Cost and limiting efficiency of silicon solar panels

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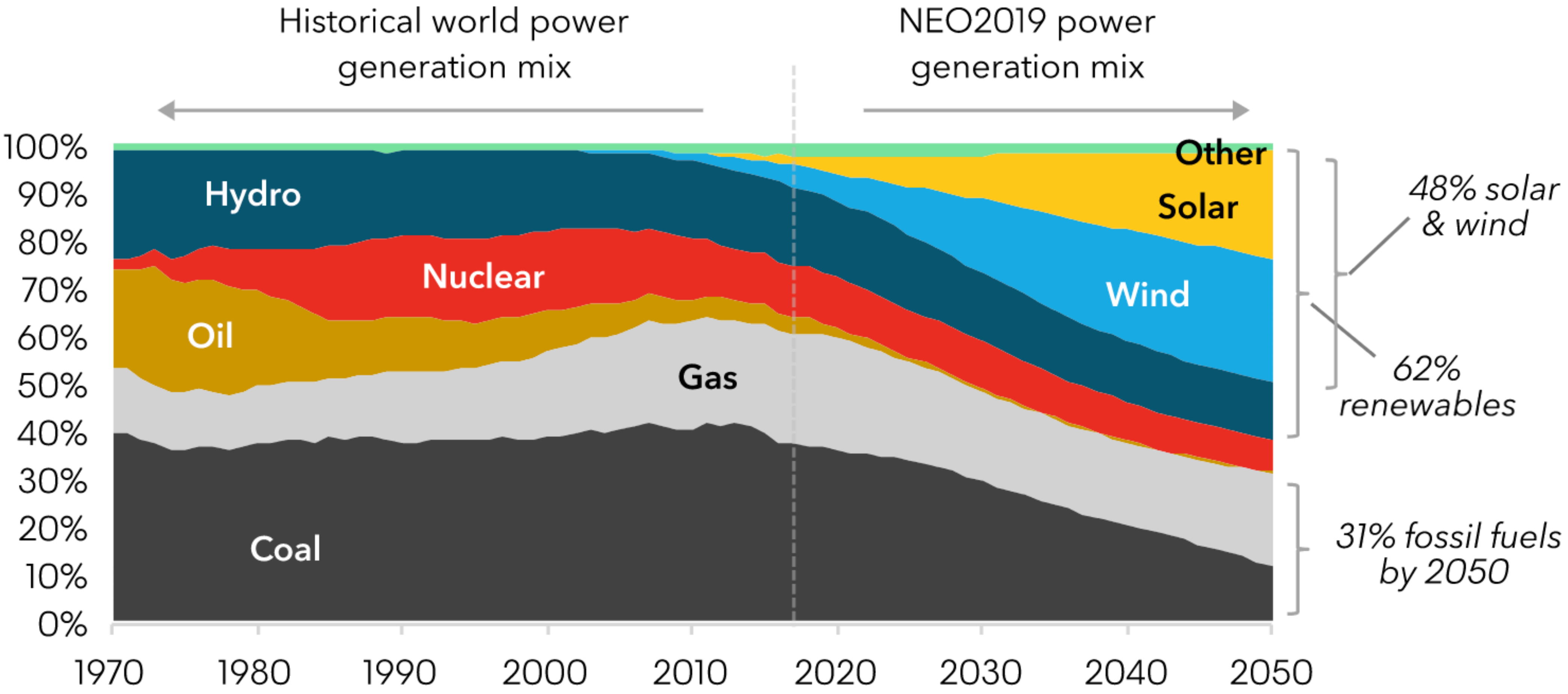
Outline

- Context, energy transition
- How silicon solar cells work
- Bifacial solar cells
- Energy conversion efficiency
- Cost of solar electricity
- Solar electricity in BC

Context: global power generation mix



77% of new investment goes to renewables.

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

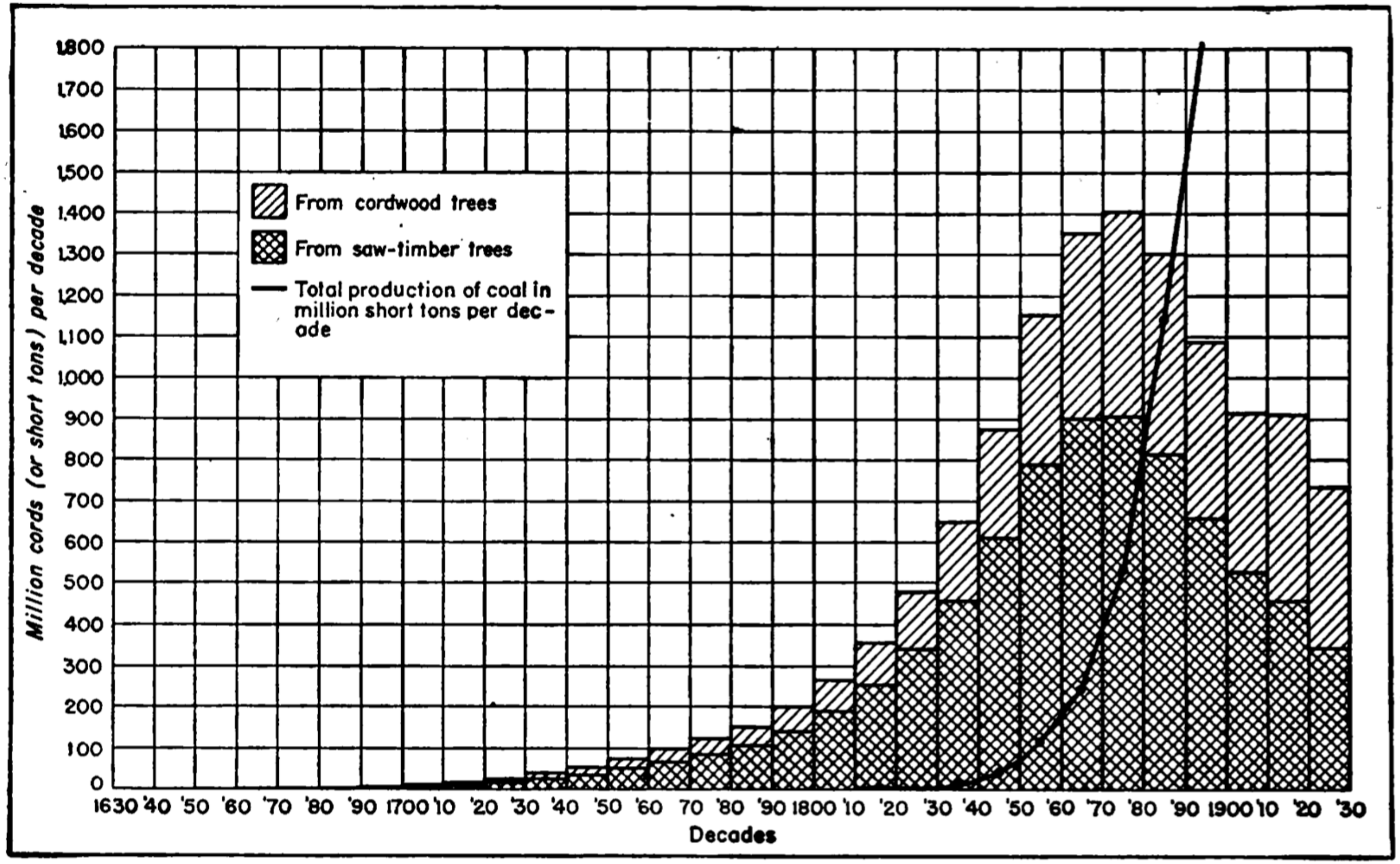


FIGURE 1.—Total fuel wood consumed in the United States, by decades, 1630–1930; and total production of coal, 1810–92. Peak production of coal was reached in 1920–29 with a total for the decade of 5,893 million tons.

