ACAP

Australian Centre for Advanced Photovoltaics

UNSW AUSTRALIA

"How Did Silicon Solar Cells Get So Cheap?"

Martin A. Green

***UNSW** Australia*

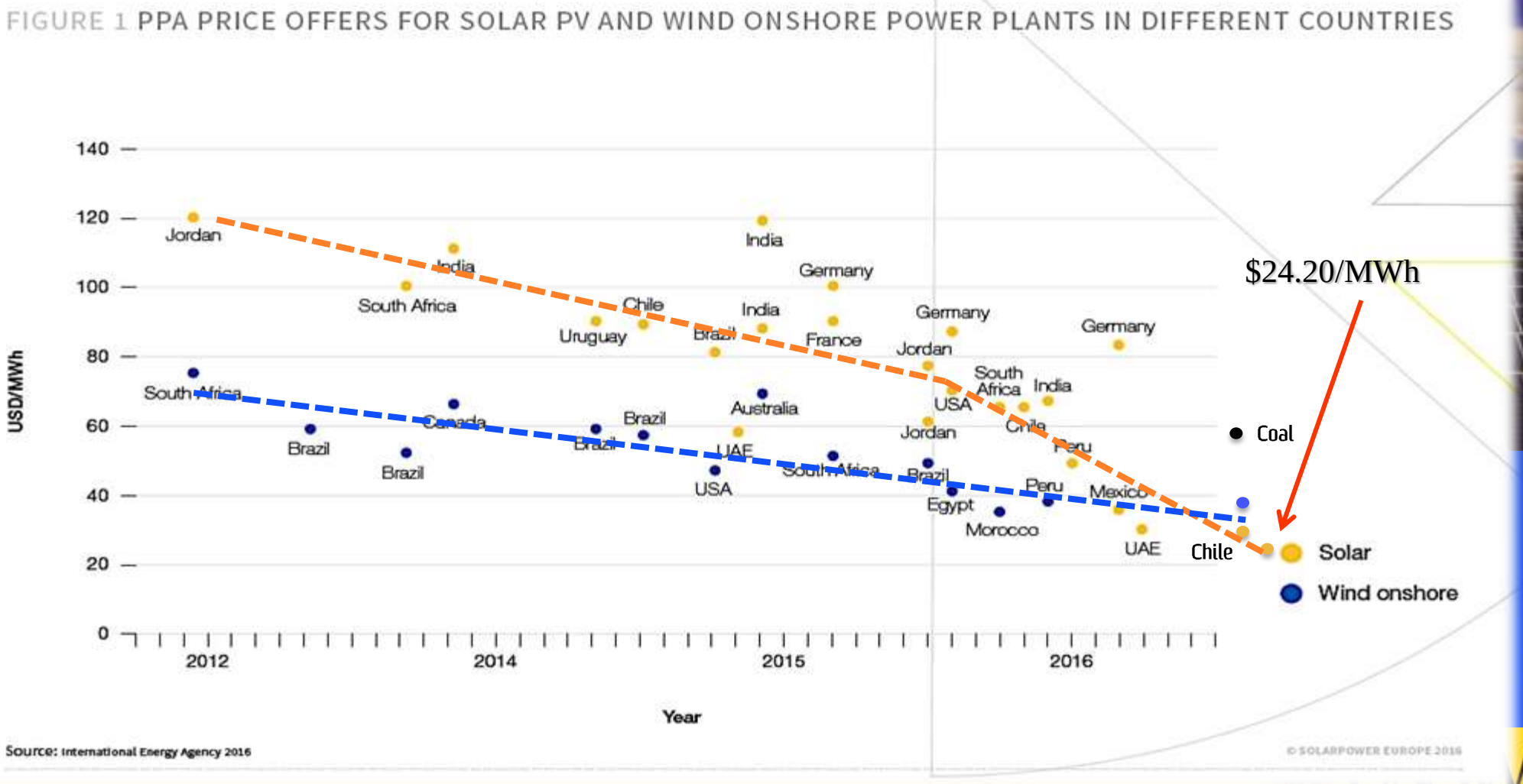
(m.green@unsw.edu.au)

ARENA

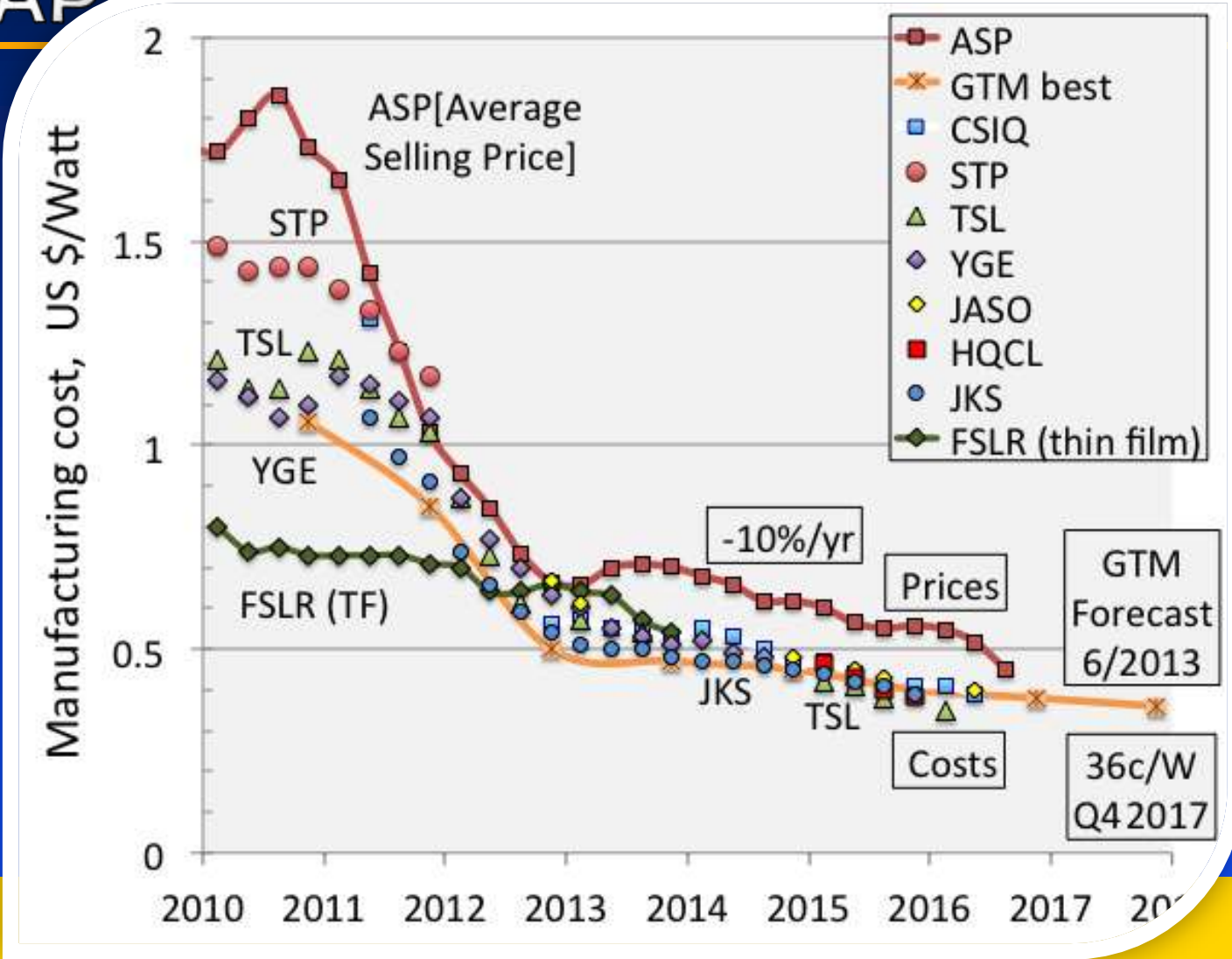
Australian Government

Australian Renewable Energy Agency

Recent PPAs (power purchase agreements)

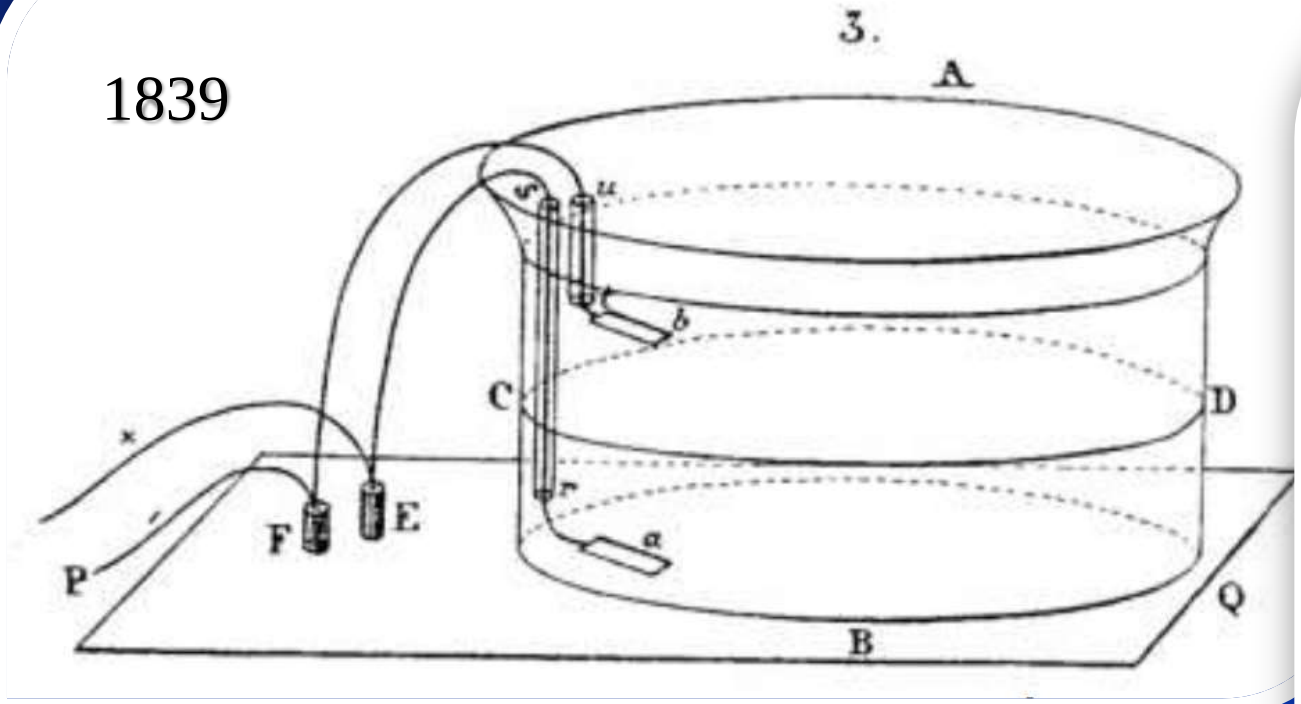


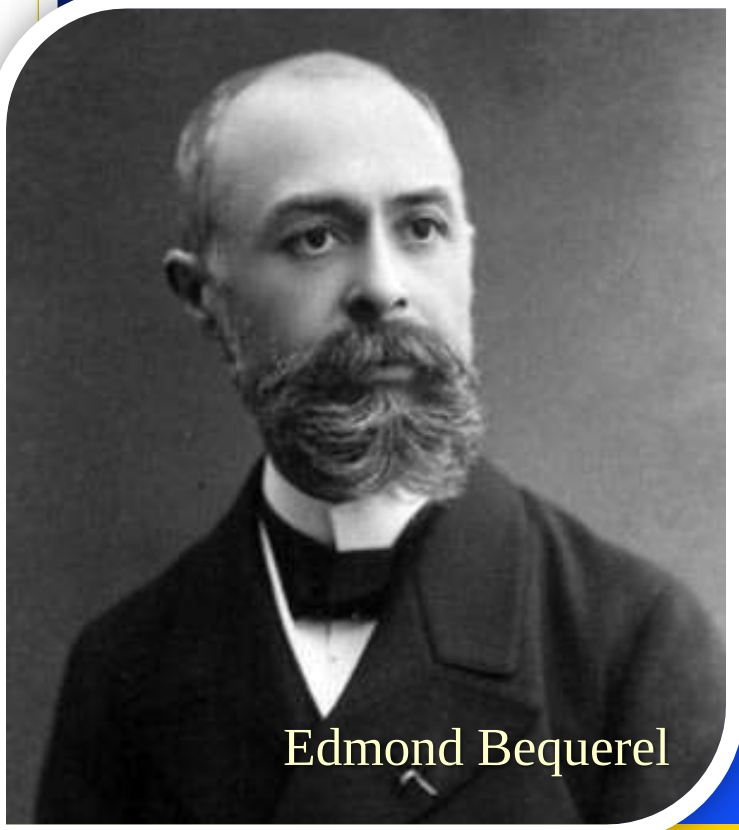
Module Cost / Price



The beginning (1839)

1839





Edmond Bequerel

The Theory of Electronic Semi-Conductors.

By A. H. Wilson, Emmanuel College, Cambridge.

(Communicated by P. A. M. Dirac, F.R.S.—Received June 18, 1931.)

Source: *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, Vol. 133, No. 822 (Oct. 1, 1931), pp. 458-491

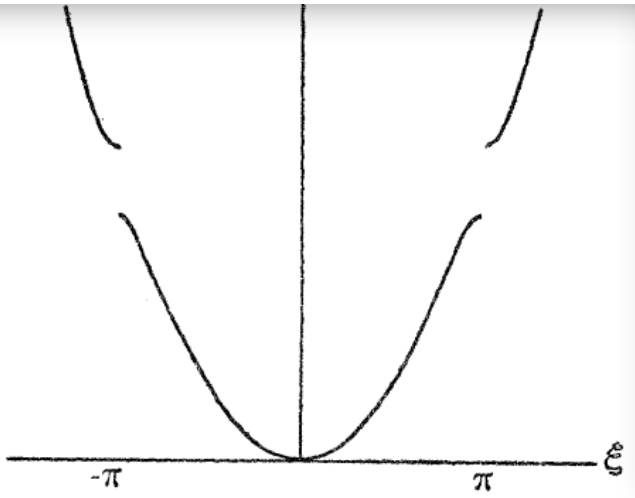
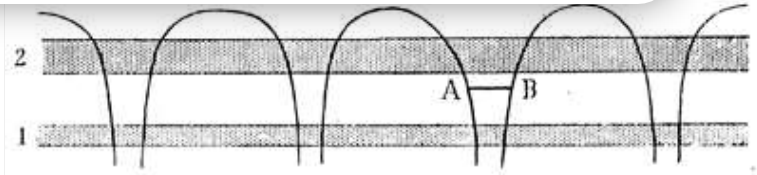


Fig. 1.



Walter Schottky

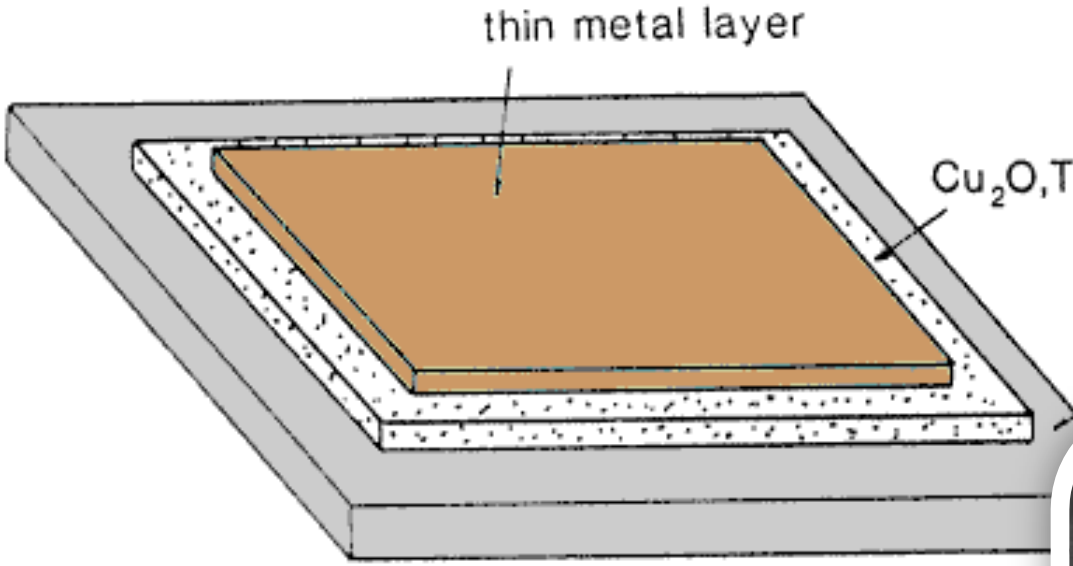
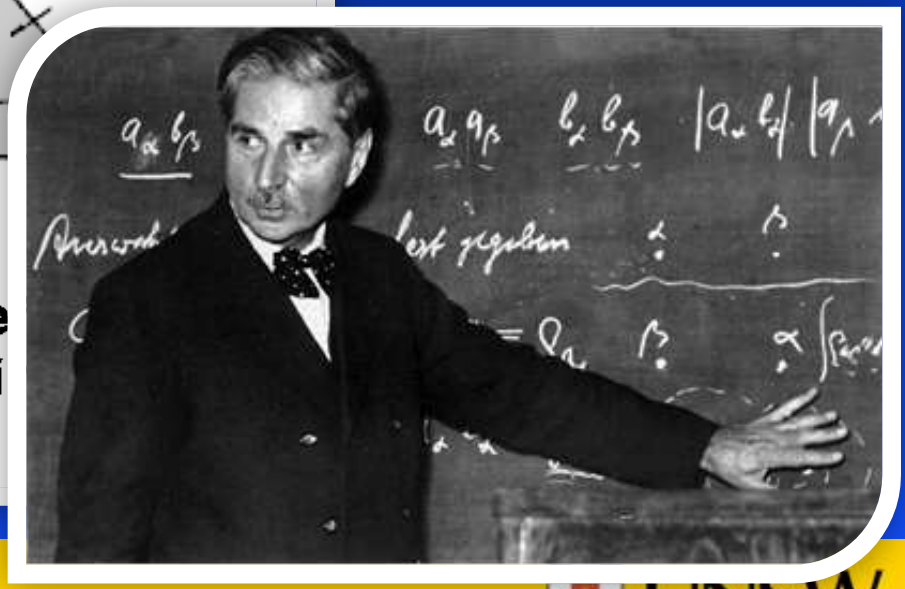
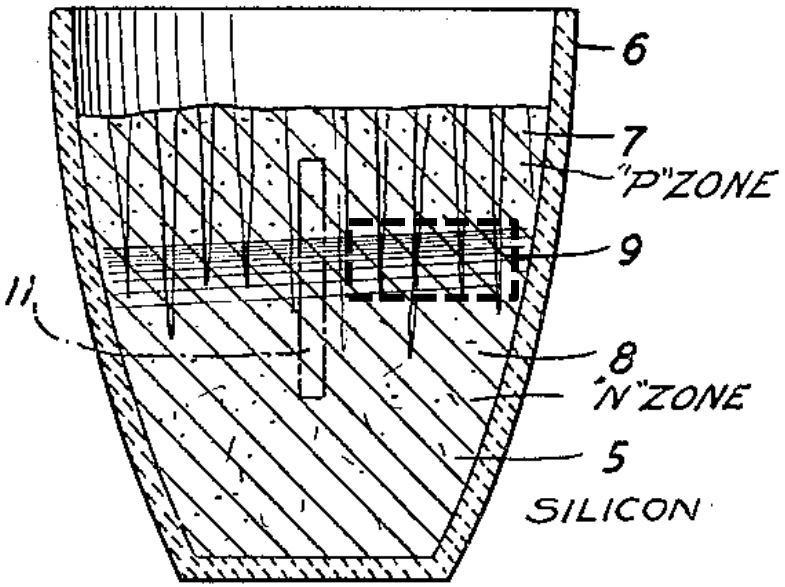


Figure 5: Structure of the most e photovoltaic devices developed duri 1930's.

