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

How to Design Cost-effective Solar Farms

M. A. Alam

alam@purdue.edu
Electrical and Computer Engineering
Purdue University
West Lafayette, IN USA

Network for Photovoltaic Technology

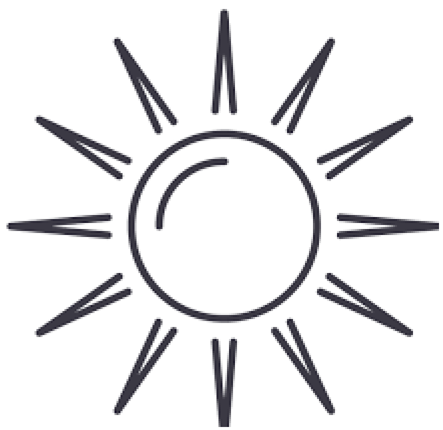
nanoHUB.org

PURDUE UNIVERSITY

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: $1.496x10^{11}\ m$
Earth Radius: 4000 miles
Temperature: 300K
Irradiance … 1000 W/m^2

PV Max. Efficiency = 1/3

Bank interest – 4-5%

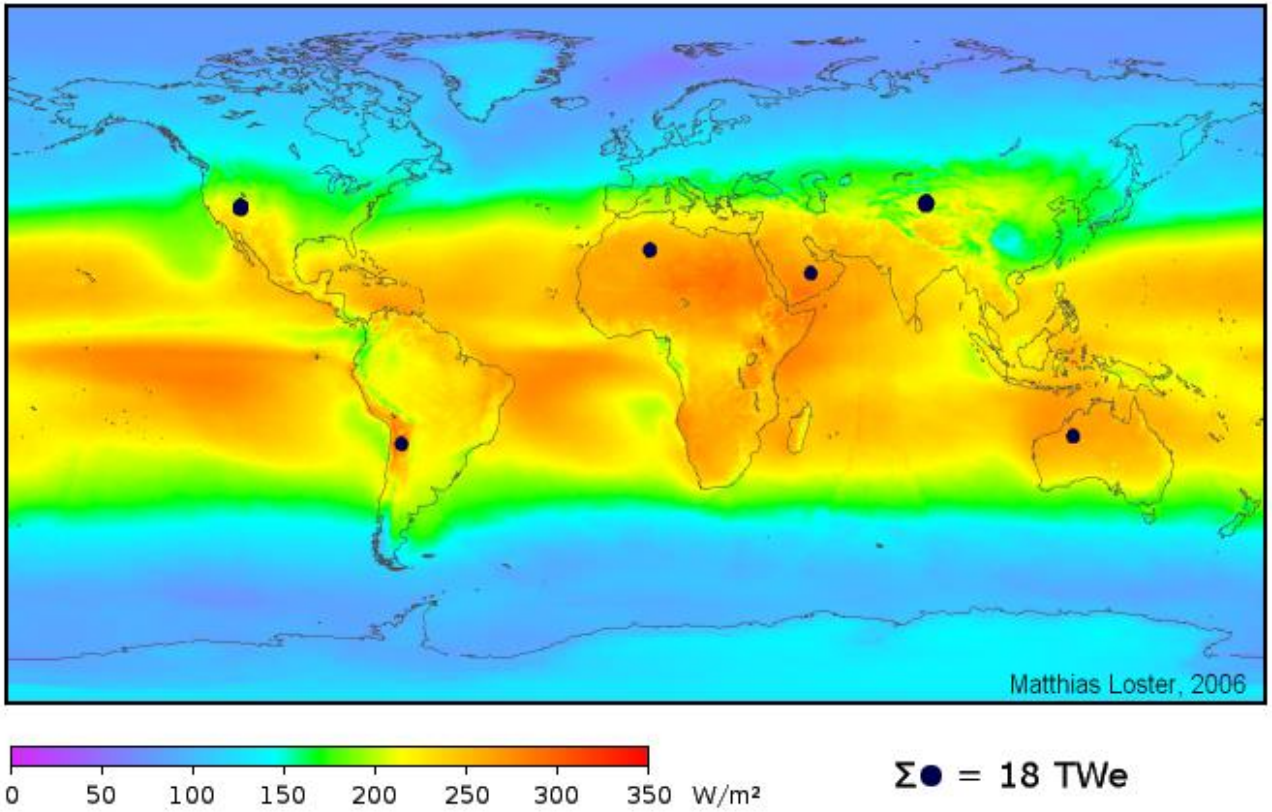
Solar energy is not free

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

Cost = cost of converter + maintenance + interest

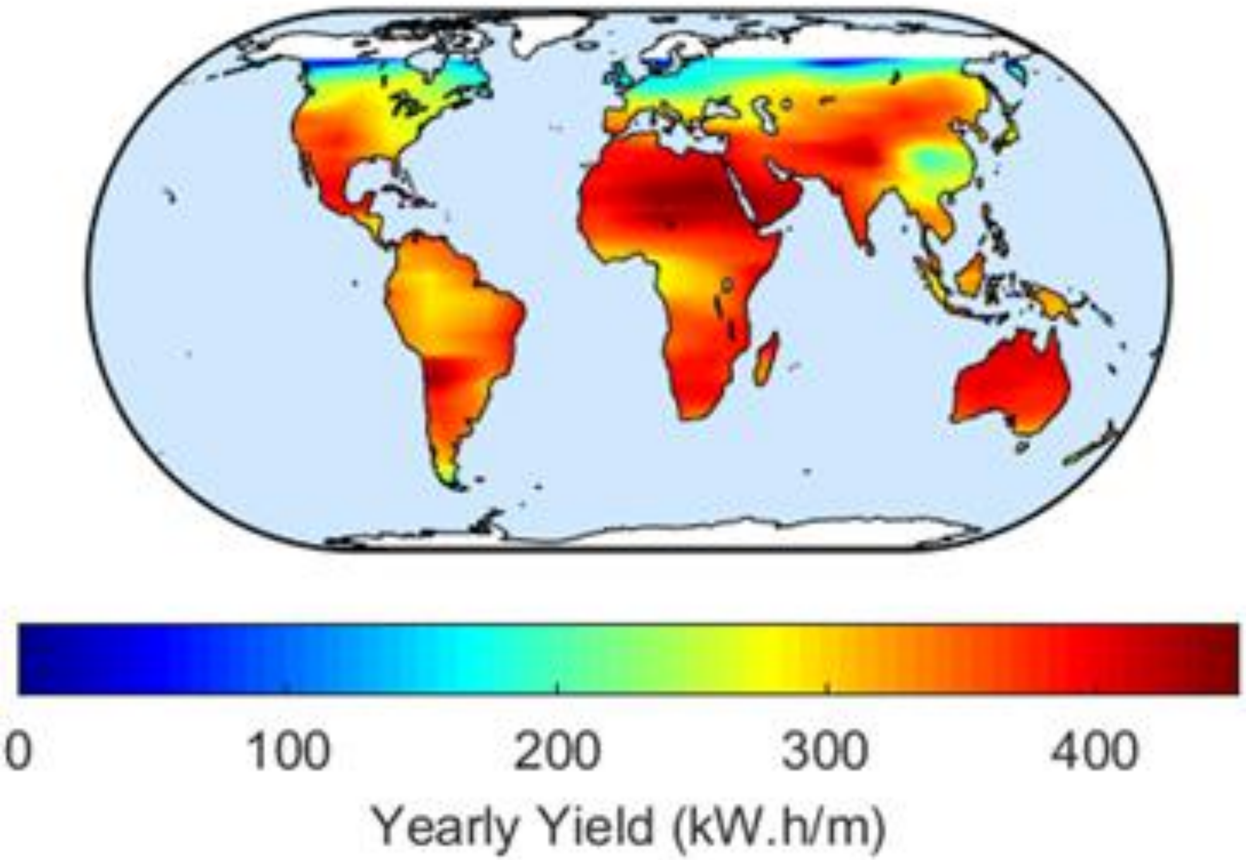
Energy produced = Insolation x efficiency x lifetime

