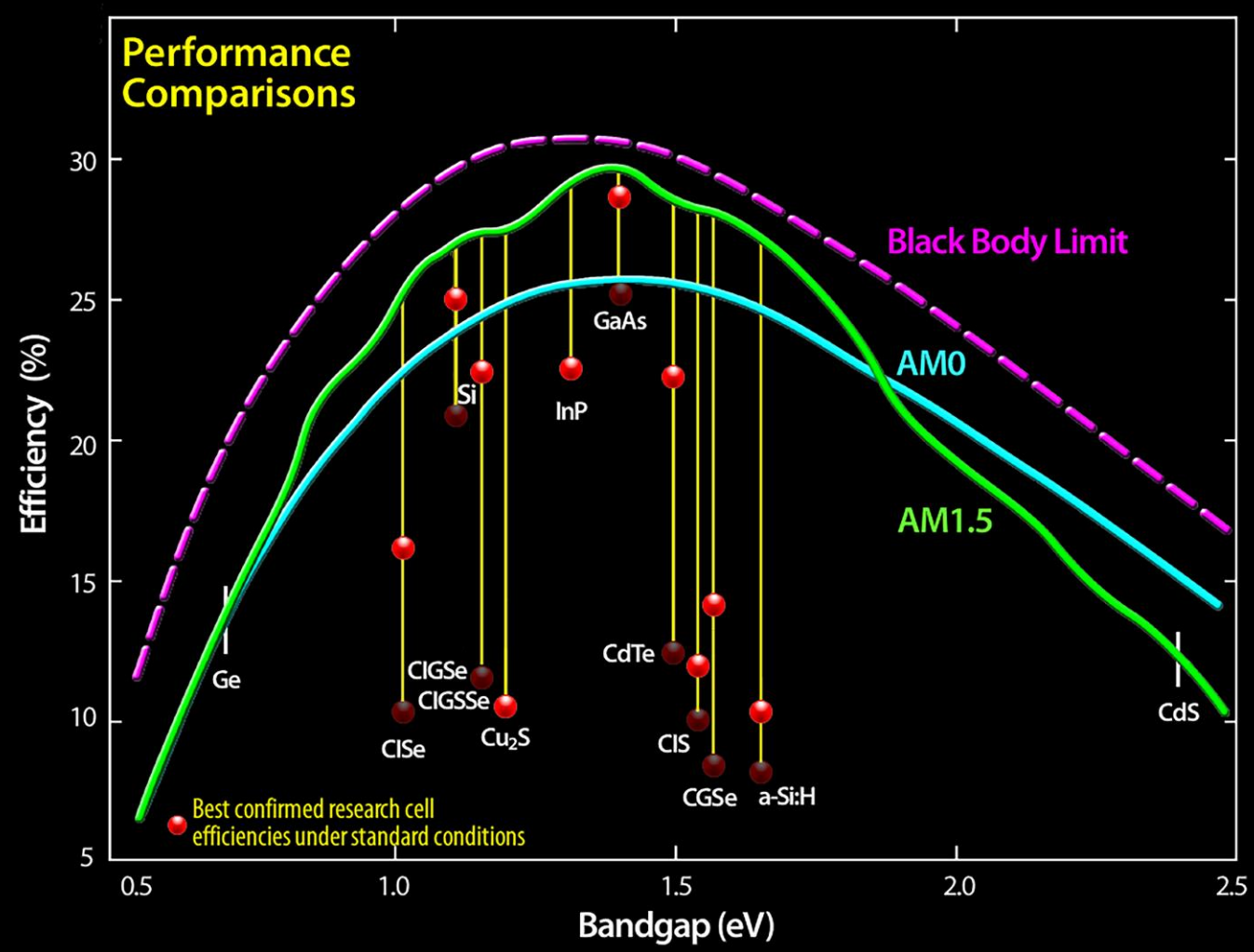

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  Direct bandgap: more-efficient light absorbers

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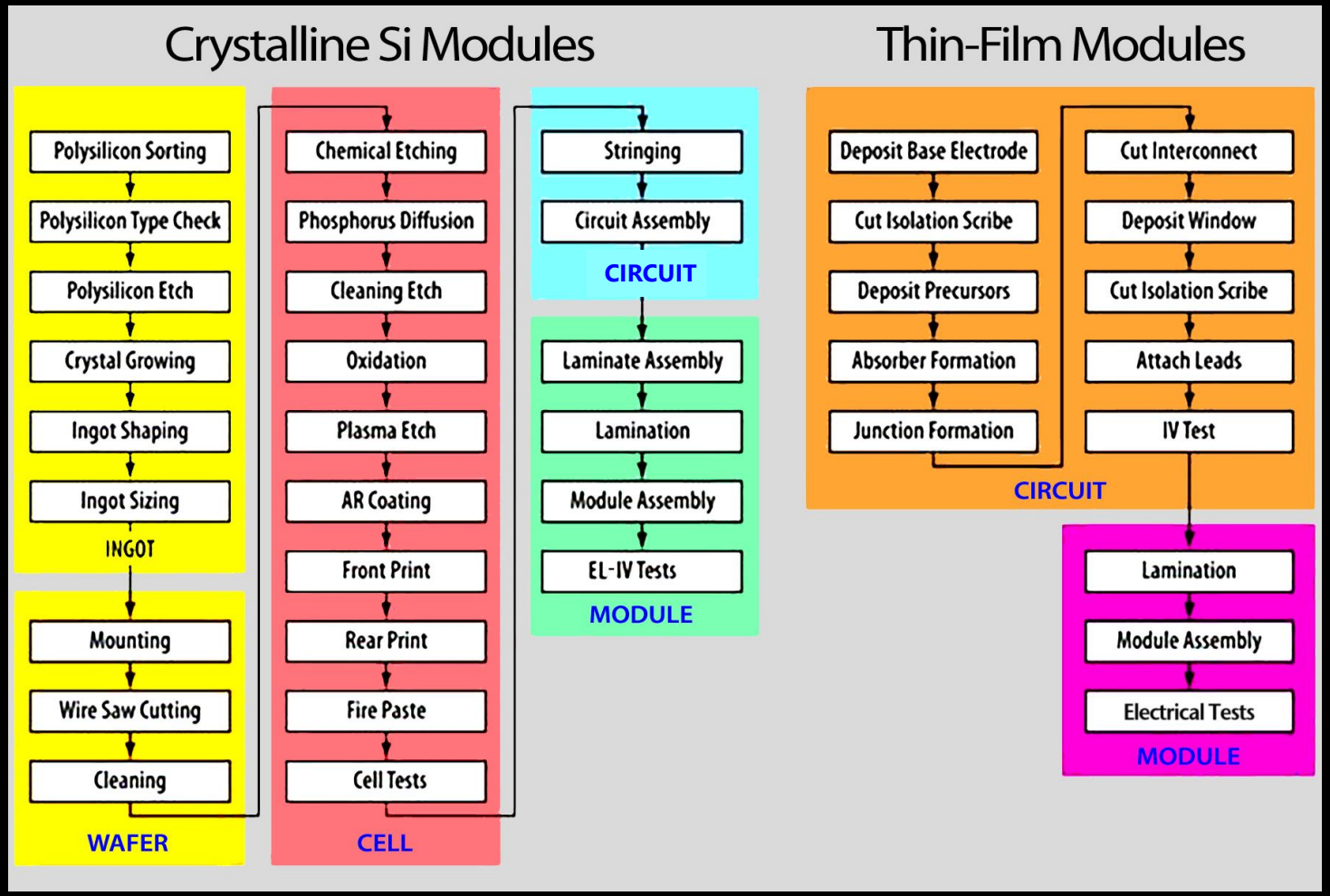
  Semiconductor bandgaps well-matched to solar spectrum and some tunability

