“How Did Silicon Solar Cells Get So Cheap?”

Martin A. Green
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Recent PPAs (power purchase agreements)

**Figure 1:** PPA Price Offers for Solar PV and Wind Onshore Power Plants in Different Countries

- **Source:** International Energy Agency 2016

- **PPA Price:** $24.20/MWh
Module Cost / Price

Graph showing the manufacturing cost of solar panels over time, with a trend line indicating a decrease of 10% per year. The graph includes data from various manufacturers such as ASP, GTM best, CSIQ, STP, TSL, YGE, JASO, HQCL, and JKS. A forecast is indicated for 6/2013 and 36c/W Q4 2017.
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.)

Figure 5: Structure of the most early photovoltaic devices developed during the 1930’s.
First silicon pn junction cell (Russell Ohl, 1941)
First efficient silicon cells (1953/4)

Pearson, Chapin & Fuller
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 (1,000,000,000,000,000,000) watt-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 translator 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 0.9 watt per 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 80,000,000 times the power of the R.C.A. atomic battery.

Silicon is a semiconductor, Continued on Page 11, Column 4
Photovoltaics - Electricity from Sunlight

- First efficient cells (1953/4)
- Telstar I (1962)
- Vanguard I (1958)
Black cell (COMSAT 1974)

- Textured surface
- "p-type"
- "p+" layer
- "thin n-type layer"

Efficiency, %

UNSW
Black cell (COMSAT 1974)

textured surface

n-type

thin n-type layer

p-type

p+ layer
Black cell (COMSAT 1974)

- **Al-BSF cell**
  - Textured surface
  - p-type
  - n-type
  - p^+
  - Rear contact

- Efficiency, %
  - Black cell (COMSAT 1974)
  - Al-BSF cell

- Graph showing efficiency from 1940 to 2010:
  - 120-150 μm
  - 2-3 mm
  - n^{++}
  - p-type
  - p^+
1975 IEEE Photovoltaic Specialists Conference

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 of a low-cost production.

A paste consisting of silver powder and organic binder was then screen printed on the front using a grid contact configuration. The back was sintered at 850°C. A sheet of glass was then sintered at 600°C. A sheet of Al-BSF glass was then spin-on coated to form an AR coating.

Figure 1
Vacuum Free Solar Cell Process

1. NaOH Etch Slice
2. Diffuse Phosphorus
3. Back Etch
4. Print Al Paste
5. Diffuse P+ 850°C
6. Print Silver Grid & Pad
7. Sinter 600°C
8. Spin-on AR
9. Bake 250°C
 Electricity from Photovoltaic Solar Cells

Flat-Plate Solar Array Project

10 Years of Progress

October 1985

United States Department of Energy
Jet Propulsion Laboratory
California Institute of Technology
National Aeronautics and Space Administration

Typical modules from Block I through V purchases.
ACAP

Photovoltaics Commercial/ Demo
Photovoltaics Commercial/ Demo

Regional experiment station

Monitored houses (~20)

System readiness experiments (~100)

Prototypes (5-10)

Initial system evaluation experiments (~15)
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

Domestic Sales of PV Cells in Japan

(Source) Data from Japan Photovoltaic Energy Association (JPEA)

Subsidy Starts!

% subsidy

Subsidy Ends!

Year


50% 40% 30% 20% 10% 0%

500,000 350,000 300,000 250,000 200,000 150,000 100,000 50,000 0

kW

World PV production 60 MW

70,000 roofs by FY 2000

1 million by FY 2010 (5 GW)

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Japanese "Million Roof" Program

UNSW
Japanese “Million Roof” Program

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Market Share of Photovoltaic Cells

- USA
- Japan

Subsidy Ends!