R. V. Reynolds, 1942

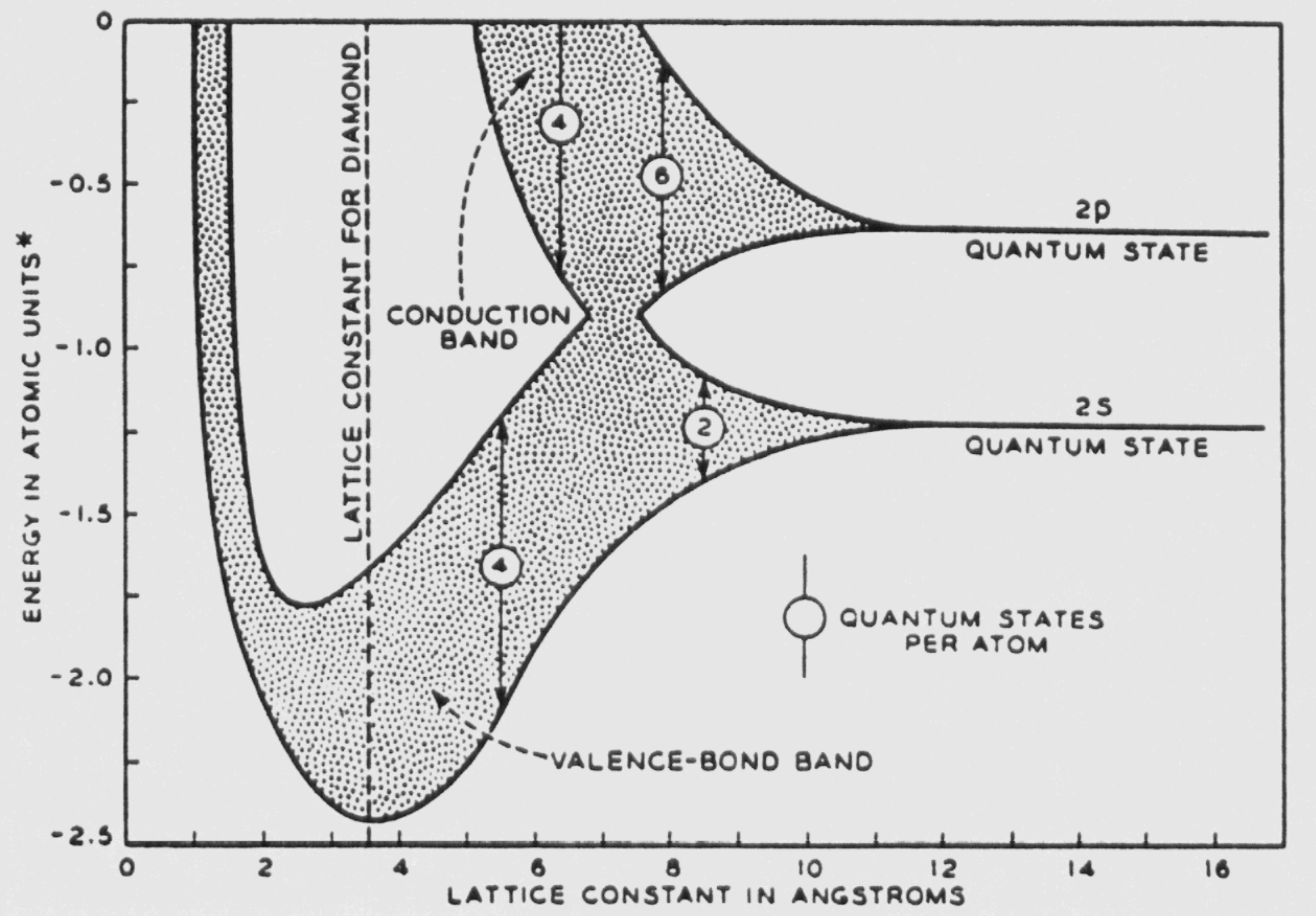
How silicon solar cells work

- 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

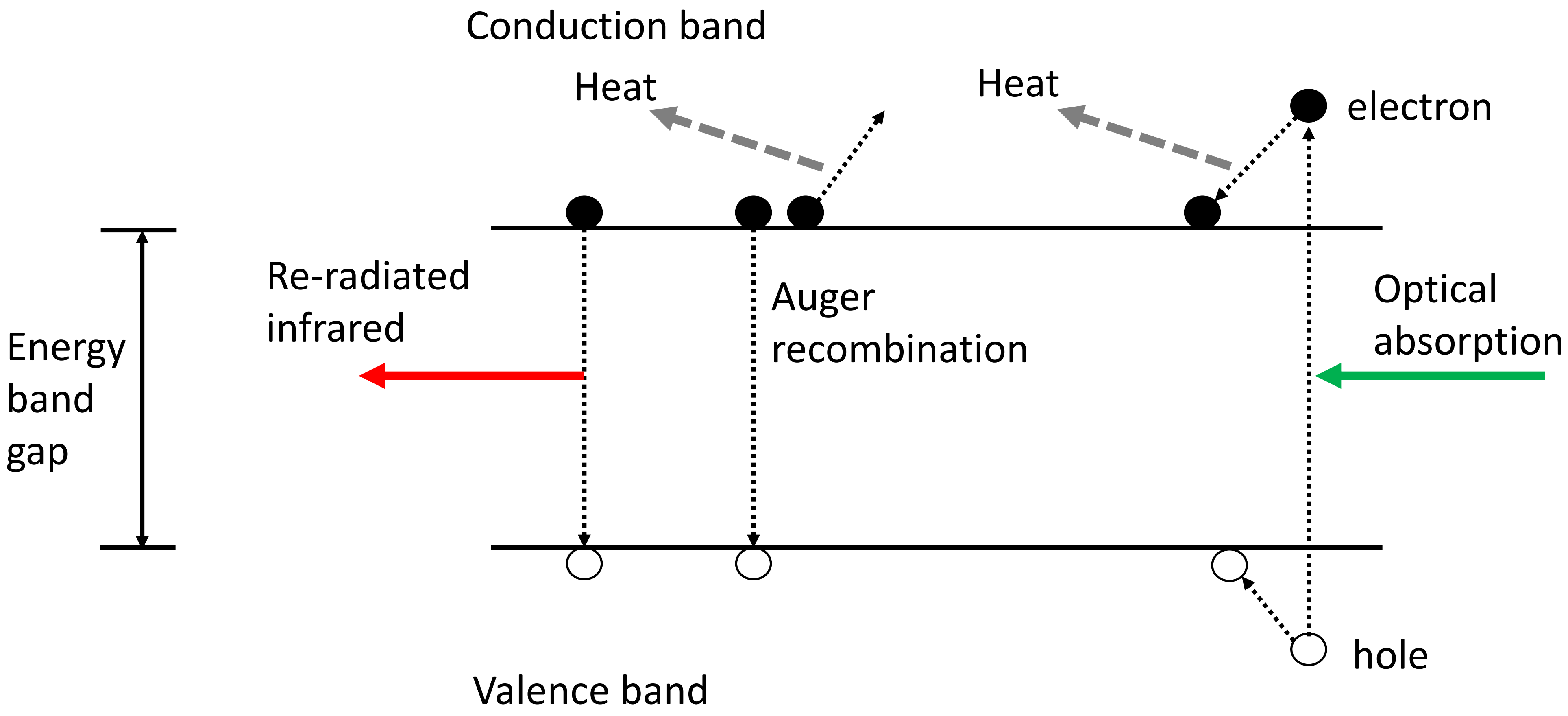
- Light can excite electrons from the lower band to the upper band



Three important factors in solar cell performance

- Electron – hole recombination
- Light trapping
- Heterojunction contacts

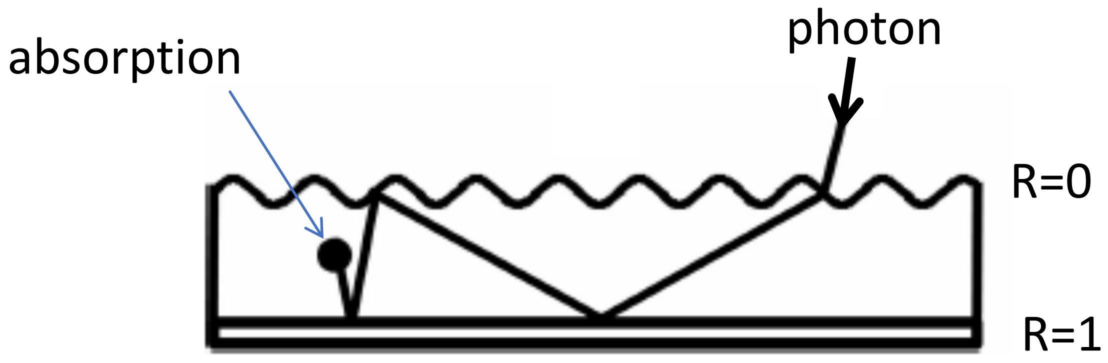
Intrinsic loss mechanisms in silicon solar cells



- 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.

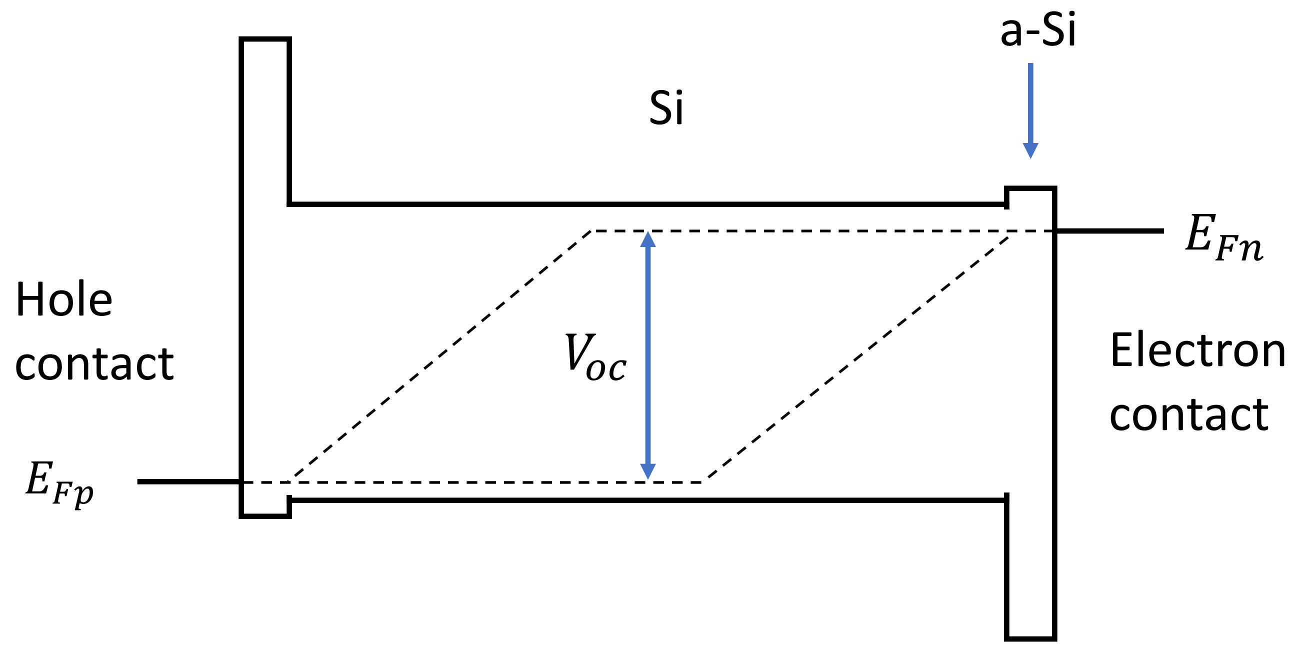


- Important for silicon, a weakly absorbing semiconductor
- Optical path length of trapped photon is $4n^2L{\sim}50L$
- Random surface texture could be replaced with specially designed periodic text for superior performance

Yablonovitch, IEEE Trans. ED 1982

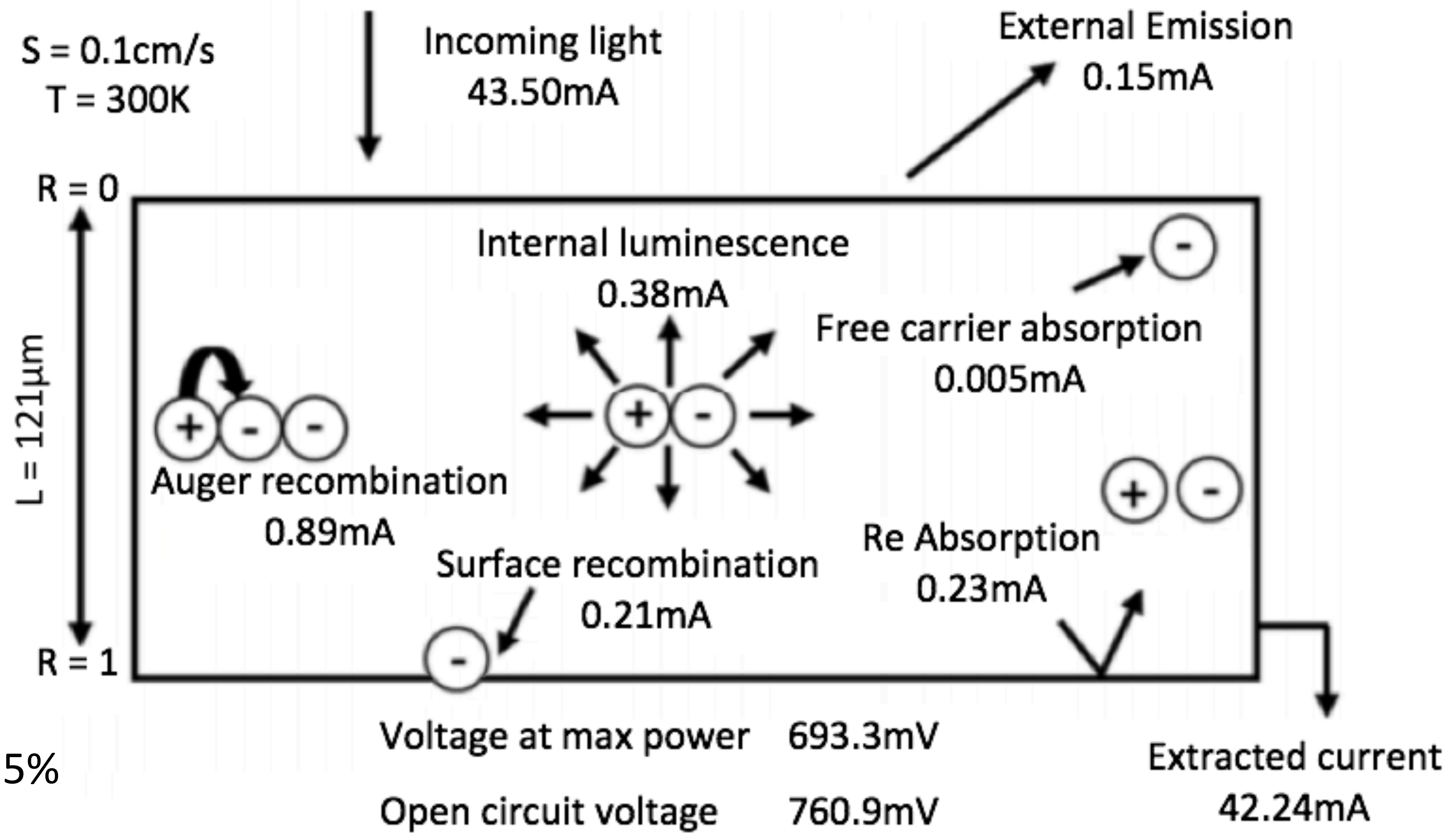
Heterojunction solar cell, preferred cell design