  Diversity of semiconductors

  Diversity of device structures

- Fewer Processing Steps



Innovation

Energy

Technology

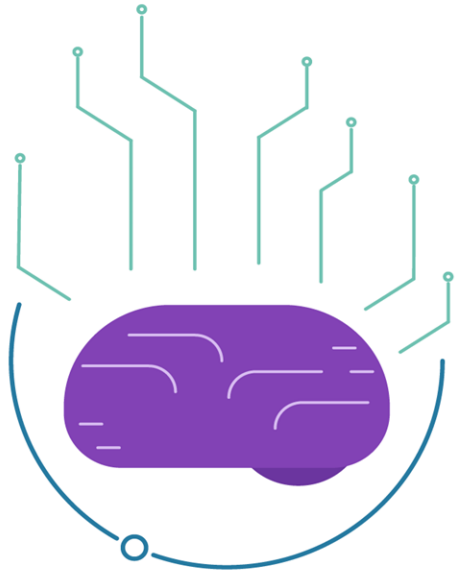
Artificial intelligence (AI) (also called "*machine learning*") is an area of computer science that emphasizes the creation of intelligent machines or operations that work and react like humans. Some of the activities for which computers with *artificial intelligence* are designed include:

- Speech recognition
- Learning
- Planning
- Problem solving
- Design

Artificial intelligence (AI) (also called "*machine learning*") is an area … on of intellige… …me of the acti… …nce are designe…

- Spee…
- Lear…
- Plan…
- Prob…

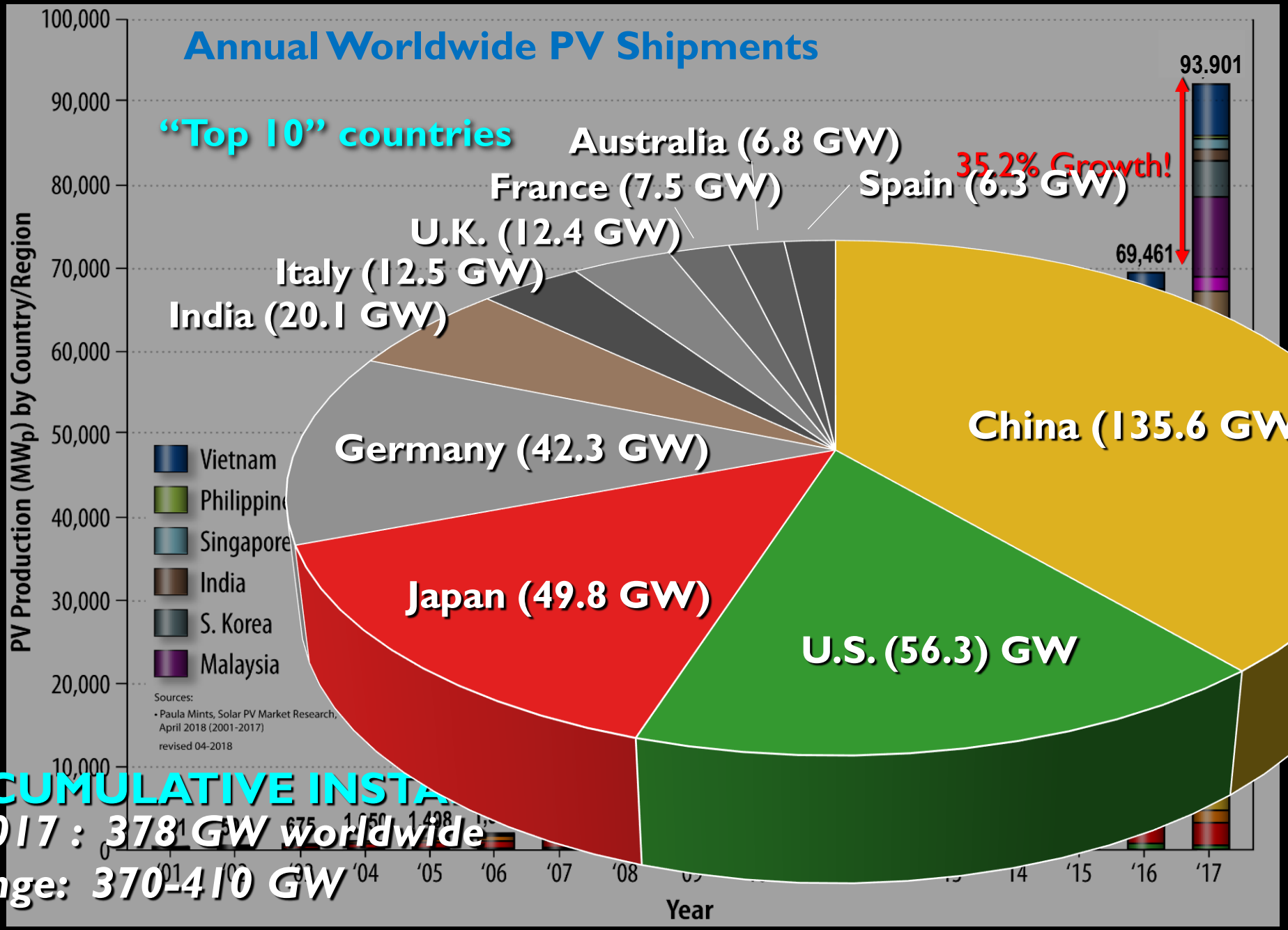
WHAT IS MACHINE LEARNING?



Machine learning, by definition, is any technology that uses algorithms to try to create repeatable results. When you talk about machine learning, you're talking about machine learning algorithms, no matter what form they may take.

Another way to put this is that the algorithms allow the machine to learn from its operations. The process is iterative – as the machine runs, it works on new sets of data to provide insights.

Much of what the algorithms do involves extrapolating from available data. Essentially, the algorithms are taking in that available data and parsing it, evaluating it and comparing different data pieces to come up with results.



TOTAL CUMULATIVE INSTA

1975 – 2017 : 378 GW worldwide

Range: 370-410 GW

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- Or were they simply impossible to synthesize?
- Or were they somehow overlooked by those meticulous encyclopedias amassed by Inorganic Crystal Structure Database, Bergerhoff and Brown, the International Centre for Diffraction Data Power Diffraction Files, and Wyckoff?

