

Theory and Practice of Solar Cells: A Cell to System Perspective

How to Design Cost-effective Solar Farms

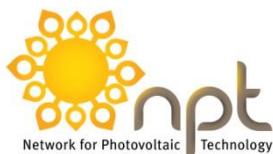
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Outline

- 1) Background: Sunlight is free, but PV is not
- 2) COE vs. LCOE: A Watt today vs. a watt tomorrow
- 3) LCOE Calculators: Origin of summary plots
- 4) LCOE* decouples land vs. technology costs
- 5) The learning curve: Rich get richer
- 6) Conclusions

Actors: Sun, Earth, Solar cell, and bank



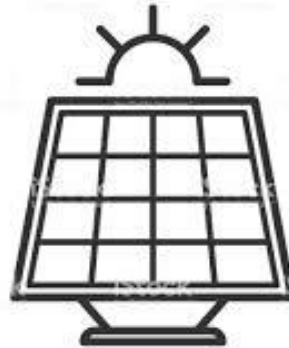
Sun Temp. 5777 K

Distance: $1.496 \times 10^{11} \text{ m}$

Earth Radius: 4000 miles

Temperature: 300K

Irradiance ... 1000 W/m^2



PV Max. Efficiency = $1/3$

Bank interest – 4-5%

Solar energy is not free

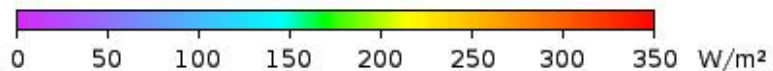
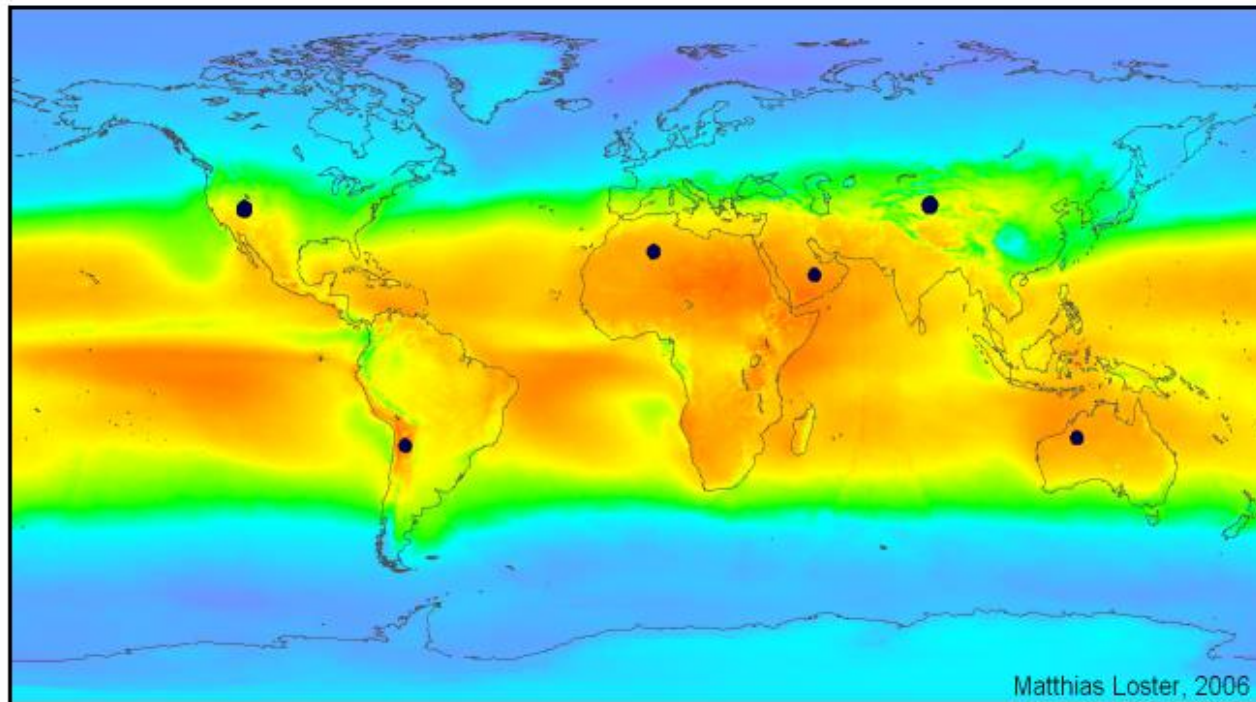


$$\text{LCOE} = \frac{\text{Cost}}{\text{Energy produced}}$$

Cost = cost of converter + maintenance + interest

Energy produced = Insolation x efficiency x lifetime

Sunlight depends on latitude

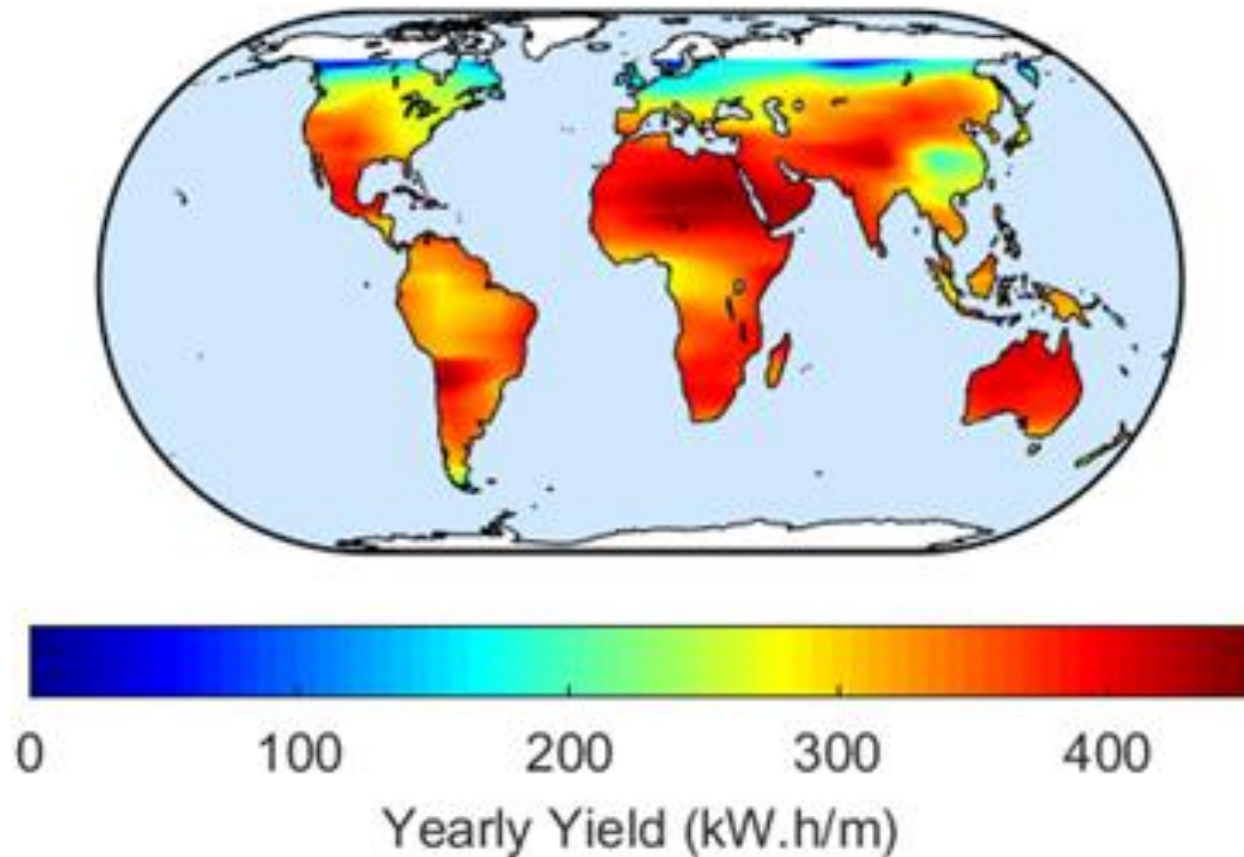


$\Sigma \bullet = 18 \text{ TWe}$

http://www.ez2c.de/ml/solar_land_area/

M. A. Alam, PV Lecture Notes

Energy Yield of by a bifacial PV technology



Cost of Energy (COE)