- 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

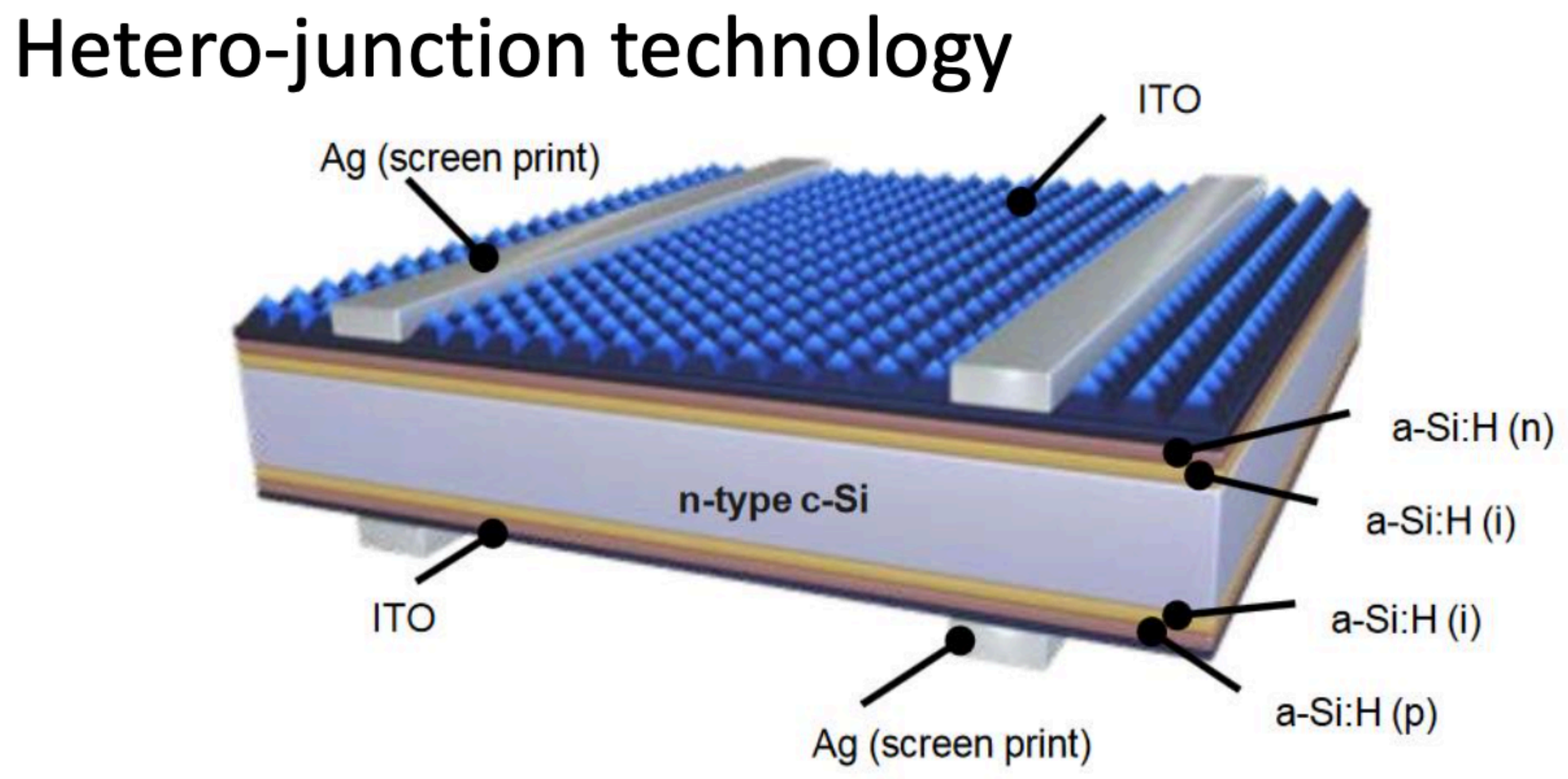
Auger recombination is the dominant loss process



Max efficiency 29.5%

Tiedje, Yablonovitch, Brookes, Cody, IEEE Trans. ED

Silicon heterojunction solar cell

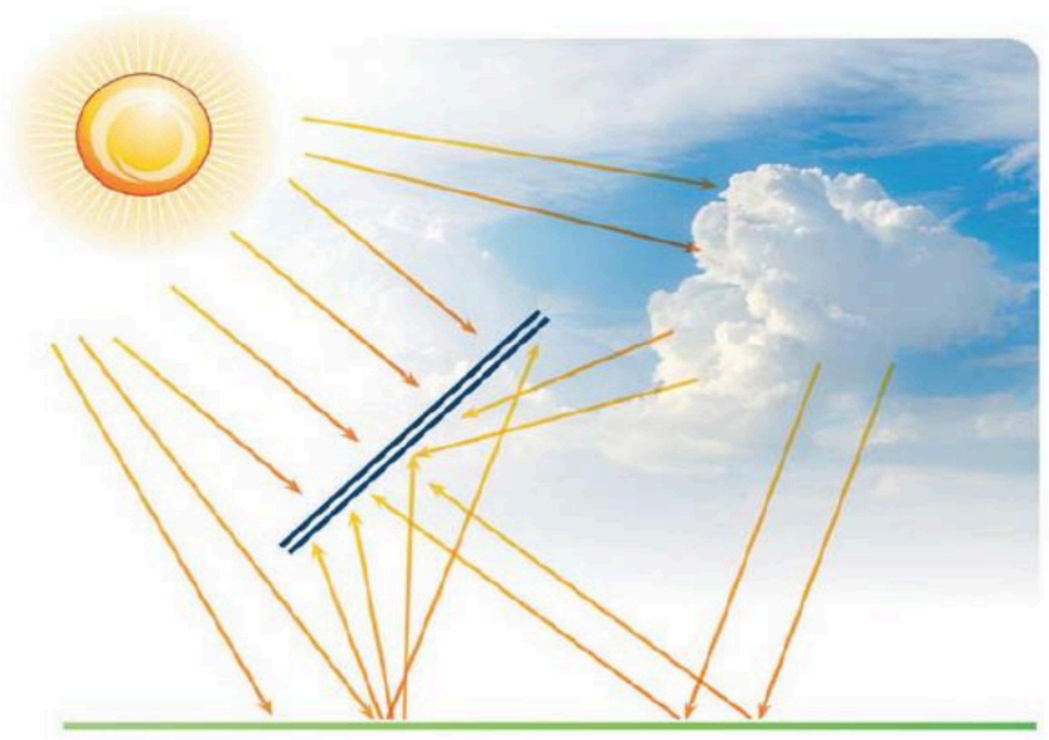


PI Photovoltaik-Institut Berlin AG

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 lattitude

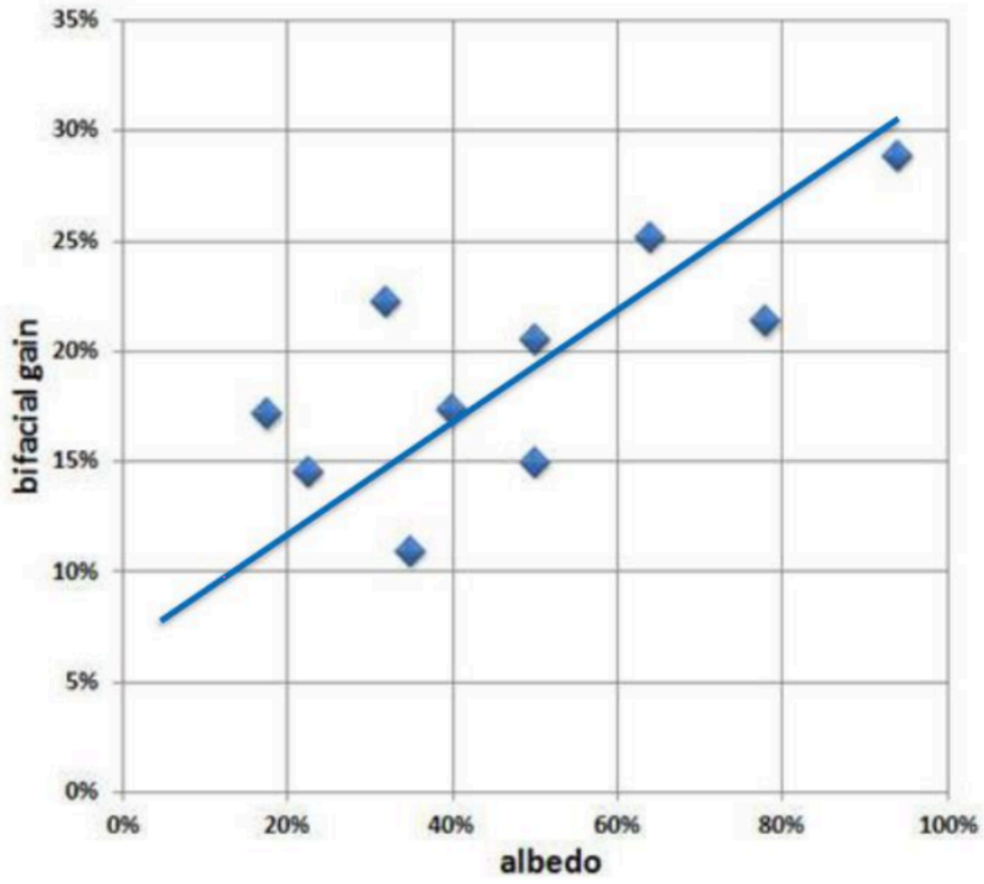
Bifacial solar panels respond to light on both sides



Source: SOLARWORLD White Paper:
"Calculating the Additional Energy Yield of Bifacial Modules"

- 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



surface	albedo [%]
water	8
dry dark soil	13
grass	17-28
dry sand	35
dune sand	37
old snow	40-70
reflective roof coatings	80-90
fresh snow	75-95