For example, in examining the A_2BX_4 spinel compounds, there are 684 possible combinations of elements that may be tabulated. Yet, only 255 combinations have been reported. For the 714 ABX compounds, only 226 are in the literature. The mystery is: *What happened to the missing 429 spinels and the 488 half-Heuslers?*

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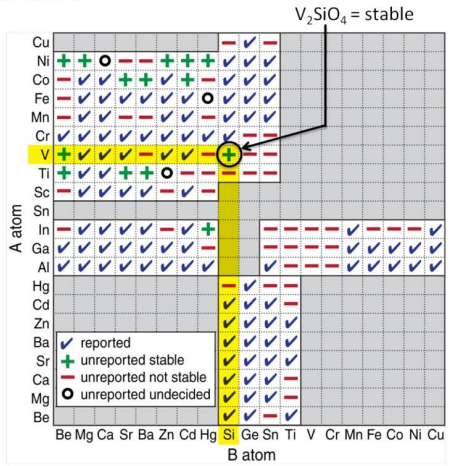
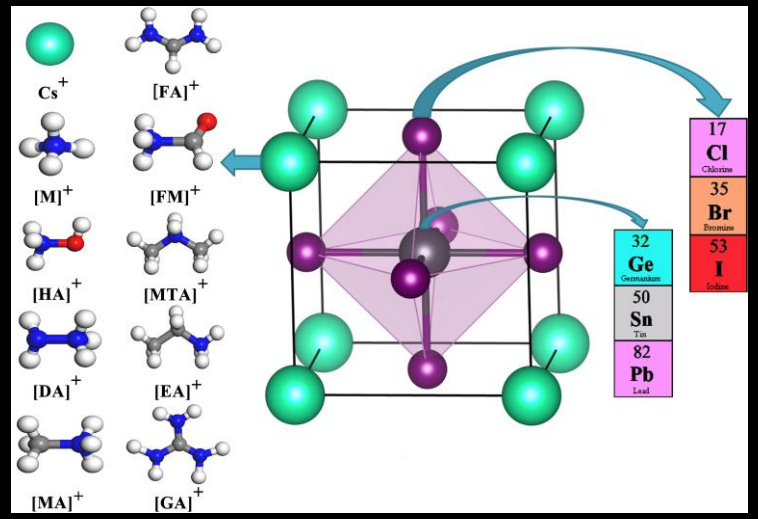
The high-throughput screening of these materials is illustrated for the case of V_2SiO_4, an oxide spinel. Applying first-principles thermodynamic theory, the scientists calculated the energy of formation for each possible combination of elements in the spinel (see the matrix below).

Results of chemical potential calculations were also plotted onto triangle diagrams for pairs of elements (e.g., see the V-Si oxide triangles on the bottom of the next page). By eliminating all the other non-spinel phases, researchers discovered a "sliver" of possibilities—an undiscovered material that should be stable according to it predicted pressure and temperature conditions. A missing material was discovered.



Matrix for A_2BO_4 showing that of the 164 possibilities, only 101 compounds are reported. Of the 63 unreported compounds, 14 are stable, 49 are not stable, and 3 are still undetermined. V_2SiO_4 is highlighted as unreported, but predicted to be stable.

High-throughput inverse-design calculations



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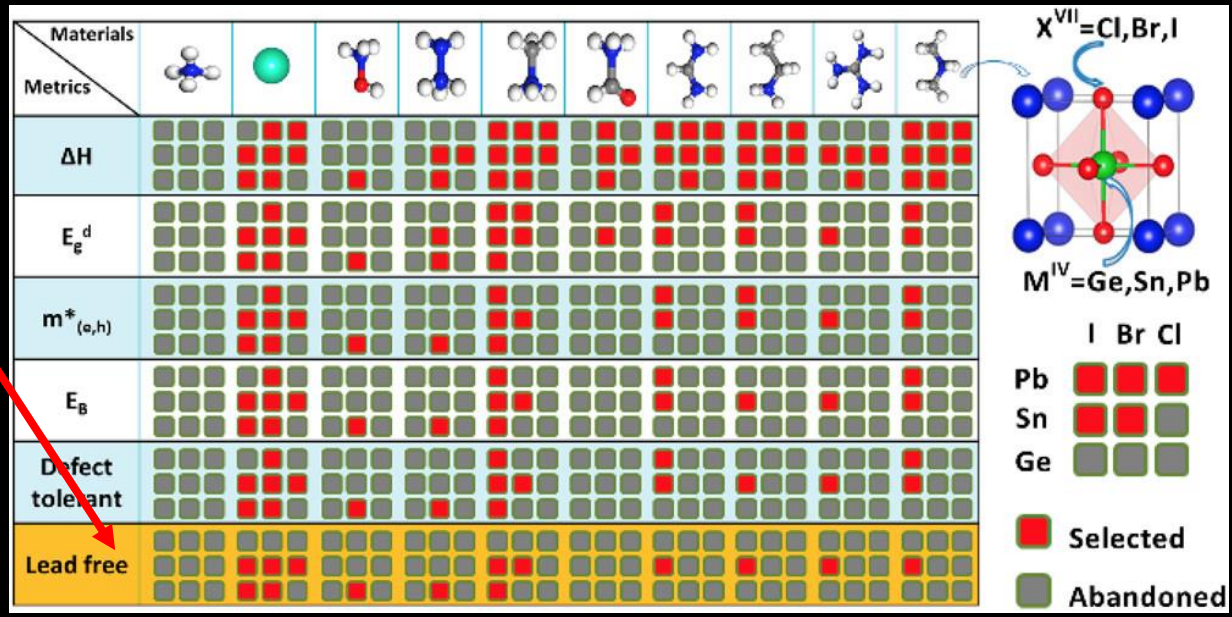
Target functionalities



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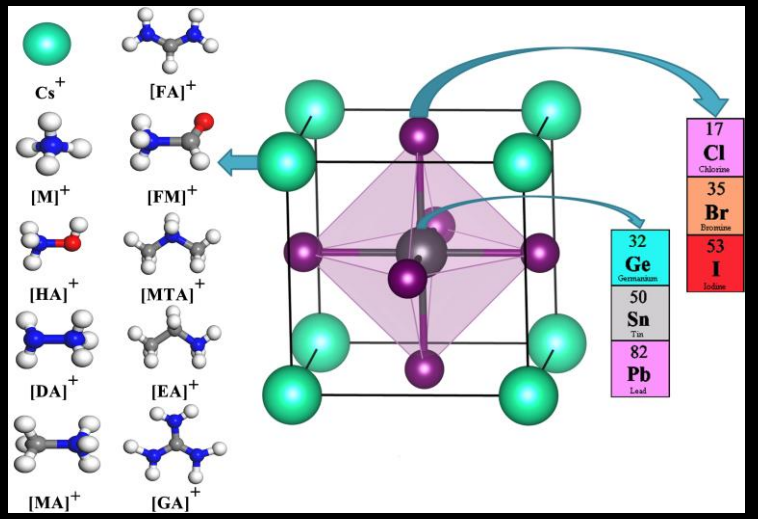

