Cost and limiting efficiency of silicon solar panels

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Outline

• Context, energy transition

• How silicon solar cells work

• Bifacial solar cells

• Energy conversion efficiency

• Cost of solar electricity

• Solar electricity in BC
77% of new investment goes to renewables.

Context: global power generation mix

Bloomberg New Energy Finance 2019
Quotes

- **1996** G. D. Cody, T. Tiedje *A learning curve approach to projecting cost and performance in thin film PV*, The current cost of electricity generated by PV power is still extremely high ... there remain questions as to whether PV power can ever be competitive with electricity generated by fossil fuels.

- **2018** S. Henbest, 2018, Bloomberg New Energy Finance, *Wind and solar have won the race to produce the lowest cost bulk electricity.*

- **2020** Li Zhenguo, Founder and president, LONGi, Ten years ago, I thought it was a life-time dream for us to reduce the cost of solar energy to a level the same as coal power through our efforts. I didn’t expect it to come true so fast.

- **2020** IEA, World Energy Outlook 2020, Solar becomes the new king of electricity... solar PV is consistently cheaper than new coal- or gasfired power plants in most countries, and solar projects now offer some of the lowest cost electricity ever seen.
Energy transitions past, present and future

- Wood to coal
- Coal to oil
- Oil to gas
- Fossil fuels to electricity from wind and solar

Old energy source is replaced by new energy source that is less expensive, better performing and/or more convenient to use.
Example: fuel wood replaced by coal in the US in the 1800’s

In late 1800’s 9%/yr growth in coal use

Figure 1.—Total fuel wood consumed in the United States, by decades, 1630–1930; and total production of coal, 1810–92. Peak production of coal was reached in 1920–29 with a total for the decade of 5,893 million tons.
How silicon solar cells work

- Electrically solar cells are large area semiconductor diodes
- Silicon solar cells are made from single crystal silicon
Solids have energy bands rather than discrete energy levels

- In a semiconductor the lower valence band is full of electrons and the upper conduction band is empty.
- Light can excite electrons from the lower band to the upper band.
Three important factors in solar cell performance

• Electron – hole recombination
• Light trapping
• Heterojunction contacts
Intrinsic loss mechanisms in silicon solar cells

- Conduction band
  - Heat
  - Re-radiated infrared
  - Auger recombination

- Valence band
  - Optical absorption
  - Heat
  - hole

- Energy band gap

- Ignore defect recombination, not important in high purity, single crystal silicon
Use light trapping increases light absorption

Rough surface scatters incoming light outside escape cone and increases absorption, raises density of electrons and holes, increasing voltage.

- Important for silicon, a weakly absorbing semiconductor
- Optical path length of trapped photon is $4n^2L \sim 50L$
- Random surface texture could be replaced with specially designed periodic text for superior performance

Yablonovitch, IEEE Trans. ED 1982
Heterojunction solar cell, preferred cell design

- p-type contact on one side, n-type contact on the other side

- Record efficiency silicon cell is a heterojunction cell
- Room for improvement in silicon heterojunctions
Auger recombination is the dominant loss process

\[ S = 0.1 \text{ cm/s} \]
\[ T = 300 \text{ K} \]
\[ R = 0 \]
\[ L = 121 \mu \text{m} \]

Incoming light:
\[ 43.50 \text{ mA} \]

External Emission:
\[ 0.15 \text{ mA} \]

Max efficiency: 29.5%

Voltage at max power:
\[ 693.3 \text{ mV} \]

Open circuit voltage:
\[ 760.9 \text{ mV} \]

Extracted current:
\[ 42.24 \text{ mA} \]

Tiedje, Yablonovitch, Brookes, Cody, IEEE Trans. ED
Silicon heterojunction solar cell

Hetero-junction technology
Bifacial solar cells

- Monofacial cells are only sensitive to light on one side
- A peak Watt (Wp) is the PV output power when a 1 watt panel is facing the sun, insensitive to latitude
Bifacial solar panels respond to light on both sides