Sunlight depends on latitude



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

Energy Yield of by a bifacial PV technology



M. A. Alam, PV Lecture Notes

Cost of Energy (COE)

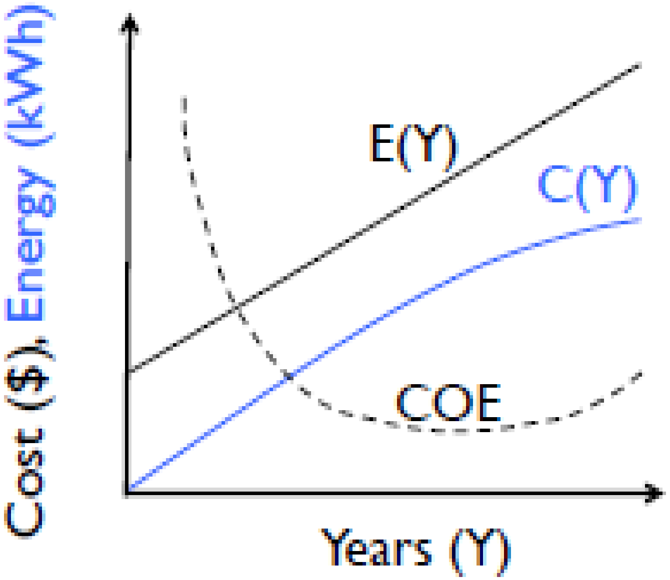
$$COE = \frac{C(Y)}{E(Y)}$$

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

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

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

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



Levelized cost of energy (LCOE)

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

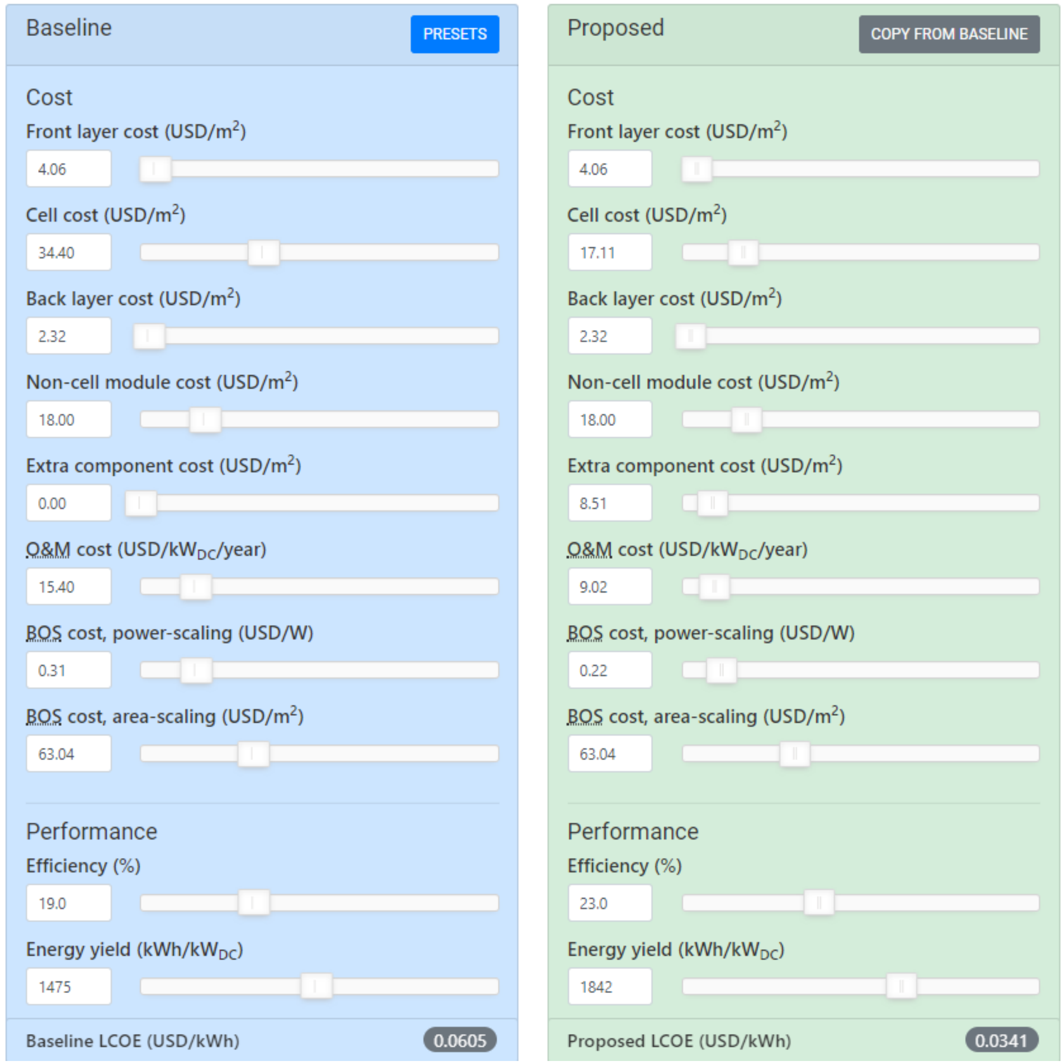
$$C(Y) = C_{sys} + \sum_{k=1}^{Y} C_{om}(1+r)^{-k} - C_{rv}(1+r)^{-k})$$