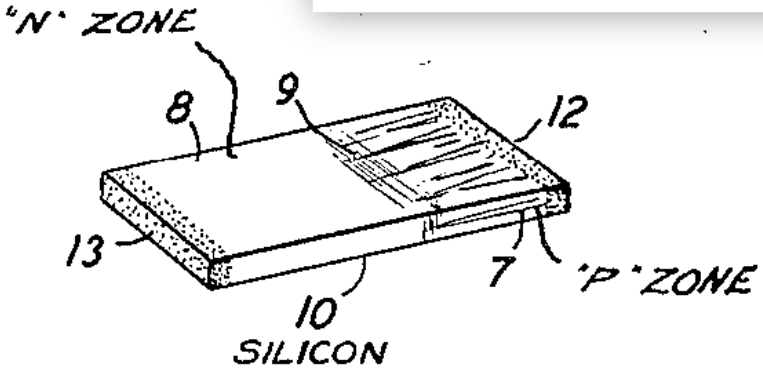


First silicon pn junction cell (Russell Ohl, 1941)

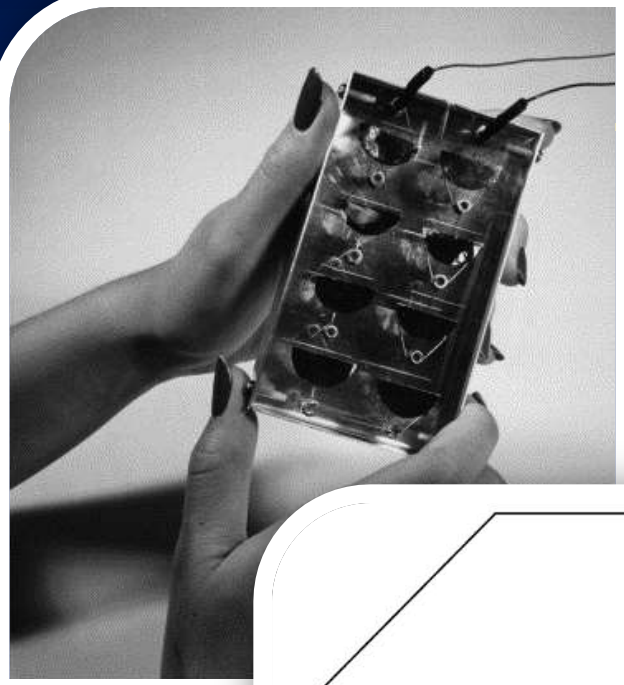
FIG. 1

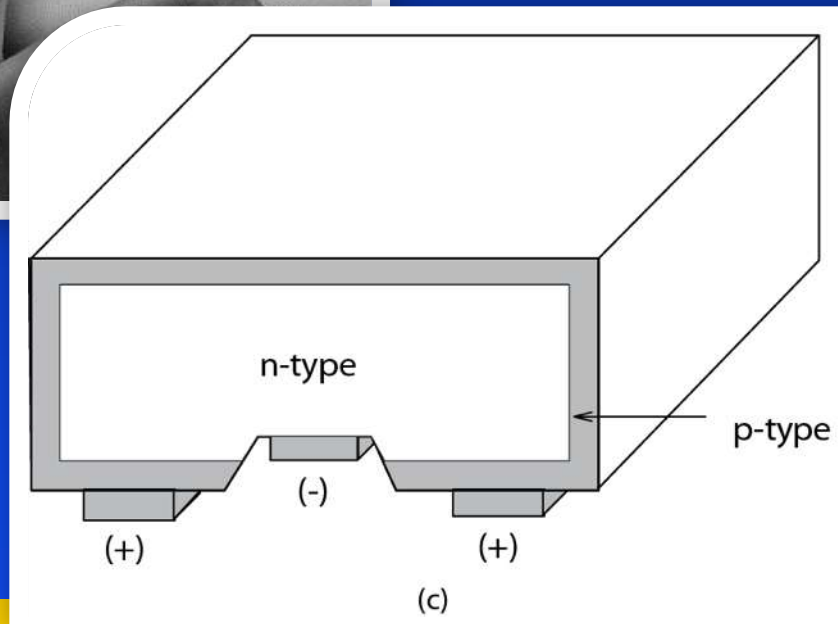


FIG

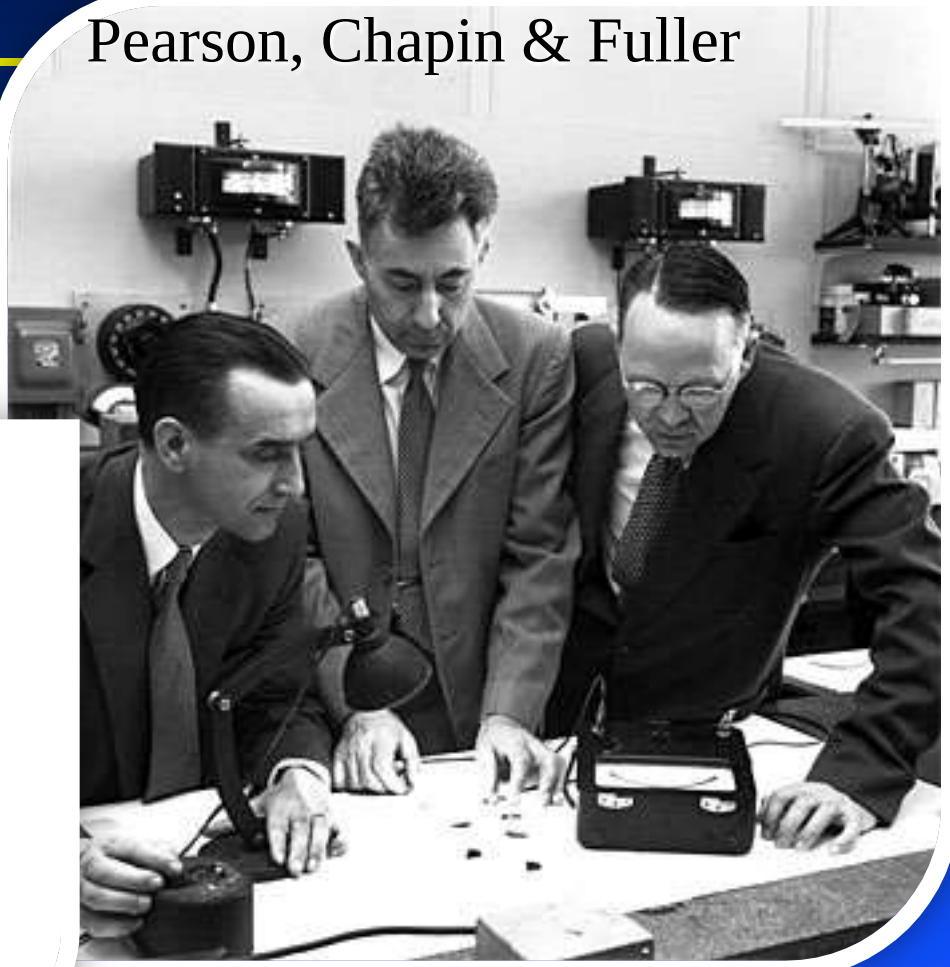


First efficient silicon cells (1953/4)





Pearson, Chapin & Fuller



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nt cells

"All the News That's Fit to Print"

The New York Times.

LATE CITY EDITION

NEW YORK, MONDAY, APRIL 26, 1954 — FIVE CENTS

JENSEN REBUTTAL ACCUSES M'CARTHY OF 'MALICIOUS LIES'

Scientists See Harm In Monmouth Inquiry

FERGUSON ASSERTS HOUSING INQUIRY MAY DELAY FUNDS

U. S. and British Leaders on Two Active Diplomatic Fronts

BRITAIN'S CABINET SEEKS WAY TO BAR AN ASIAN DISASTER

QUILL STILL HINTS AT TIE-UP OF BUSES

AUSTRALIA SPURNS MOSCOW'S DEMAND

U. S. Backs Efforts by Paris To End War in Indo-China

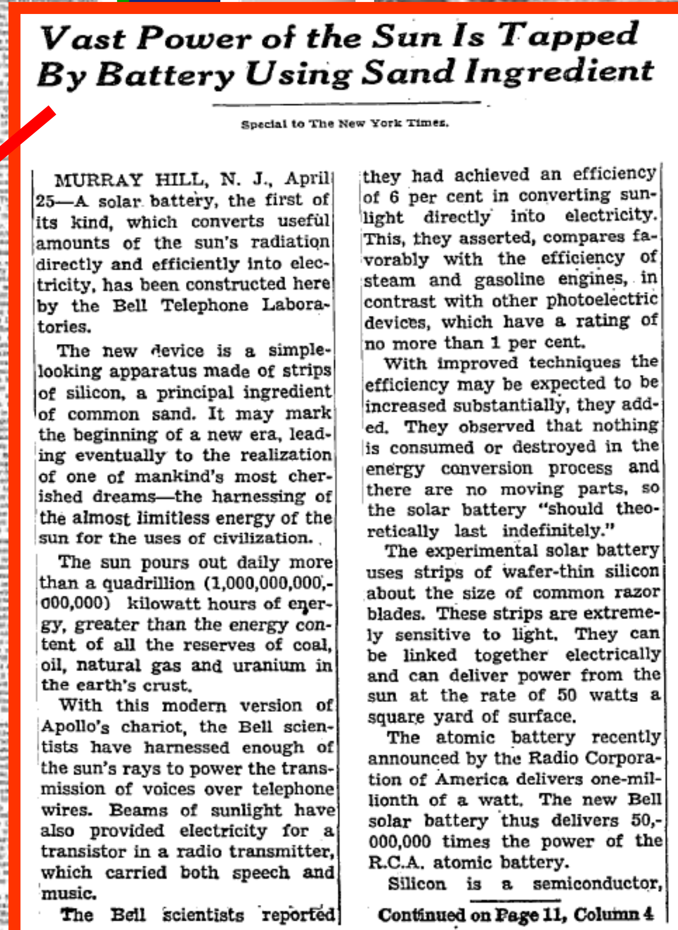
FRENCH HANG ON UNDER FOE'S FIRE

IRAQ WILL RECEIVE U. S. MILITARY HELP

Vast Power of the Sun Is Tapped By Battery Using Sand Ingredient

Polio Vaccine Test Will Start Today

3 Killed During Argentine Voting; Clear Victory for Peron Conceded



Vast Power of the Sun Is Tapped By Battery Using Sand Ingredient

Special to The New York Times.

MURRAY HILL, N. J., April 25—A solar battery, the first of its kind, which converts useful amounts of the sun's radiation directly and efficiently into electricity, has been constructed here by the Bell Telephone Laboratories.

The new device is a simple-looking apparatus made of strips of silicon, a principal ingredient of common sand. It may mark the beginning of a new era, leading eventually to the realization of one of mankind's most cherished dreams—the harnessing of the almost limitless energy of the sun for the uses of civilization.

The sun pours out daily more than a quadrillion (1,000,000,000,000,000) kilowatt hours of energy, greater than the energy content of all the reserves of coal, oil, natural gas and uranium in the earth's crust.

With this modern version of Apollo's chariot, the Bell scientists have harnessed enough of the sun's rays to power the transmission of voices over telephone wires. Beams of sunlight have also provided electricity for a transistor in a radio transmitter, which carried both speech and music.

The Bell scientists reported they had achieved an efficiency of 6 per cent in converting sunlight directly into electricity. This, they asserted, compares favorably with the efficiency of steam and gasoline engines, in contrast with other photoelectric devices, which have a rating of no more than 1 per cent.

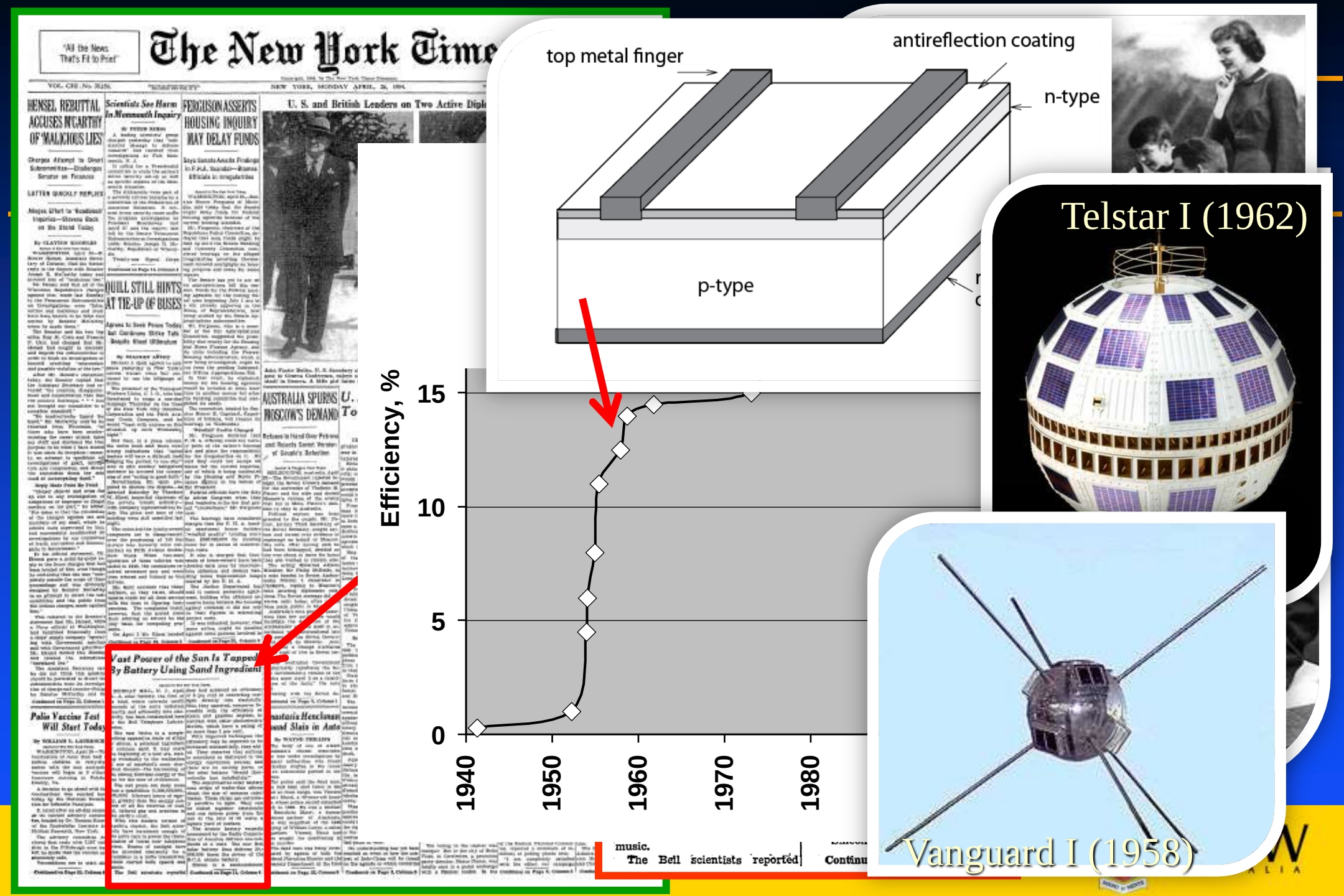
With improved techniques the efficiency may be expected to be increased substantially, they added. They observed that nothing is consumed or destroyed in the energy conversion process and there are no moving parts, so the solar battery "should theoretically last indefinitely."

The experimental solar battery uses strips of wafer-thin silicon about the size of common razor blades. These strips are extremely sensitive to light. They can be linked together electrically and can deliver power from the sun at the rate of 50 watts a square yard of surface.

The atomic battery recently announced by the Radio Corporation of America delivers one-millionth of a watt. The new Bell solar battery thus delivers 50,000,000 times the power of the R.C.A. atomic battery.

Silicon is a semiconductor,

Continued on Page 11, Column 4


The New York Time
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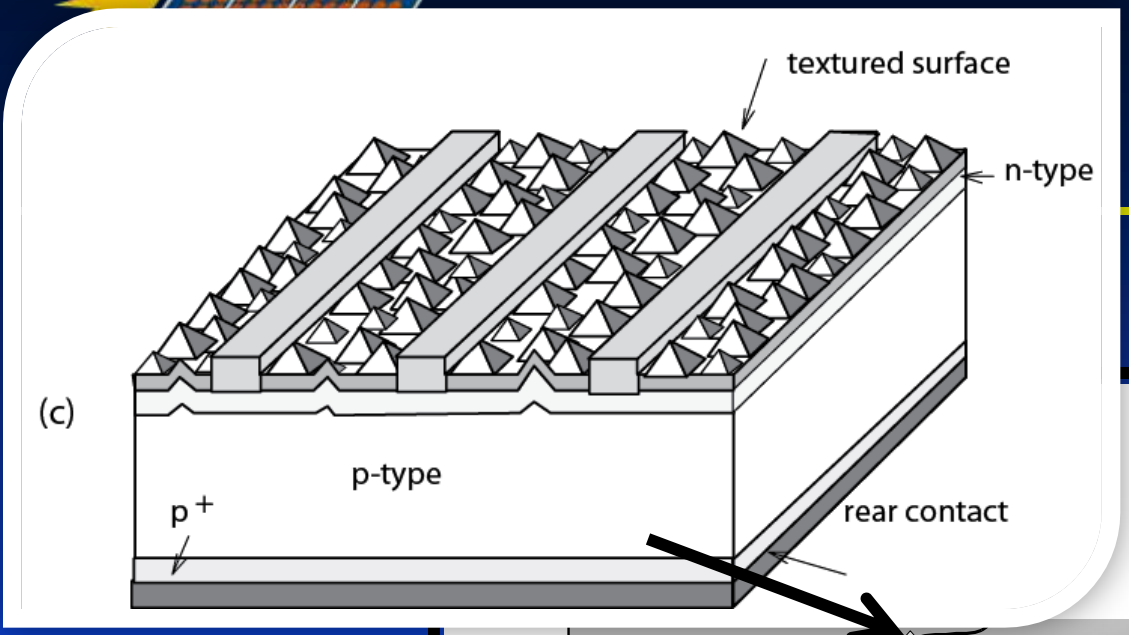
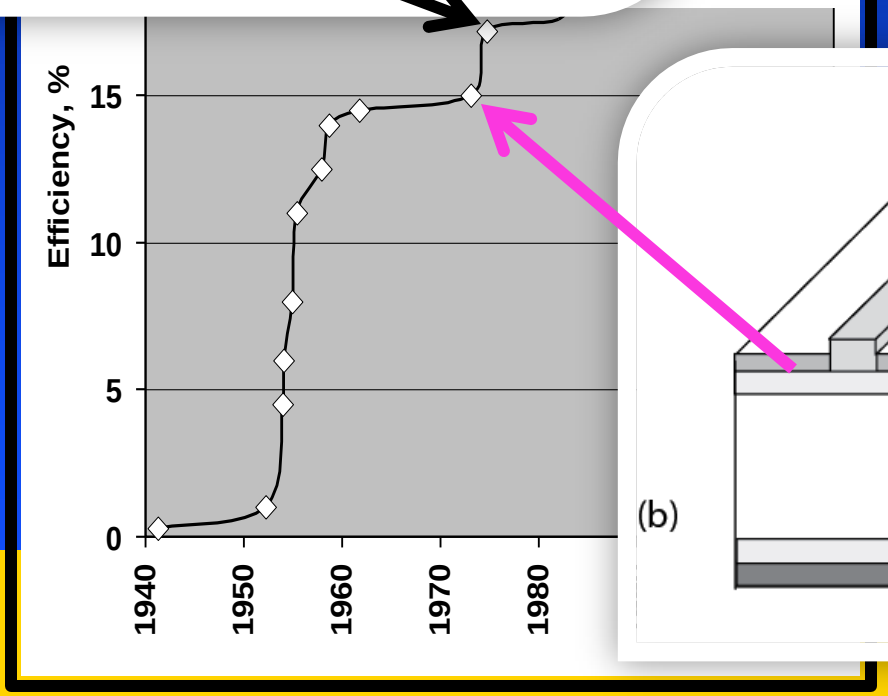
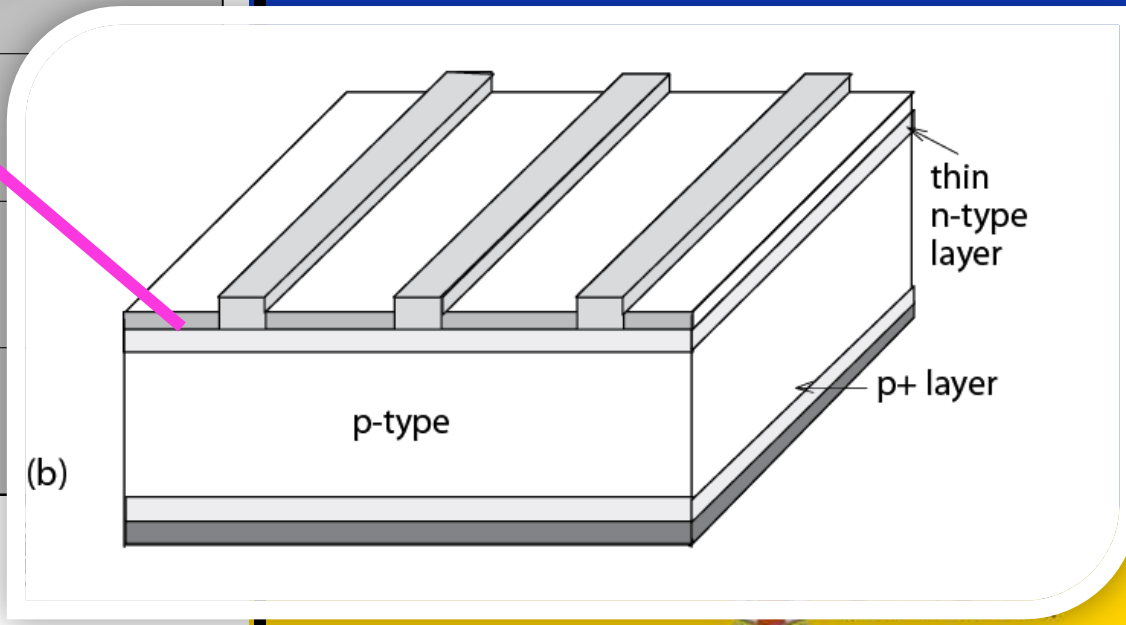
Vast Power of the Sun Is Tapped By Battery Using Sand Ingredient
Polio Vaccine Test Will Start Today
top metal finger
antireflection coating
n-type
p-type
Efficiency, %
0
5
10
15
1940
1950
1960
1970
1980
Telstar I (1962)
Vanguard I (1958)