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

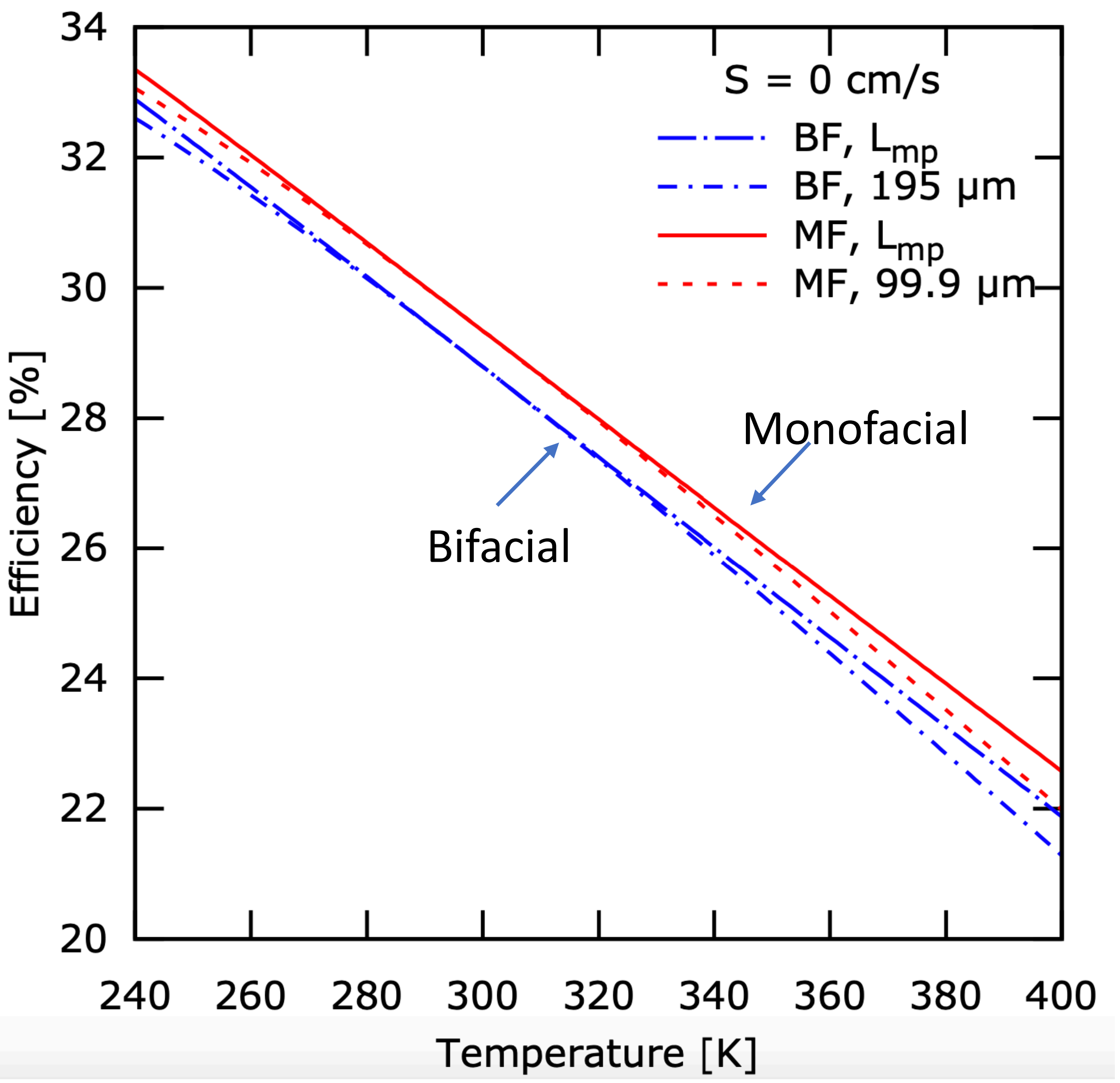
Energy conversion efficiency

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

Maximum efficiency of silicon solar cells as a function of temperature

Thermodynamic limit

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

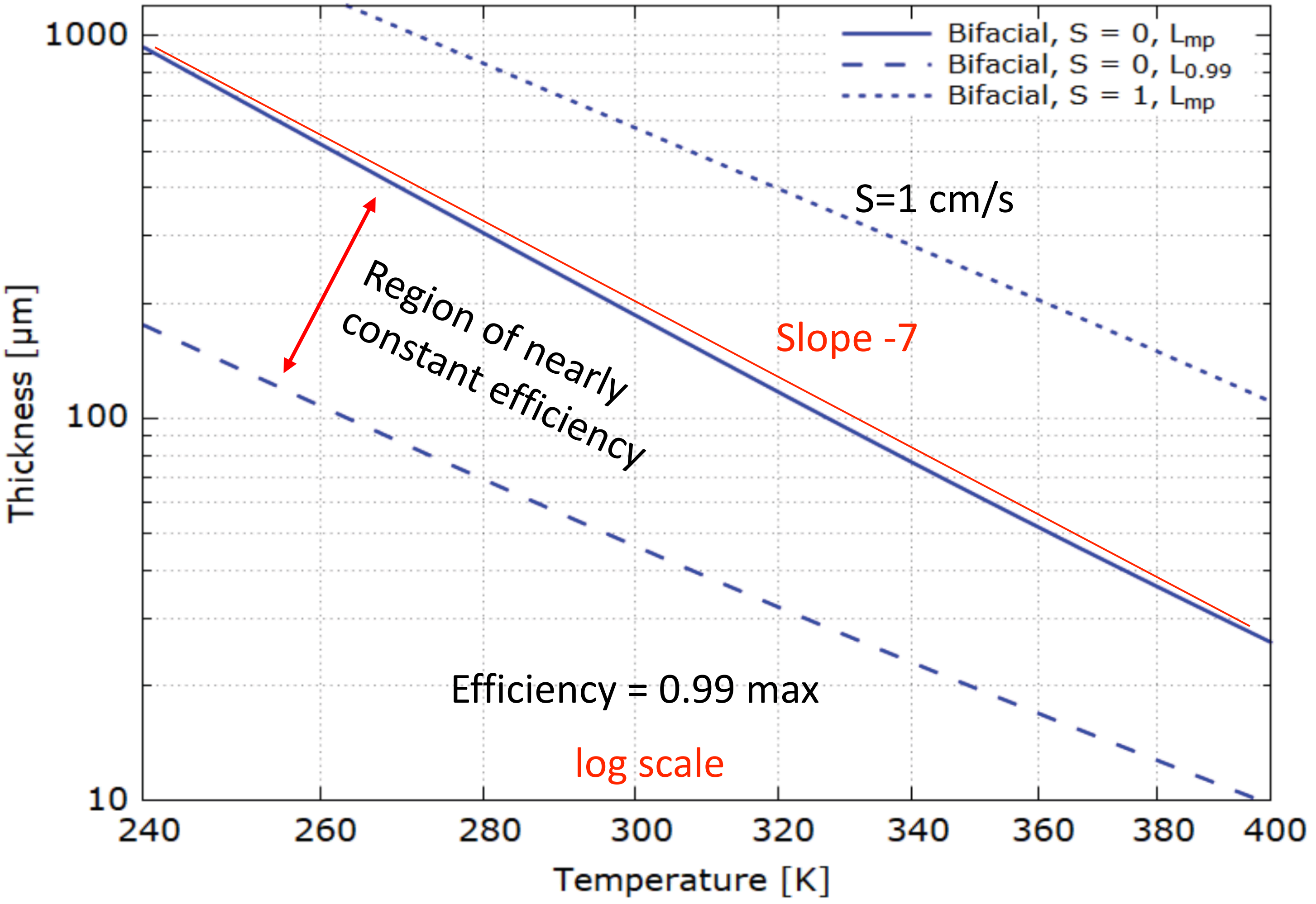


Engelbrecht, Tiedje

Optimum thickness decreases with the 7th power of the temperature

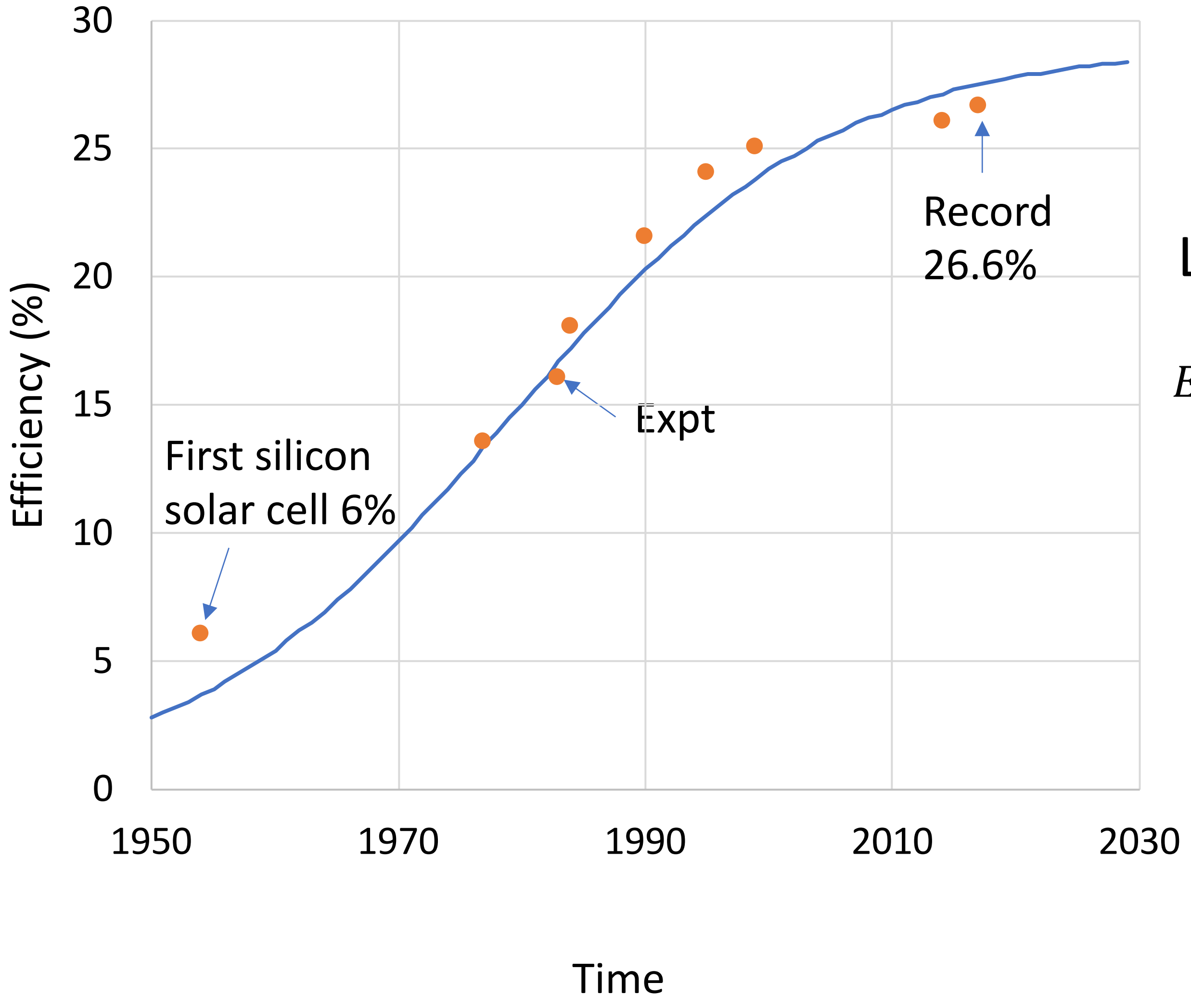
- Optimum thickness
  ~0.1 mm

- Wafers made by sawing bulk Si crystals



Engelbrecht, Tiedje

Silicon solar cell efficiency has improved over time



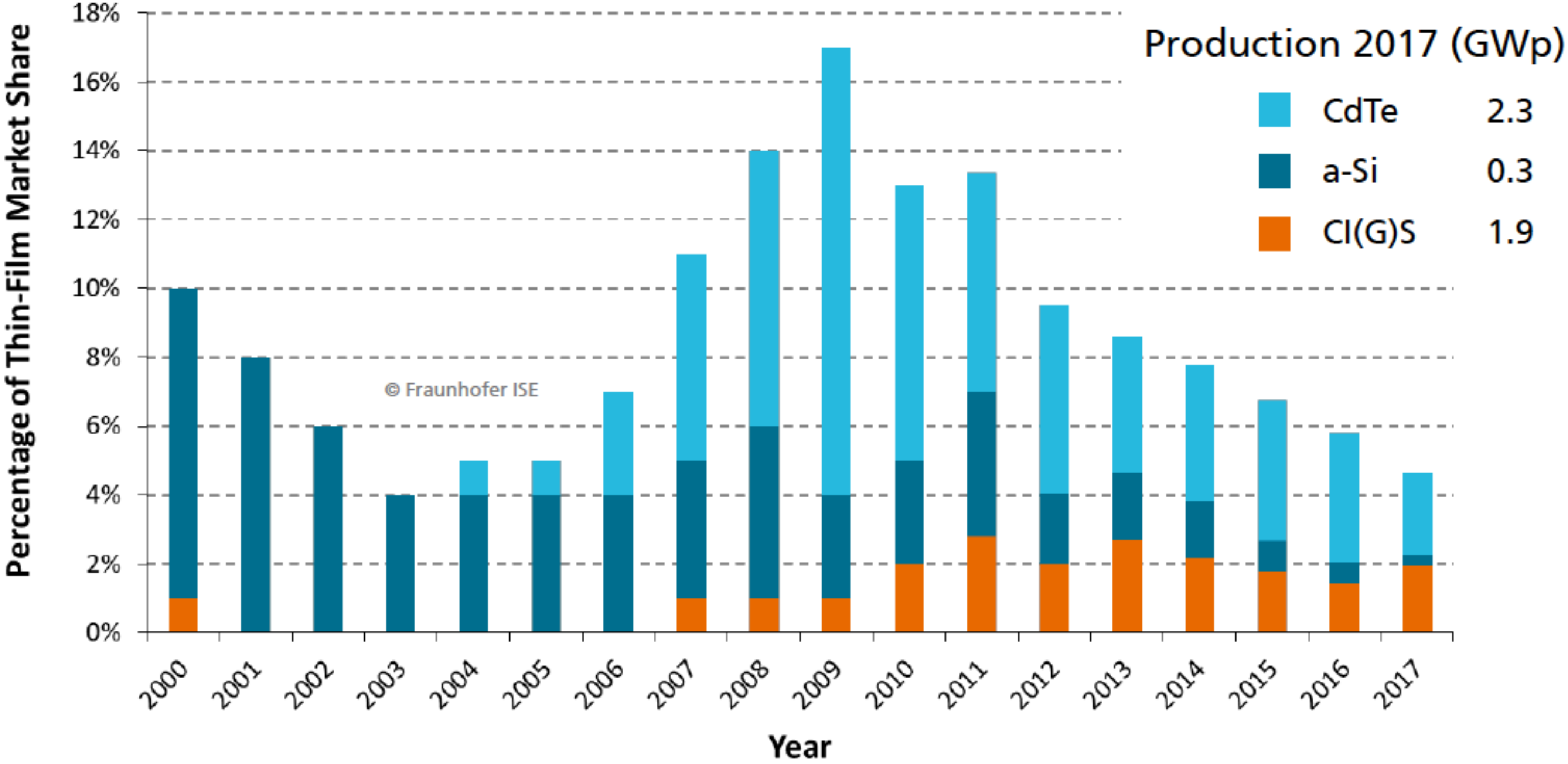