Discount rate

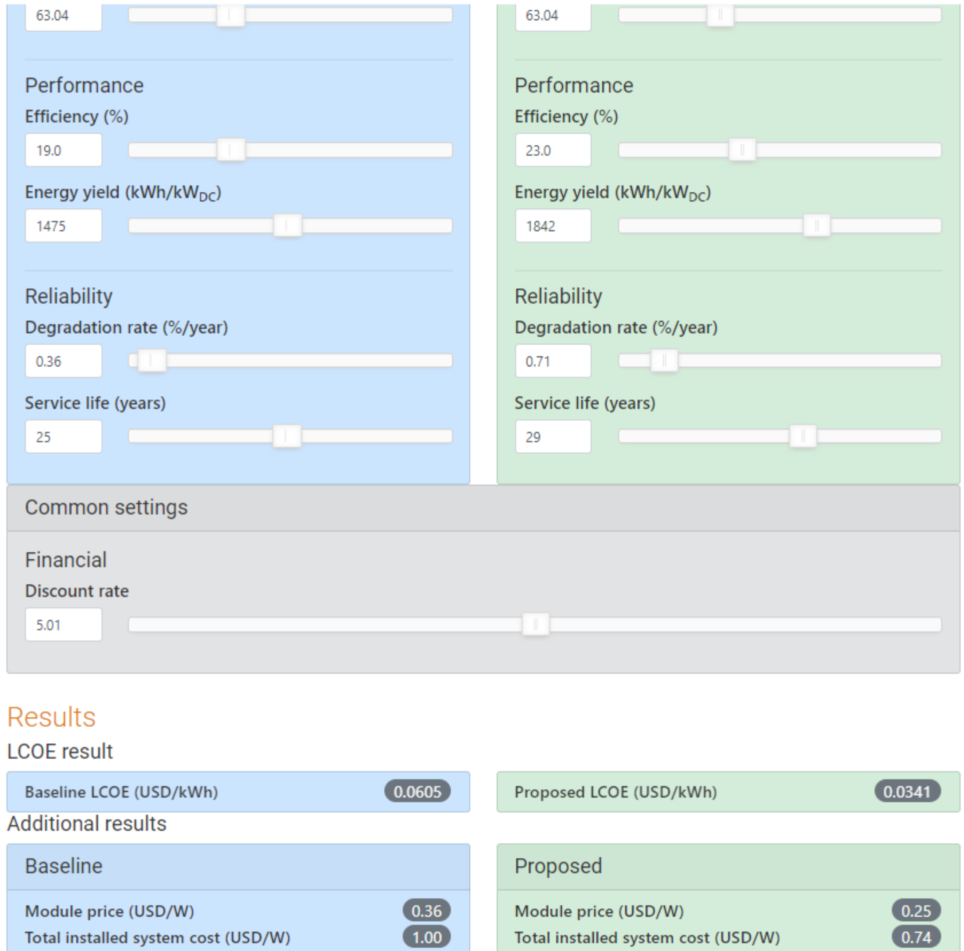
$$E(Y) = \sum_{k=1}^{Y} P_0(1-d)^{k}(1+r)^{-k}$$

LCOE Calculator

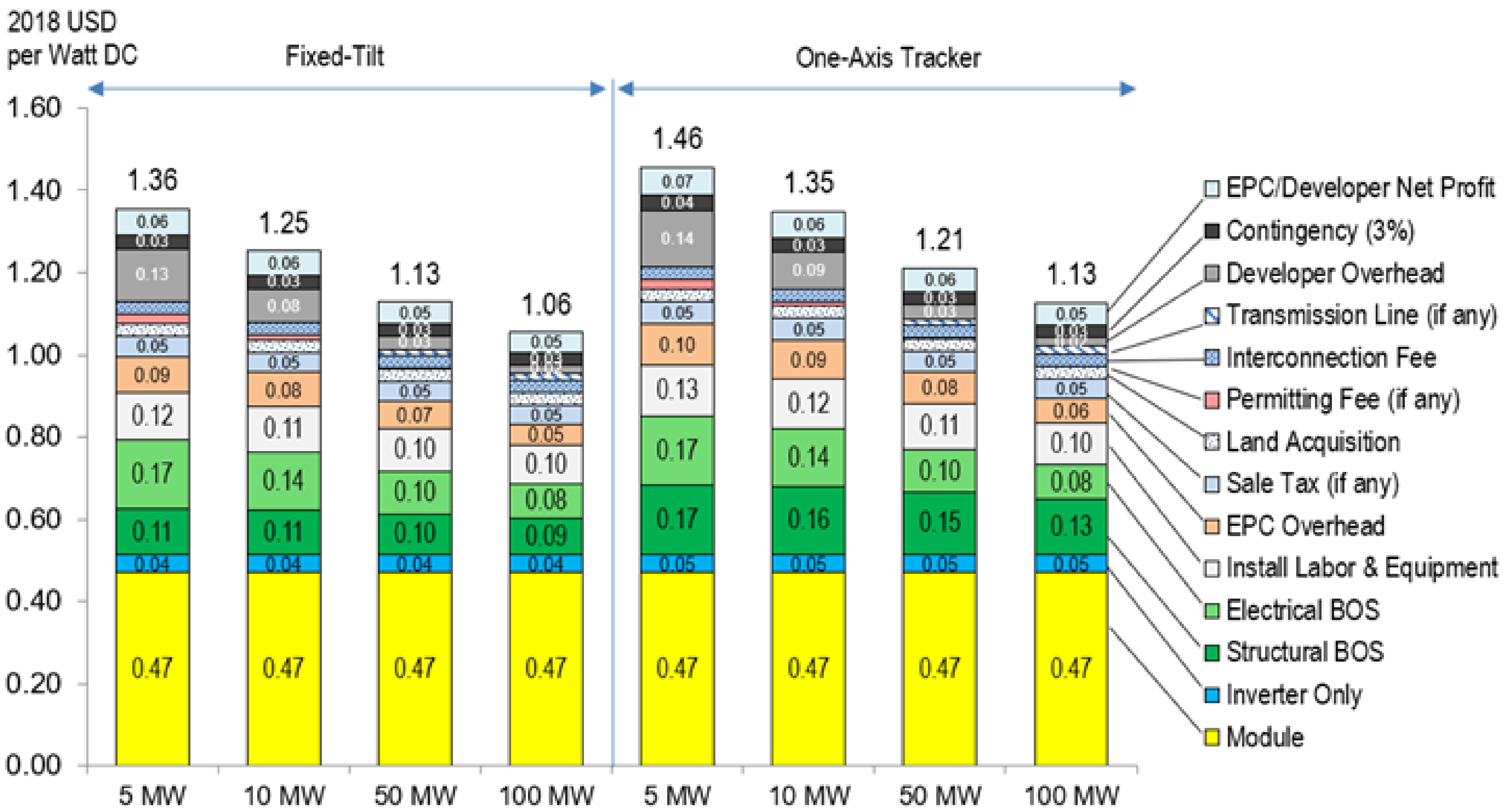
(https://www.nrel.gov/pv/lcoe-calculator/)