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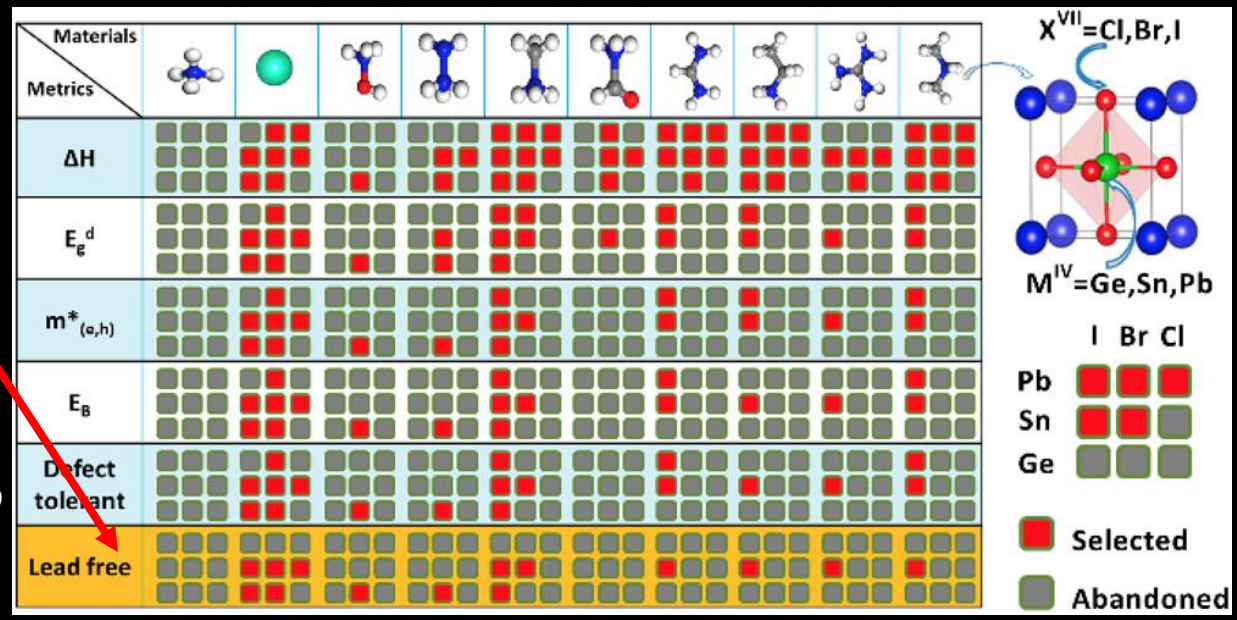

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Frontier Research
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er tetrahedral
ch have great
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otical applications.

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turned to the highly
lations of
rganic compounds,
most families of these
rials were *missing*!
feasible
cally?
simply impossible to

somehow overlooked
culous
amassed
Crystal
base,
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Data
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"In solving a problem of this sort, the grand thing is to be able to reason backward." (*A Study in Scarlet*, 1887)

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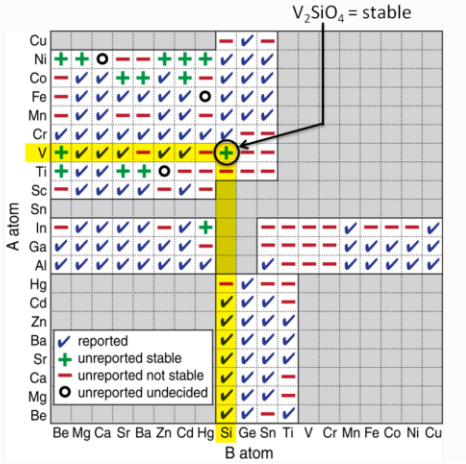

Matrix for A_2BO_4 showing that of the 164 possibilities, only 101 compounds are reported. Of the 63 unreported compounds, 14 are stable, 49 are not stable, and 3 are still undetermined. V_2SiO_4 is highlighted as unreported, but predicted to be stable.

"When you have eliminated the impossible, whatever remains, however improbable, must be the truth." (*Sign of the Four*, 1890)

The high-throughput screening of these materials is illustrated for the case of V_2SiO_4, an oxide spinel. Applying first-principles thermodynamic theory, the scientists calculated the energy of formation for each possible combination of elements in the spinel (see the matrix below).

Results of chemical potential calculations were also plotted onto triangle diagrams for pairs of elements (e.g., see the V-Si oxide triangles on the bottom of the next page). By eliminating all the other non-spinel phases, researchers discovered a "sliver" of possibilities—an undiscovered material that should be stable according to it predicted pressure and temperature conditions. A missing material was discovered.

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The Mystery of the Missing Materials

Stay alert, Sherlock Holmes. The Center for Inverse Design is "afoot"!

The Center (CID)—an Office of Science Energy Frontier Research Center—is in hot pursuit of new materials with extraordinary properties. And under CID's magnifying glass is the vast materials space containing the promising A_2BX_4 spinel metal-chalcogenide and ABX half-Heusler tetrahedral compounds, which have great potential for solar-cell and other electronic and optical applications.

Curiously and unexpectedly, when CID researchers turned to the highly respected compilations of documented inorganic compounds, they found that most families of these interesting materials were *missing*!

- Were they not feasible thermodynamically?
- Or were they simply impossible to synthesize?
- Or were they somehow overlooked by those meticulous encyclopedias amassed by Inorganic Crystal Structure Database, Bergerhoff and Brown, the International Centre for Diffraction Data Power Diffraction Files, and Wyckoff?

For example, in examining the A_2BX_4 spinel compounds, there are 684 possible combinations of elements that may be tabulated. Yet, only 255

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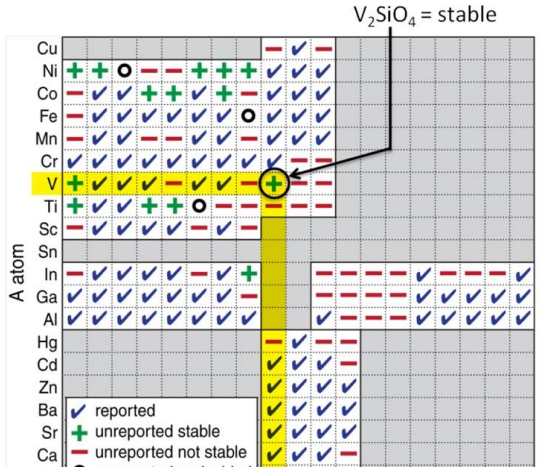