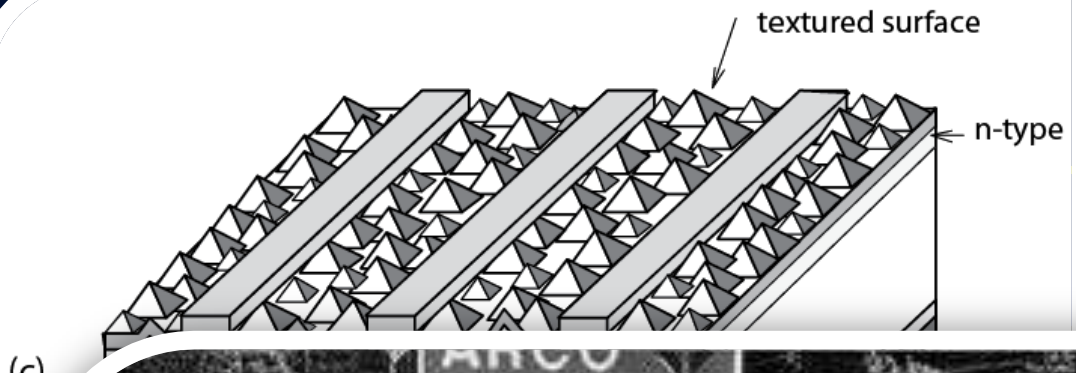
Black cell (COMSAT 1974)



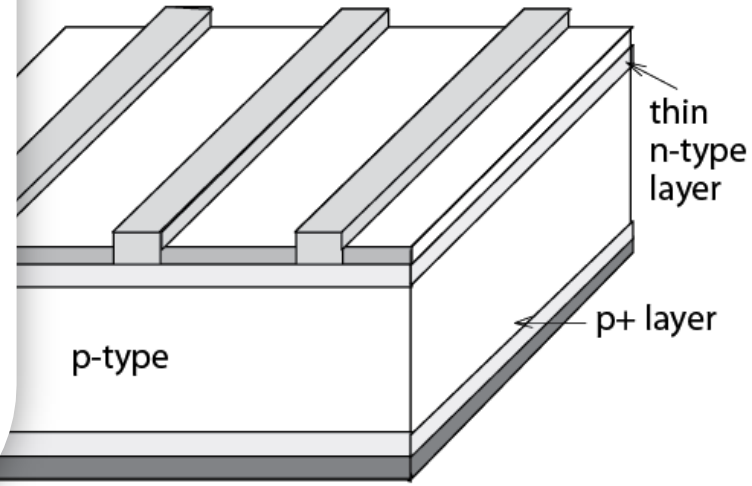




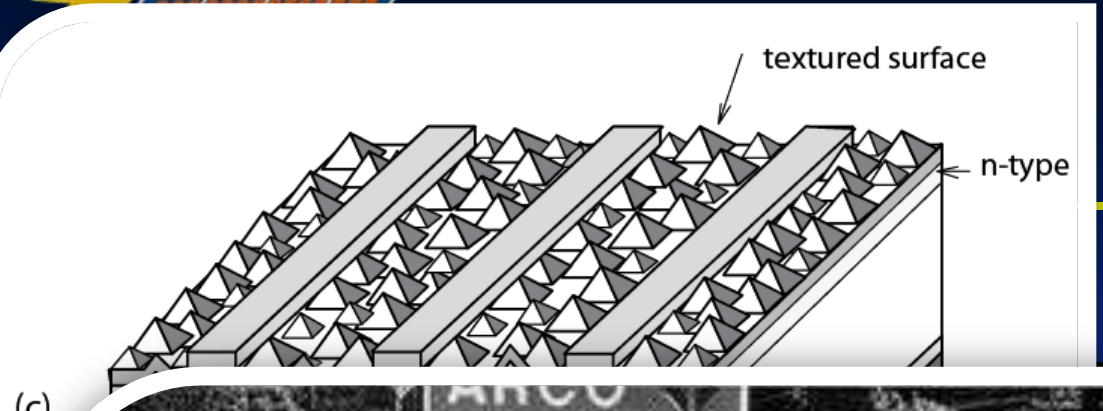
Black cell (COMSAT 1974)

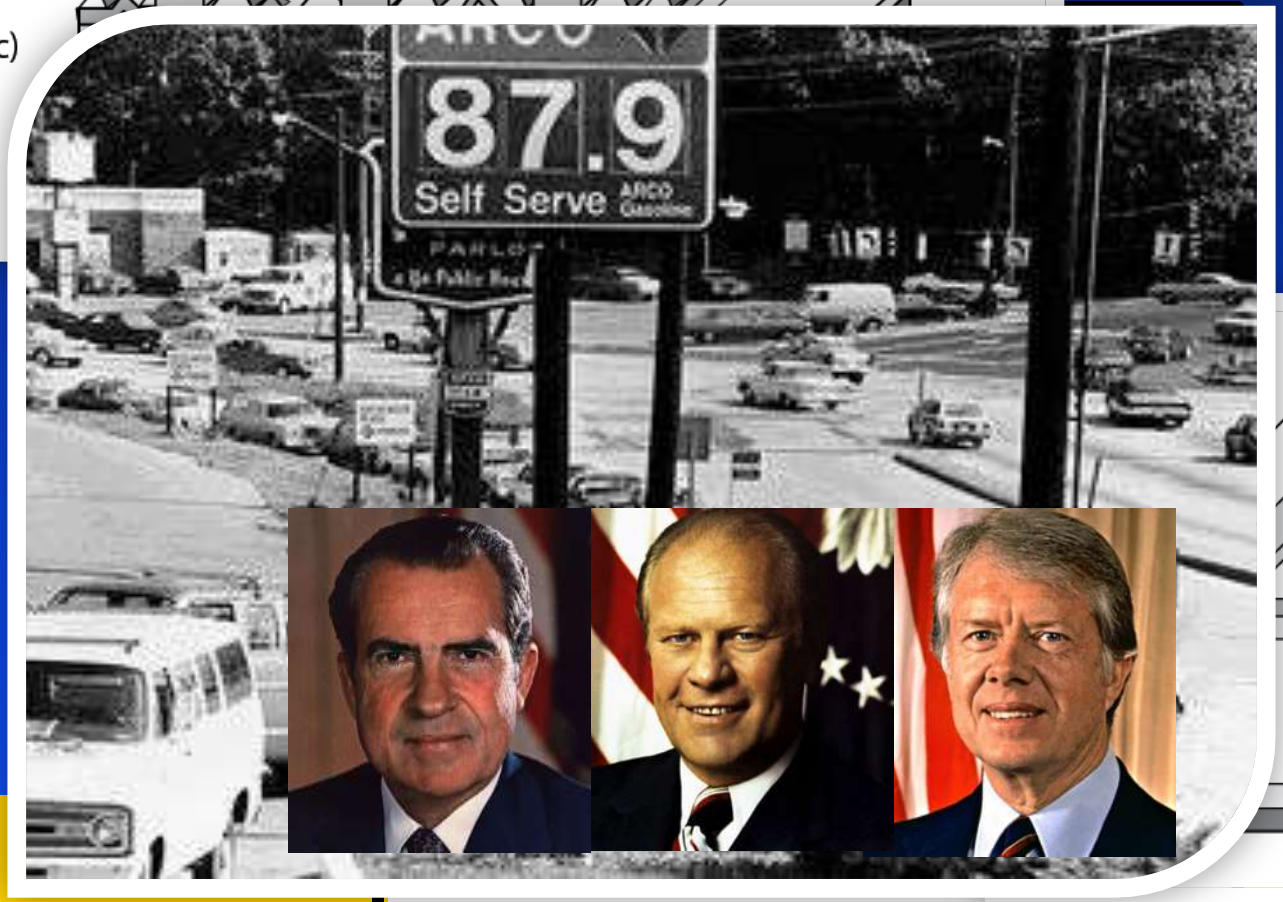


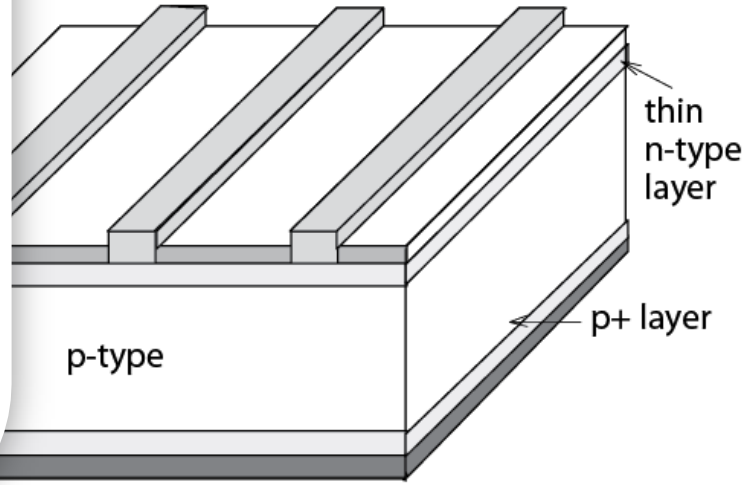
(c)



Black cell (COMSAT 1974)







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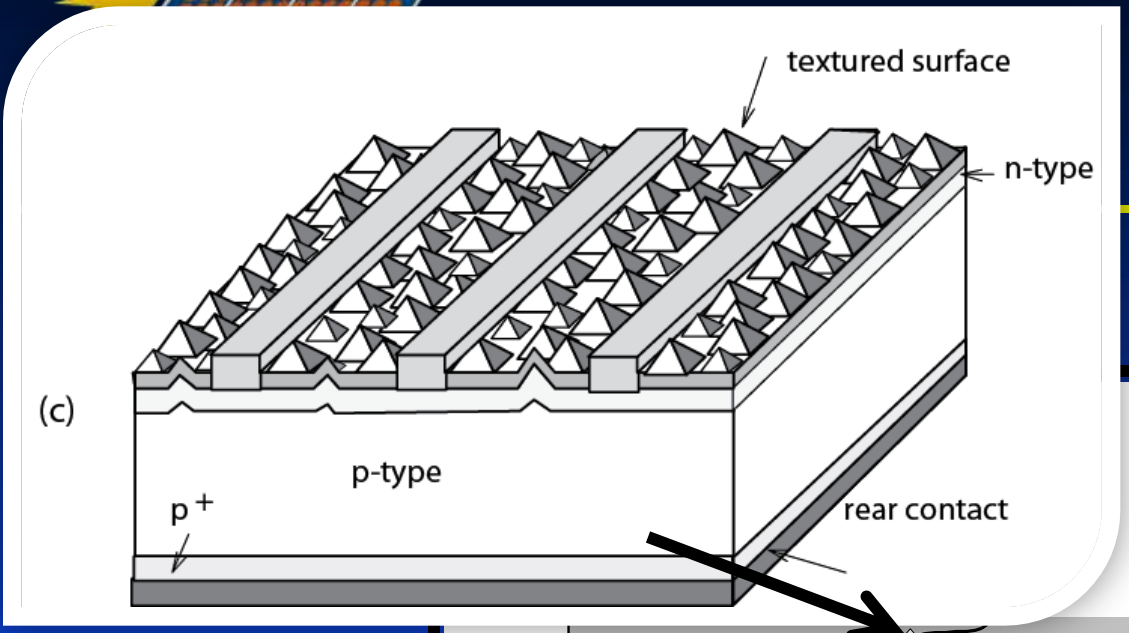

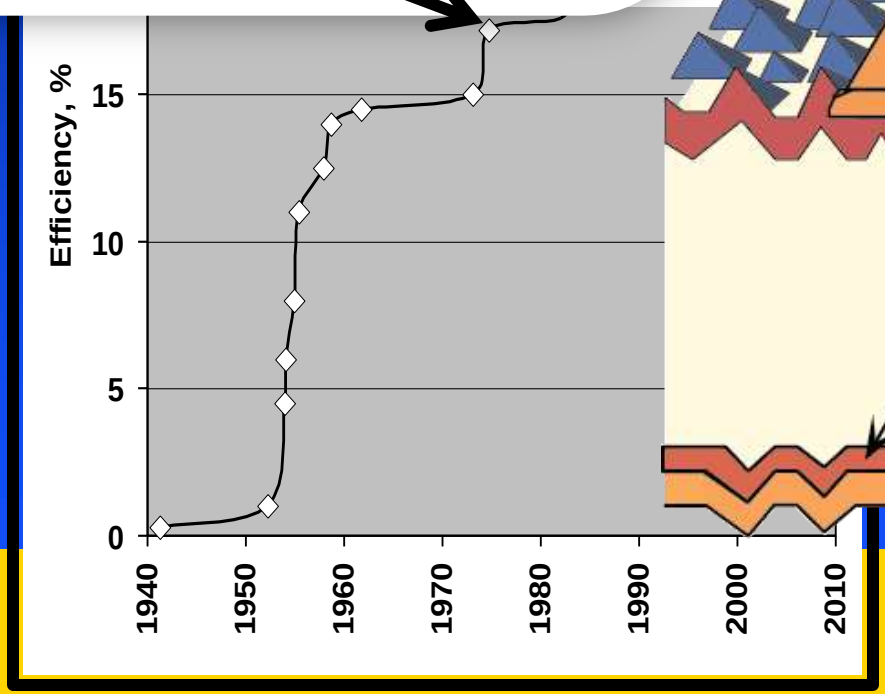

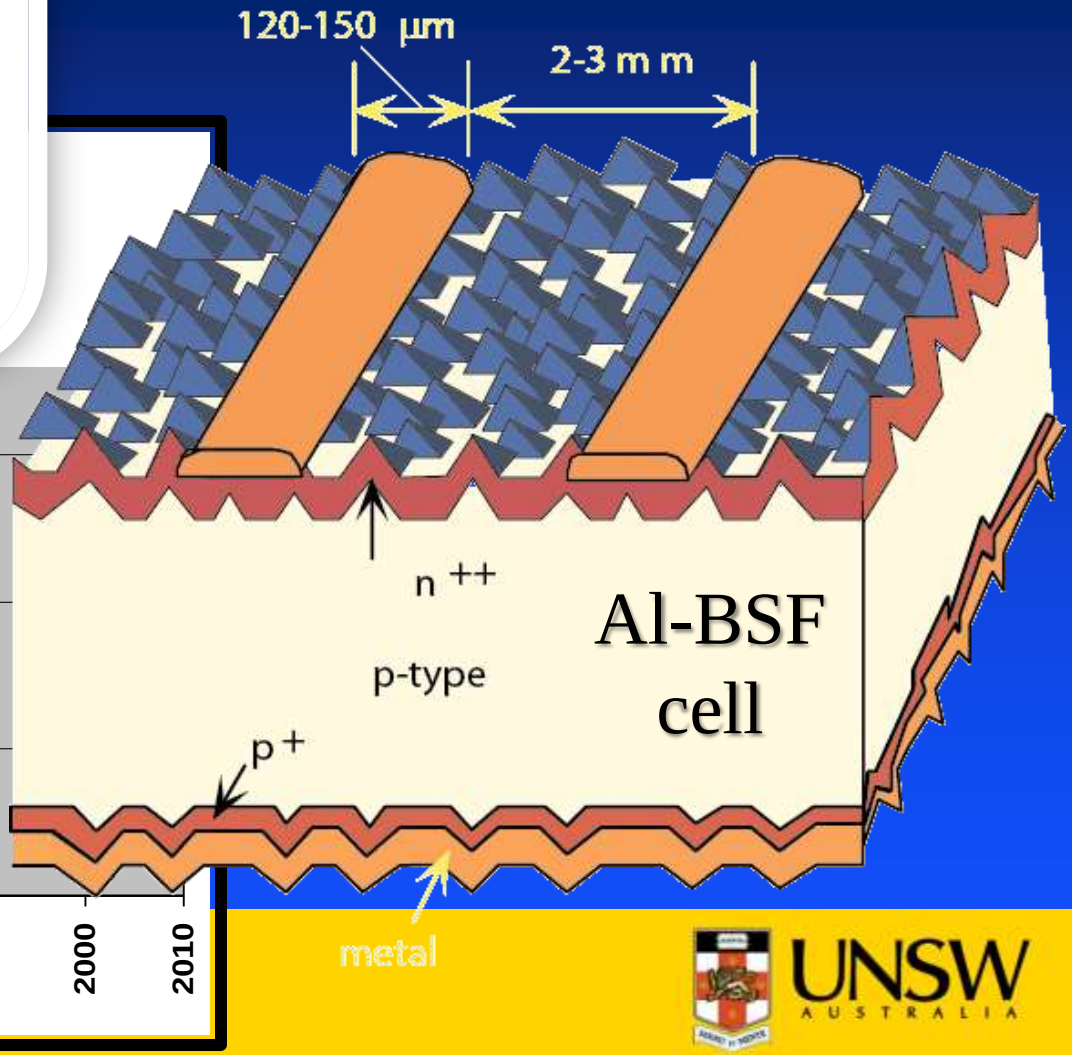

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1975 IEEE Photovoltaic Specialists Conference

RECENT ADVANCEMENTS
IN LOW COST SOLAR CELL PROCESSING

E. L. Ralph
Spectrolab Inc., Sylmar, California

SUMMARY

A proof-of-concept solar cell process has been developed that is adaptable to automation. This involved the development of a new contact system, a new antireflection coating system, a drift field cell design and a new contoured surface treatment. All these processes are performed without the use of vacuum chambers and expensive masking techniques, thus providing the possibility

A paste consisting of silver powd
and organic binder was then scree
front using a grid contact config
the back to form a solderable are
were then sintered at 600°C. A s
TiO_2-SiO_2 glass was then spun-on
to form an AR coating.