LCOE Calculator (Continued)



Summary of LCOE calculation



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Local Banker's dilemma




Deconvolving Land and Module costs

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

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

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

$$LCOE = \frac{\mathbb{C}_M(r).\,h.\,M.\,Z + \mathbb{C}_L(r).\,p.\,M.\,Z + C_{bos,fixed}}{YY.\,M.\,Z.\,h.\,\chi}$$

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

$$LCOE^* = \frac{LCOE.\,\chi}{\mathbb{C}_L} = \frac{\mathbb{C}_M/\mathbb{C}_L + p/h}{YY(p,h,\beta,\gamma,R_A)}$$

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

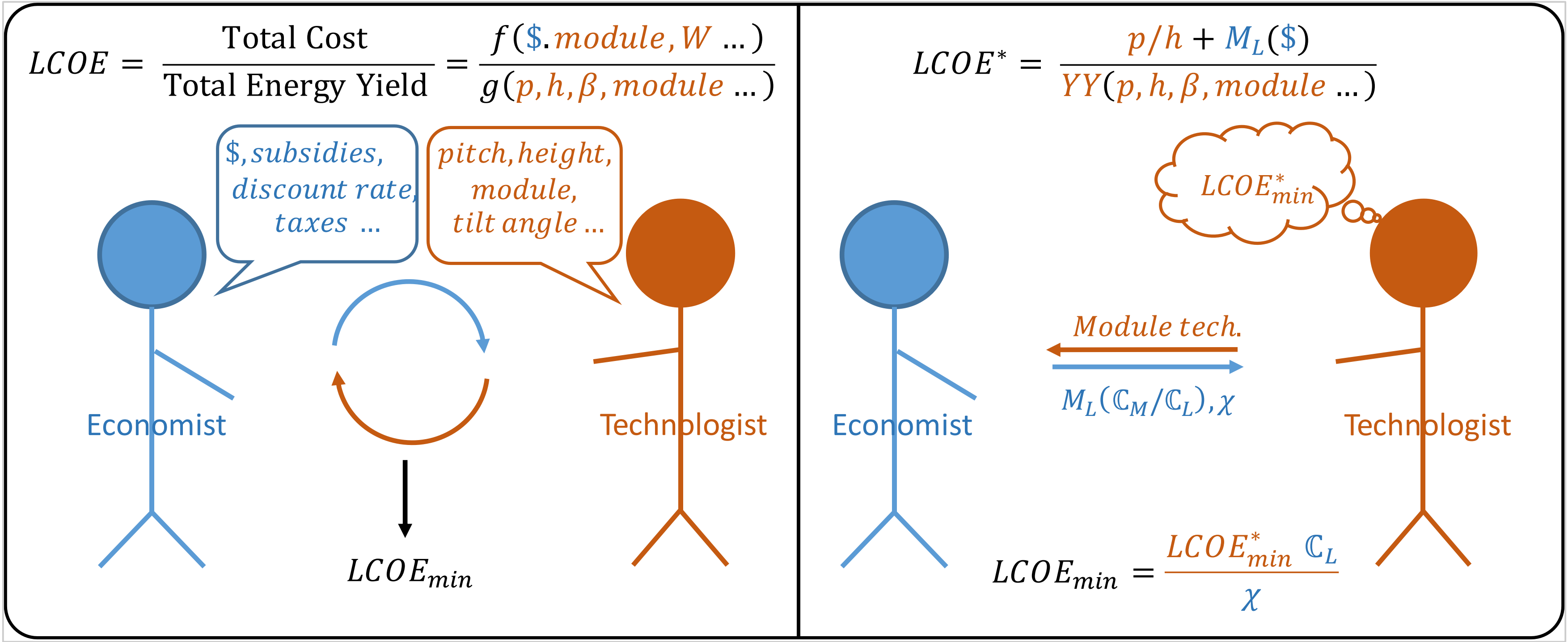
$$C_L = \begin{array}{l}(c_{l,0}) \\ + \sum_{k=1}^{Y}\left(c_{om,l}(k)\right)(1+r)^{-k} \\ - \sum_{k=1}^{Y}\left(c_{rv,l}(k)\right)(1+r)^{-k}\end{array}$$

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

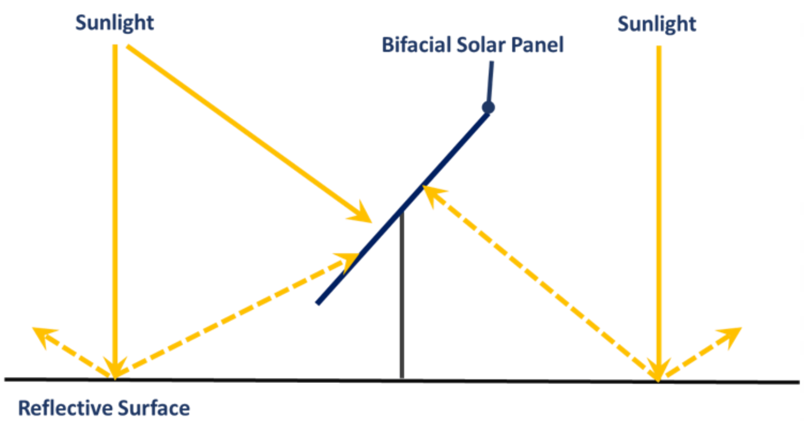
$$E(Y) = \sum_{k=1}^{Y} P_0\,(1-d)^k(1+r)^{-k}$$