Logistic Equation

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

Market Share of Thin-Film Technologies

Percentage of Total Global PV Production

Fraunhofer ISE



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

PV

LCOE $/MWh	PV Utility	PV Utility US subsidized	PV Rooftop Residential
2009	323-394		
2020	31-42	31	150-227

Coal, Gas, Nuclear

LCOE $/MWh	Coal	Combined Cycle Gas	Nuclear
New build	65-159	44-73	129-198
Avg marginal cost	41	28	29

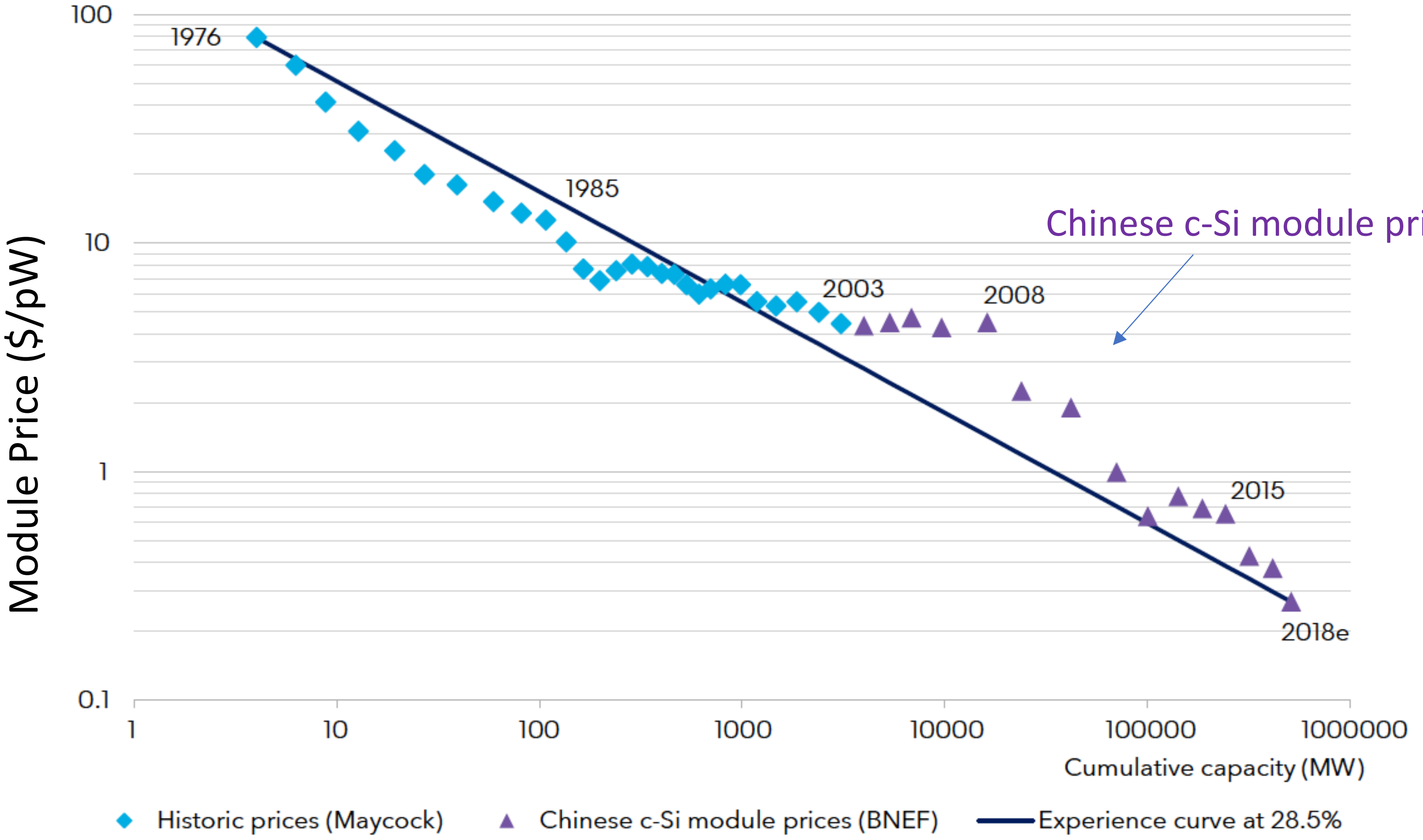
- Solar (and wind) competitive with cost of fuel alone for coal and gas plants

Lazard, Oct 2020: https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2020/