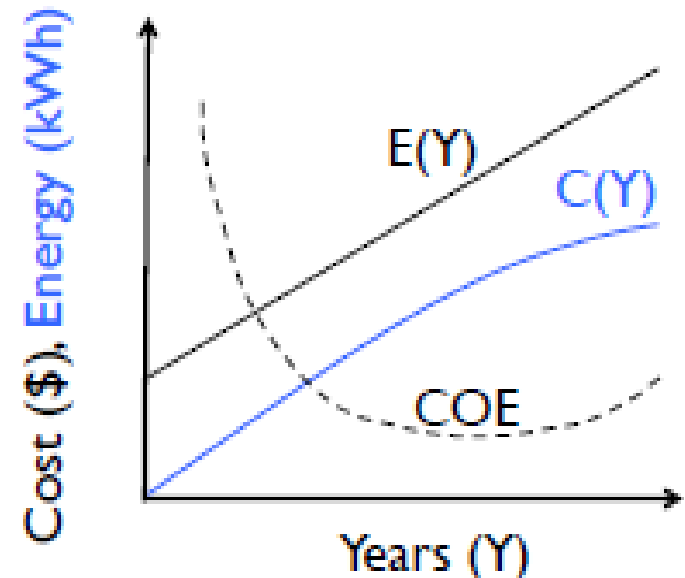
$$COE = \frac{C(Y)}{E(Y)}$$

$$C(Y) = C_{sys} + C_{om}(Y) - C_{rv}(Y)$$

$$C_{sys} = N_{mod} C_{mod} + N_{mod} C_{BOS}$$

$$E(Y) = P_0 \frac{1 - (1 - d)^Y}{d}$$

$$P_0 + P_0 (1 - d) + P_0 (1 - d)^2 + \dots$$



Levelized cost of energy (LCOE)



$$LCOE = \frac{C(Y)}{E(Y)}$$

$$C(Y) = C_{sys} + \sum_{k=1}^Y (C_{om}(1+r)^{-k} - C_{rv}(1+r)^{-k})$$

Discount rate

$$E(Y) = \sum_{k=1}^Y P_0(1-d)^k(1+r)^{-k}$$

LCOE Calculator

(<https://www.nrel.gov/pv/lcoe-calculator/>)

The image shows a side-by-side comparison of the LCOE Calculator interface. The left panel is titled 'Baseline' and has a blue background. The right panel is titled 'Proposed' and has a green background. Both panels feature a 'PRESETS' button (on the left) and a 'COPY FROM BASELINE' button (on the right). Each panel contains a list of input parameters with numerical values and sliders. The 'Baseline' panel shows a LCOE of 0.0605 USD/kWh, while the 'Proposed' panel shows a LCOE of 0.0341 USD/kWh. The 'Proposed' panel has higher values for Front layer cost, Cell cost, and Q&M cost, and a higher efficiency and energy yield.

Parameter	Baseline Value	Proposed Value
Front layer cost (USD/m ²)	4.06	4.06
Cell cost (USD/m ²)	34.40	17.11
Back layer cost (USD/m ²)	2.32	2.32
Non-cell module cost (USD/m ²)	18.00	18.00
Extra component cost (USD/m ²)	0.00	8.51
Q&M cost (USD/kW _{DC} /year)	15.40	9.02
BOS cost, power-scaling (USD/W)	0.31	0.22
BOS cost, area-scaling (USD/m ²)	63.04	63.04
Efficiency (%)	19.0	23.0
Energy yield (kWh/kW _{DC})	1475	1842
LCOE (USD/kWh)	0.0605	0.0341

LCOE Calculator (Continued)

The screenshot shows the LCOE Calculator interface with two columns of input parameters. The left column is blue and represents the 'Baseline' scenario, while the right column is green and represents the 'Proposed' scenario. Both columns have a total value of 63.04 at the top. The 'Common settings' section at the bottom is shared and grey.

Parameter	Baseline (Blue)	Proposed (Green)
Performance		
Efficiency (%)	19.0	23.0
Energy yield (kWh/kW _{DC})	1475	1842
Reliability		
Degradation rate (%/year)	0.36	0.71
Service life (years)	25	29
Common settings		
Financial		
Discount rate	5.01	5.01

Results

LCOE result

Baseline LCOE (USD/kWh)

0.0605

Proposed LCOE (USD/kWh)

0.0341

Additional results

Baseline

Module price (USD/W)

0.36

Total installed system cost (USD/W)

1.00

Proposed

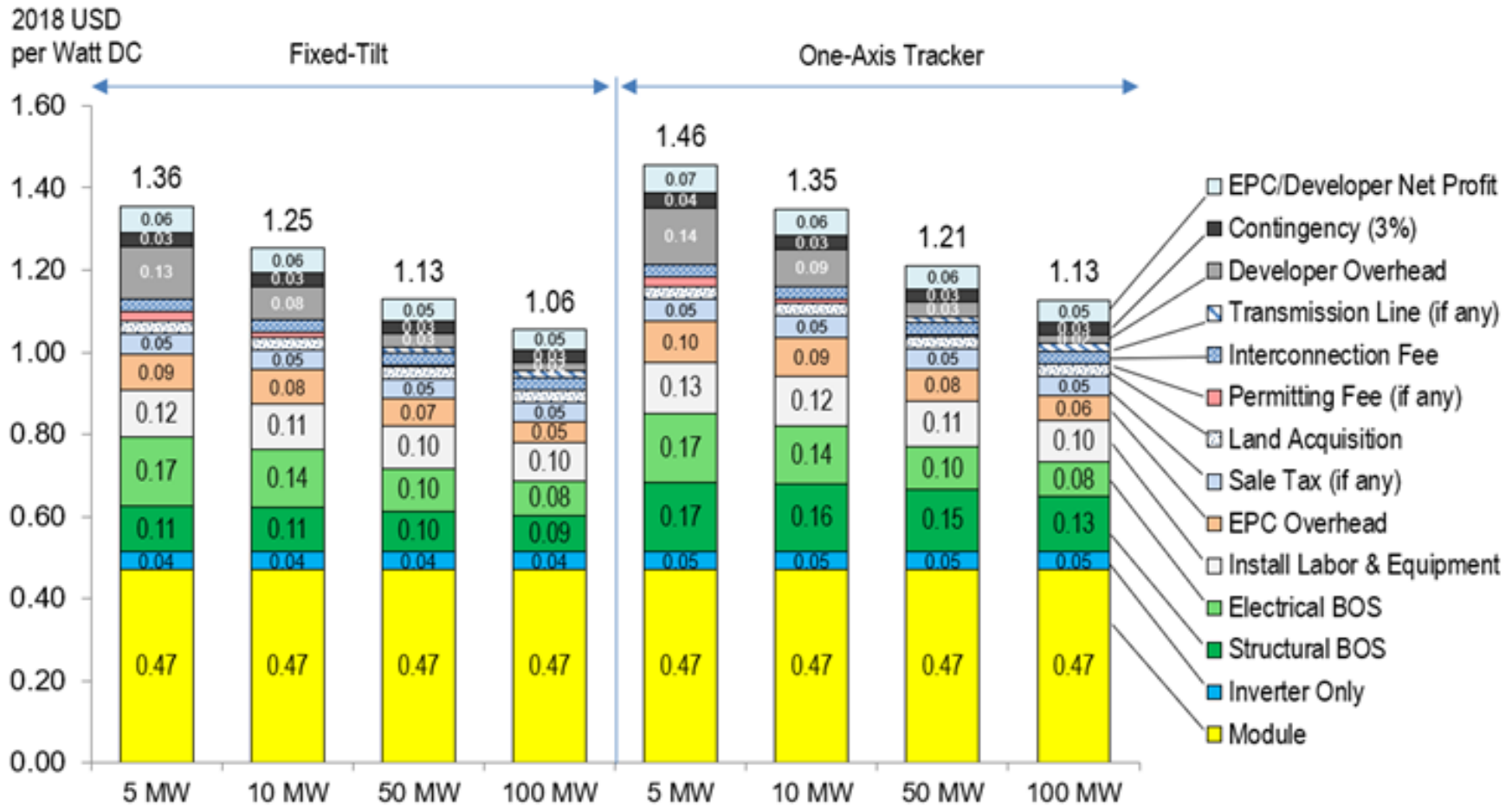
Module price (USD/W)