120-150 Ωcm 2-3 Ωcm

TEST RESULTS

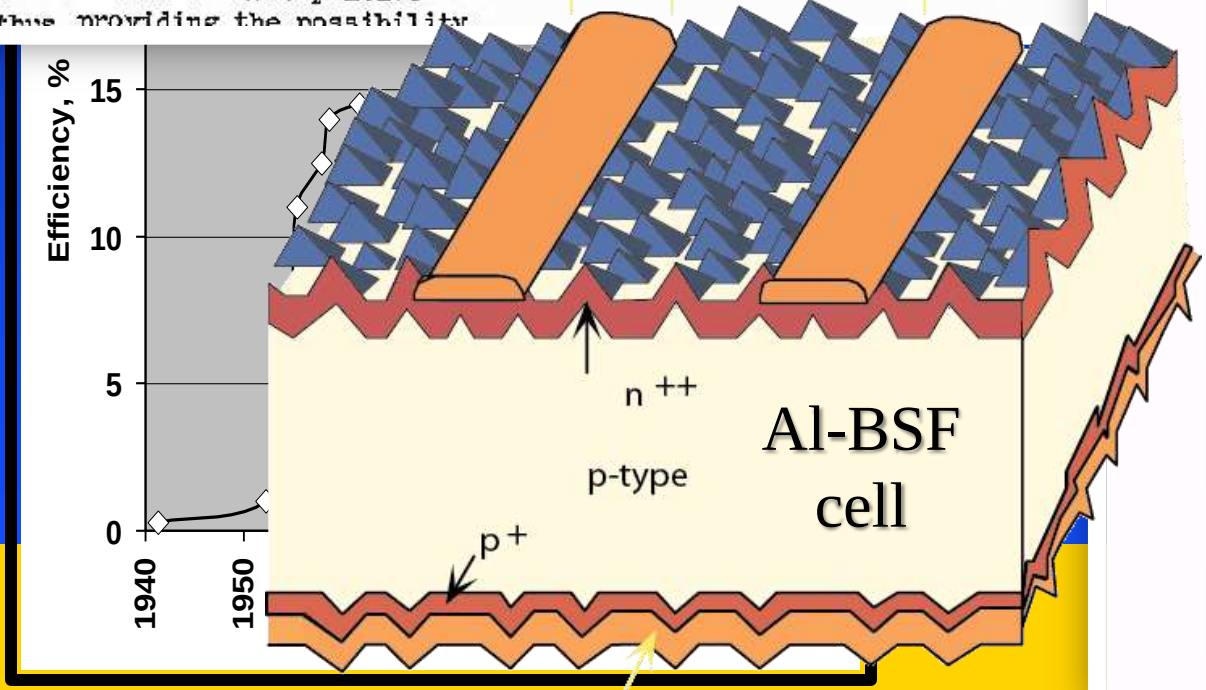
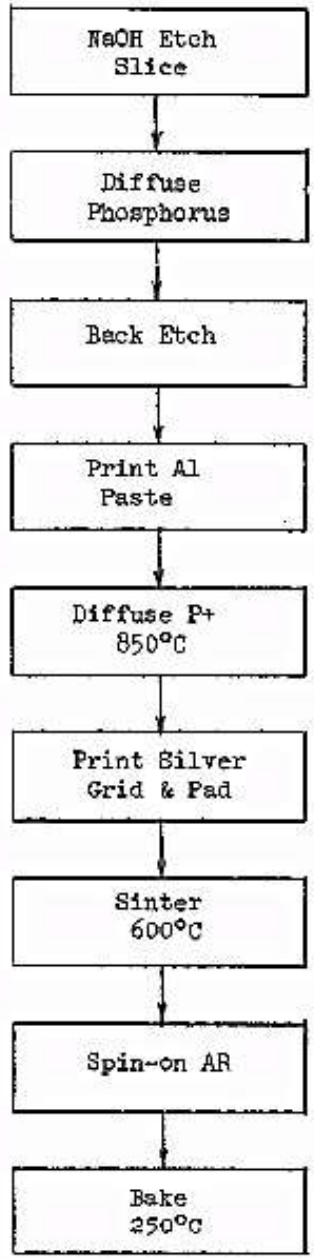


Figure 1
Vacuum Free Solar Cell Process



ACAP

Electricity from Photovoltaic Solar Cells

Flat-Plate Solar Array Project

10 Years of Progress

October 1985

United States Department of Energy

JPL Jet Propulsion Laboratory California Institute of Technology

NASA National Aeronautics and Space Administration

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ACAP

Electricity from Photovoltaic Solar Cells

Flat-Plate Solar Array Project

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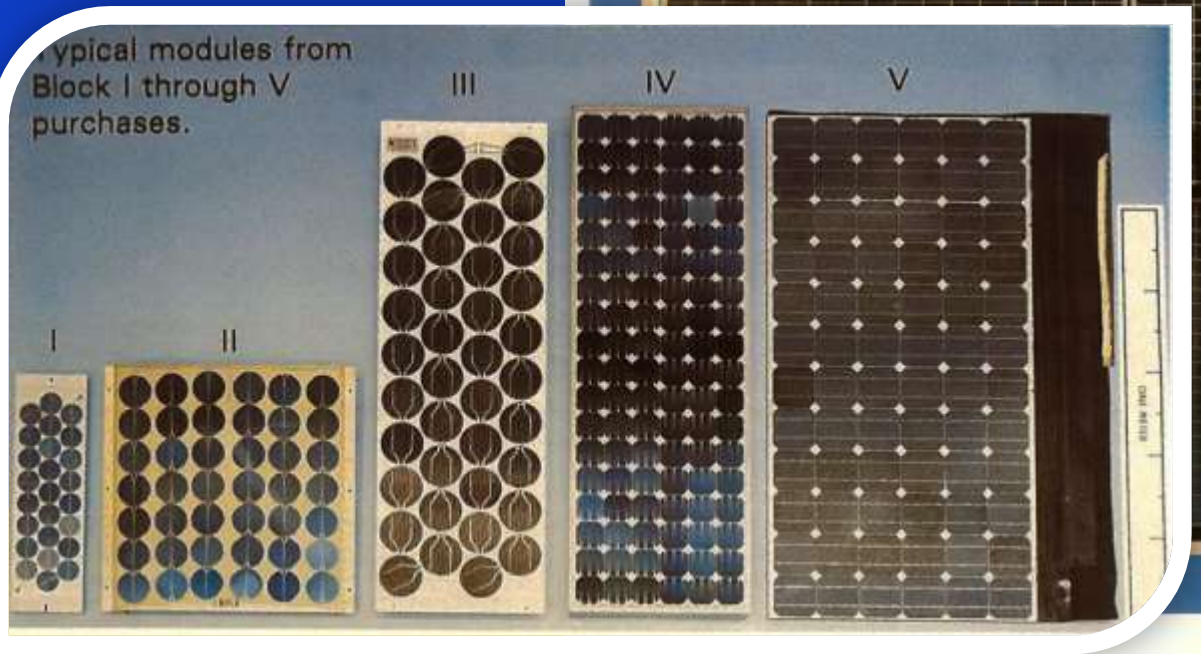

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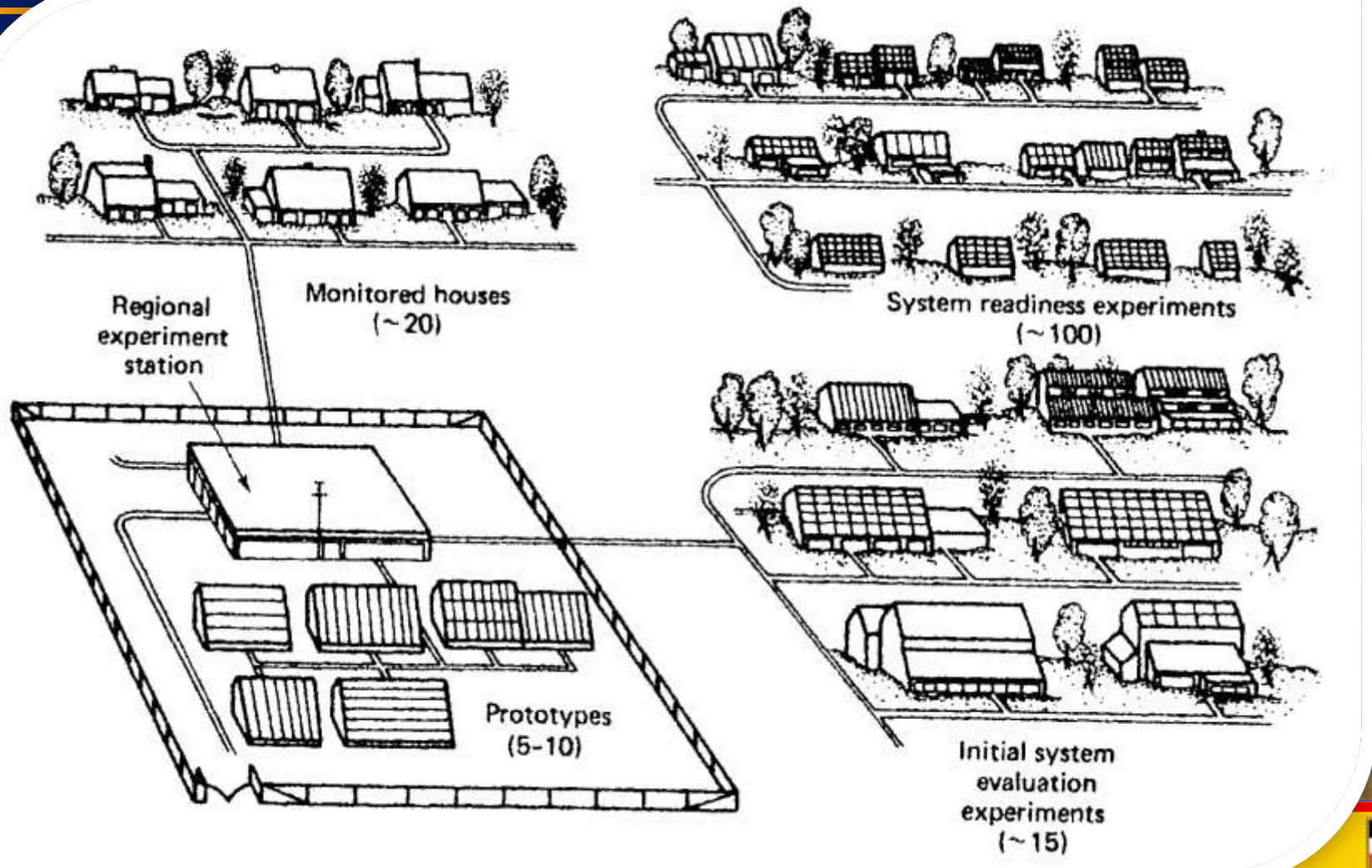
Photovoltaics Commercial/ Demo

Photovoltaics Commercial/ Demo



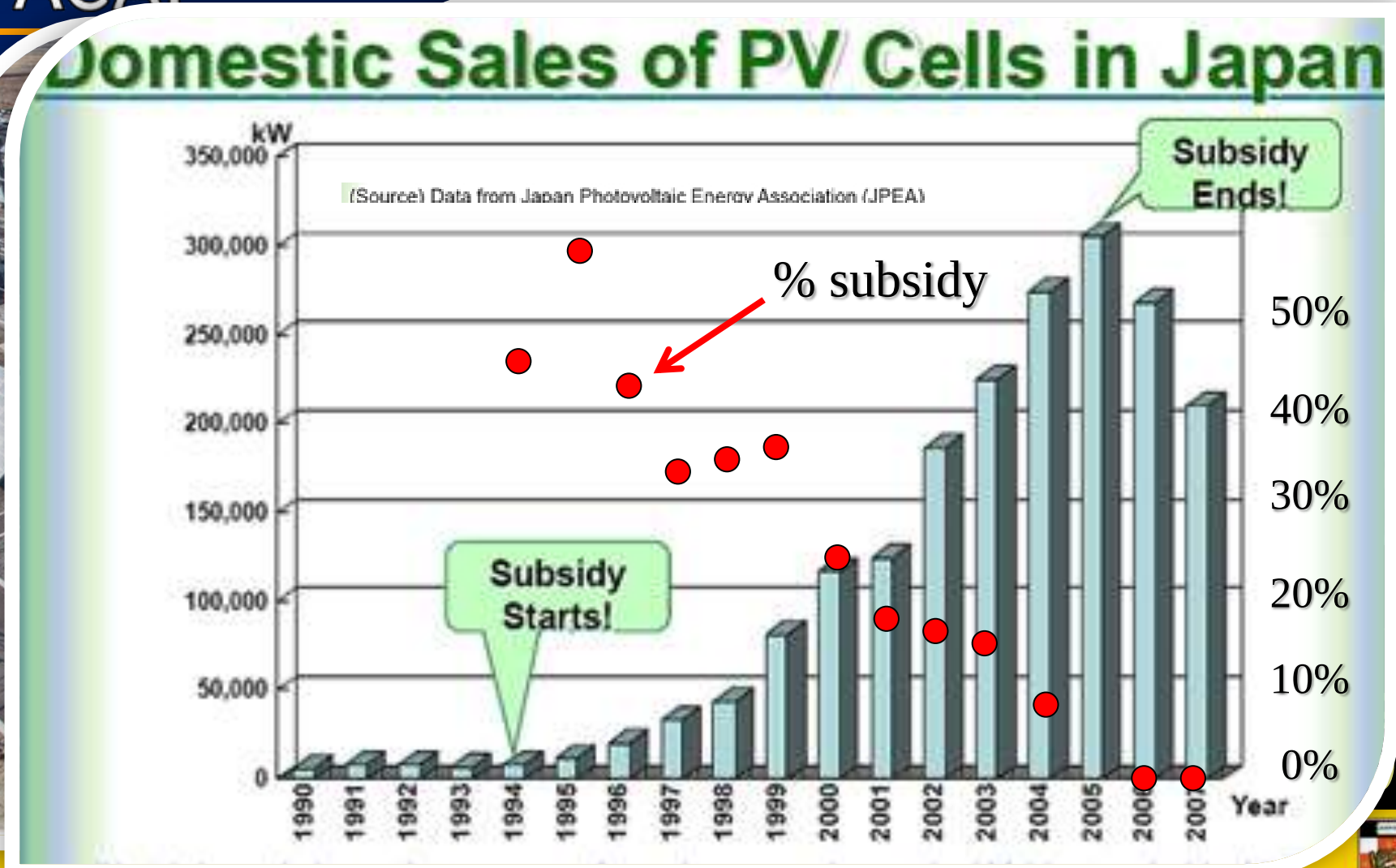
Japanese “Million Roof” Program

Rokko Island
1986

Japanese “Million Roof” Program

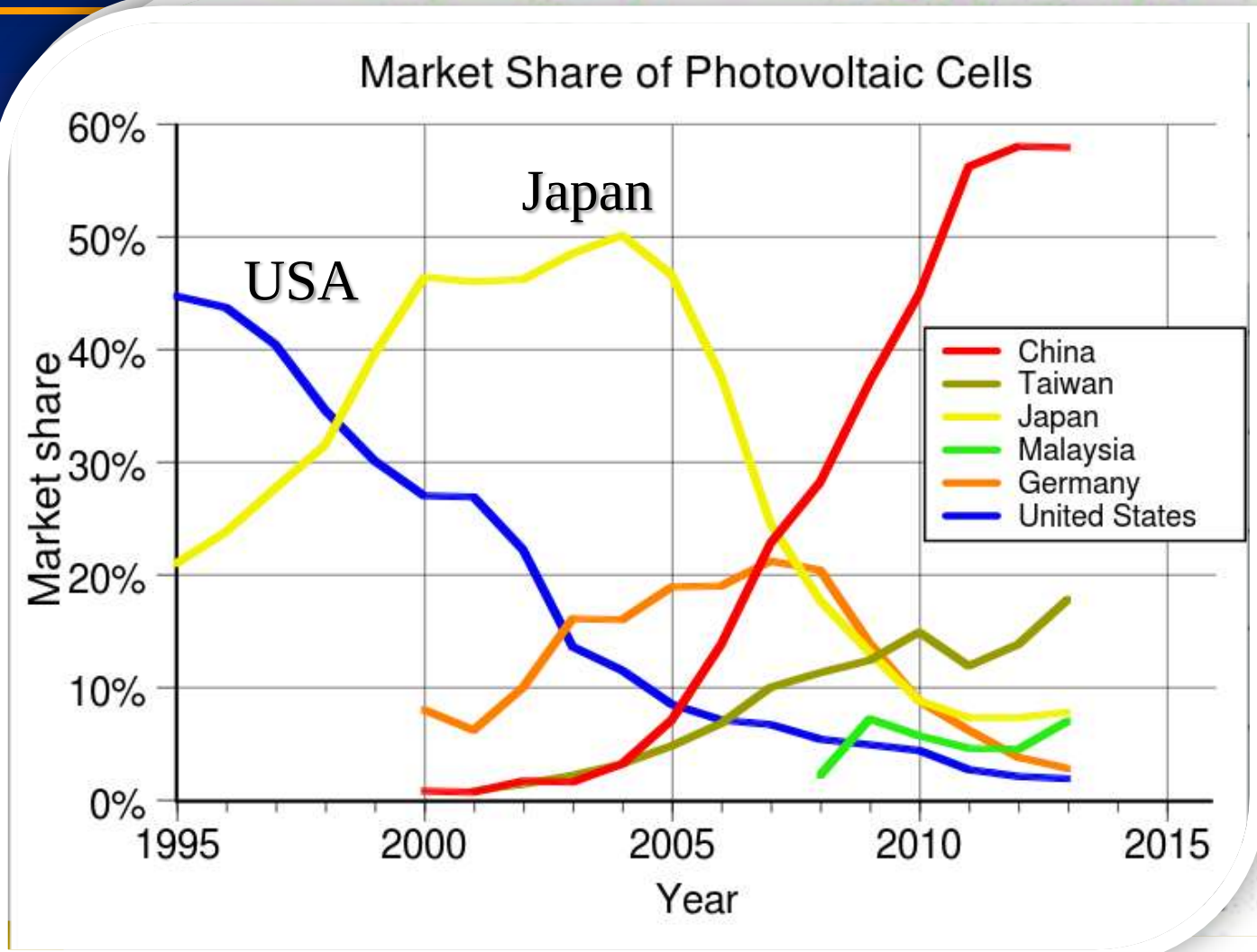
Launched 1993/4
(World PV production 60 MW)
70,000 roofs by FY 2000
1 million by FY 2010 (5 GW)

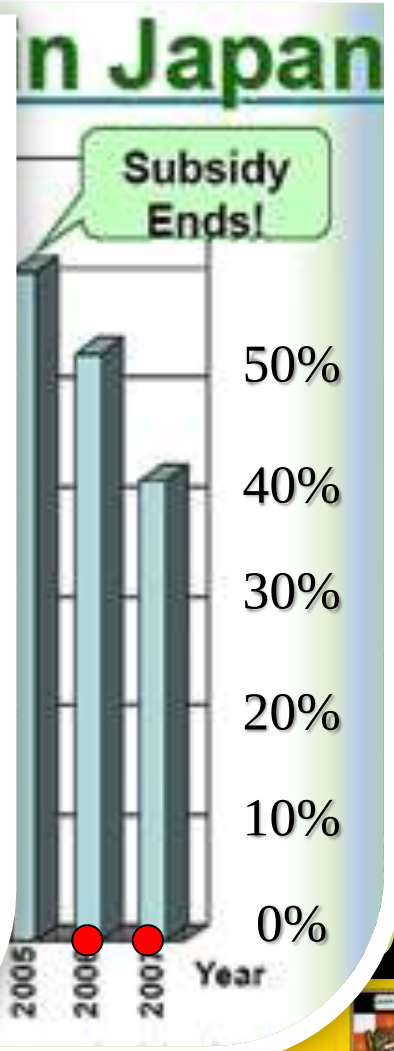
Japanese “Million Roof” Program



on 60 MW)
000
(5 GW)

Japanese “Million Roof” Program





on 60 MW)
000
(5 GW)