PV module experience curve

Bloomberg New Energy Finance

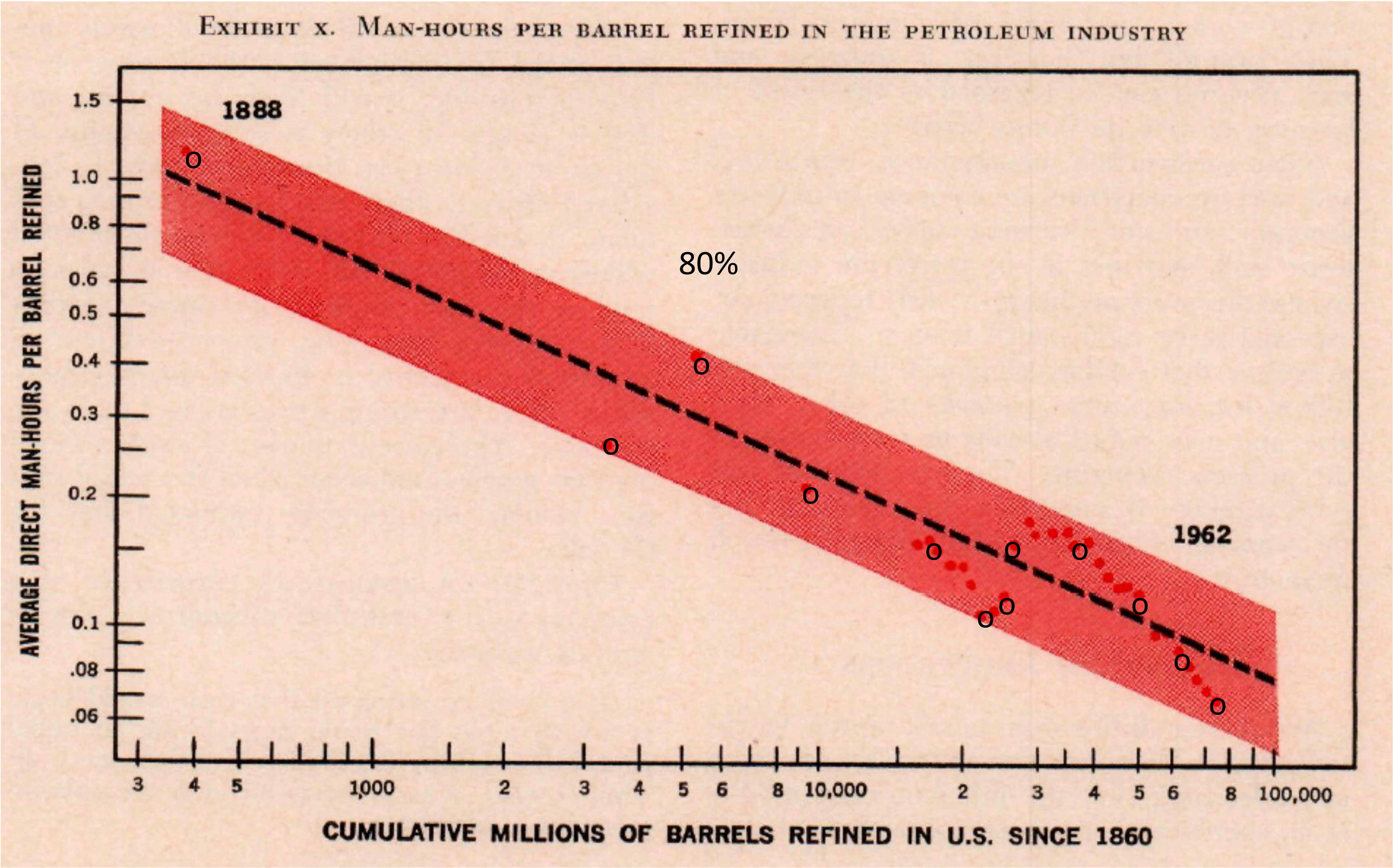
Moore's law for electrical power



- "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 to 80% of original cost

Commonly observed in manufactured products

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

W. B. Hirschmann, Harvard Business Review 1964

Predicting the future in 1988

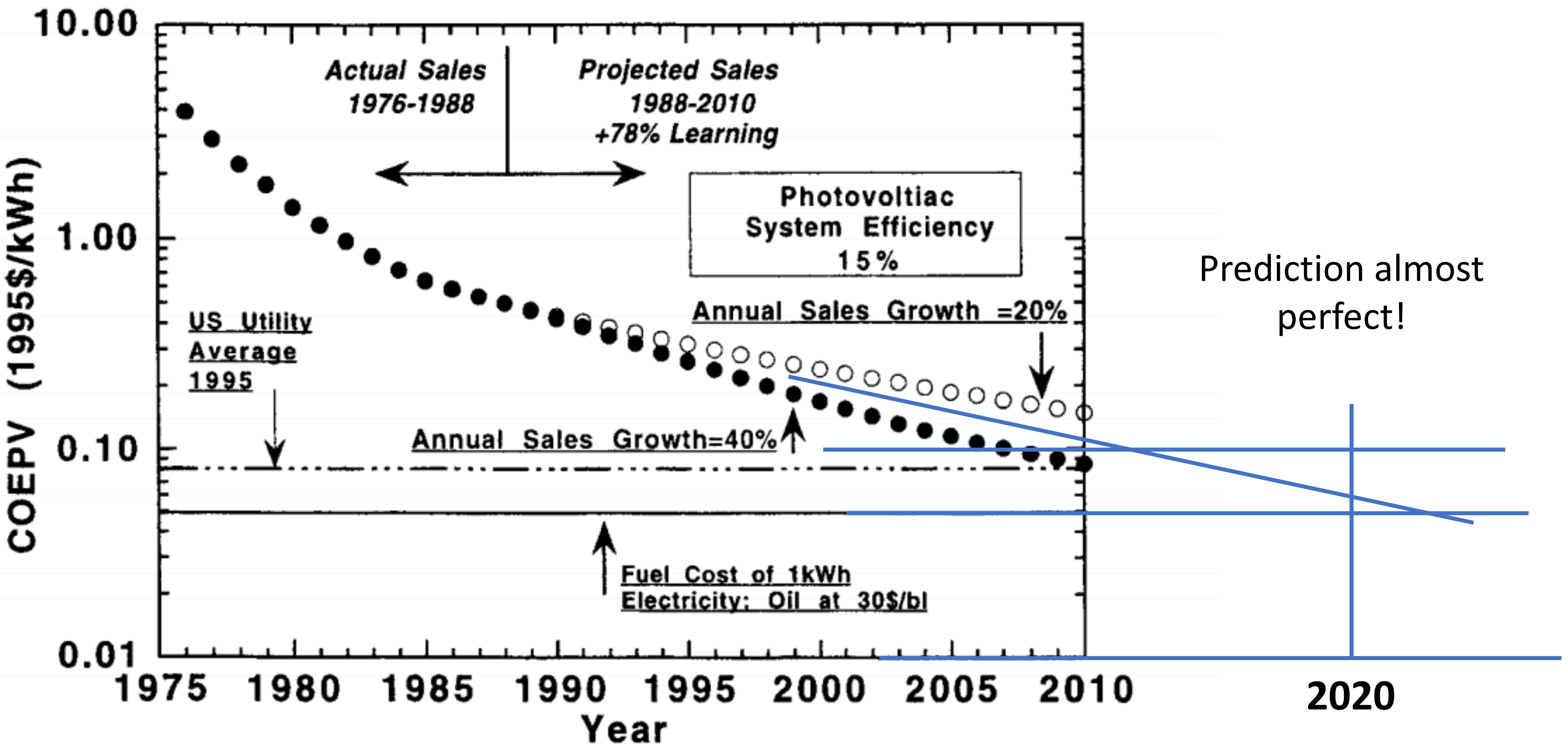
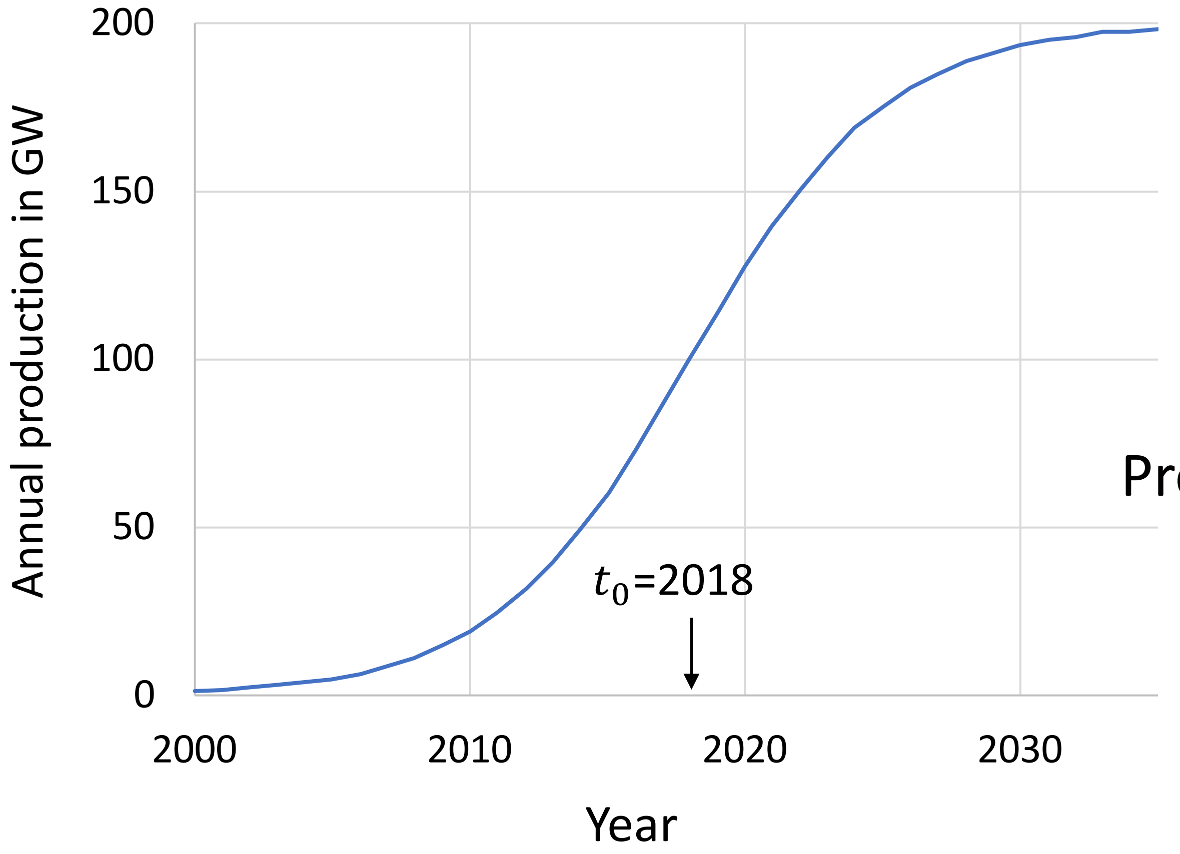


Figure 3. Experience curve projections in time for COEPV in constant dollars for a system efficiency of 15%, for two "annual growth" scenarios of 20 and 40% per year and the technical and economic factors of Eq.(3) given in the text.

Prediction almost perfect!

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

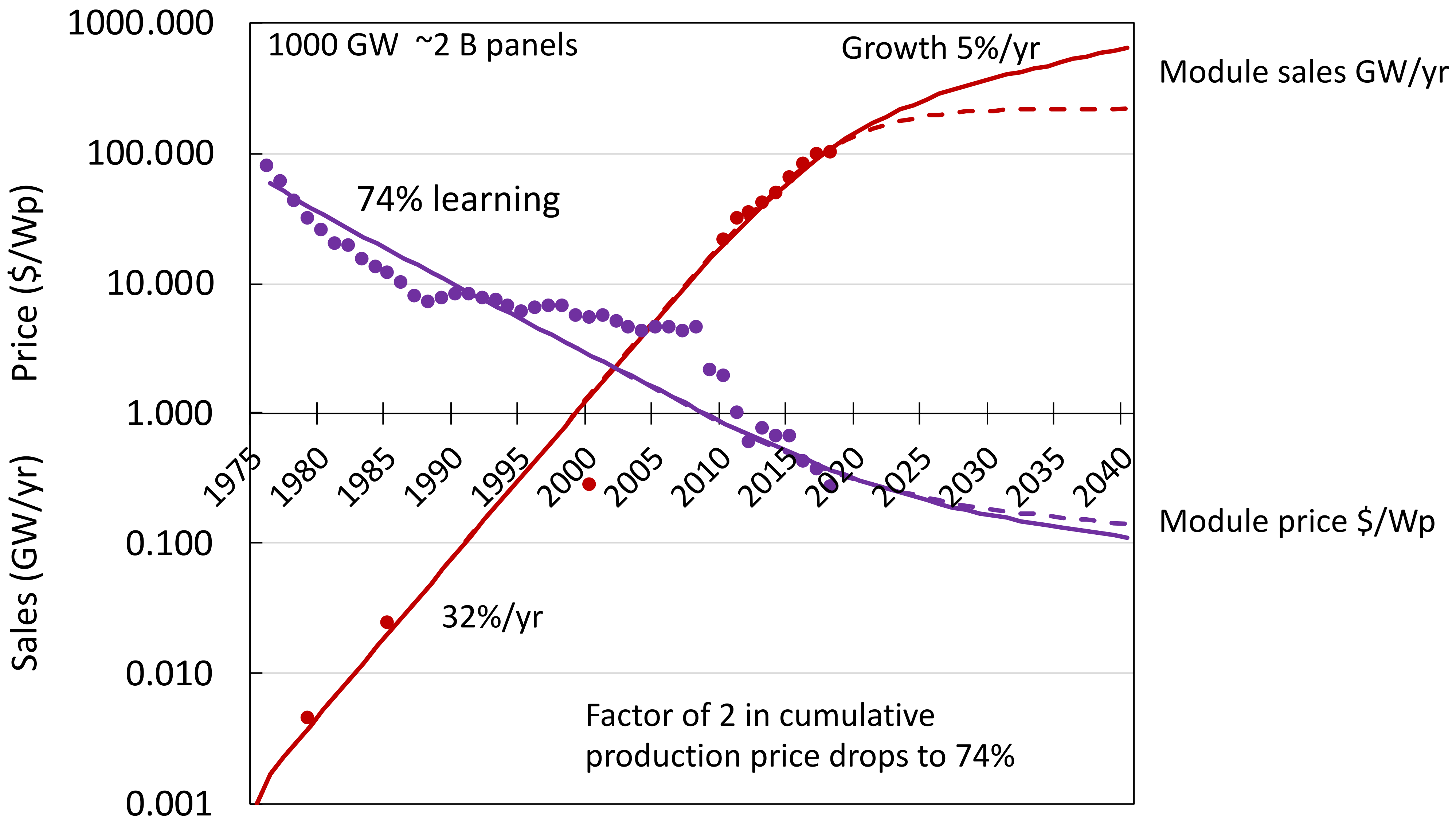
What happens to solar panel production in the future?