0.25

Total installed system cost (USD/W)

0.74

Summary of LCOE calculation



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Local Banker's dilemma

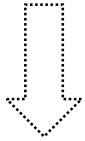


Deconvolving Land and Module costs

$$LCOE = \frac{\text{Total Cost (\$)}}{\text{Total Energy Yield (kWh)}}$$

$$= \frac{C_{sys}(Y=0) + \sum_{k=1}^Y (C_{om}(k) - C_{rv}(k))}{E(Y)}$$

$$\equiv \frac{C_M + C_L + C_{bos,f}}{E(Y)}$$



$$LCOE = \frac{C_M(r) \cdot h \cdot M \cdot Z + C_L(r) \cdot p \cdot M \cdot Z + C_{bos, fixed}}{YY \cdot M \cdot Z \cdot h \cdot \chi}$$

$$\chi = \sum_1^Y (1-d)^k (1+r)^{-k}$$



$$LCOE^* = \frac{LCOE \cdot \chi}{C_L} = \frac{C_M/C_L + p/h}{YY(p, h, \beta, \gamma, R_A)}$$

$$= \frac{p/h + M_L}{YY}$$

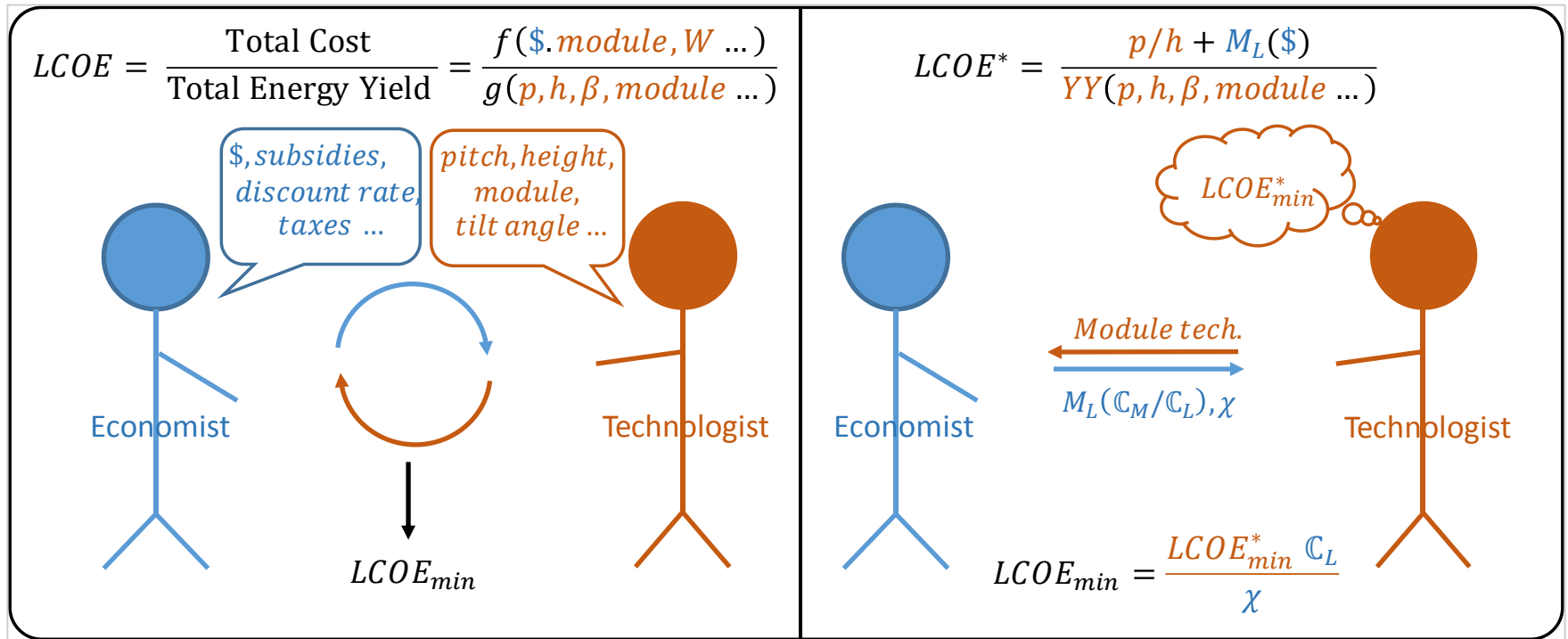
$$C_L = \begin{matrix} (c_{l,0}) \\ + \sum_{k=1}^Y (c_{om,l}(k)) (1+r)^{-k} \\ - \sum_{k=1}^Y (c_{rv,l}(k)) (1+r)^{-k} \end{matrix}$$

$$C_M = \begin{matrix} (c_{m,0}) \\ + \sum_{k=1}^Y (c_{om,m}(k)) (1+r)^{-k} \\ - \sum_{k=1}^Y (c_{rv,m}(k)) (1+r)^{-k} \end{matrix}$$