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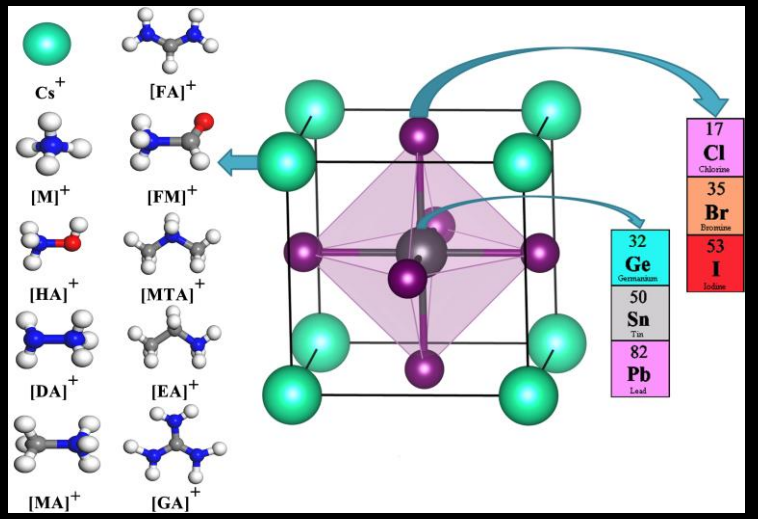
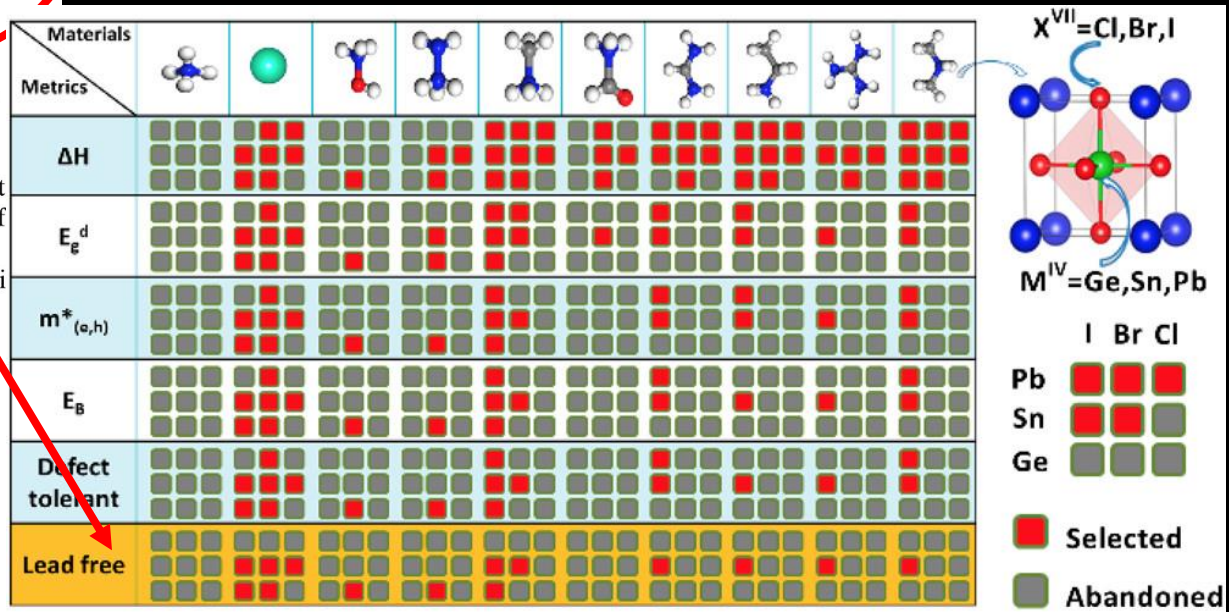
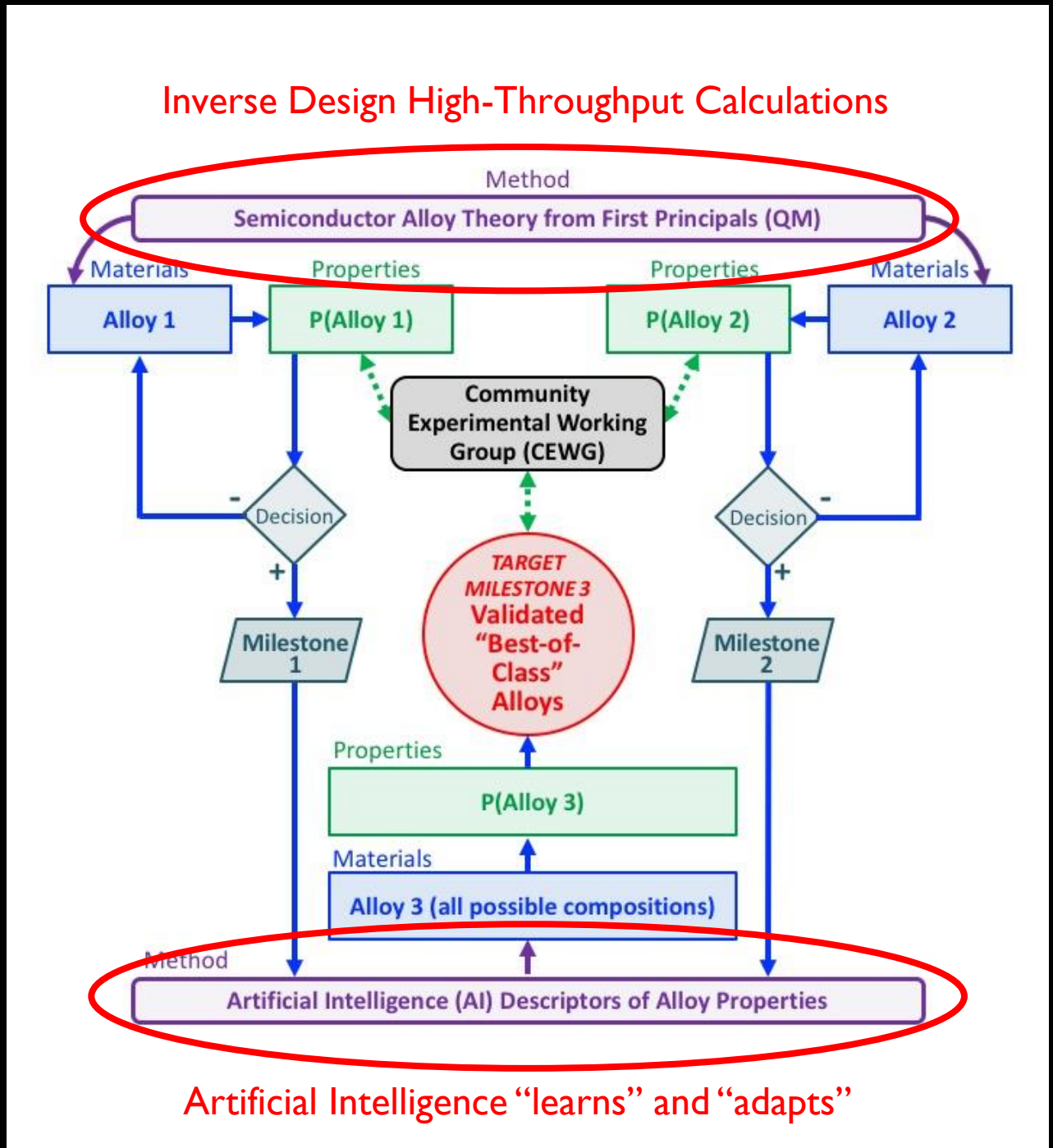
-throughput inverse-design calculations



famous halide perovskite is $MAPbI_3$. Our target is to design rials with **comparable performance** & **better stability.**