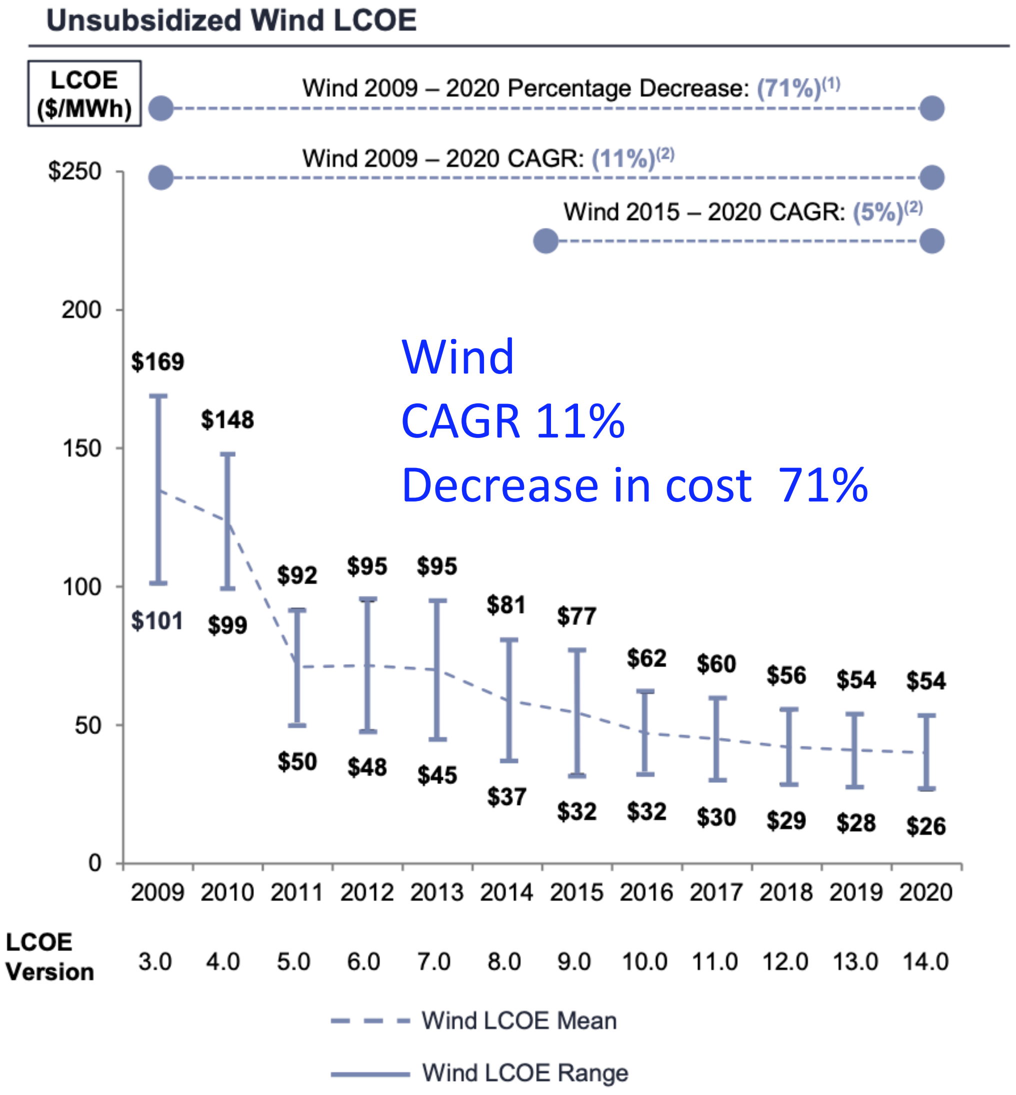
Logistic function

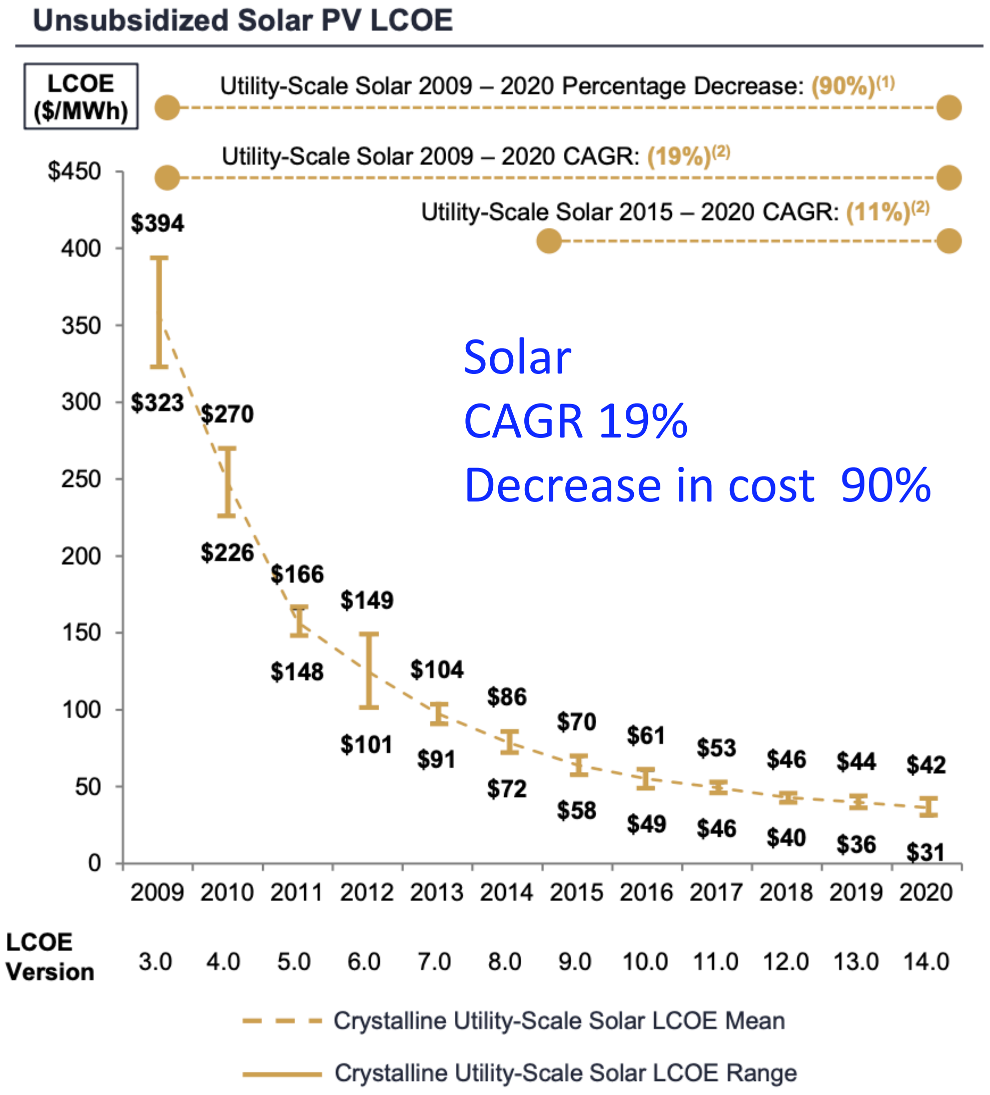
$$\text{Production} = \frac{200}{1+e^{0.28(t_0-t)}}$$

Predicted module sales and price



Cost of Electricity – Wind and Solar





LAZARD

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

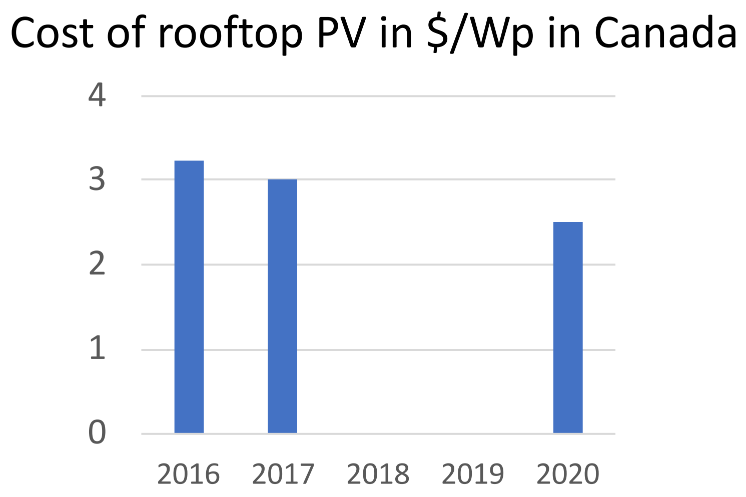
Economics of rooftop residential solar panels in BC

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 = PV cost/energy charge = 22 years (step 1) @$2/Wp

Calculation 2

- Return on investment is 0.0935/2.00 = 4.5%, tax free
- Since BC Hydro is increasing rates your return
- will increase by 4-5%/yr