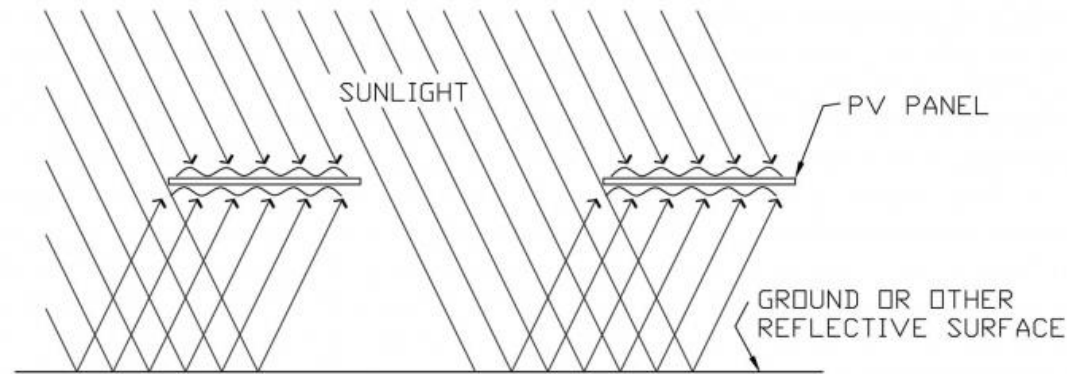
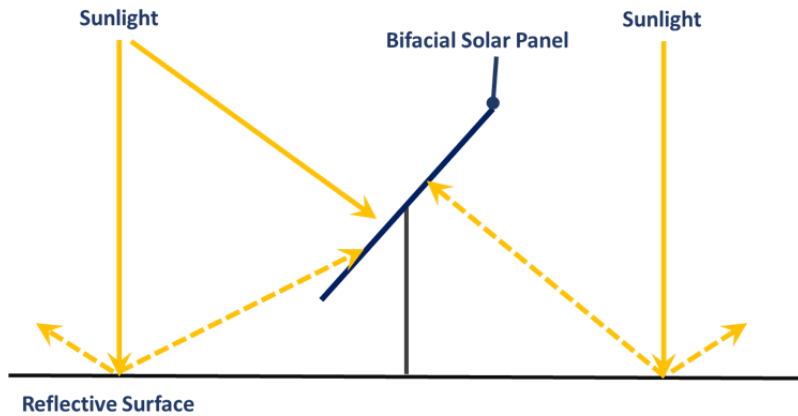
$$E(Y) = \sum_{k=1}^Y P_0 (1-d)^k (1+r)^{-k}$$

Deconvolving Land and Module costs

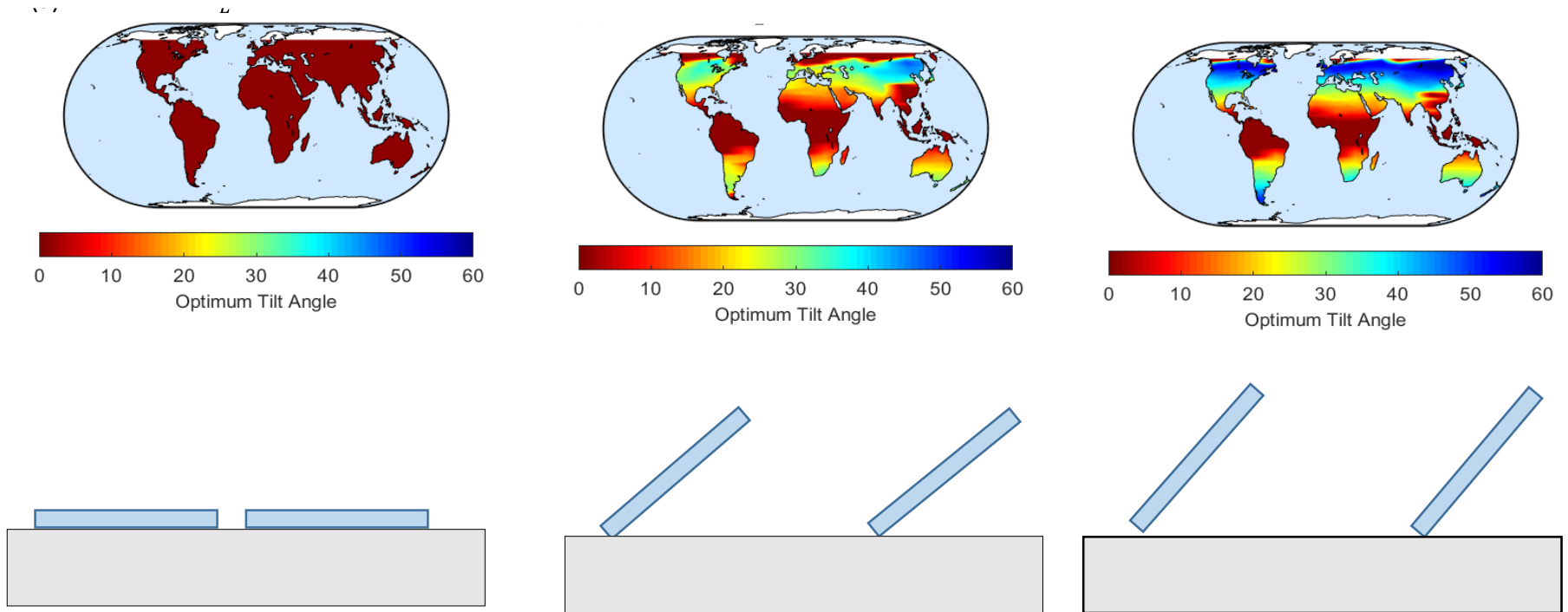
$$LCOE^* = \frac{LCOE \cdot \chi}{C_L} = \frac{C_M/C_L + p/h}{YY(p, h, \beta, \gamma, R_A)} = \frac{p/h + M_L}{YY}$$



An example: Bifacial Solar cells



Optimum tilt angle

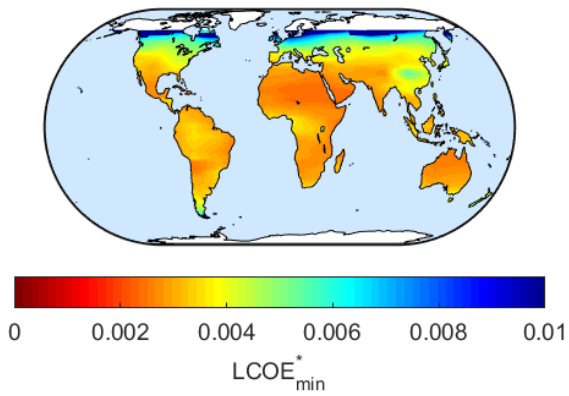


$$\beta_{opt}^{ana} = c_1 M_L + \exp \left(c_2 \left(1 - \frac{1}{(M_L - M_L^*)^{c_3}} \right) \right)$$