Materials Design with Artificial Intelligence



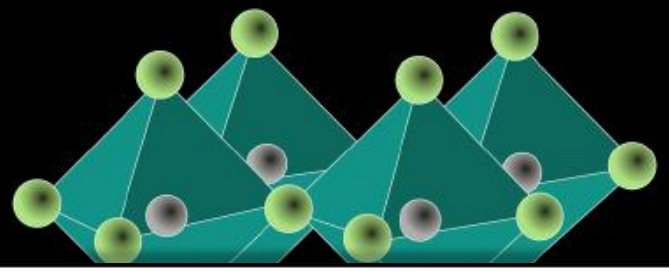
Varieties of Perovskites

Methyl-ammonium lead halide [$(MA)PbX_3$]

$(MA)GeI_3$
$(MA)SnI_3$
$(MA)PbI_3$

Oxide-Perovskites

ABO_3
A_2BO_4

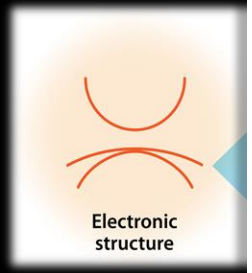


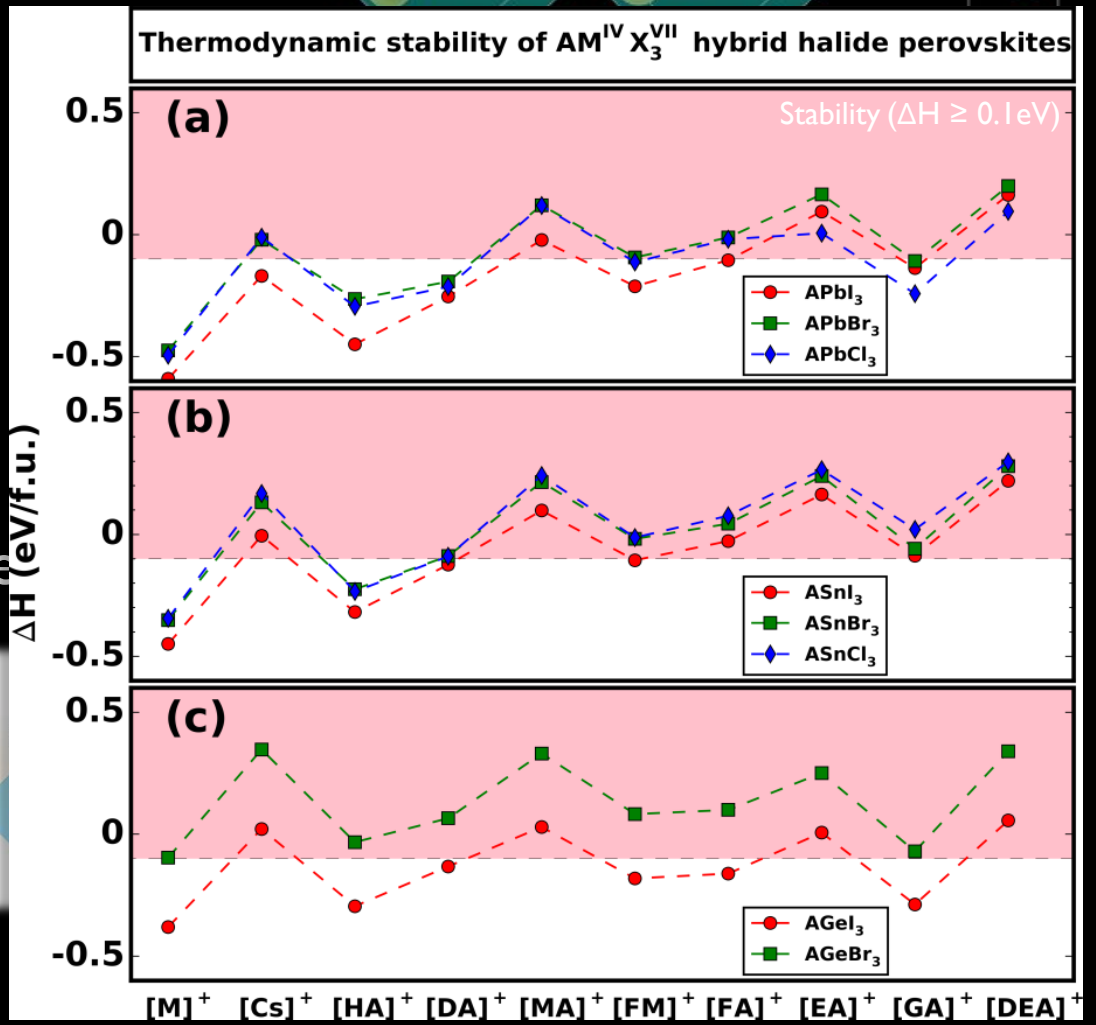
"Materials-by-Design" Rese

Stability?

Chlorides and bromides are more stable to decomposition than iodides.

Sn more stable than Pb for "MA" or "DA"





Example: Materials by Design

Not your father's materials science anymore!

"Edisonian Approach" - *Conventional trial-by-error science*

"Materials-by-Design" - *Inverse process: Define desired materials functionalities and work backward to computationally define (determine) best-of-class materials*

