“Solar Photovoltaics: Power Source for the Future”

Martin Green, UNSW Sydney, Australia
Part 1: Introduction
Solar cell
Solar module

Diagram showing the layers of a solar module:
- Frame
- Glass
- Encapsulant
- Solar Cells
- Encapsulant
- Backsheet
- Junction Box

UNSW Sydney logo
Solar Panel Size Vs Power Output

- 60 cells (120 HC): 300W - 380W
- 72 cells (144 HC): 350W - 450W

Panel dimensions:
- ~1.0 m width
- ~1.65 m height
- ~2.0 m height

Cardboard Cutout:
- 3’ x 6’
- Using your photo
- Self-standing
Solar PV Global Capacity and Annual Additions, 2010-2020

Source: REN21
Solar to the rescue?

Sample 2°C pathway with a 66% chance

1TW solar

Unresolved problem!
Module cost history

- US$4.12/W 2008 Q2
- US$0.17/W 2020 Q2

24x in 12 years!
Module cost history

US$4.12/W 2008

US$0.17/W 2020 Q2

Poly-BSF -23%/year

Mono-PERC -21%/year

PV Module Weekly Spot Price

0, o - auction results
Lowest PPA bids

PPA = Power Purchase Agreement

1c/kWh!
International Energy Agency says (2020):

"solar is now the cheapest source of electricity in most countries"

"now offer some of the lowest cost electricity ever seen"
Part 2: How cheap can solar become?
History of PV cost/price reduction

- A reduction of more than Moore's law is observed
- From $1/W to <$0.20/W
- A decrease of -7%/year
- A decrease of -20%/year to 2020
History of PV cost/price reduction

>$1/W

<$0.20/W

2020 - 7%/year

More than Moore! - 20%/year
History of PV cost/price reduction

- $1/W
- < $0.20/W

2020 - 7%/year

More than Moore!

-7%/year

-20%/year

>$1/W

<=$0.20/W
History of PV cost/price reduction

>$1/W

<$0.20/W

2020 - 7%/year

More than Moore!

Poly-BSF

Mono-PERC

-12%/year

-24%/year

-22%/year

Break point

PERC era

PV Module Weekly Spot Price

0, o - auction results

US$/W

PV Module Weekly Spot Price

0, o - auction results

-7%/year

>$1/W

-20%/year

<$0.20/W

1/1/12

31/12/13

1/1/16

31/12/17

1/1/20

31/12/17

1/1/24

1975

1980

1985

1990

1995

2000

2005

2010

2015

years


More than Moore!
History of PV cost/price reduction

$1/W

<$.20/W

2020 - 7%/year

More than Moore! - 20%/year

Poly-

BSF

Mono-

PERC

24%/year

22%/year

12%/year

Break point

PERC era

PV Module Weekly Spot Price

o, o - auction results

1/1/12

31/12/13

1/1/16

31/12/17

1/1/20

31/12/21

1/1/22

1/1/24

US$/W

0.1

1


UNSW

Sydney
Part 2: Will PV costs keep decreasing?
PERC transforms industry!

Cell Production (MW)

- Thin-film
- c-Si p-mono PERC
- c-Si p-multi PERC
- c-Si n-type (n-PERT/TOPCon, HJT, IBC)
- c-Si p-mono Al-BSF
- c-Si p-multi Al-BSF

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Process Optimization of Ingots Pulling Technology

Continuous increase of feeding rate
- Large scale thermal field
- RCz ingot pulling technology (applied since 2013)
- 60kg/crucible
- 175kg/crucible
- 700kg/crucible
- 1500kg+/crucible

High speed ingot pulling technology
- Pulling speed increased 80%+ since 2013

Production line automation
- Automatic control system
- Automatic edge cleaning system
- Automatic loading technology
Mono Wafer Cost Reduction

Mass Production Cost Down

- Wafer slicing cost
- Ingot pulling cost

<table>
<thead>
<tr>
<th>Year</th>
<th>Wafer Slicing Cost</th>
<th>Ingot Pulling Cost</th>
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<tbody>
<tr>
<td>2011</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>2012</td>
<td>95%</td>
<td>82%</td>
</tr>
<tr>
<td>2013</td>
<td>88%</td>
<td>71%</td>
</tr>
<tr>
<td>2014</td>
<td>78%</td>
<td>62%</td>
</tr>
<tr>
<td>2015</td>
<td>52%</td>
<td>43%</td>
</tr>
<tr>
<td>2016</td>
<td>41%</td>
<td>31%</td>
</tr>
<tr>
<td>2017</td>
<td>30%</td>
<td>25%</td>
</tr>
<tr>
<td>2018</td>
<td>25%</td>
<td>22%</td>
</tr>
<tr>
<td>2019</td>
<td>21%</td>
<td>20%</td>
</tr>
</tbody>
</table>
PERC offers new functionalities: Cheap bifacial cells!
PERC: Cheap bifacial cells! Half-cut cells, shingling