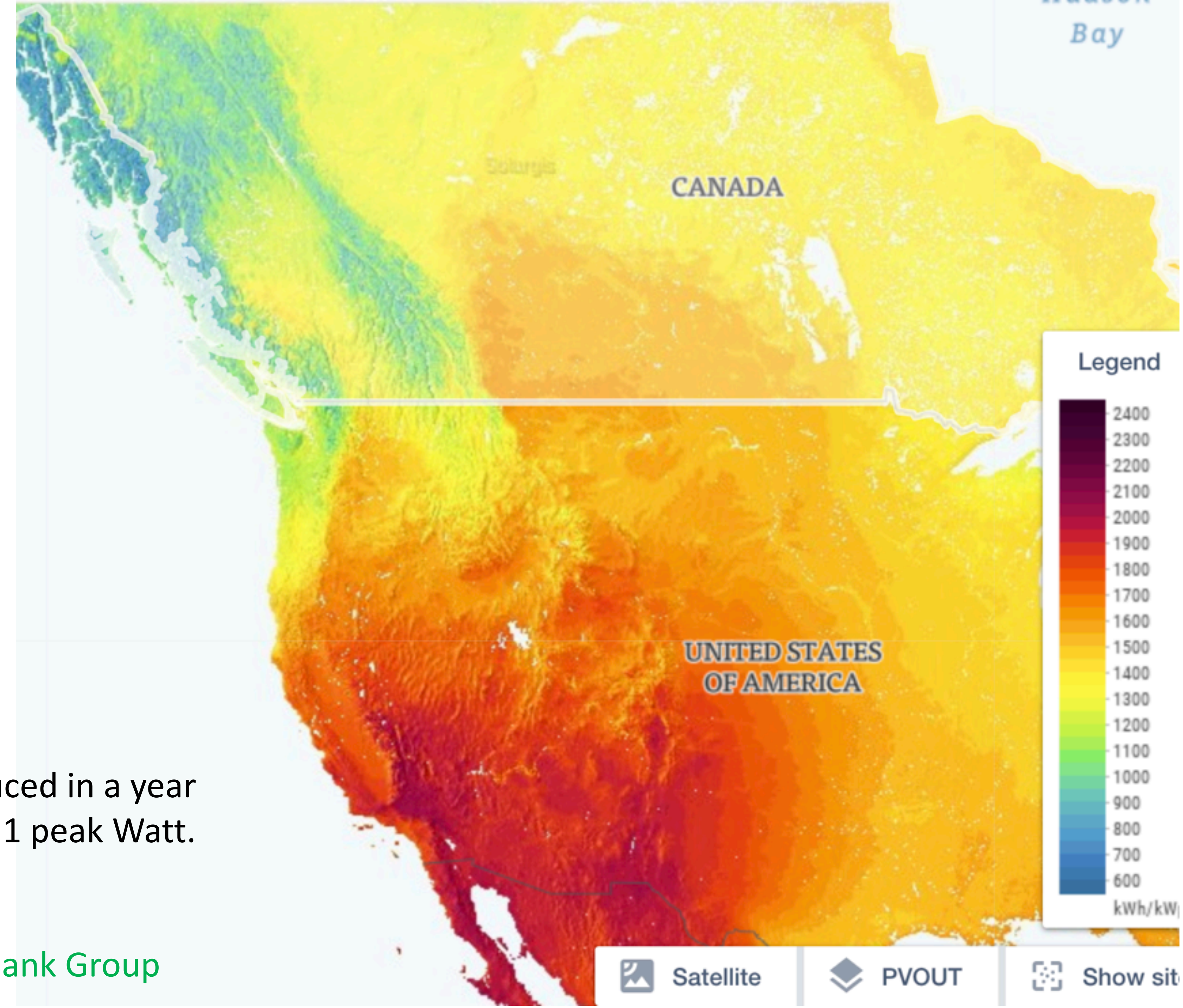


Insolation western North America

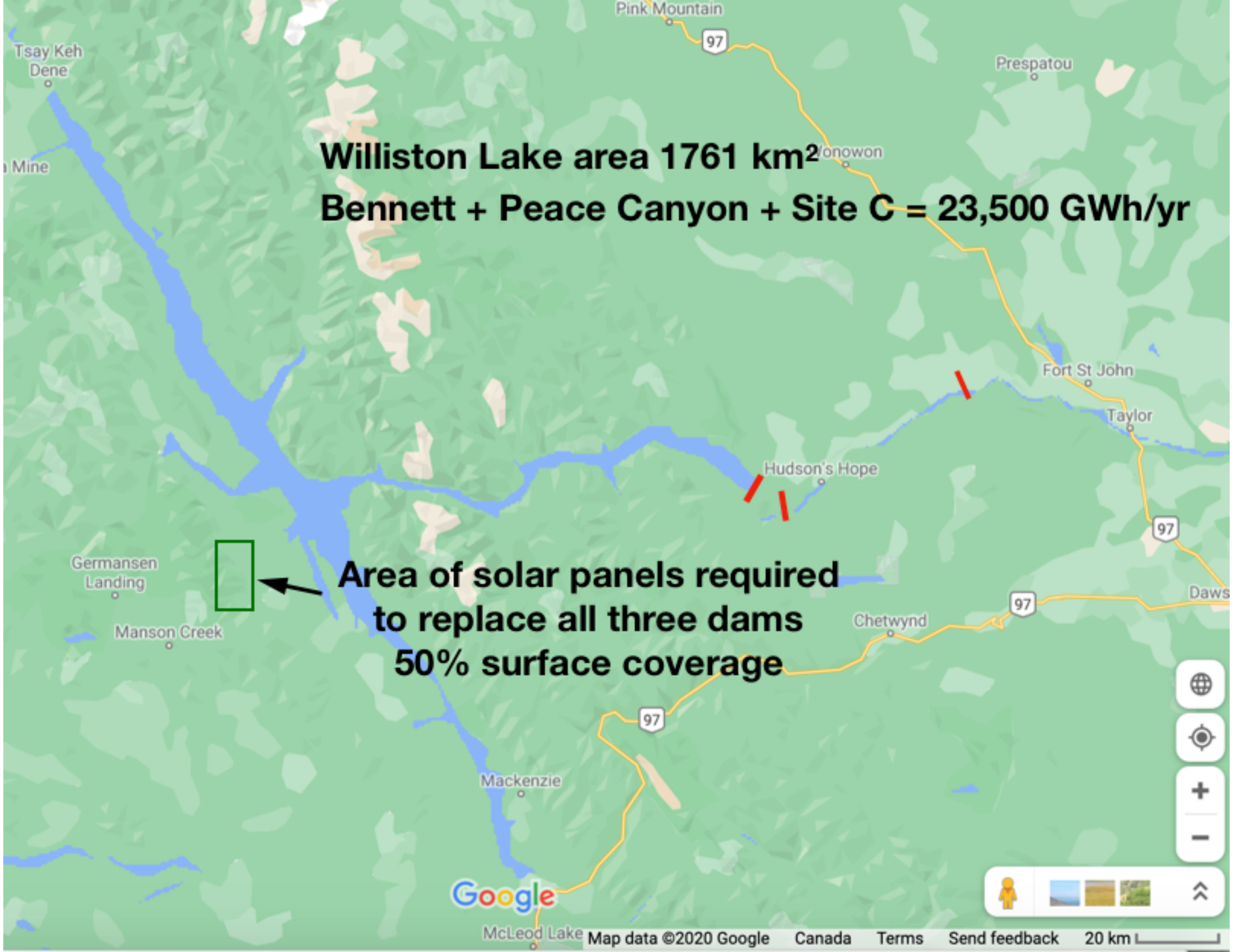
Low output in winter in the north is made up by long days in the summer

Victoria 1100 Wh/Wp
Arizona 1700 Wh/Wp

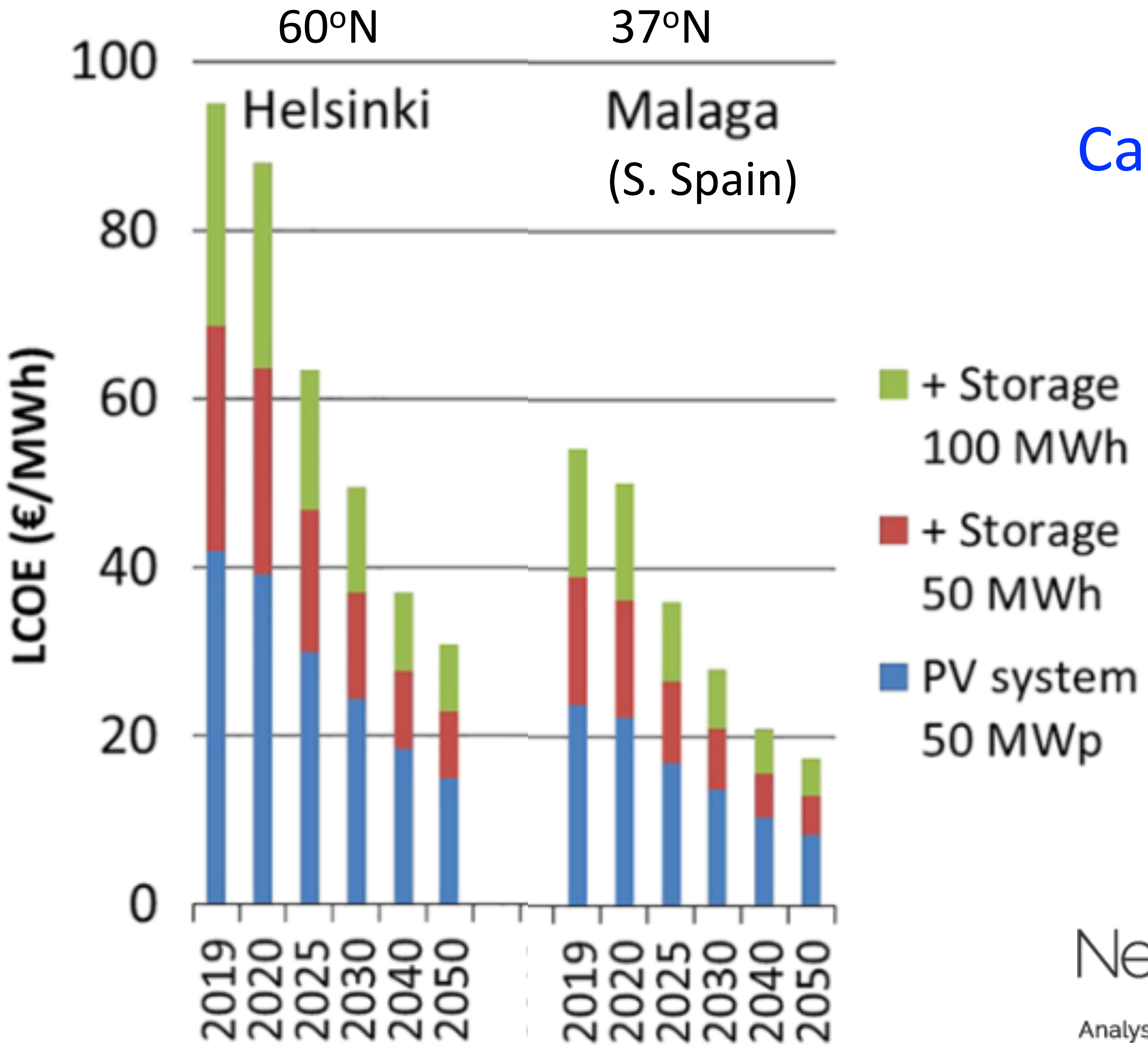
Units: Wh/Wp
Number of Watt-hours produced in a year by a a generating capacity of 1 peak Watt.



Global Solar Atlas by World Bank Group



Williston Lake area 1761 km²
Bennett + Peace Canyon + Site C = 23,500 GWh/yr
Area of solar panels required
to replace all three dams
50% surface coverage
Pink Mountain
97
Tsay Keh Dene
Prespatou
Mine
Fort St John
Taylor
Hudson's Hope
Germansen Landing
Manson Creek
Chetwynd
Daws
Mackenzie
McLeod Lake
Google
Map data ©2020 Google
Canada
Terms
Send feedback
20 km



Canada is *not* too far north!

- Cold is good, ~6% more power at -5ºC than at 25ºC
- Rapid reduction in cost of lithium batteries driven by mass production of electric vehicles

NewEnergyUpdate: PV

Analysis for the renewable energy community

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