Innovation, Artificial Intelligence and Robotics …

Wind Energy

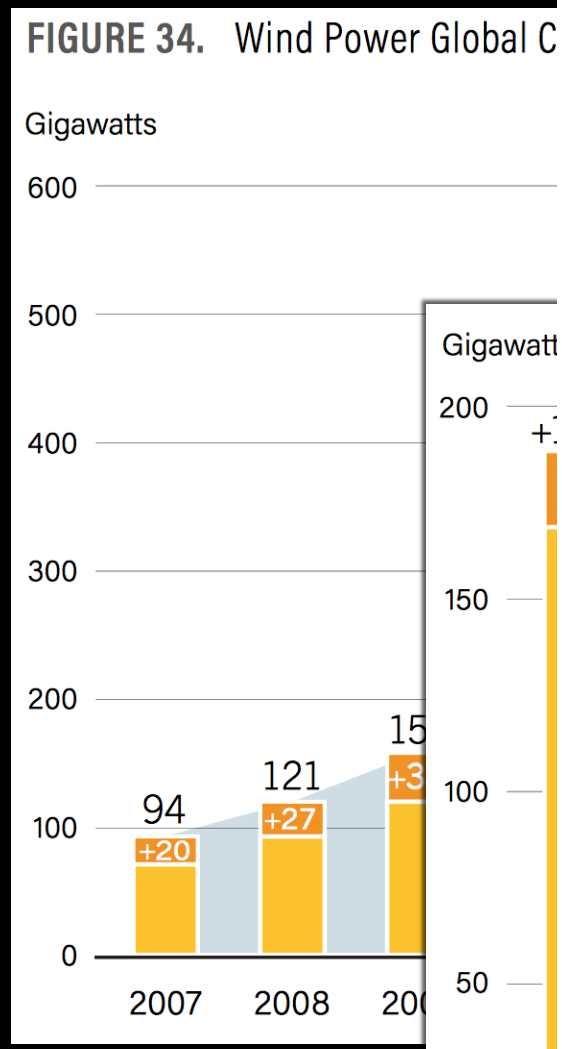
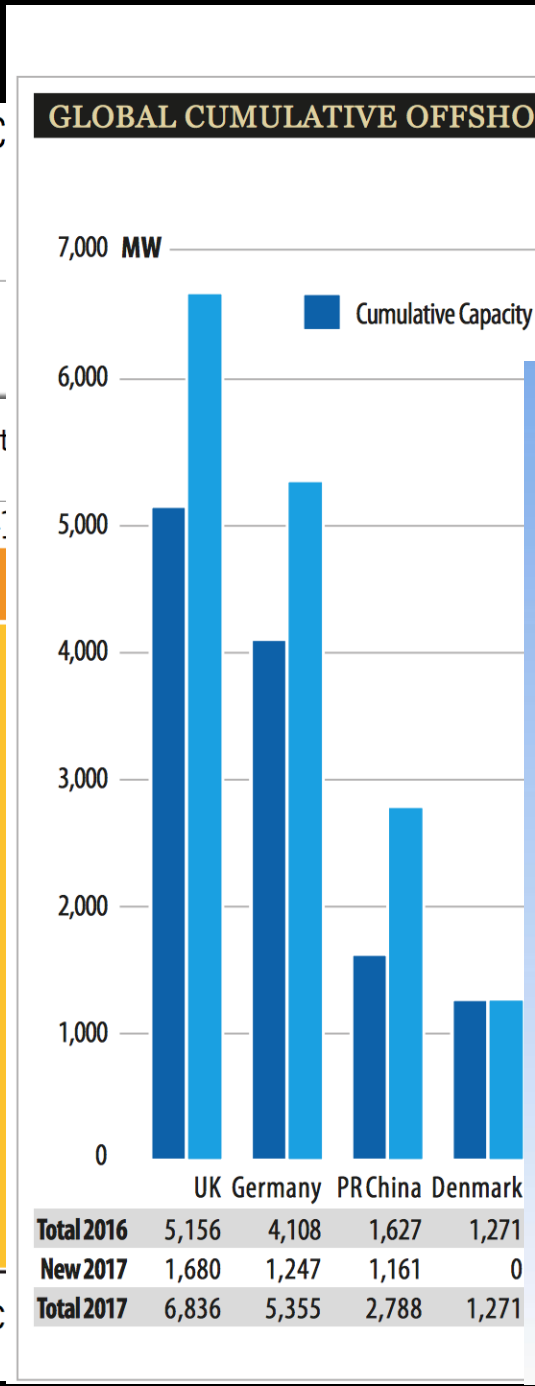
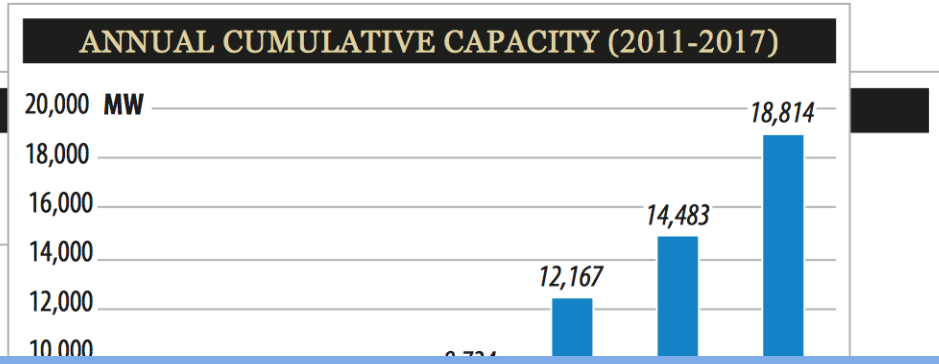
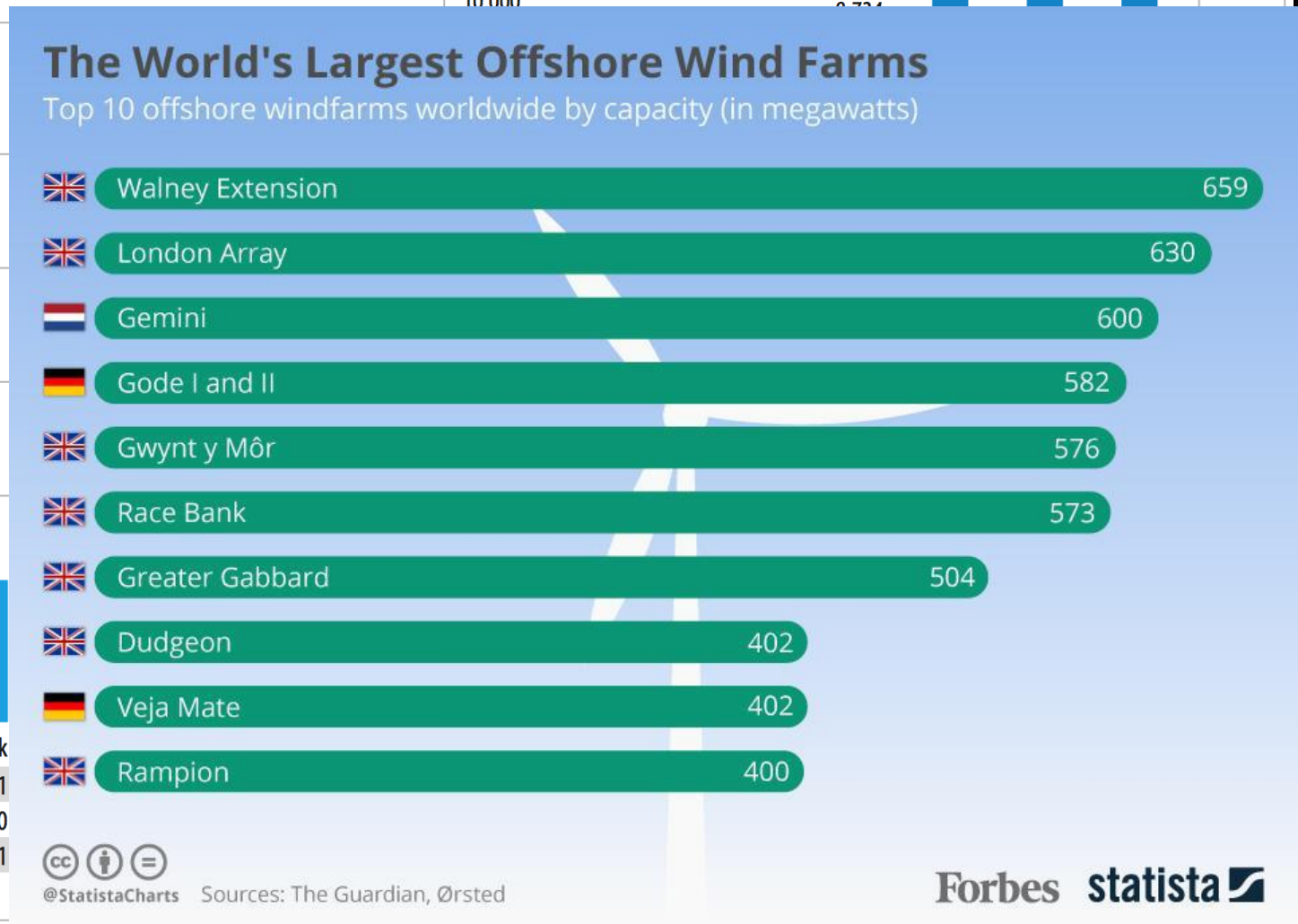