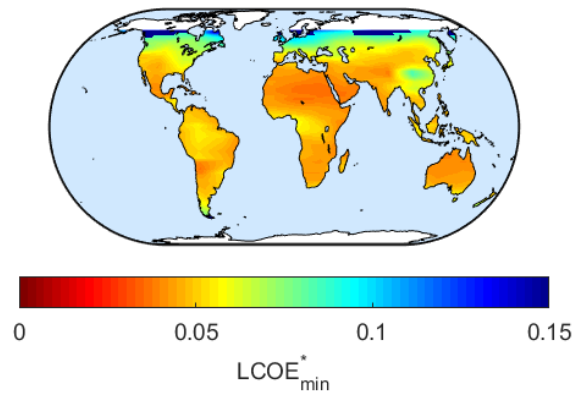
$LCOE_{min}^*$

$$LCOE_{min}^* = \frac{p_{ns}^{opt}/h + M_L}{YY(\beta_{opt})}$$

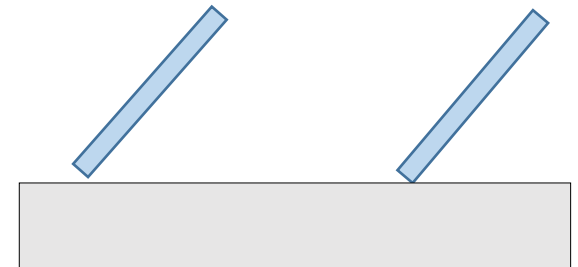
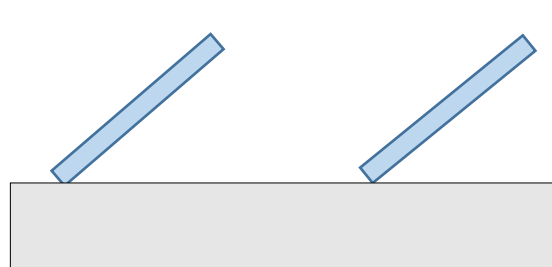
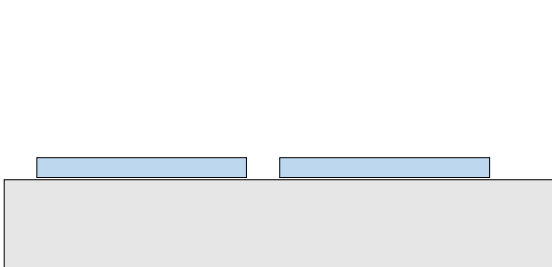
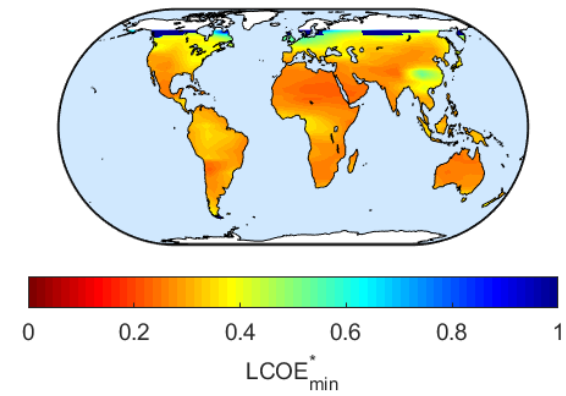
(a) $M_L = 0$



(b) $M_L = 15$

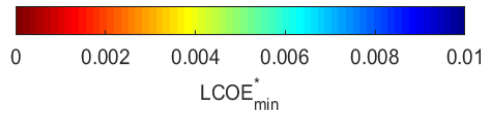
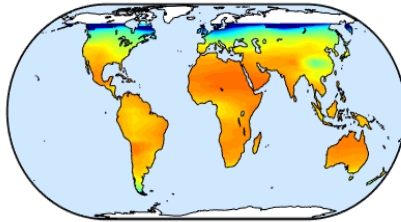


(c) $M_L = 100$

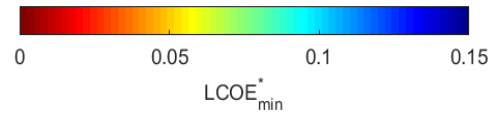
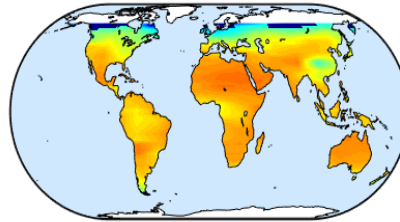


Comparing technologies

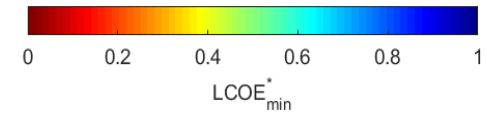
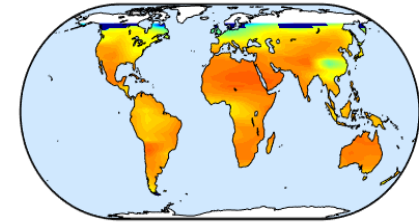
(a) $M_L = 0$



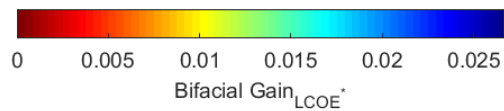
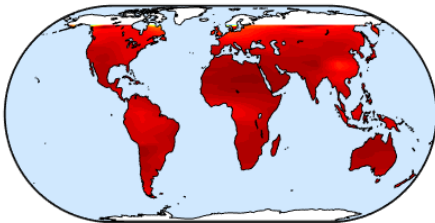
(b) $M_L = 15$



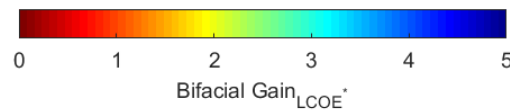
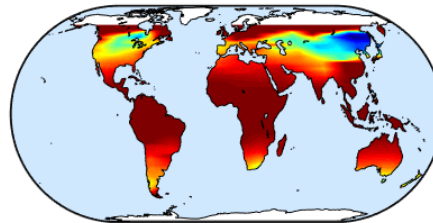
(c) $M_L = 100$



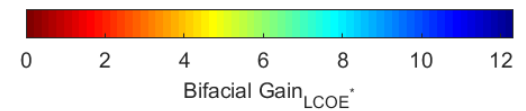
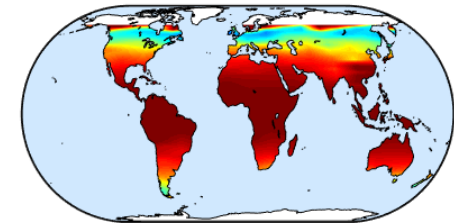
(a) $M_L = 0$



(b) $M_L = 15$



(c) $M_L = 100$



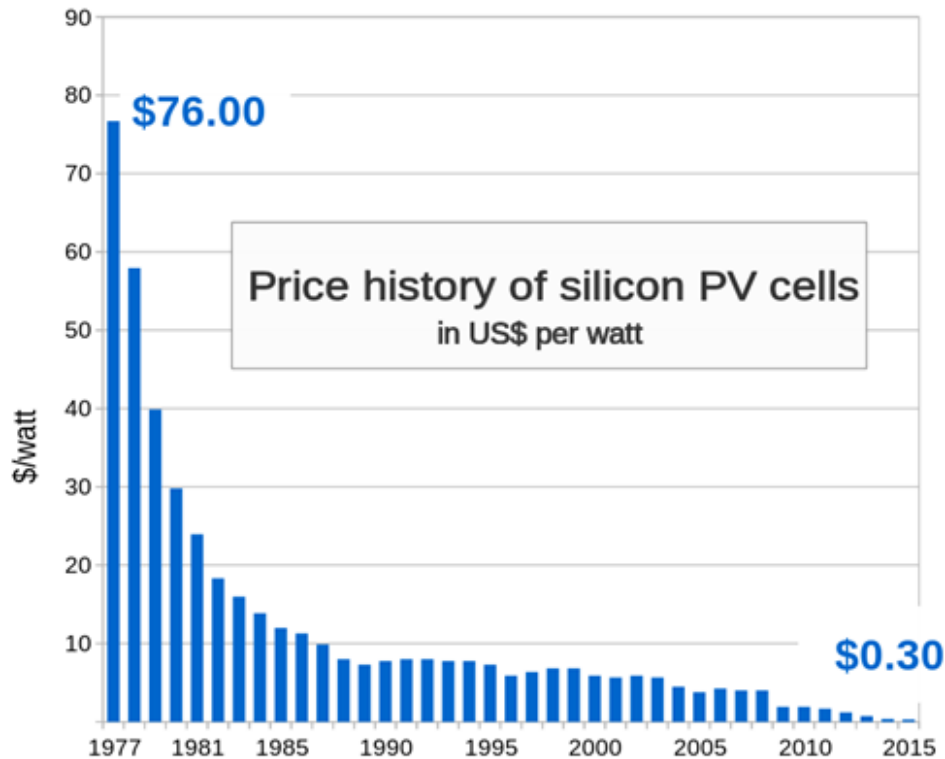
Bifacial is beneficial for locations with high diffuse light