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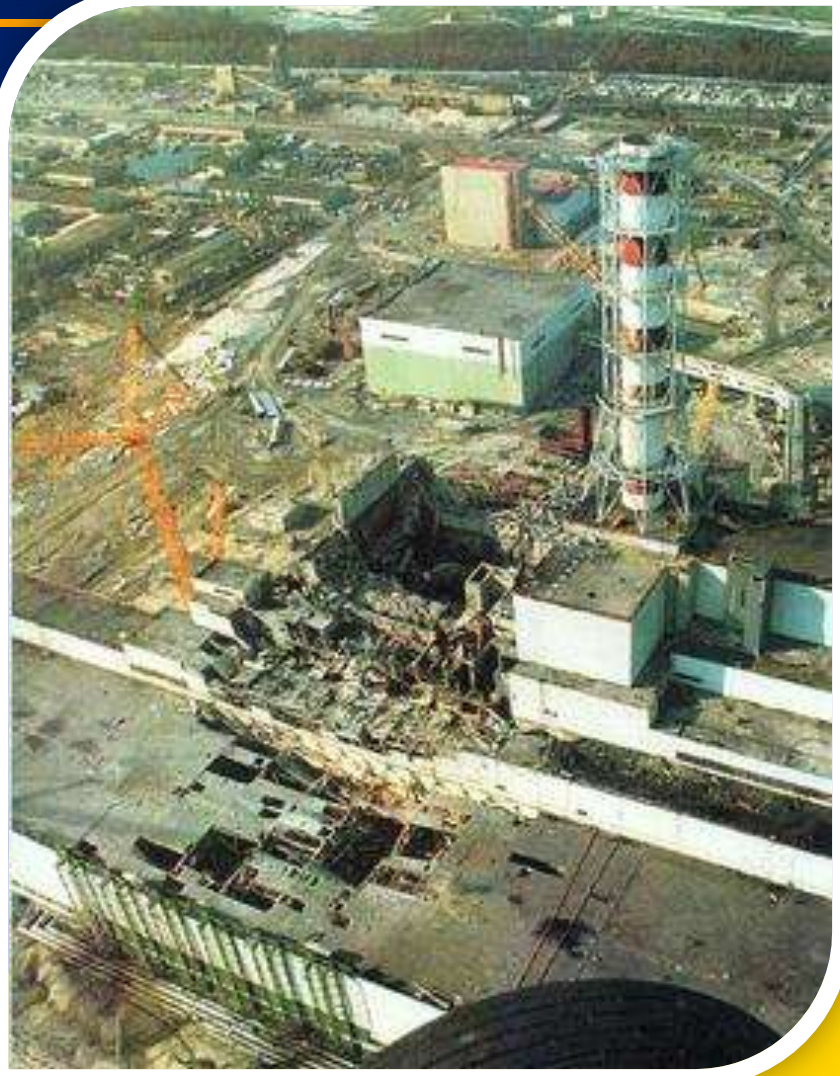
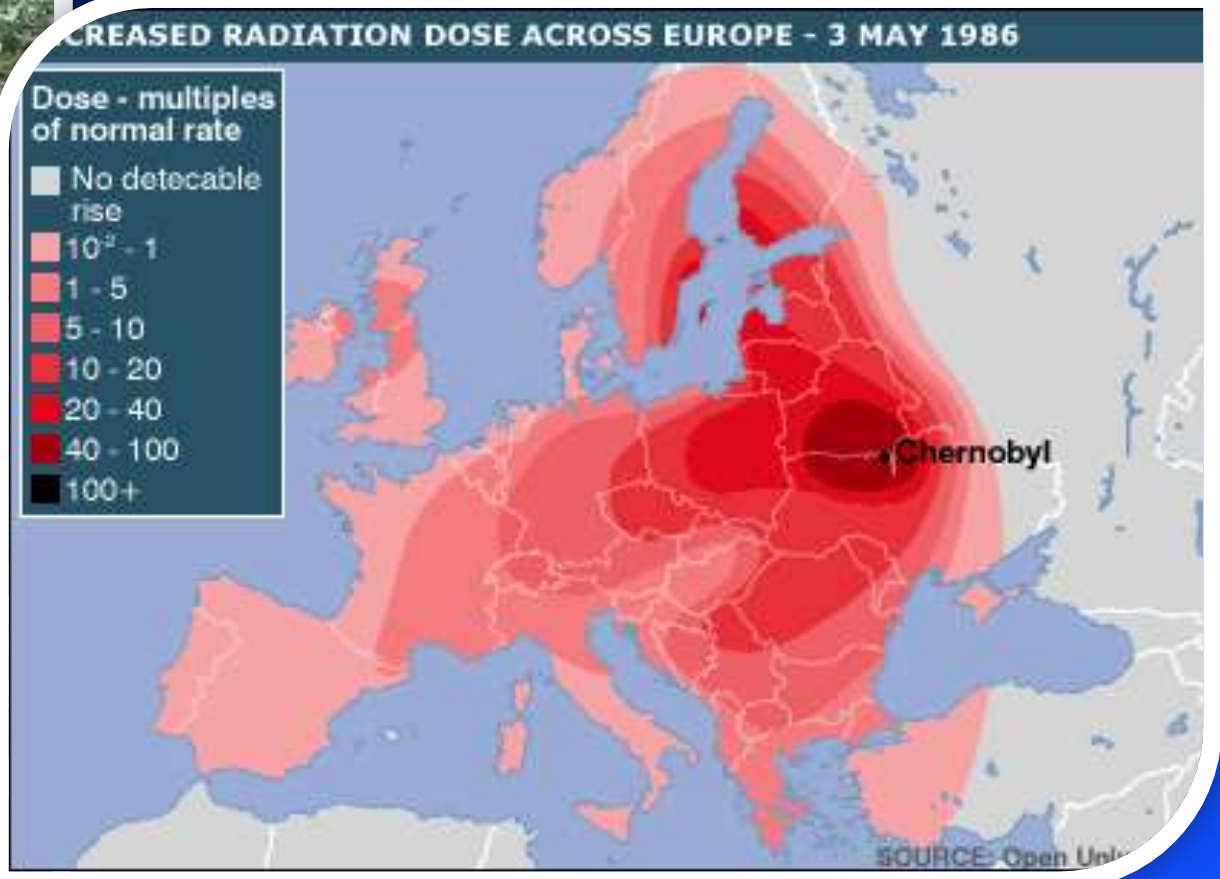
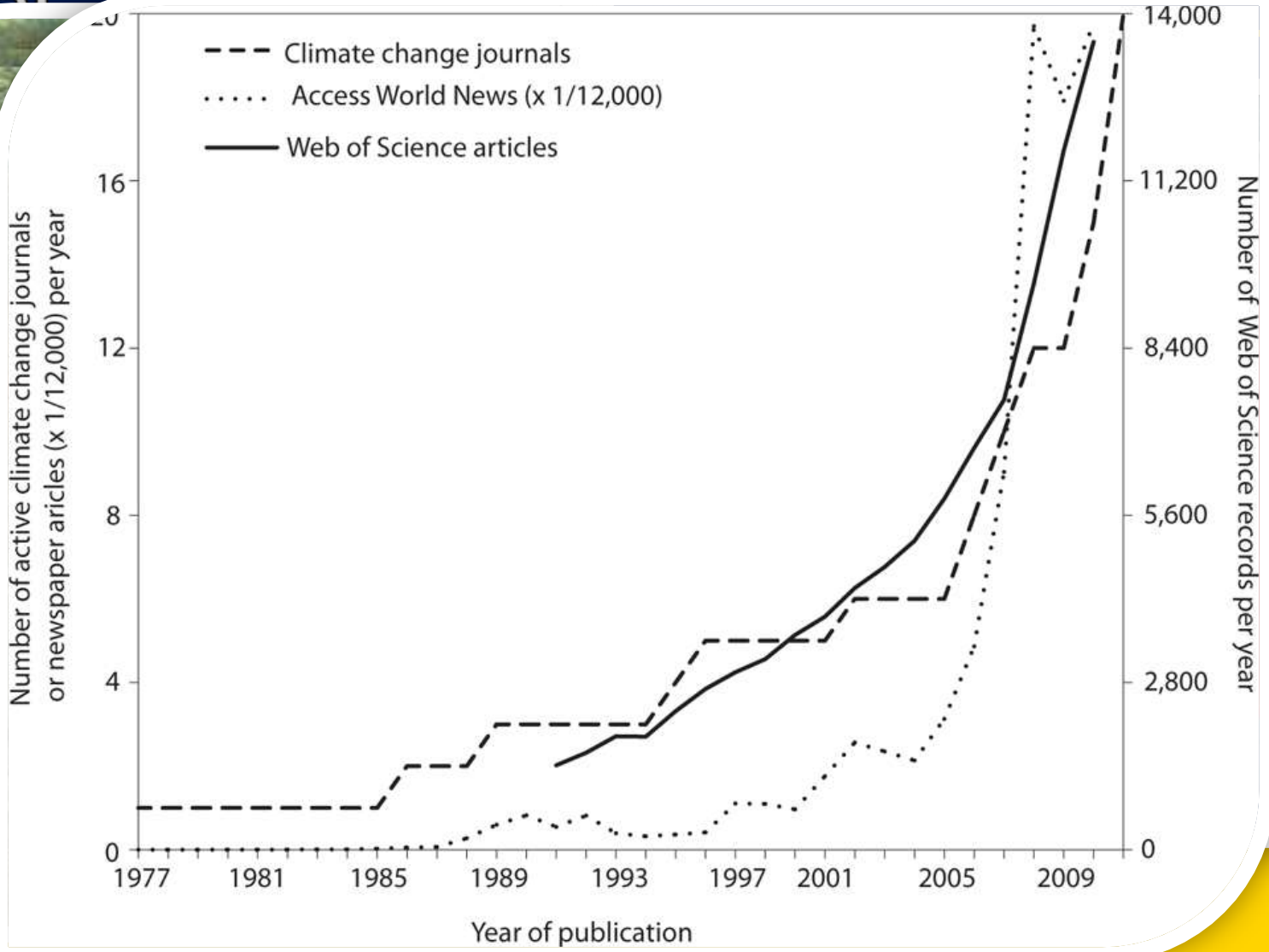
Chernobyl



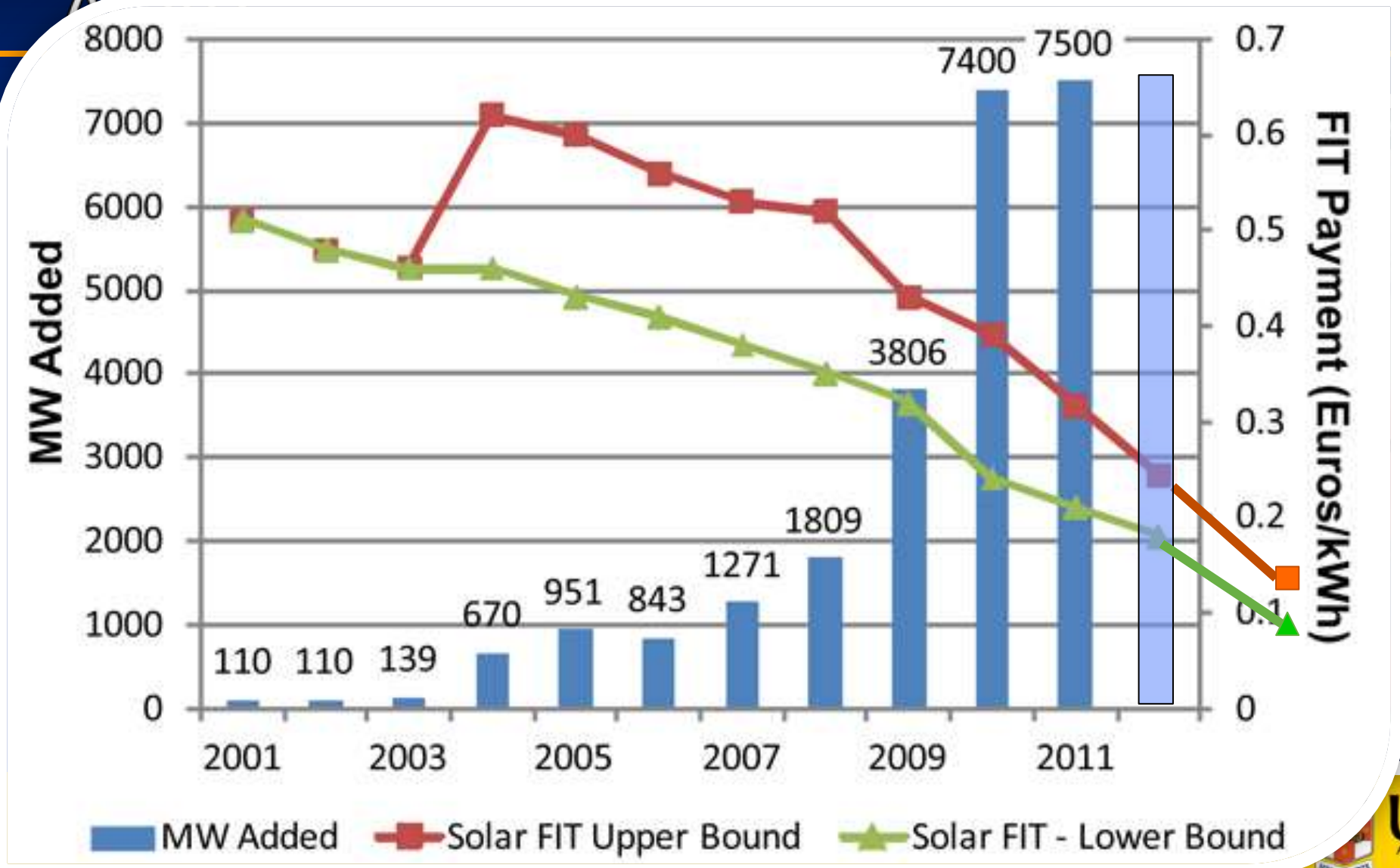
Chernobyl

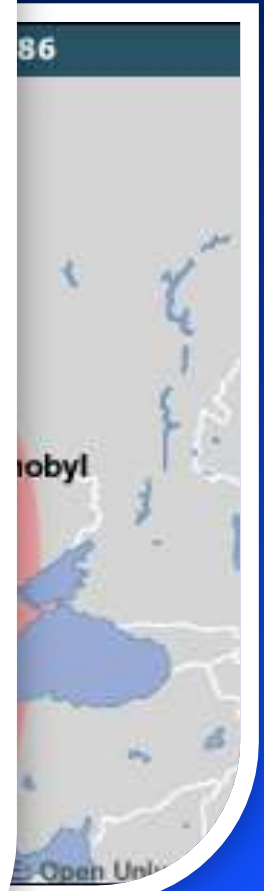

CREASED RADIATION DOSE ACROSS EUROPE - 3 MAY 1986
Dose - multiples of normal rate
No detecable rise
10⁻² - 1
1 - 5
5 - 10
10 - 20
20 - 40
40 - 100
100+
Chernobyl

Global Warming



German Feed-In Tariff (FIT)





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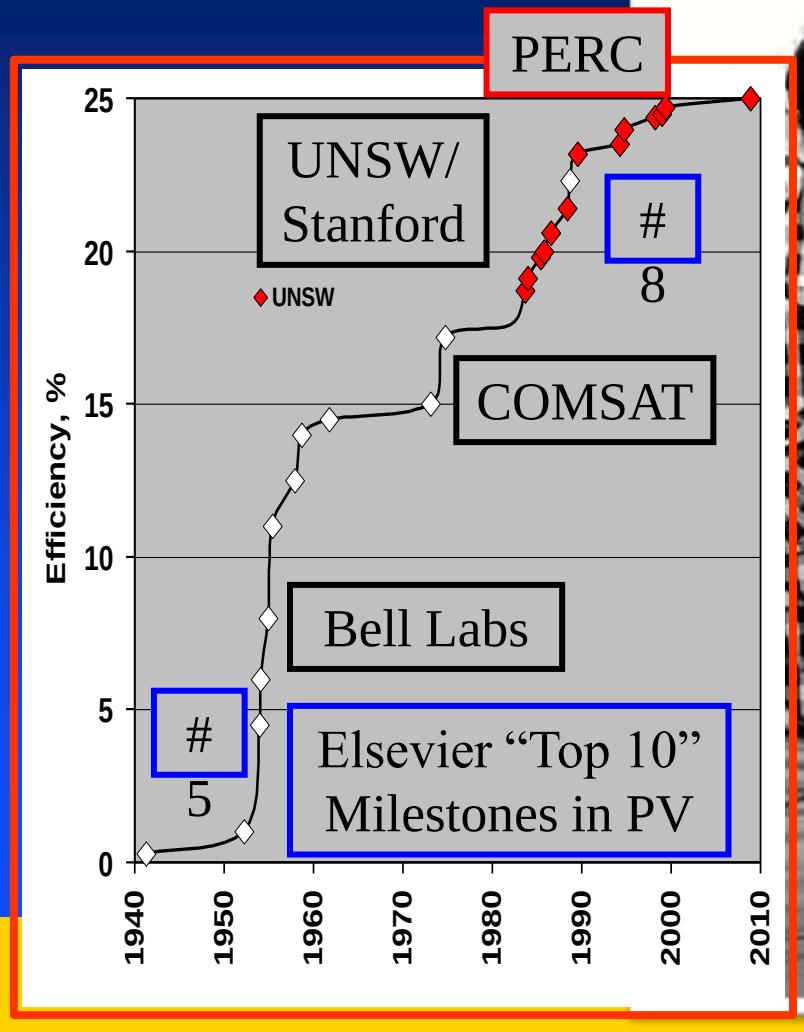
First World Record (1983)



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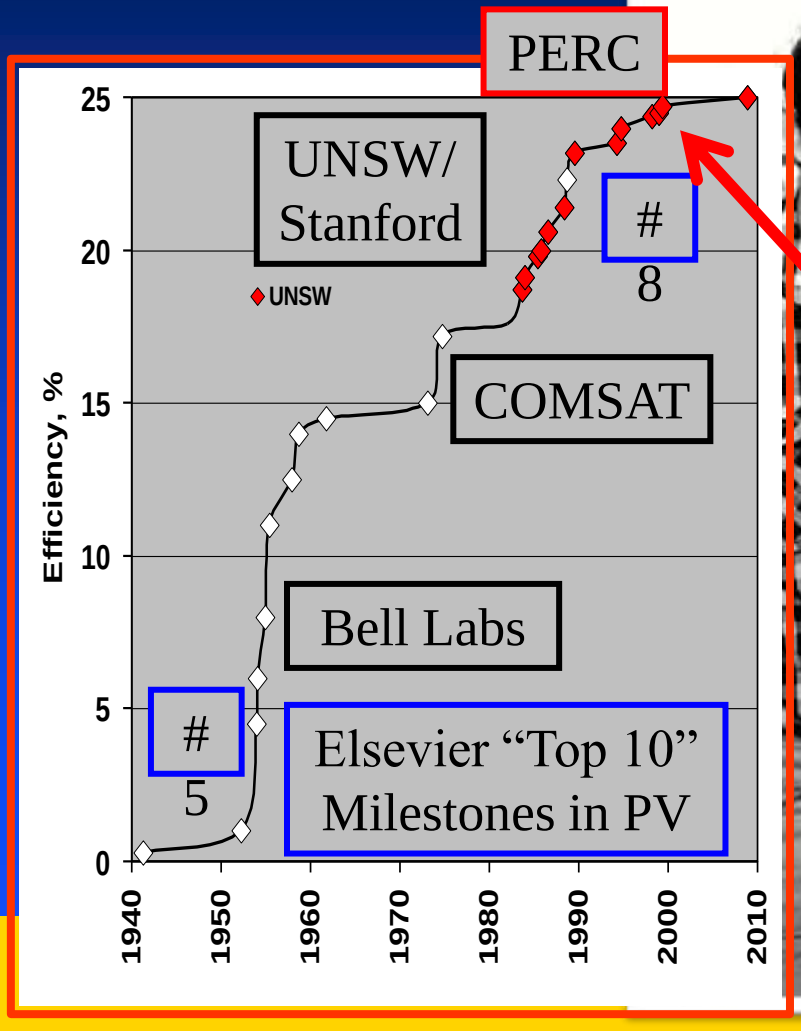
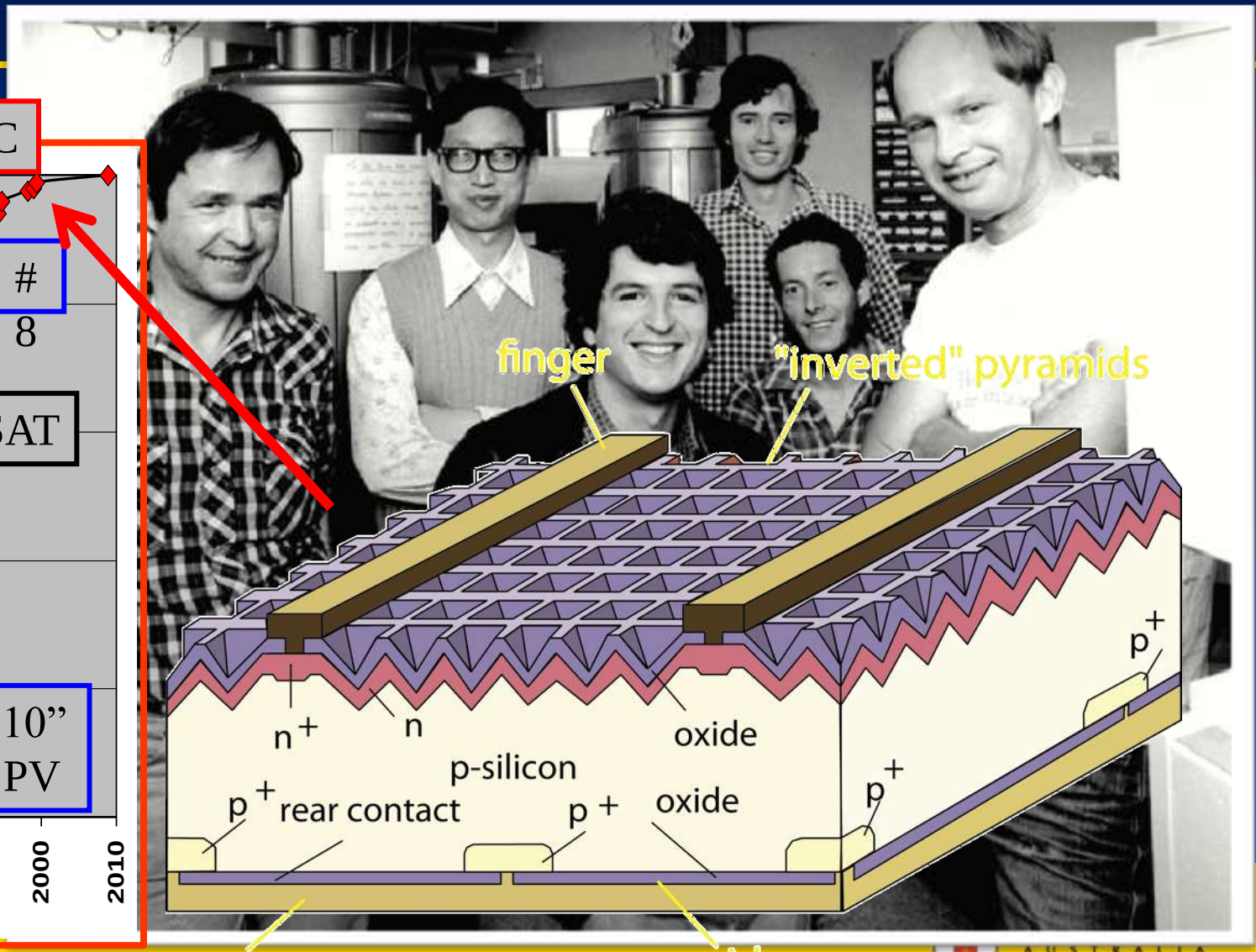
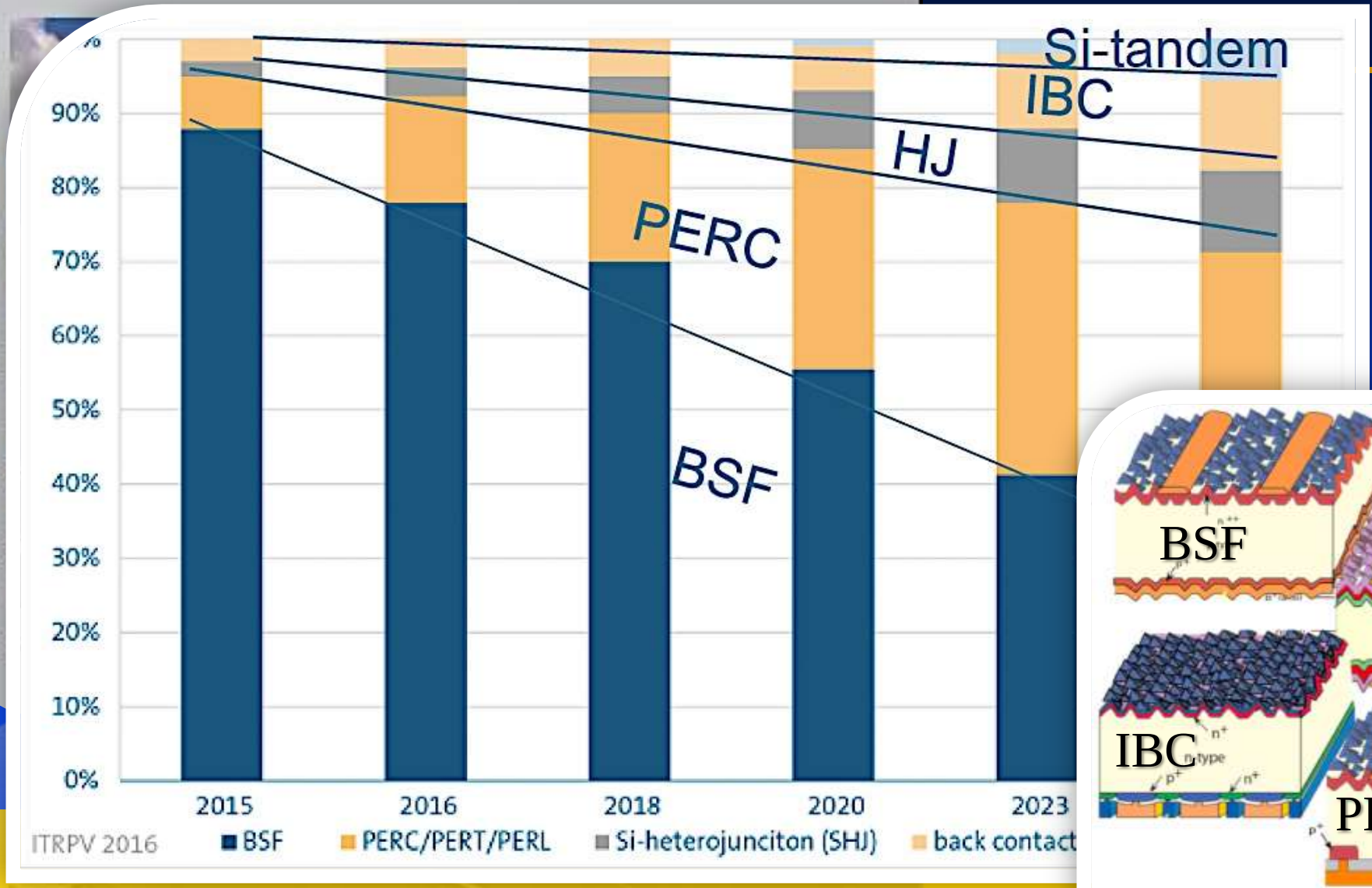