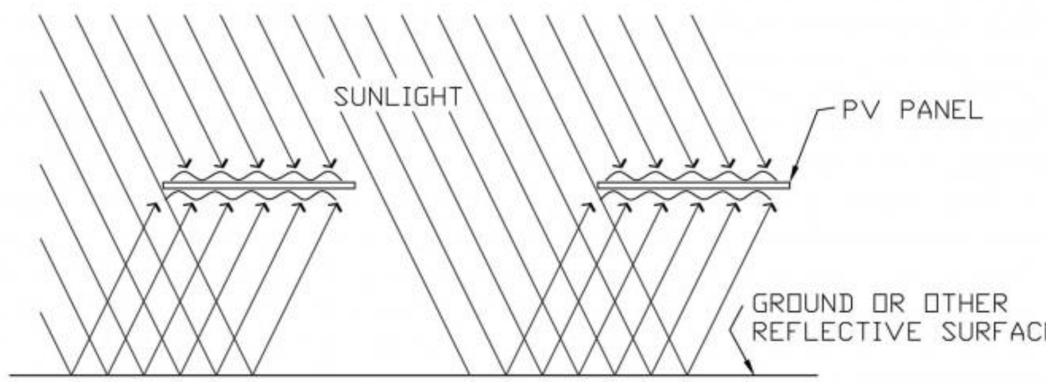
Deconvolving Land and Module costs

$$LCOE^* = \frac{LCOE.\chi}{\mathbb{C}_L} = \frac{\mathbb{C}_M/\mathbb{C}_L + p/h}{YY(p,h,\beta,\gamma,R_A)} = \frac{p/h + M_L}{YY}$$