Outline

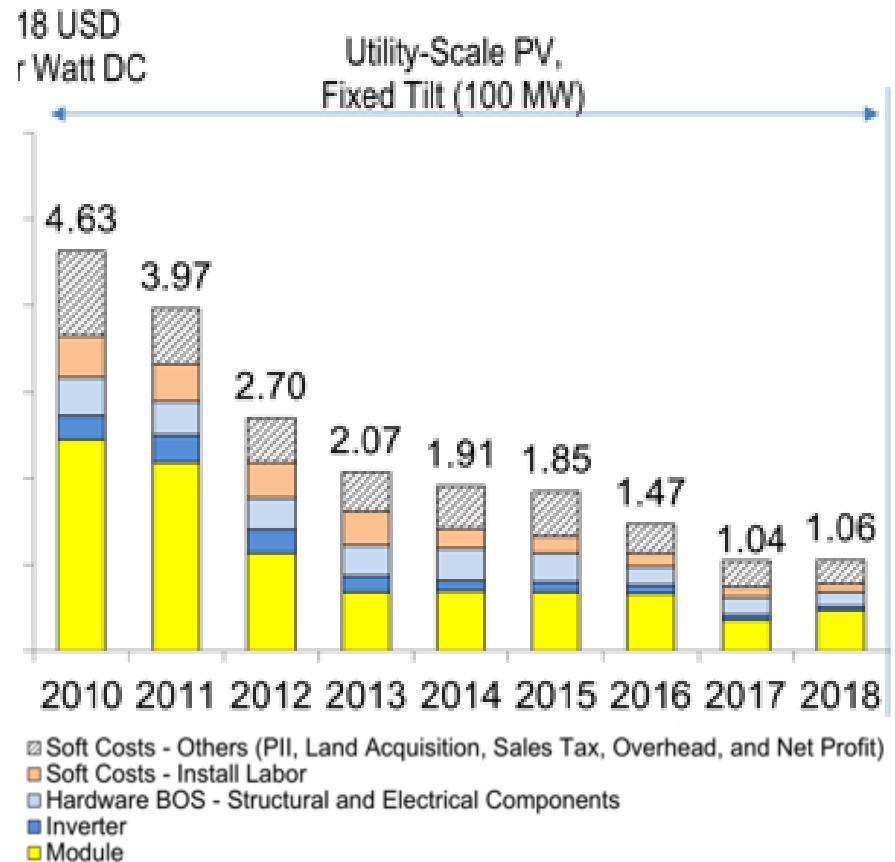
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Anticipating tomorrow's cost today

C. Ran Fu et al., "U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018," *Natl. Renew. Energy Lab.*, no. November, 2018.

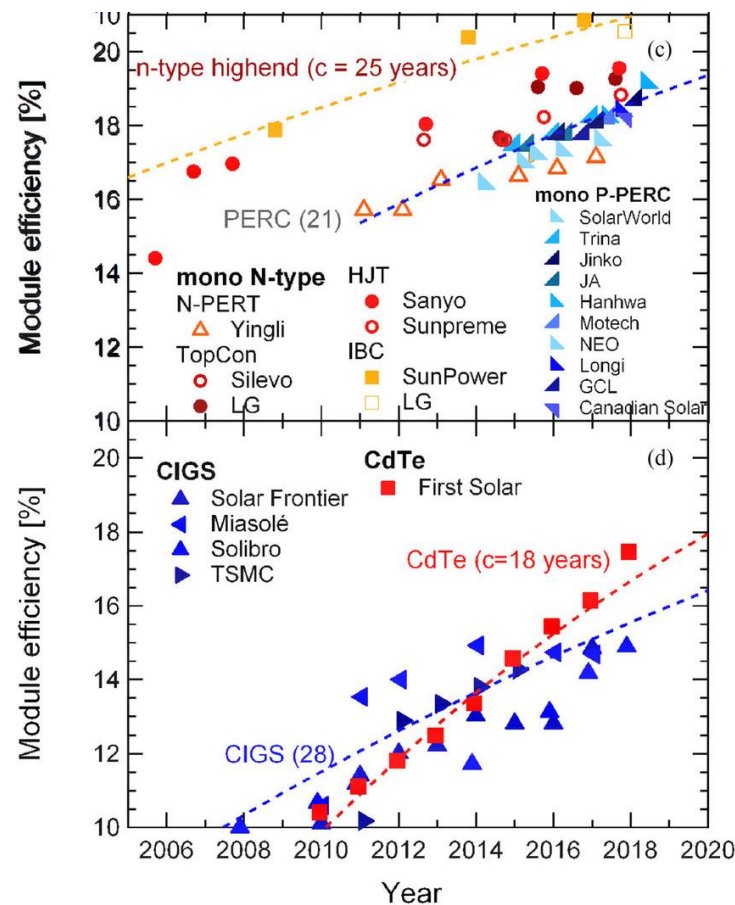
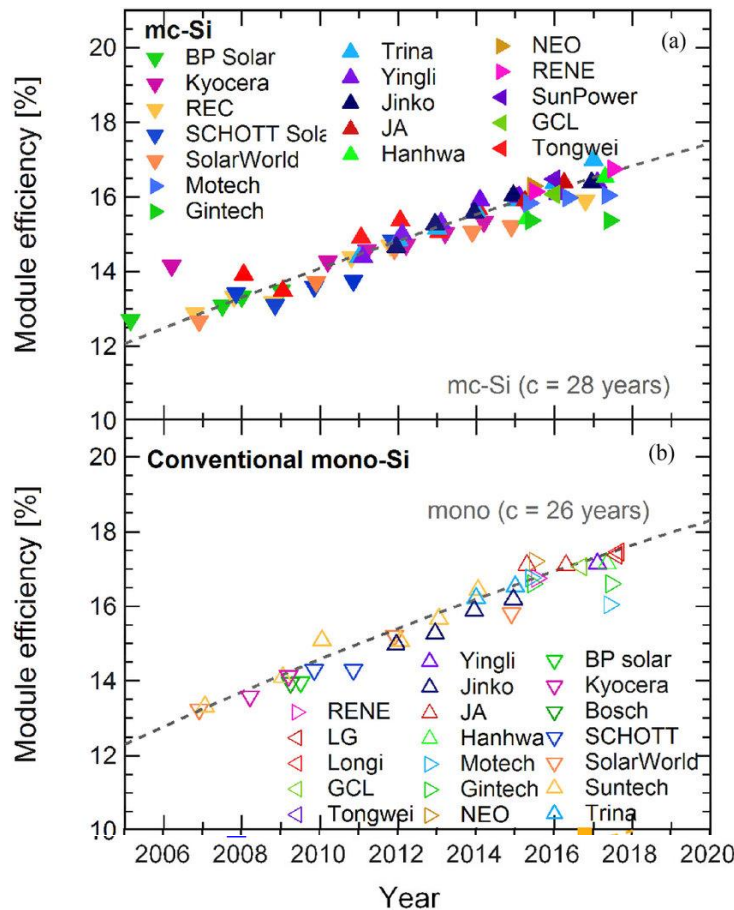