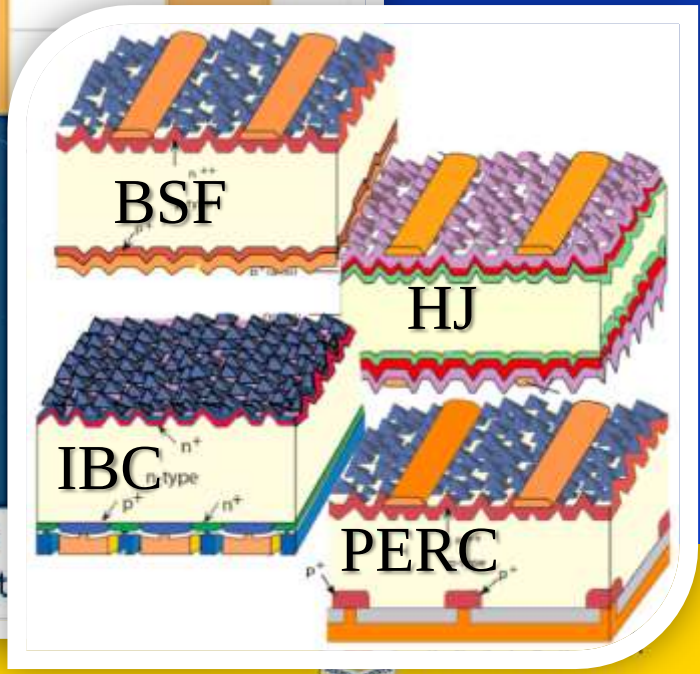


Cell technology

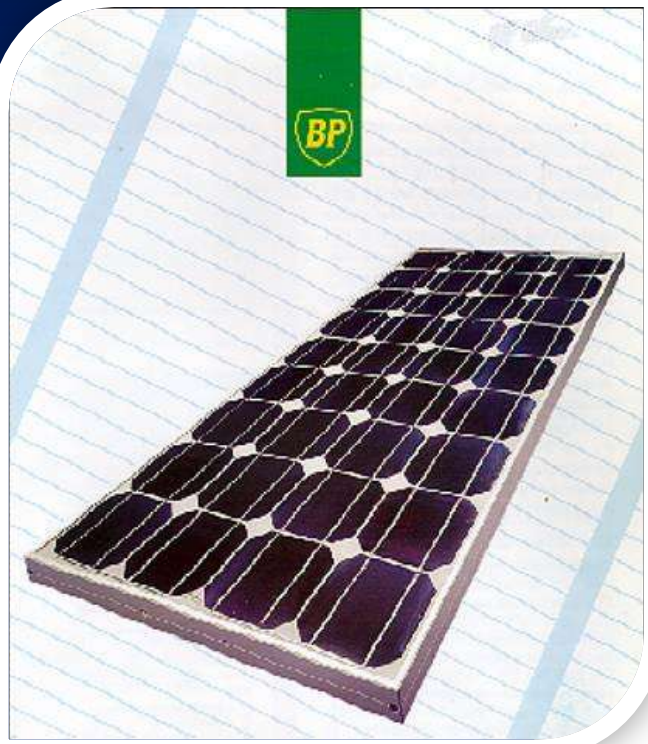
International Technology Roadmap for Photovoltaic (ITRPV)

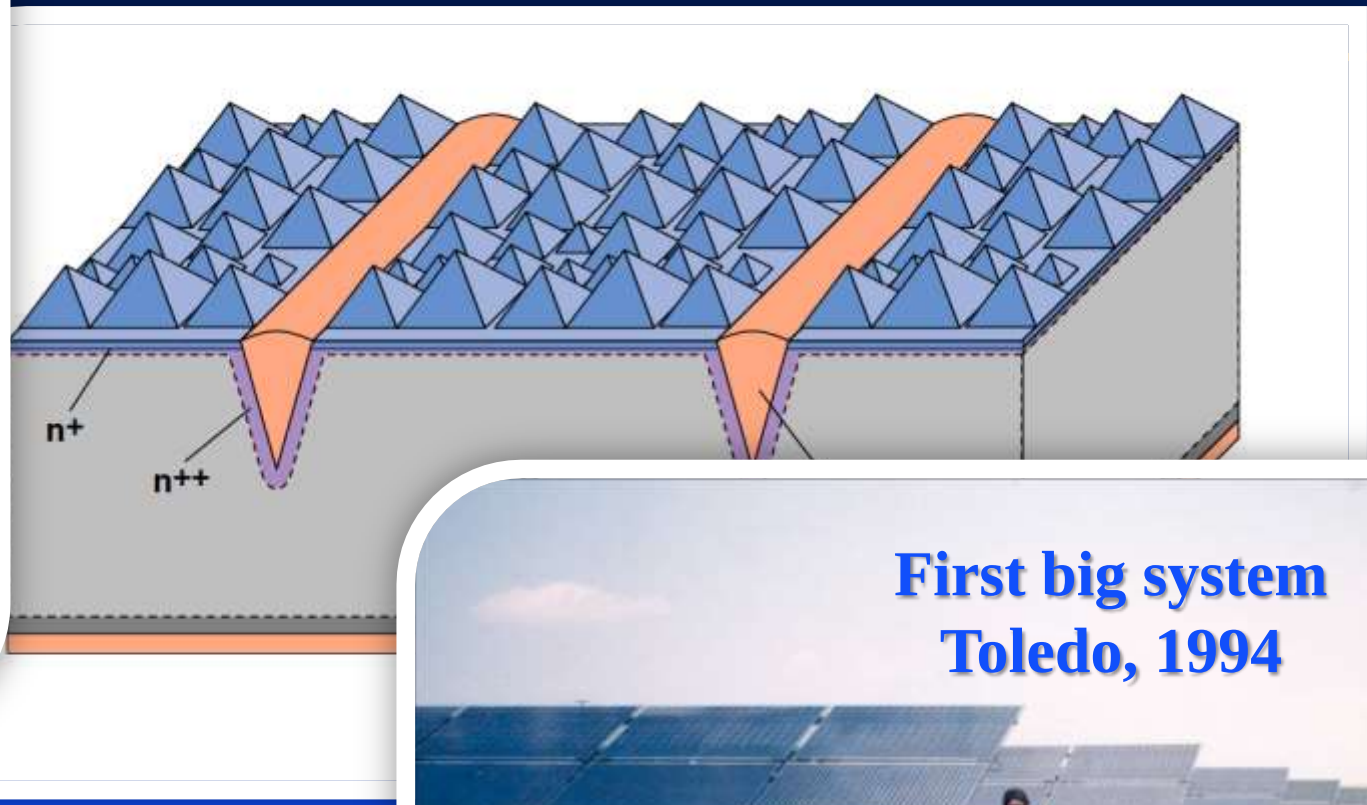
2015 Results



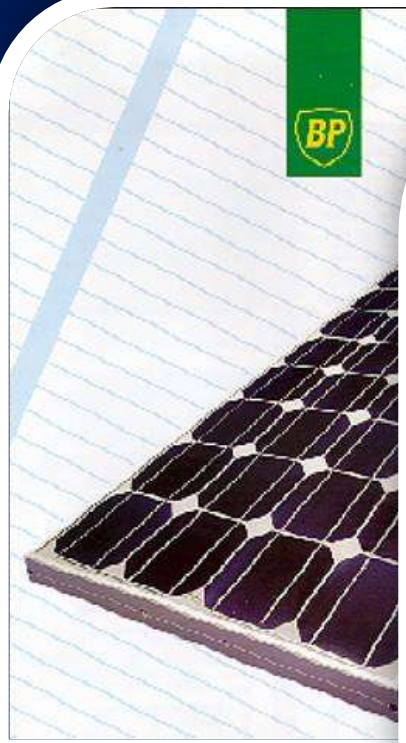


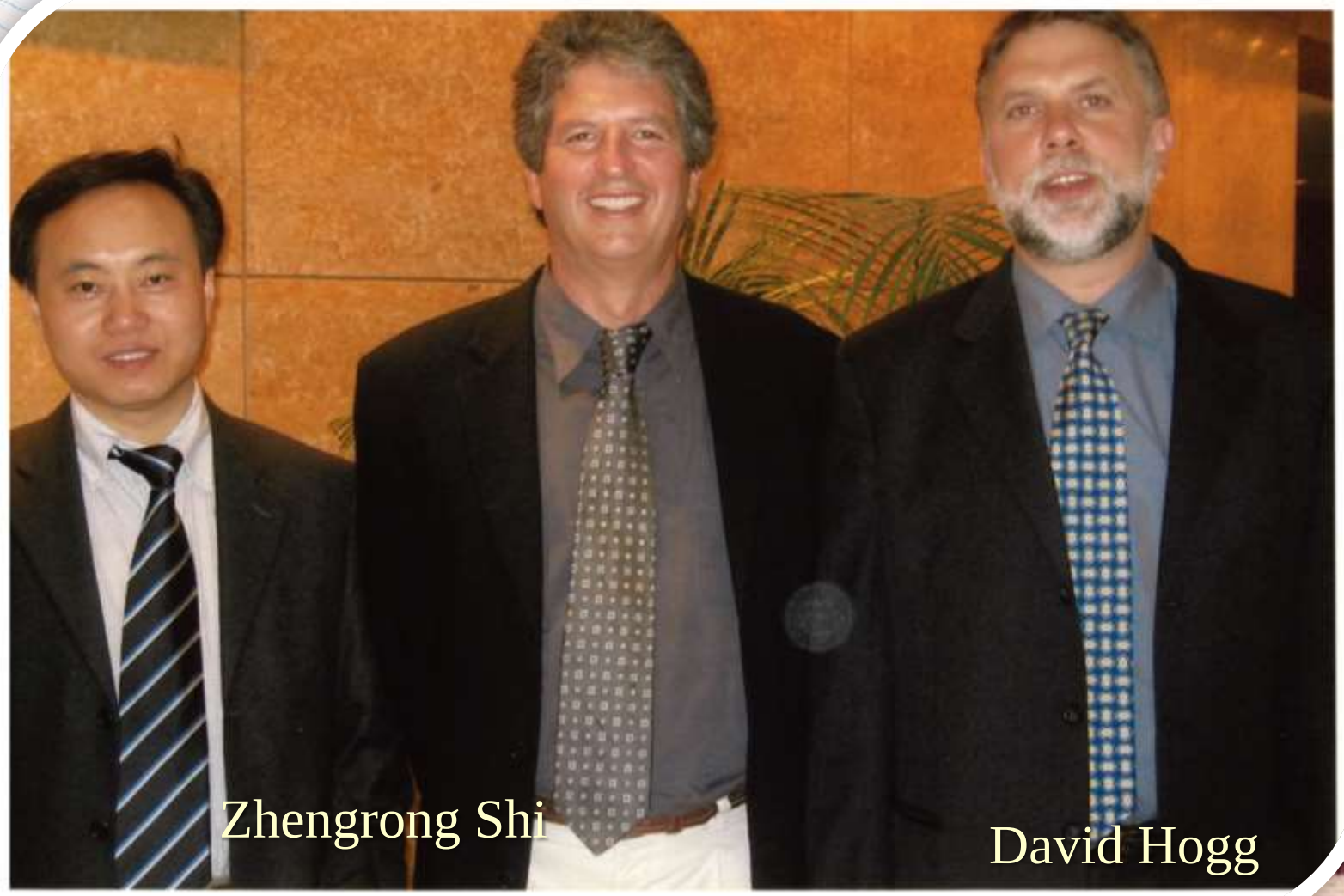
Buried contact solar cell (Saturn cell)





China visit, 1994
(“Devoid of all appropriate infrastructure”)

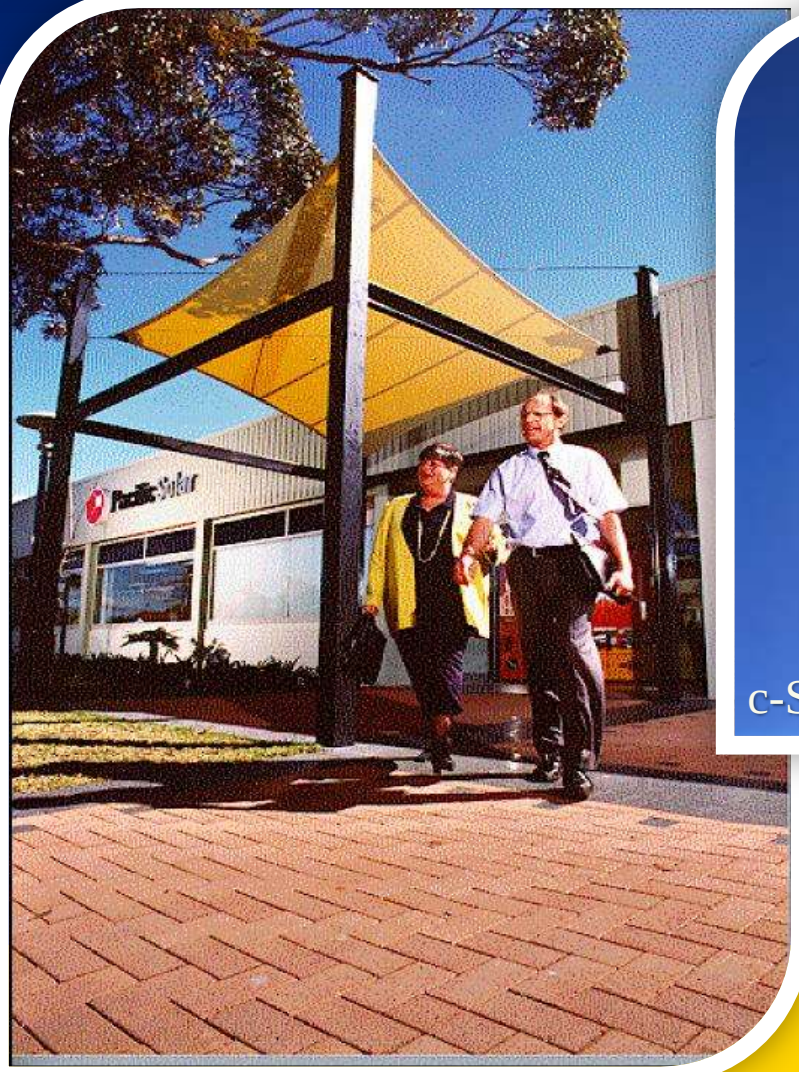


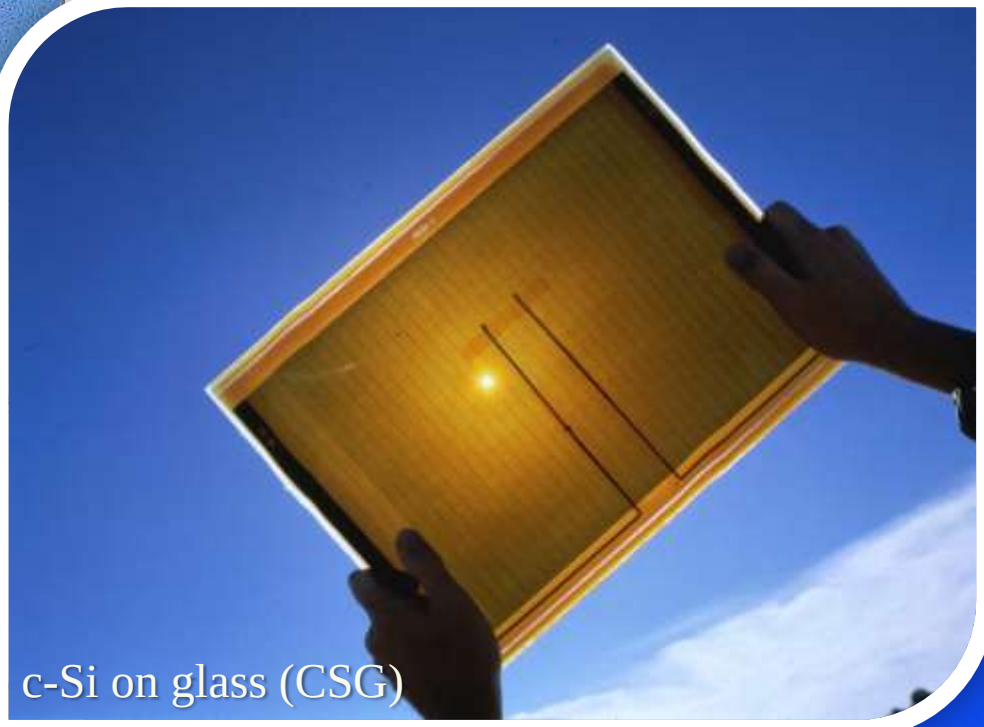


Zhengrong Shi

David Hogg

Pacific Solar, 1995
Training ground for Chinese industry





c-Si on glass (CSG)