- China
- Taiwan
- Japan
- Malaysia
- Germany
- United States


Market share 0% 10% 20% 30% 40% 50% 60%
Chernobyl
German Feed-In Tariff (FIT)
First World Record (1983)
First World Record (1983)

Milestones in PV

- UNSW/Stanford
- COMSAT
- Bell Labs
- Elsevier “Top 10”

PERC

ACAP

fingers

“Inverted” pyramids

rear contact

oxide

n+ n p-silicon oxide p+ p+ p+ p+
Buried contact solar cell (Saturn cell)

First big system
Toledo, 1994
China visit, 1994
(“Devoid of all appropriate infrastructure”)

Zhengrong Shi
David Hogg
ACAP

Pacific Solar, 1995
Training ground for Chinese industry

c-Si on glass (CSG)
Pacific Solar, 1995
Training ground for Chinese industry

TF c-Si on glass (CSG)

Solar Valley, Thalheim, 2004
9/9/2002: Launch of Chinese PV Industry
### Capitalization

**UNSW Australia**

<table>
<thead>
<tr>
<th>Firm</th>
<th>Date</th>
<th>Investment form</th>
<th>Amount</th>
<th>Investor/Exchange</th>
<th>Nationality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suntech</td>
<td>2001.1</td>
<td>Equity Financing</td>
<td>$2M</td>
<td>Zhengrong Shi (Founder)</td>
<td>China</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Equity Financing</td>
<td>$6M</td>
<td>Wuxi's Municipal venture capital firm and seven Wuxi-based corporations</td>
<td>China</td>
</tr>
<tr>
<td></td>
<td>2005.1</td>
<td>Convertible Debt</td>
<td>$8.4M</td>
<td>Million Power Finance</td>
<td>HK</td>
</tr>
<tr>
<td></td>
<td>2005.5</td>
<td>Equity Financing</td>
<td>$80M</td>
<td>Goldman Sachs, DragonTech Ventures, Actis Capital, Prax Capital, Natixis</td>
<td>USA, HK, UK, China, France</td>
</tr>
<tr>
<td></td>
<td>2005.12</td>
<td>IPO</td>
<td>$400M</td>
<td>NYSE</td>
<td>USA</td>
</tr>
</tbody>
</table>
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
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**Australian links to some of the key firms in the Chinese PV Industry**

- **UNSW 1974; Pacific Solar 1995**
  - Gintech (Taiwan) 2005
    - CTO (2005)
    - CTO (2006)
  - Yingli 1998
    - CTO (2007)
  - E-Ton (Taiwan) 2001
    - VP (2012)
  - Jinko 2006
    - CTO (2011)

- **Suntech 2001 (60%)**
  - CTO (2005)
  - CoO (2012)

- **Sunenergy 2004 (49%)**
  - Founders, VPs (2004)

- **JA Solar 2004 (45%)**
  - Founders (2005)
  - CTO (2007)

- **Shunfeng 2005**
  - CTO (2005)

- **Solarfun 2004**
  - VP (2009)

- **Trina 1997**
  - CTO (2007)

- **CSI 2001**
  - CTO (2007)
  - CoO (2005)

- **Reliance (India)**
  - CTO (2006)

- **LDK 2005**
  - VP (2010)

**NOTES:**
- *Australian founders peak ownership
- Orange represents UNSW/Pacific Solar trained or co-founded, green represents “second generation” linkages, and blue “others.”
1. Establishes first viable private cell production facility in China
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**First wave**
- Suntech
- Yingli
- Trina
- Canadian Solar
- Sunergy
- Solarfun
- Renesola
- JA Solar
- LDK Solar
- Jinko

**Second wave**

- UNSW/Pac Sol appointment

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**Legend:**
- Orange represents UNSW/AGa ownership
- Black European Union flag represents UNSW/AGa ownership

**Graph:**
- 1998-2011 timeline
- Various companies listed along timeline with production milestones and financial details.
. **Local Government:**

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

*(Suntech still had to approach many before getting backer)*
Chinese Government Involvement

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**Polysilicon spot price**

Dollars per kilogram

- Feb. 25, 2008: $475
- July 15: $17.04
- Dec. 23, 2012: $15.83

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- China
- Taiwan
- Japan
- Malaysia
- Germany
- United States
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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"
### Local Government:
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### Federal Government:
"the central government did not provide direct financial or political support to the private sector before 2009"

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

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

*Source: Mercom Capital Group, llc*

All amounts in millions of dollars.

*As of Sept 26, 2011*
Chinese Renewable Companies Slow to Tap $47 Billion Credit

by Sally Bakewell

November 16, 2011 — 10:08 PM AEDT

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) 6
“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
Thank you!