An example: Bifacial Solar cells

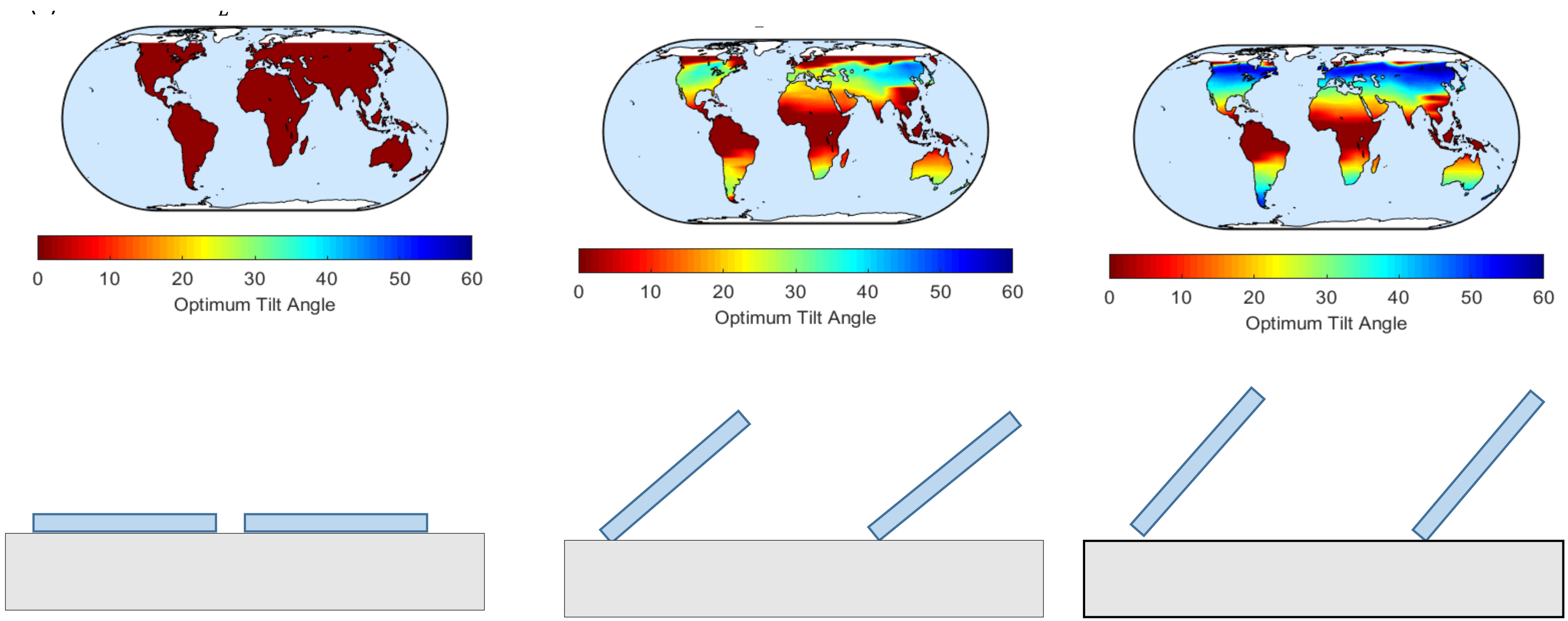




a

b

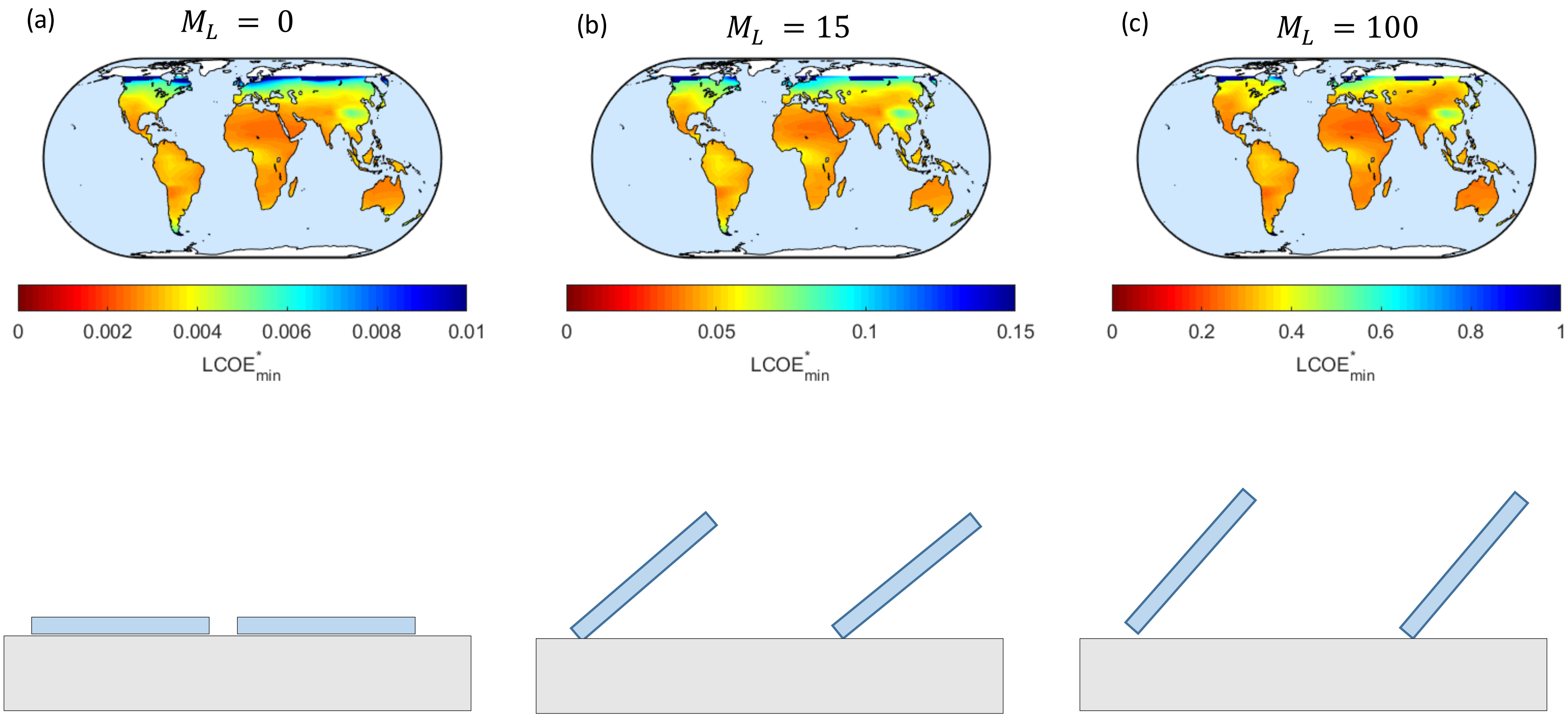
Optimum tilt angle



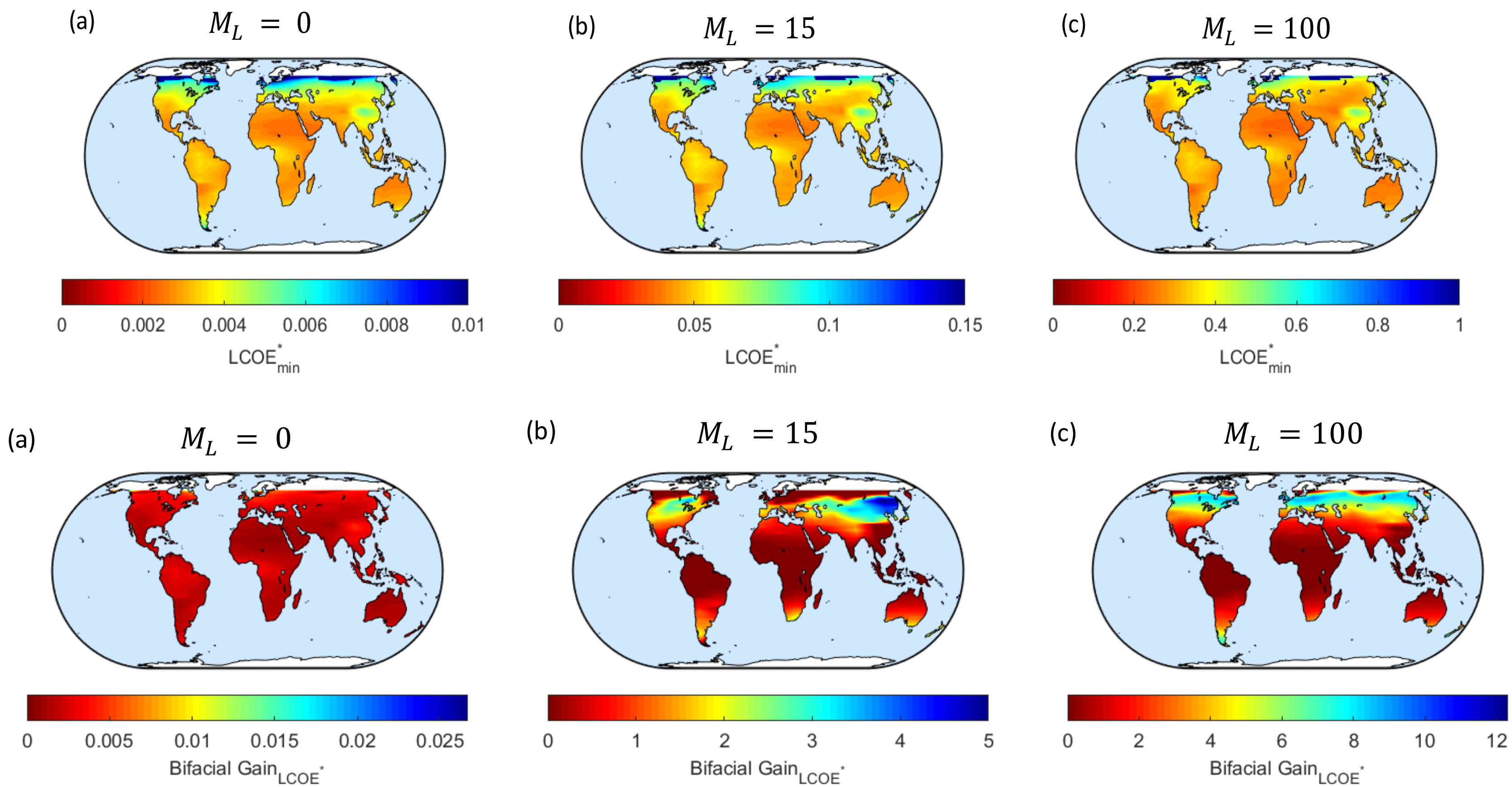
$$\beta_{opt}^{ana} = c_1 M_L + \exp\left(c_2\left(1 - \frac{1}{(M_L - M_L^*)^{c_3}}\right)\right)$$