Source: Bloomberg New Energy Finance & pv.energytrend.com



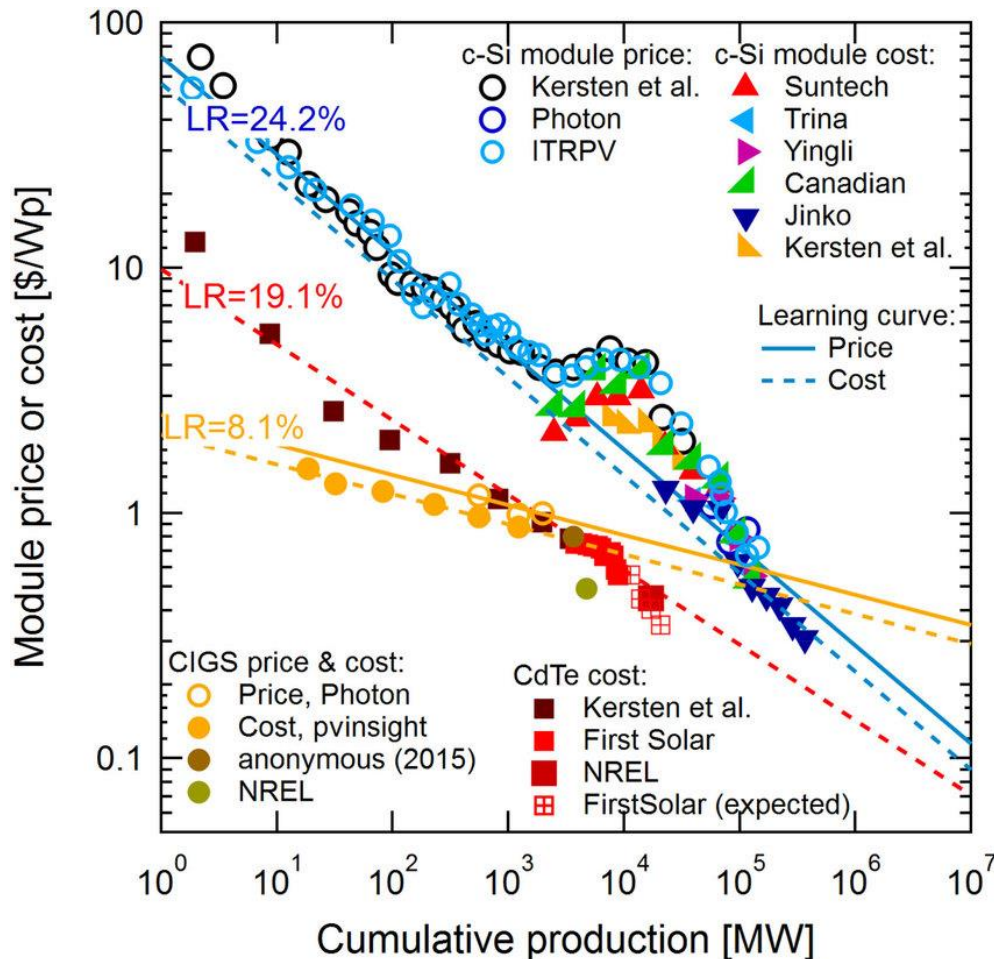
Learning curve 1: Goetzberger Law

$$\eta(t) = \eta_{max} [1 - \exp(t_0 - t)/c)]$$



Y. Chen, JPV, 2018

Learning curve 2: Swanson law



$$C_t = C_0 \left(\frac{q_t}{q_0} \right)^{-b}$$

Costs at time t and 0
 Production at time t and 0
 b is the learning coefficient

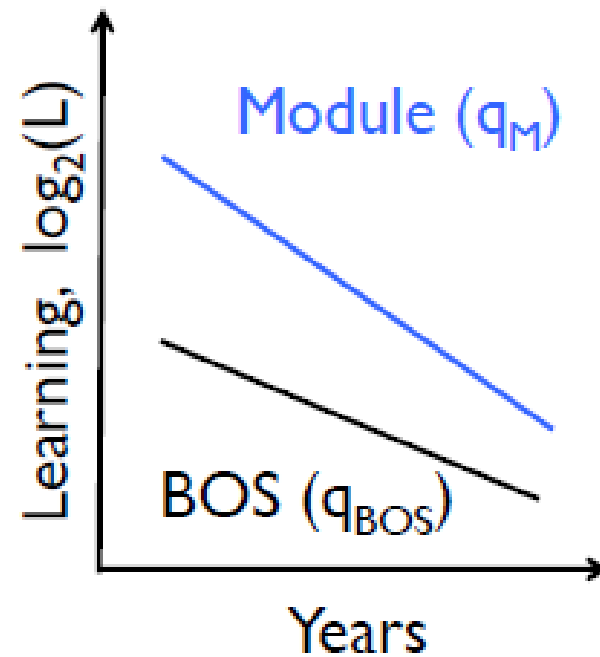
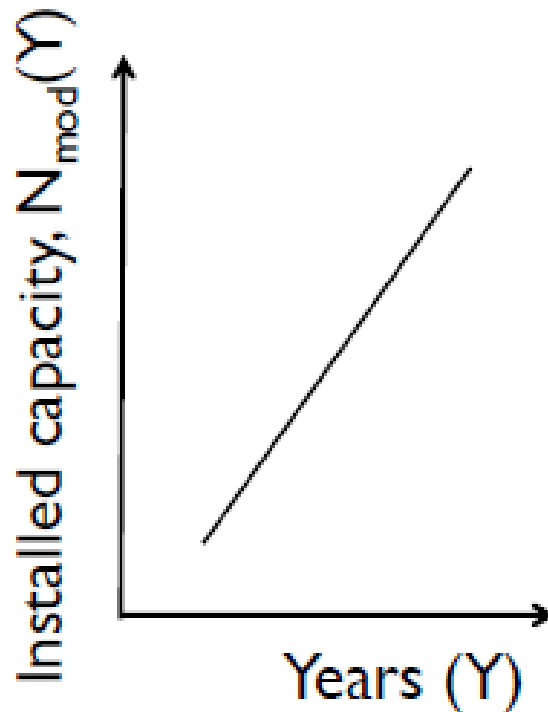
Learning curves for each technology