- Albedo (which is not constant over the day and also seasonally)
- Level above ground
- Row spacing
  - Uniformity of backside irradiance
  - Tilt angle
  - Light spectrum onto rear side
  - Backside IAM
  - Obstructions from racking structure
  - Modules portrait or landscape
  - Tracking algorithm

Bifacial panel output increases with albedo of the ground

Source: R. Kopeczek (ISC Konstanz): Presentation at the “HERCULES” workshop 2018
Bifacial panel installation

System data:
Capacity: 6 MWp DC
Installation: fixt-tilt agro-PV
Location: Jiangsu (China)

Source: own photo
Bifacial panel installation

System data:
Capacity: 3 MWp DC
Installation: carport
Location: Qidong (China)

Source: own photo
Vertical bifacial panel installation

System data:
Capacity: 1 MWp DC
Installation: vertical east-west agro-PV
Location: Germany

Source: www.next2sun.de
Energy conversion efficiency

Solar cells are heat engines and can be described by the laws of thermodynamics
Thermodynamic limit

- Max room temperature efficiency 29.5%
- Efficiency drops with temperature 1%/3°C
- Bifacial less efficient than monofacial ~0.7%

Engelbrecht, Tiedje
Optimum thickness decreases with the 7\textsuperscript{th} power of the temperature

- Optimum thickness ~0.1 mm
- Wafers made by sawing bulk Si crystals

Efficiency = 0.99 max

Engelbrecht, Tiedje
Silicon solar cell efficiency has improved over time

Efficiency = \frac{29\%}{1 + e^{(1979-t)/13}}

Logistic Equation

First silicon solar cell 6%

Record 26.6%
Market Share of Thin-Film Technologies
Percentage of Total Global PV Production

Fraunhofer ISE

Production 2017 (GWp)
- CdTe: 2.3
- a-Si: 0.3
- Cl(G)S: 1.9

Percentage of Thin-Film Market Share

Year
- 2000
- 2001
- 2002
- 2003
- 2004
- 2005
- 2006
- 2007
- 2008
- 2009
- 2010
- 2011
- 2012
- 2013
- 2014
- 2015
- 2016
- 2017

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Advantages of silicon

- Optical absorption well-matched to solar spectrum
- Non-toxic and earth abundant
- Elemental semiconductor, easy to purify and process
- Stable in sunlight for 30+ years
Silicon challengers – so far all have failed

- Polycrystalline chalcogenide films (CIGS, CdTe, CZTS)
- III-V thin films
- Perovskite/Si dual junction ??
- Multijunction
- Concentrator
- Amorphous silicon
- Quantum dots
- Quantum wires
- Organic
- Dye sensitized
- Rectenna
- Intermediate band solar cells
- Hot electron devices
Cost of solar electricity

- Wholesale price of electricity is in $/MWh
- Retail price is in cents/kWh
- $100/MWh = 10 cents/kWh
## Cost of Electricity in US

<table>
<thead>
<tr>
<th>PV</th>
<th>LCOE $/MWh</th>
<th>PV Utility</th>
<th>PV Utility US subsidized</th>
<th>PV Rooftop Residential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2009</td>
<td>323-394</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>31-42</td>
<td>31</td>
<td>150-227</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coal, Gas, Nuclear</th>
<th>LCOE $/MWh</th>
<th>Coal</th>
<th>Combined Cycle Gas</th>
<th>Nuclear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New build</td>
<td>65-159</td>
<td>44-73</td>
<td>129-198</td>
</tr>
<tr>
<td>Avg marginal cost</td>
<td>41</td>
<td>28</td>
<td>29</td>
<td></td>
</tr>
</tbody>
</table>

- Solar (and wind) competitive with cost of fuel alone for coal and gas plants

“This is arguably the most important data set in energy economics today.”