$LCOE^*_{min}$

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



Comparing technologies



Bifacial is beneficial for locations with high diffuse light

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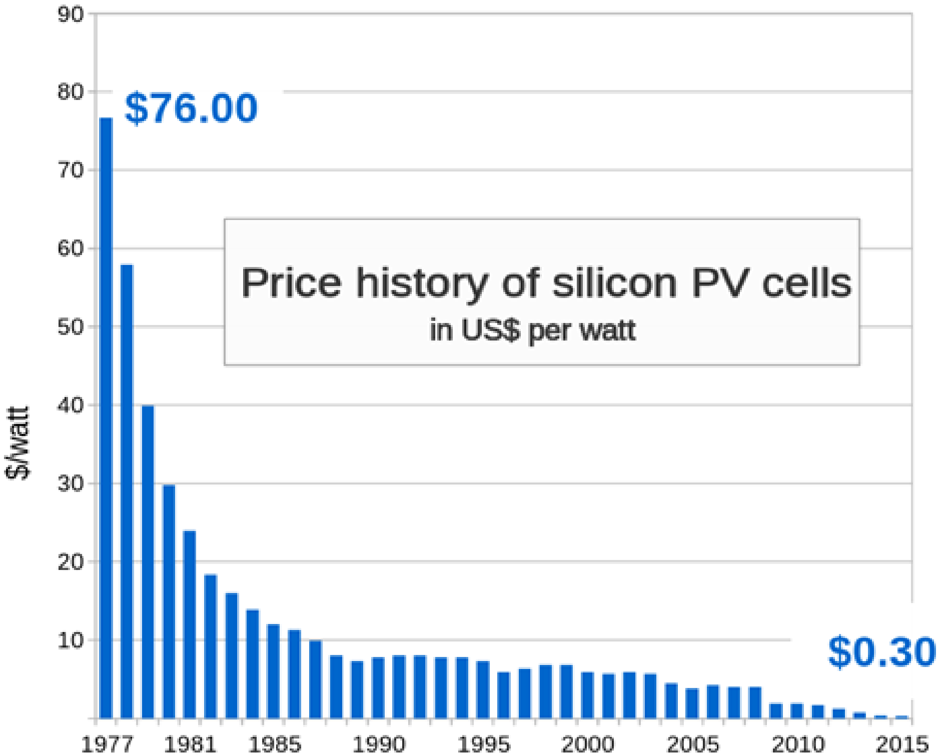
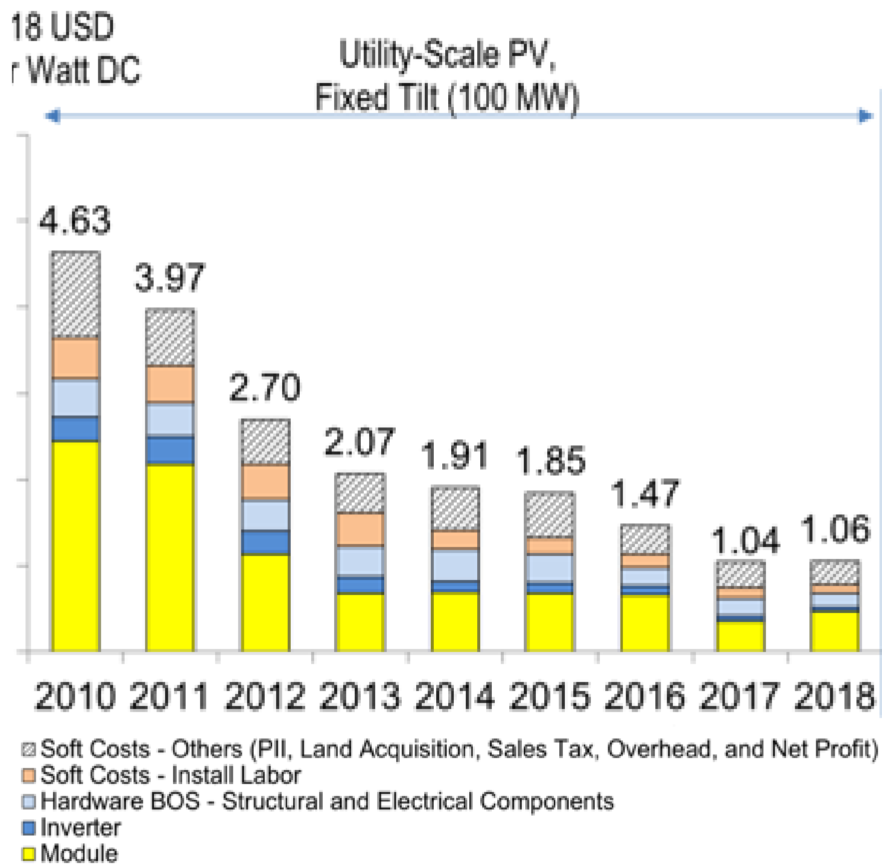
Anticipating tomorrow's cost today