Pacific Solar, 1995
Training ground for Chinese industry

csgsolar taking the next step

Solar Valley, Thalheim, 2004

TF c-Si on glass (CSG)

ACA

PacificSolar

Management

David Hogg (Managing Director, Rehabilitation Co-ordinator)

Martin Green (Research Director)
Stuart Wenham (Co-Research Director)
Paul Basore (Manufacturing Development, Deputy Research Director)
Zhengrong Shi (Process and Technology Development, Deputy Research Director)
Sean Edmiston (Power Electronics)
Ted Szpitalak (Acquisitions)
Peter Lawley (Company Secretary, Business Development, Chief Warden)
Michael Taouk (Operations, Quality Representative, Deputy Chief Warden)
Louise Mitchell (Administration, Chairman OH&S Workplace Committee)

Kathleen Ryan (Secretary – Management Meetings)

Research & Development

Martin Green (Research Director)

Stuart Wenham (Co-Research Director)
Joyce Ho (Research Secretary)

Process & Technology Development

[achieving cell performance milestones; developing process sequences; characterisation]

Zhengrong Shi

Vincent Chin (Quality Liaison, Chairman SAC, Characterisation Lab Supervisor)
Cheng Tsien Chou (Microscopy Supervisor)
Yidan Huang
Jing-Jia Ji
Arthur Simonian
Wah-Chung Wong
Siyong Wu (PECVD Co-ordinator)
Wei Zhang
Jing Bing Zhu
Fengming Zhang
Shijun Cai
GuangChun Zhang
James Xia
Tanya Sakalo
Alistair Sproul (Device Characterisation Supervisor)
Ximing Dai
Christopher Fell

Manufacturing Development

[development of production sequences; cost analysis; quality control; technical strategies]

Paul Basore

Neil Barrett
Trevor Young
Stefan Jarnason (Quality Co-ordinator, PEF Supervisor)
Claude Naoum
Rhett Potter
Renate Egan (PPF Supervisor)
Declan Farrelly
Sergey Varlamov

Operations

[technical support; safety]

Michael Taouk

Ted Szpitalak
Cathryn Ellison (Operations Assistant)

Facilities

[maintenance & operation of facilities; logistics]

Naim Sayah (Facility Supervisor, Drawing Control and Calibration Co-ordinator)

Kevin Bates
Bruce Beilby (Web Site Officer)
Graeme Lennon (Workshop)
Peter Succar (Logistics Co-ordinator, Security Warden, Stores Officer)
Fuzu Zhang (Systems Analyst)
Garry Pitt
Andrew Simpson
Eugene Khazanov

DoE
Design of Experiments

Engineering Design

[engineering support; commissioning and modification of apparatus]

Adrian Turner (Engineering Supervisor, Laser Safety Officer)

Jeremy Chu
Pat Lasswell
Choo Kuang Lee
Scott Olsen (Safety Co-ordinator)
Lionel Windsor (Quality Liaison)
Nathan Chang
David O'Donovan

ISO 9001
Registered Quality System

1997

the next step

PacificSolar

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1997

DoE Design of Experiments

9/9/2002: Launch of Chinese PV Industry

Capitalization

9 September 2001
Suntech Power Co. Ltd. is founded

9 September 2002
Suntech's first 10MW PV cell production line begins operation

December 2002
Suntech signs R&D cooperation agreement with the photovoltaic research centre at the University of New South Wales, Australia

18 December 2003
New 15MW solar cell line begins operation

18 August 2004
New 25MW cell line begins operation

14 December 2005
Suntech raises almost $400 million in its initial public offering on the New York Stock Exchange

2001 2002

Firm	Date	Investment form	Amount	Investor/Exchange	Nationality
Suntech	2001.1	Equity Financing Equity Financing	$2M $6M	Zhengrong Shi (Founder) Wuxi's Municipal venture capital firm and seven Wuxi-based corporations	China China
	2005.1	Convertible Debt	$8.4M	Million Power Finance	HK
	2005.5	Equity Financing	$80M	Goldman Sachs, DragonTech Ventures, Actis Capital, Prax Capital, Natixis	USA, HK, UK, China, France
	2005.12	IPO	$400M	NYSE	USA

ACAP

UNSW AUSTRALIA

Ca

First private Chinese NYSE
Largest tech float 2005

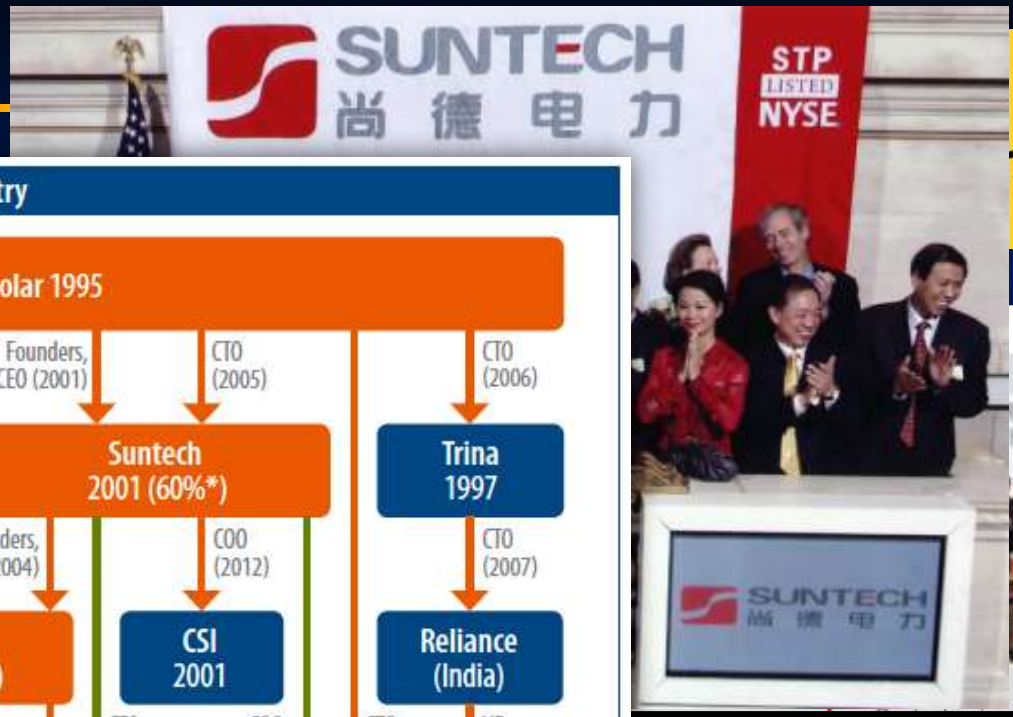
9 September 2001
Suntech Power Co. Ltd. is founded

9 September 2002
Suntech's first 10MW PV cell production line begins

14 December 2005

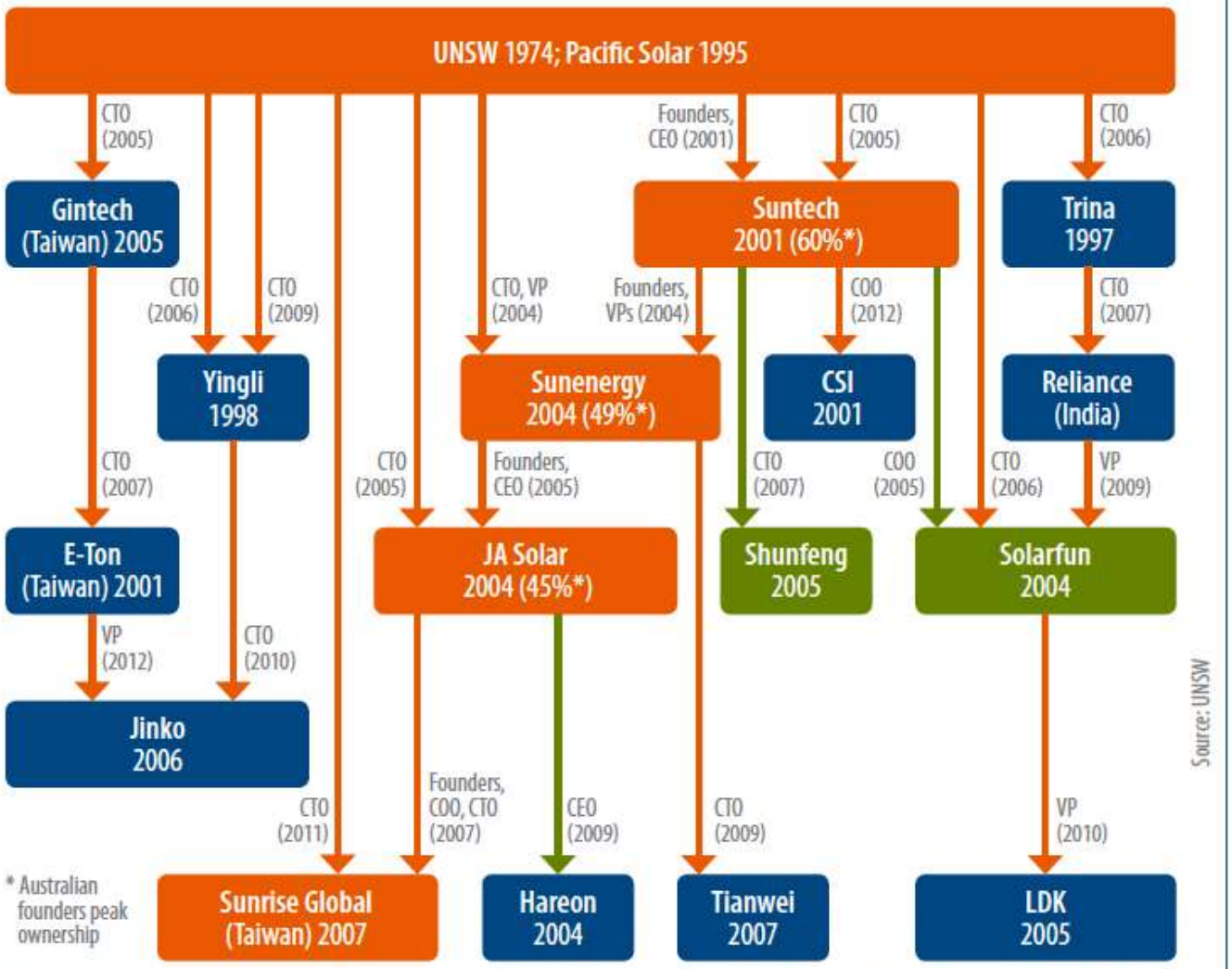
1. Establishes first viable private cell production facility in China
2. Establishes competitive position internationally for Chinese modules
3. Helps build up local supply chain to reduce costs
4. Pioneers capital raising on US markets to finance PV growth in China

Name of Company	Exchange	Date IPO Completed	Completed IPO Value	Date Follow-On Funding Completed	Completed Follow-On value	Date Debt Issue	Completed Debt Amount (Convertible senior notes)	Total Funding Raised
Suntech Power	NYSE	12/14/2005	396	5/29/2009	277	9/30/2008 12/31/2008	500 557	1,730



UNSW AUSTRALIA

Australian links to some of the key firms in the Chinese PV Industry



Orange represents UNSW/Pacific Solar trained or co-founded, green represents "second generation" linkages, and blue "others".

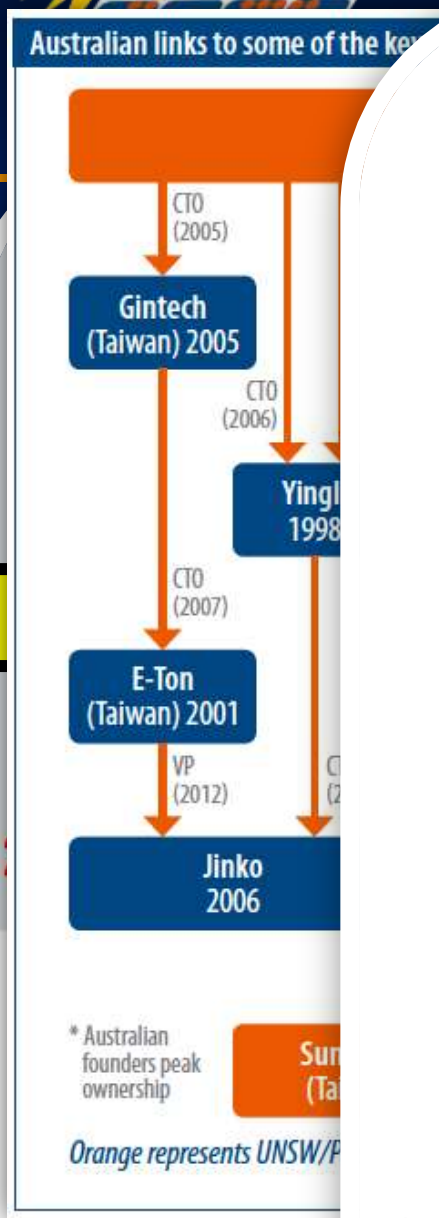
acility in China

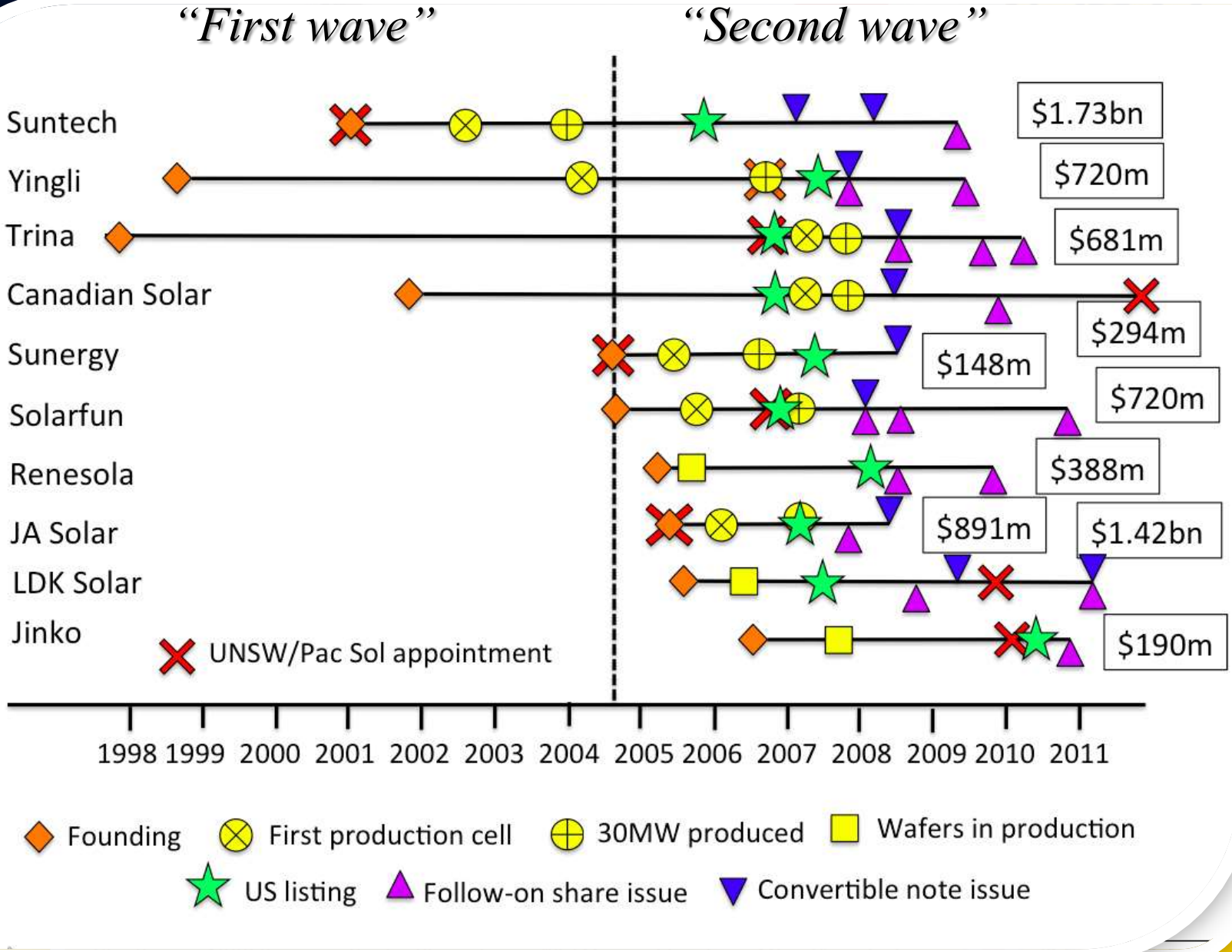
for Chinese modules

osts

nce PV growth in China

Date Debt Issue	Completed Debt Amount	Total Funding Raised
(Convertible senior notes)		
9/30/2008	500	1,730
12/31/2008	557	


Australian links to some of the ke
CTO (2005)
Gintech (Taiwan) 2005
CTO (2006)
Yingl 1998
CTO (2007)
E-Ton (Taiwan) 2001
VP (2012)
Jinko 2006
* Australian founders peak ownership
Orange represents UNSW/P


"First wave"
"Second wave"
Suntech
Yingli
Trina
Canadian Solar
Sunergy
Solarfun
Renesola
JA Solar
LDK Solar
Jinko
$1.73bn
$720m
$681m
$294m
$148m
$720m
$388m
$891m
$1.42bn
$190m
UNSW/Pac Sol appointment
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011
Founding
First production cell
30MW produced
Wafers in production
US listing
Follow-on share issue
Convertible note issue

Chinese Government Involvement

. **Local Government:**

From 1994, strong incentives to promote local industry development (taxes, promotions)

(Suntech still had to approach many before getting backer)