Honda Dream 1996
PERC: Cheap bifacial cells! Half-cut cells, shingling (now tiling)

Honda Dream 1996

Source: PVTECH
PERC: Cheap bifacial cells! Half-cut cells, shingling

New Solar PV Cell Sizes

- 156 mm x 156 mm (Introduced 2012)
- 166 mm x 166 mm
- 182 mm x 182 mm (180 - 182 mm)
- 210 mm x 210 mm (New cell sizes in 2020)
PERC: Cheap bifacial cells! Half-cut cells, shingling

Source: GS-Solar

Solar PV Cell Sizes

- 156 mm: Introduced 2012
- 166 mm: New cell size 2019
- 180 - 182 mm: New cell sizes in 2020
- 210 mm
Size trend of silicon wafer in semiconductor and PV industry

- **1965**: 2"
- **1975**: 3"
- **1985**: 4"
- **1995**: 5"
- **2005**: 6"
- **2015**: 8"
- **2020-2025**: 12" (Semiconductor)

For PV:
- **1965**: 2"
- **1975**: 3"
- **1985**: 4"
- **1995**: 5"
- **2005**: 6"
- **2015**: 8"
- **2020-2025**: 12" (PV)

**Future Trends**:
- 2020-2025: 18X mm
- 2025+: 21X mm

**Sizes**:
- 2" mm: 100 mm
- 3" mm: 156 mm
- 4" mm: 158 mm
- 5" mm: 161 mm
- 6" mm: 166 mm
- 8" mm: 125 mm
- 12" mm: 160 mm
200mm/1990  300mm/2001  450mm/2012  675mm/2019?
(125/150mm - 1981)

9 yrs + 2 yrs delay*   11 yrs + 0 yrs delay   9 yrs + 0 yrs delay
Solar Panel Size Vs Power Output

- **60 cells (120 HC)**: 300W - 380W, ~1.0 m x ~1.65 m
- **72 cells (144 HC)**: 350W - 450W, ~1.0 m x ~2.0 m
- **78 cells (156 HC*)**: 450W - 600W+, ~1.1 m x ~1.1 m

*Cardboard Cutout: 3’ x 6’ Using Your Photo Self Standing*
Part 3: Longer term cell technology?
Contending technologies

- PERC, n-PERT
- TOPCon
- HJT
- IBC
- UNSW (p-type)
- Panasonic HIT (n-type)
- SunPower (n-type)
- Rear HJT (n-type)
- PERC (p-type)
- TOPCon (n-, p-, p-type)
What comes after PERC? – longer term

more sophisticated “active” AR coat?

Supercharged tandem PERC?
What comes after PERC? – longer term

Free choice or Si

25% UNSW PERC

Number of cells

AM1.5G

Efficiency

Free choice
Si bottom cell

41%?

33%

47.5%

50.5%
Like silicon, needs to be abundant, non-toxic, stable, efficient (>20%)

<table>
<thead>
<tr>
<th>Material</th>
<th>Abundant</th>
<th>Non-toxic</th>
<th>Stable</th>
<th>Efficient</th>
<th>Perovskite</th>
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<tr>
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<td>X</td>
<td>✓</td>
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<tr>
<td>Organics (OPV)</td>
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<td>✓</td>
<td>X</td>
<td>X</td>
<td>✓</td>
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<tr>
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<td>✓</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>Cu(In:Ga)(S:Se)$_2$</td>
<td>X</td>
<td>?</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>(Cd:Zn:Mg)(Se:Te)</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>(Al:Ga:In)(As:P)</td>
<td>X</td>
<td>?</td>
<td>✓</td>
<td>✓</td>
<td>?</td>
</tr>
</tbody>
</table>

What comes after PERC? – longer term

II-VI

III-V

Si
What then? – the end for silicon?

Si - 3 cell tandem

4-6 cell thin-film tandem
Part 4: Can solar power the world?
Recent studies suggest so!
300MW, 450MWh Li-ion battery
GREEN HYDROGEN COST REDUCTION
SCALING UP ELECTROLYSERS TO MEET THE 1.5°C CLIMATE GOAL

RENEWABLE POWER GENERATION COSTS IN 2020
Volvo Group and SSAB to collaborate on the world’s first vehicles of fossil-free steel

’World first’ as hydrogen used to power commercial steel production
Si PV to become “insanely cheap”!  
(Ramez Naam)

PERC accelerates change

US10c/Watt, 22-23% efficient modules within next few years (+1c/kWh electricity prices)!

Solar with wind, storage and H₂ will play major role mitigating global warming.