$$N_R \equiv \frac{N_{mod}(X)}{N_{mod}(0)} = 1 + f_0 \sum_{k=1}^X (1+g)^k$$

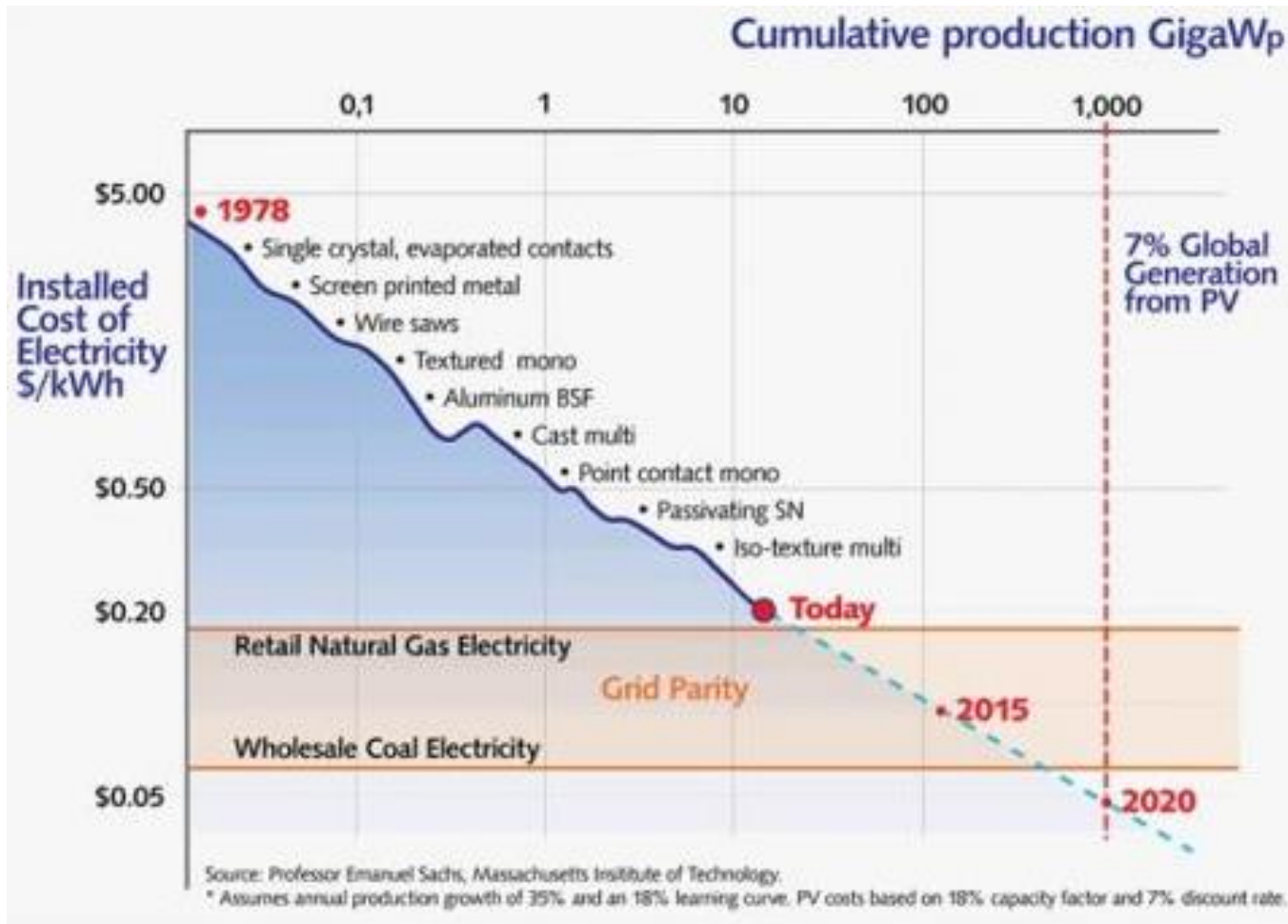
$$L_m(Y, q_m, g) \equiv \frac{C_{mod}(X)}{C_{mod}(0)} = N_R^{\log_2(1-q_m)}$$

$$C_{mod}(X) = C_{mod}(0) \times L_m(X, q_m, g)$$

$$C_{BOS,V}(X) = C_{BOS,V}(0) \times L_{BOS,V}(X, q_{BOS}, g)$$



... will drop cost of energy produced



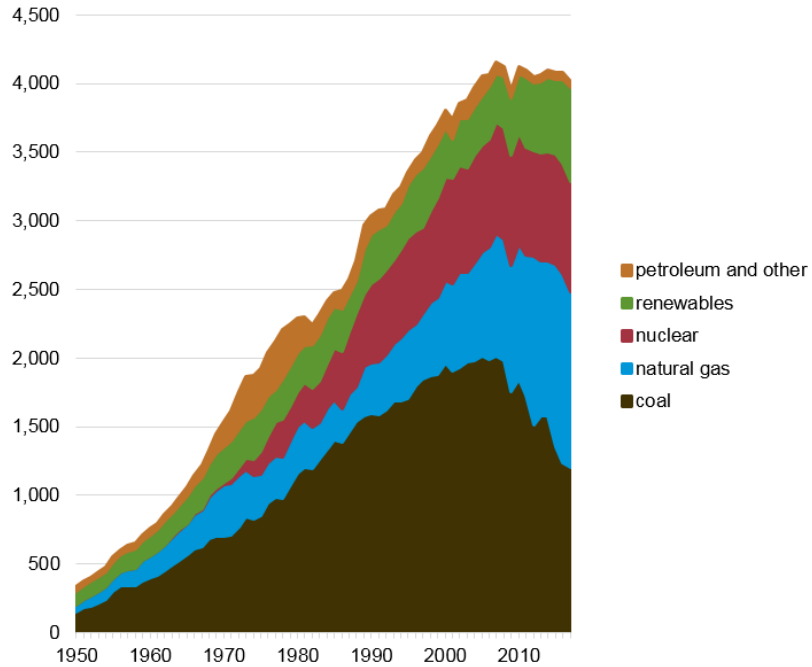
Acwa Power
5.84 cents!

Taqnia
5 cents!

LCOE compared

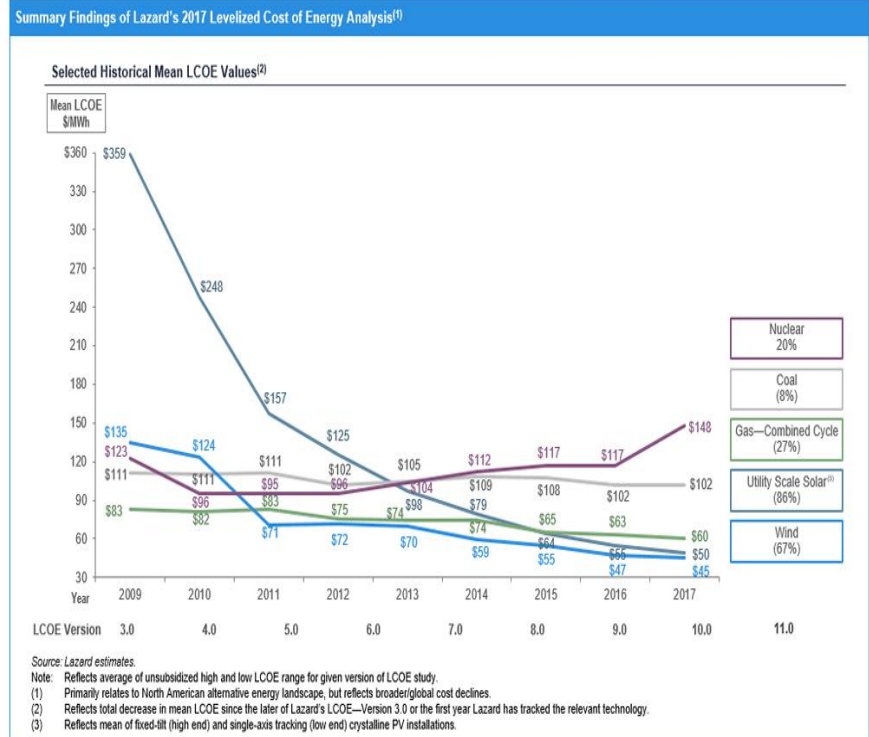
<https://www.lazard.com/perspective/levelized-cost-of-energy-2017/>

U.S. electricity generation by major energy source, 1950–2017
billion kilowatthours



Note: Electricity generation from utility-scale facilities.

Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 7.2a, March 2018, preliminary data for 2017



Conclusions

- 1) Sunlight is free, but PV is not
- 2) LCOE allows “apples-to-apples” comparison of energy costs. Does not account for environmental costs, or cost to society.
- 3) LCOE* decouples land vs. technology costs. Allows one to compare technologies even when the bank-costs are unknown.
- 4) The learning curve ensures that Silicon remains a dominant force.

Self-test questions

- 1) What is typical degradation rate of a solar farm? What is typical bank discount rates?
- 2) What is the difference between COE and LCOE?
- 3) What is the advantage of using LCOE*?
- 4) What are two aspects of Learning curve? How does it explain the success of Si PV industry.
- 5) What is typical LOCE for PV today?