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ACAP

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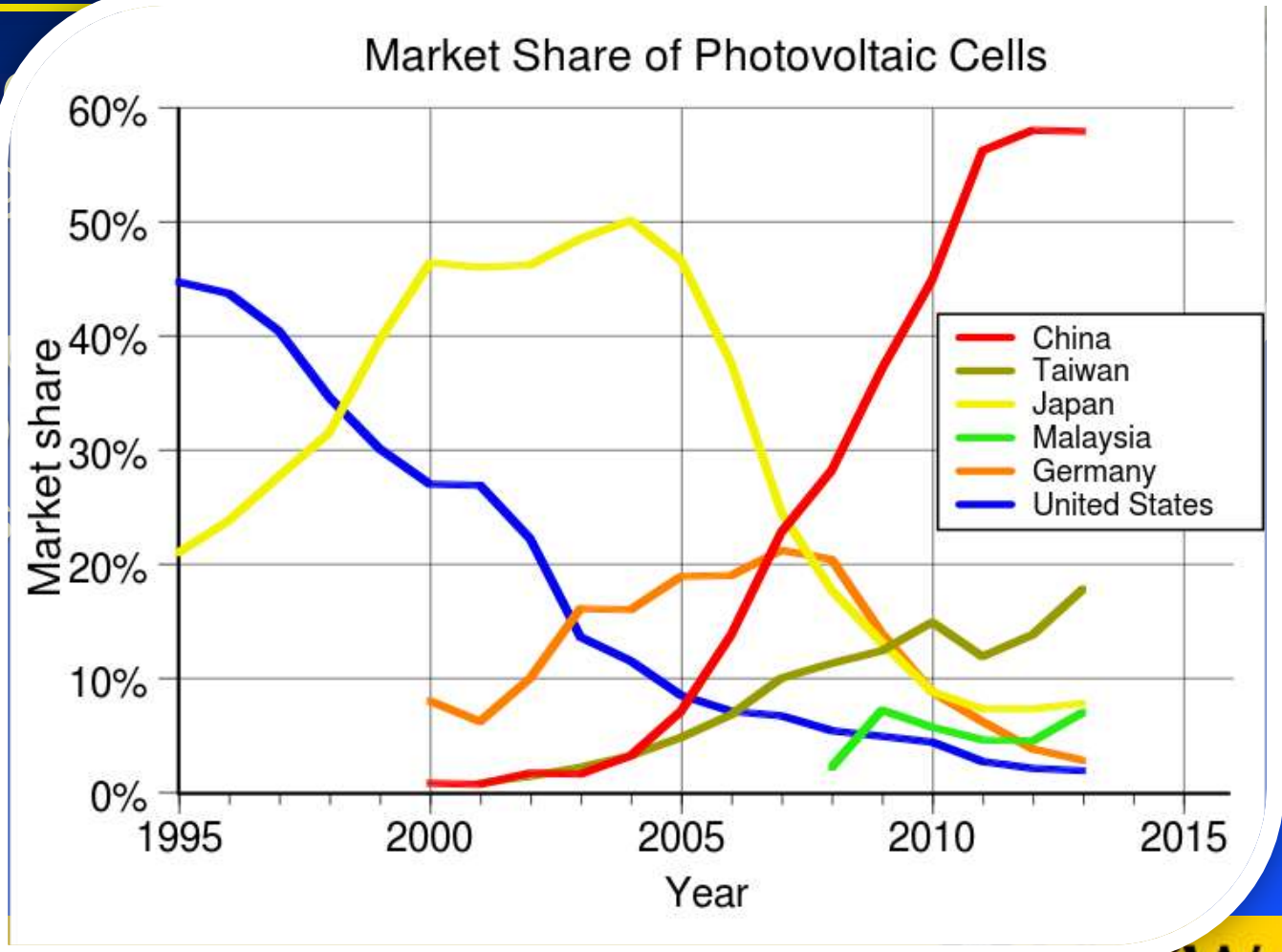
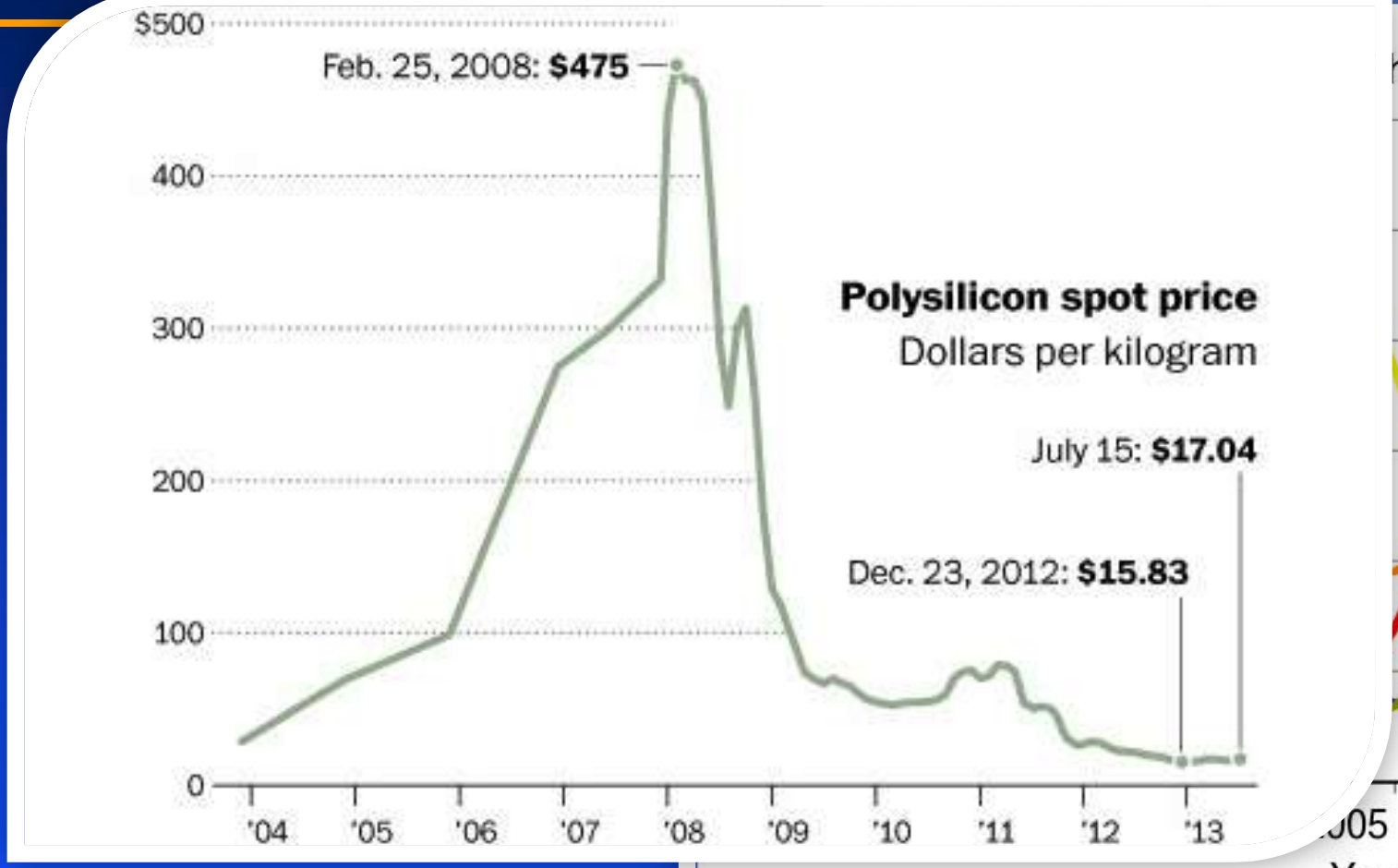
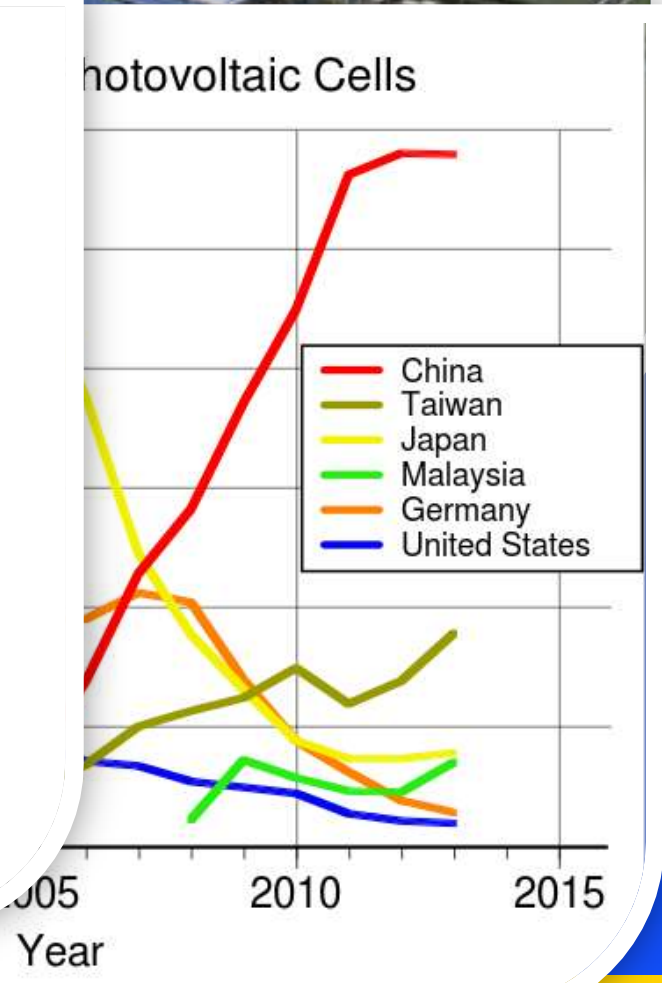


UNSW AUSTRALIA

Chinese Gove





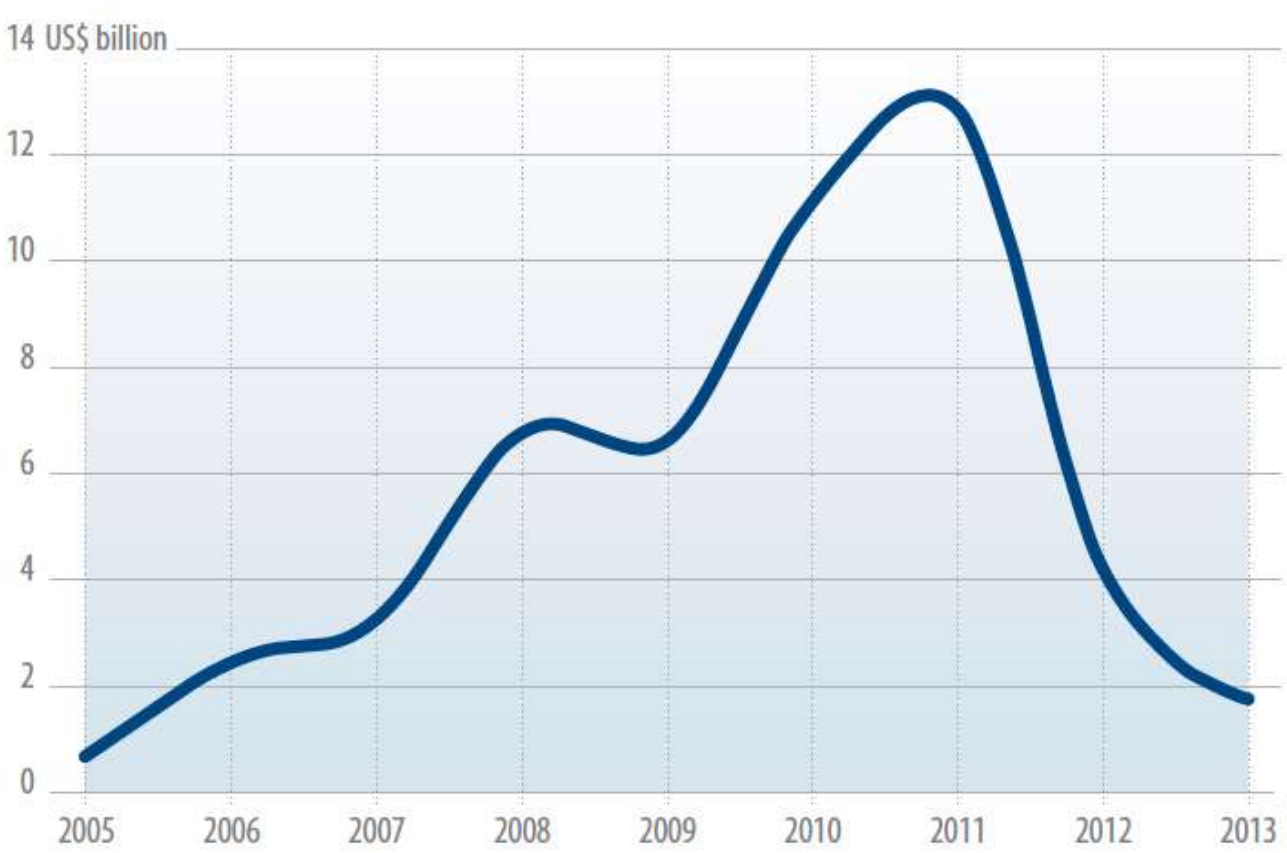
Chinese Gove

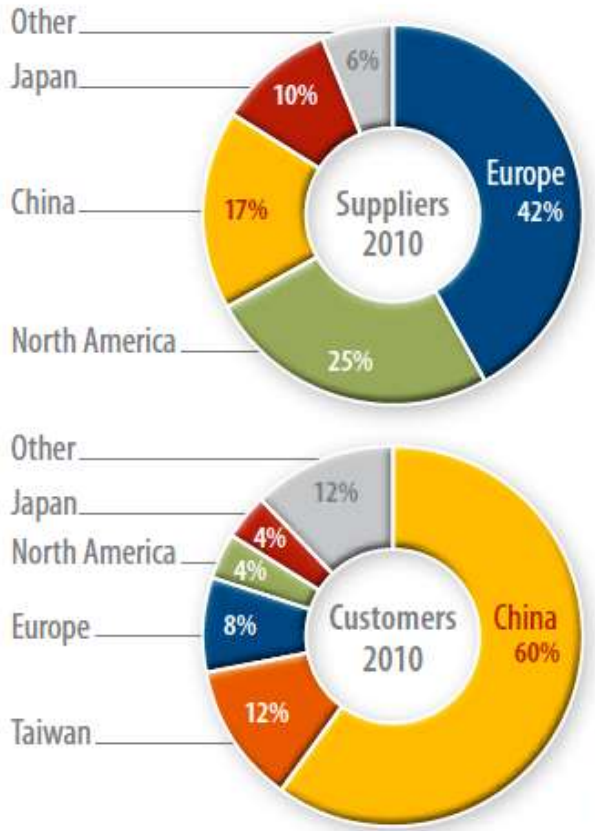
$500

Feb. 25, 2008: **$475**

hotovoltaic Cells

Annual PV equipment sales





U.S.-China Solar Energy - Related Trade Flows, 2010

IMPORTS

PV CAPITAL EQUIPMENT
$93M

PV POLYSILICON
$4M

THIN FILM PV FEEDSTOCK
$7M

PV WAFERS
$120M

PV CELLS
$38M

PV MODULES
$1,154M

PV INVERTERS
$20M

SHC
$7M

EXPORTS

PV CAPITAL EQUIPMENT *
HIGH- $1,000M
LOW- $708M

PV POLYSILICON
$873M

THIN FILM PV FEEDSTOCK
< $1.0M

PV WAFERS
$26M

PV CELLS
$65M

PV MODULES
$17M

PV INVERTERS
< $1.0M

SHC
< $1.0M

$1,441M
TOTAL IMPORTS

HIGH- $1,981M
LOW- $1,688M
TOTAL EXPORTS *

LOW	HIGH
$247M	$539M

NET EXPORTS

GTM RESEARCH

*Estimate provided as a range due to corporate confidentiality policies

IMPORTS

PV CAPITAL EQUIPMENT
$93M

EXPORTS

UNITED STATES OF AMERICA

PV CAPITAL EQUIPMENT *
HIGH- $1,000M
LOW- $708M

PV POLYSILICON
$873M

THIN FILM PV FEEDSTOCK
< $1.0M

PV WAFERS
$26M

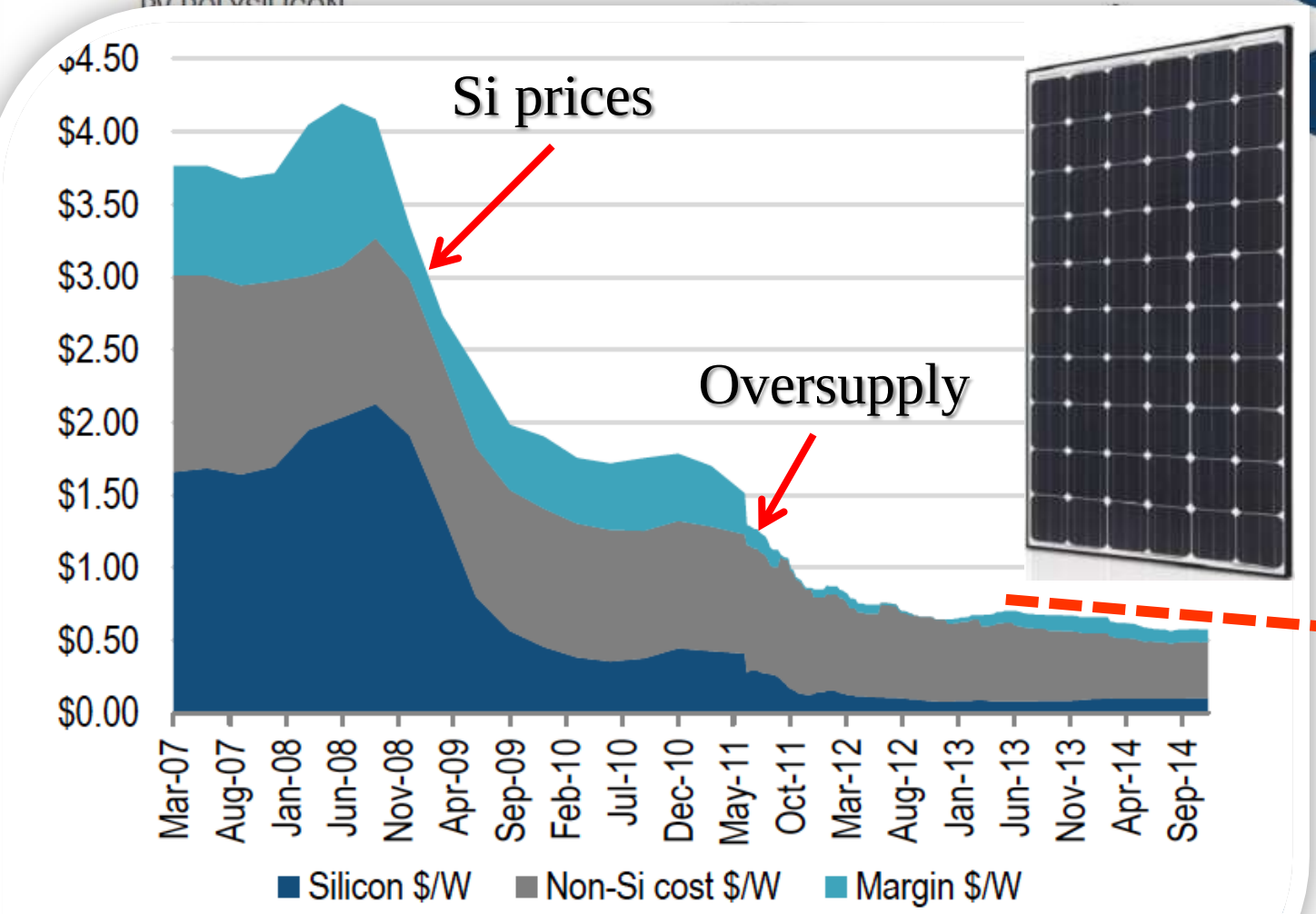
PV CELLS
$65M

PV MODULES
$17M

PV INVERTERS
< $1.0M

SHC
< $1.0M

RESEARCH



Source: EnergyTrend, Company data, Credit Suisse estimates.

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. Federal Government:

"the central government did not provide direct financial or political support to the private solar PV sector before 2009"

W. Zhang, S. White / Research Policy 45 (2016) 604–617

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. **Federal Government:**

"the central government did
political support to the privat

Loan Transactions involving Chinese Banks to Chinese Solar Companies since Jan 2010*

Company	Amount ($M)	Banks
China Sunergy	160	China Development Bank
Daqo New Energy	154	Bank of China
Hanwa SolarOne	1,000	Bank of China
Hanwa SolarOne	885	Bank of Shanghai
JA Solar	4,400	China Development Bank
Jinko Solar	7,600	Bank of China
LDK Solar	8,900	China Development Bank
Suntech	7,330	China Development Bank
Trina Solar	4,400	China Development Bank
Yingli Green Energy	179	China Citic Bank, Bank of China
Yingli Green Energy	5,300	China Development Bank
Yingli Green Energy	144	Bank of Communications
Yingli Green Energy	257	Bank of Communications
Total	40,709	

Source: Mercom Capital Group, llc
All amounts in millions of dollars.
*As of Sept. 26, 2011

W. Zhang, S. White / Research Policy 45 (2016) 6

ment Involvement

BloombergBusiness | News | Markets | Insights | Video

Chinese Renewable Companies Slow to Tap $47 Billion Credit

by Sally Bakewell

November 16, 2011 – 10:08 PM AEDT

Suntech 4%
Trina 1.4%
Yingli 1.4%
JA Solar 0%

n Transactions involving Chinese Banks to Chinese Solar Companies since Jan 2010*

Company	Amount ($M)	Banks
ina Sunergy	160	China Development Bank
o New Energy	154	Bank of China
wa SolarOne	1,000	Bank of China
wa SolarOne	885	Bank of Shanghai
JA Solar	4,400	China Development Bank
Jinko Solar	7,600	Bank of China
LDK Solar	8,900	China Development Bank
Suntech	7,330	China Development Bank
Trina Solar	4,400	China Development Bank
Yingli Green Energy	179	China Citic Bank, Bank of China
Yingli Green Energy	5,300	China Development Bank
Yingli Green Energy	144	Bank of Communications
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Total	40,709	

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W. Zhang, S. White / Research Policy 45 (2016) 6

UNSW AUSTRALIA

“How so cheap?”

Government programs:

US: Flat-plate solar array (FSA) 1975-1986

- *standardized, reliable module design (EVA, Al-BSF, multi-Si, FBR Si)*

Germany: Feed-in Tariff (EEG) 2001-2012

- *reliable, profitable market for emerging industry*

Australia: Centres of Excellence 1981-2010

- *expertise underpinning manufacturing diversification*

China: Local government initiatives 2006-2010

- *created oversupply accelerating cost reduction*

Private: Chinese companies, US Investors

ACAP

Australian Centre for Advanced Photovoltaics

ARENA

Australian Government

Australian Renewable Energy Agency