FIGURE 34. Wind Power Global C
Gigawatts
600
500
400
300
200
100
0
94
+20
121
+27
15
+3
2007
2008
20

Gigawatt
200
150
100
50
0
C


GLOBAL CUMULATIVE OFFSHORE WIND CAPACITY IN 2017
7,000 MW
6,000
5,000
4,000
3,000
2,000
1,000
0
Cumulative Capacity 2016
Cumulative Capacity 2017
UK
Germany
PR China
Denmark
Total 2016 5,156 4,108 1,627 1,271
New 2017 1,680 1,247 1,161 0
Total 2017 6,836 5,355 2,788 1,271

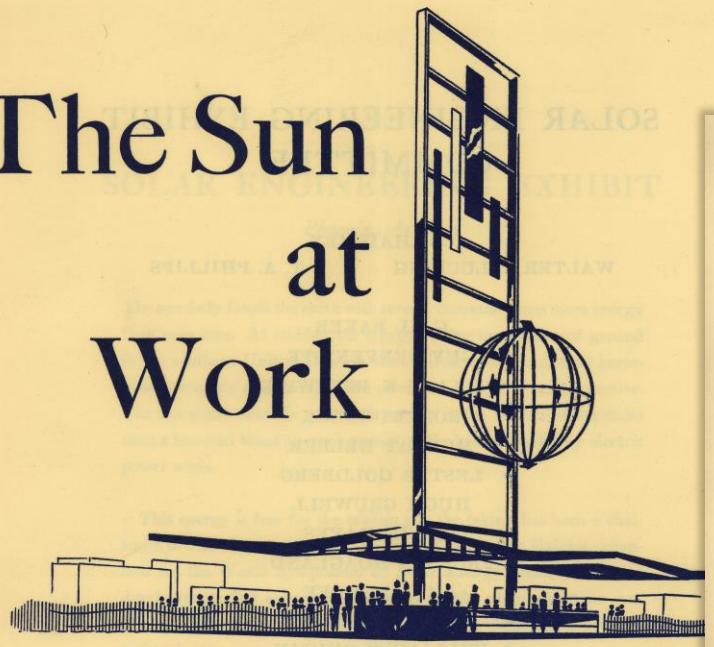

ANNUAL CUMULATIVE CAPACITY (2011-2017)
20,000 MW
18,000
16,000
14,000
12,000
10,000
12,167
14,483
18,814


The World's Largest Offshore Wind Farms
Top 10 offshore windfarms worldwide by capacity (in megawatts)
Walney Extension 659
London Array 630
Gemini 600
Gode I and II 582
Gwynt y Môr 576
Race Bank 573
Greater Gabbard 504
Dudgeon 402
Veja Mate 402
Rampion 400
@StatistaCharts
Sources: The Guardian, Ørsted
Forbes
statista

At the same time . . .

Phys Rev. 96, 533 (1954).

The Sun at Work



SOLAR ENGINEERING EXHIBI

October 29 - November 13, 1955

Hours: 9 A.M. to 4 P.M. Daily

Civic Center — Central Avenue at McDowell Road

Phoenix, Arizona

presented in conjunction with

CLEVITE®

Exhibit Section G

SALINE WATER STILLS

In many dry desert areas of the world there is an abundant supply of saline or brackish waters. If these supplies could be converted cheaply into fresh water, waste land areas could be made habitable. The solar distillers developed to date can be, and are, used where fresh water is needed for human or industrial consumption. In most of the stills in this section, water is evaporated from a thin water layer on a blackened surface surrounded by transparent walls on which condensation takes place.

G1. Tilted Solar Still
Tilted stills are able to collect more solar radiation per unit area than horizontal units.
Developed by: Maria Telkes
New York University
New York, N. Y.
For the Saline Water Conversion Program of the United States Department of the Interior.

G2. Two Plastic Stills
These stills illustrate the possible use of inexpensive plastics to reduce costs.
Developed by:
Bjorksten Research Laboratories, Inc.
Madison, Wisconsin
For the Saline Water Conversion Program of the United States Department of the Interior.

G3. Life Raft Still
These stills were developed during World War II by Dr. Maria Telkes, and are now often supplied with raft equipment
Exhibited by: Wright Air Development Center
Wright-Patterson Air Force Base
Dayton, Ohio

G4. Two-Cylinder Glass Solar Still
This still was developed by Everett D. Howe at the University of California in Berkeley.
Exhibited by: University of California
Berkeley, California

G5. Still for Farm Use
This still was designed by F. A. Brooks and Harold D. Lewis of the Department of Agricultural Engineering of the University of California.
Exhibited by: University of California
Davis, California

G6. SOMOR Still
Exhibited by: Societa Motori Recuperi (SOMOR)
Lecco, Italy

G7. Solar Fountain
Built by: F. A. Bonaventura and D. E. Plympton
San Diego, California

G8. Description of Saline Water Conversion Programs (panels)
Prepared by: Saline Water Conversion Program
United States Dept. of the Interior
Washington, D. C.

Exhibit Section H

PHOTOVOLTAIC CONVERTERS

Various laboratories have recently developed photovoltaic materials capable of converting a substantial percentage, sometimes as much as 10 percent of the incident solar energy directly into electricity! These converters have been named "solar batteries" and have received considerable attention in recent years.

ry and Motor
owered by electrical current gen-
the silicon solar battery when
diation.
Telephone Laboratories
rray Hill, New Jersey

Process
ates zone melting, a step in the
silicon solar battery.
Telephone Laboratories
ray Hill, New Jersey

useful to supply power to iso-
n equipment. This exhibit shows
hone repeater station.
Telephone Laboratories
ray Hill, New Jersey

H4. Display of Commercial Silicon Solar Batteries
Exhibited by: National Fabricated Products
Chicago, Illinois

H5. Cadmium Sulfide Solar Battery
A different photovoltaic material, cadmium sulfide (instead of silicon) has been used in this solar battery.
Developed by: Wright Air Development Center
Wright-Patterson Air Force Base
Dayton, Ohio

H6. Solar-powered Experimental Radio Transmitter
This transmitter is self-contained. Transistors are used instead of electron tubes. A selenium cell supplies the necessary power.
Developed by: Edward Keonjian
General Electric Company
Syracuse, New York

1962-1972: Shiozawa, Cusano, Shirland . . .


The Washington Post