S. Henbest, Bloomberg New Energy Finance, 2018
Person-hours required to refine a barrel of petroleum

Every factor of 2 increase in cumulative production, there is a cost reduction to 80% of original cost.

Commonly observed in manufactured products.

Describes long term trend, not a useful predictor of short term price movements.

Figure 3. Experience curve projections in time for COEPV in constant dollars for a system efficiency of 15%, for two "annual growth" scenarios of 20 and 40% per year and the technical and economic factors of Eq.(3) given in the text.

G.D. Cody, T. Tiedje, Energy and the Environment, 1992

Prediction almost perfect!
What happens to solar panel production in the future?

Logistic function

Production = \( \frac{200}{1+e^{0.28(t_0-t)}} \)

\( t_0 = 2018 \)

Annual production in GW

Year
Predicted module sales and price

- Module sales GW/yr
- Module price $/Wp

1000 GW ~2 B panels

Growth 5%/yr

74% learning

32%/yr

Factor of 2 in cumulative production price drops to 74%
Cost of Electricity – Wind and Solar

Unsubsidized Wind LCOE

- **LCOE ($/MWh)**
  - Wind 2009 – 2020 Percentage Decrease: (71%)
  - Wind 2009 – 2020 CAGR: (11%)
  - Wind 2015 – 2020 CAGR: (5%)

- **Wind**
  - CAGR 11%
  - Decrease in cost 71%

Unsubsidized Solar PV LCOE

- **LCOE ($/MWh)**
  - Utility-Scaled Solar 2009 – 2020 Percentage Decrease: (90%) (1)
  - Utility-Scaled Solar 2009 – 2020 CAGR: (19%) (2)
  - Utility-Scaled Solar 2015 – 2020 CAGR: (11%)

- **Solar**
  - CAGR 19%
  - Decrease in cost 90%

Source: Lazard estimates:

1. Represents the average percentage decrease of the high end and low end of the LCOE range.
2. Represents the average compounded annual rate of decline of the high end and low end of the LCOE range.
Solar electricity in BC

• The average output energy from a 1 peak Watt solar panel over the year is measured in Wh/Wp or kWh/kW
• Typical values in BC are 1000 – 1300 Wh/Wp, lower values on the coast and higher values inland
Economics of rooftop residential solar panels in BC

Calculation 1
• 1100 hours of full sun equivalent in one year in Victoria
• BC Hydro reimburses “Energy Charge” of $0.0935 /kWh Step 1 or $0.01403 /kWh (Step 2)
• PV panel installation cost in Victoria is $1.75-$2.50/Wp
• Payback time in years is: \( t = \frac{PV \text{ cost}}{energy \text{ charge}} = 22 \text{ years} \) (step 1) @$2/Wp

Calculation 2
• Return on investment is \( \frac{0.0935}{2.00} = 4.5\% \), tax free
• Since BC Hydro is increasing rates your return
• will increase by 4-5%/yr
Insolation western North America

Low output in winter in the north is made up by long days in the summer.

Victoria 1100 Wh/Wp
Arizona 1700 Wh/Wp

Units: Wh/Wp
Number of Watt-hours produced in a year by a generating capacity of 1 peak Watt.
Williston Lake area 1761 km\(^2\)
Bennett + Peace Canyon + Site C = 23,500 GWh/yr

Area of solar panels required to replace all three dams
50% surface coverage
Canada is not too far north!

- Cold is good, ~6% more power at -5°C than at 25°C

- Rapid reduction in cost of lithium batteries driven by mass production of electric vehicles
Summary and conclusions

• Canada has strong solar resource but is a laggard in PV
• Wind and solar PV are the lowest cost ways to generate electricity
• Wind and solar are competitive with running cost of coal and gas plants
• Rooftop solar cost effective in some locations (Australia, sw USA)
• Cost continues to decline as does the cost of Li batteries
• Growing number of combined PV plus battery storage projects
• PV technology has developed faster than expected
• Transition to renewable electricity will happen faster than most people expect