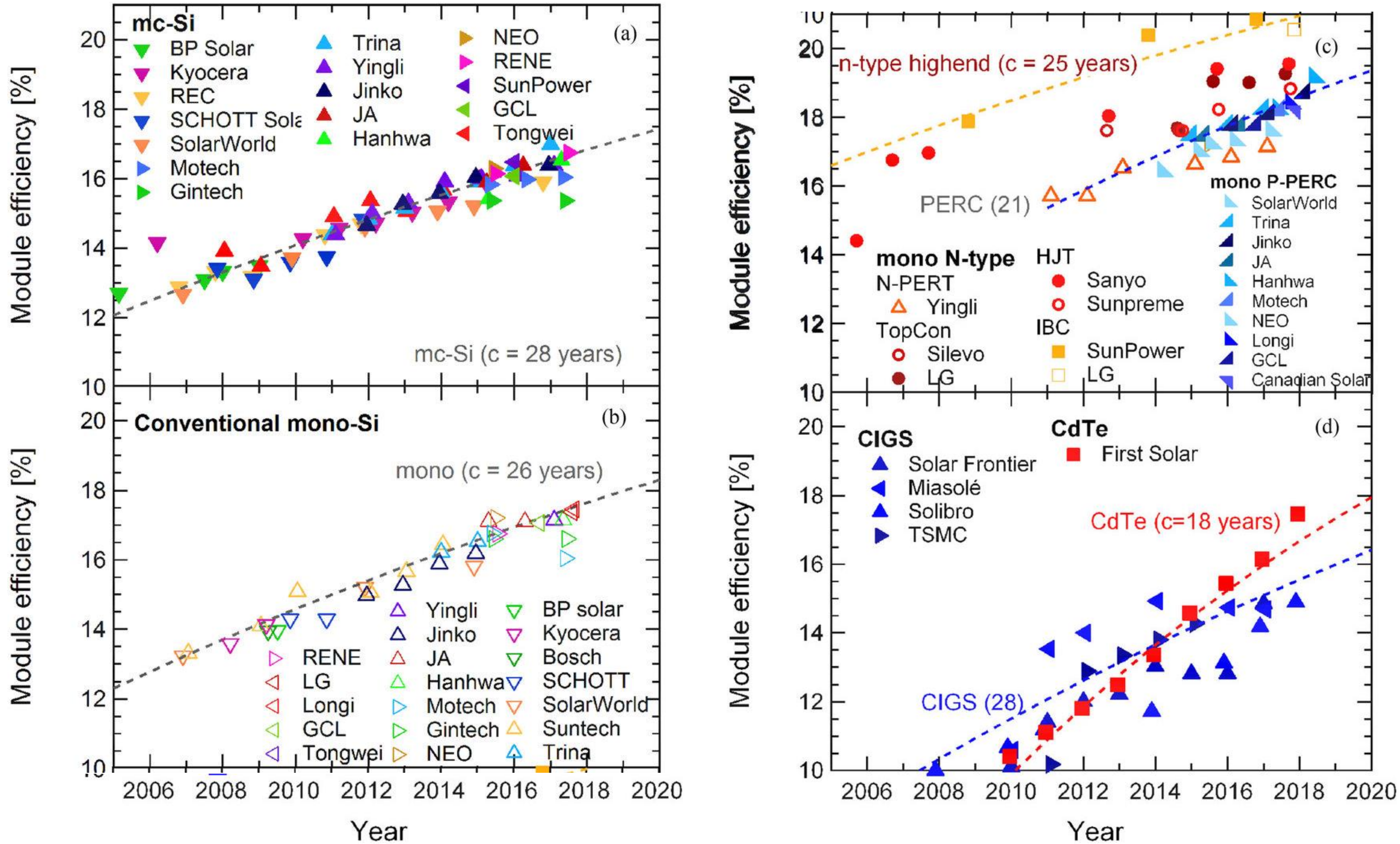
Source: Bloomberg New Energy Finance & pv.energytrend.com

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



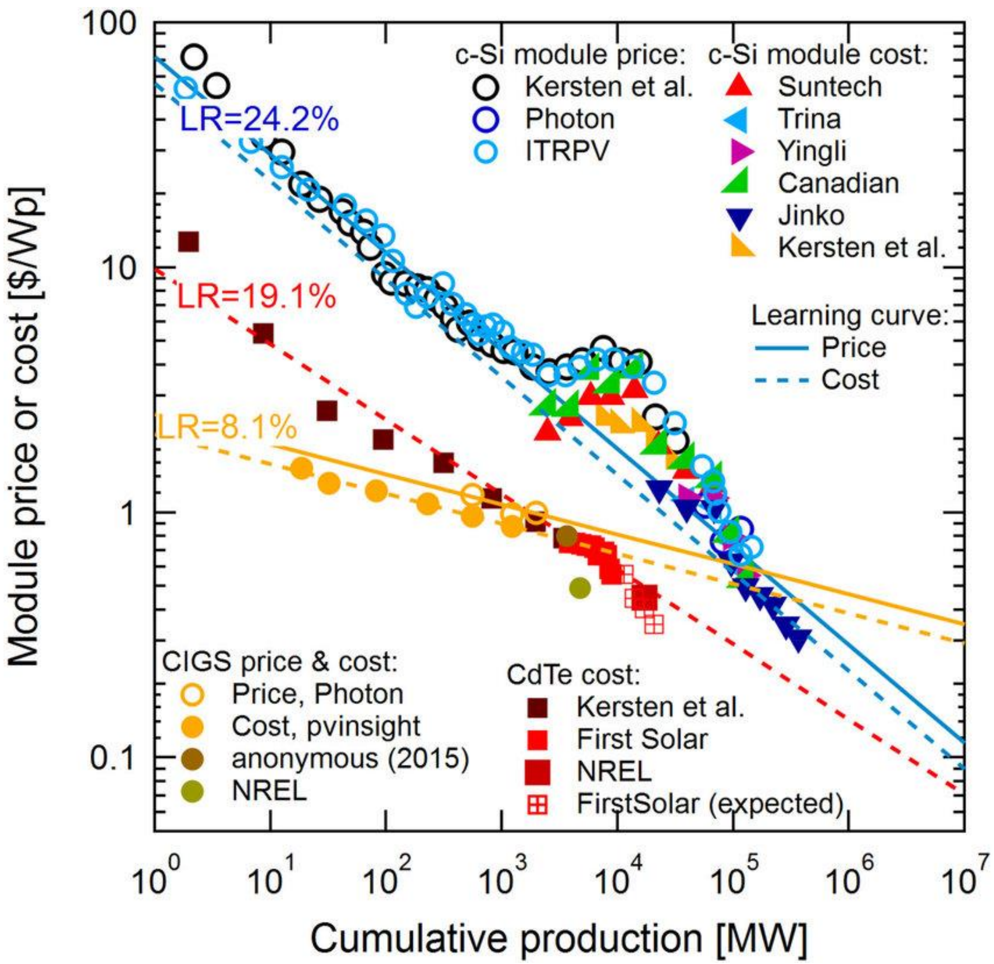
Learning curve 1: Goetzberger Law

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



Y. Chen, JPV, 2018

Learning curve 2: Swanson law



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

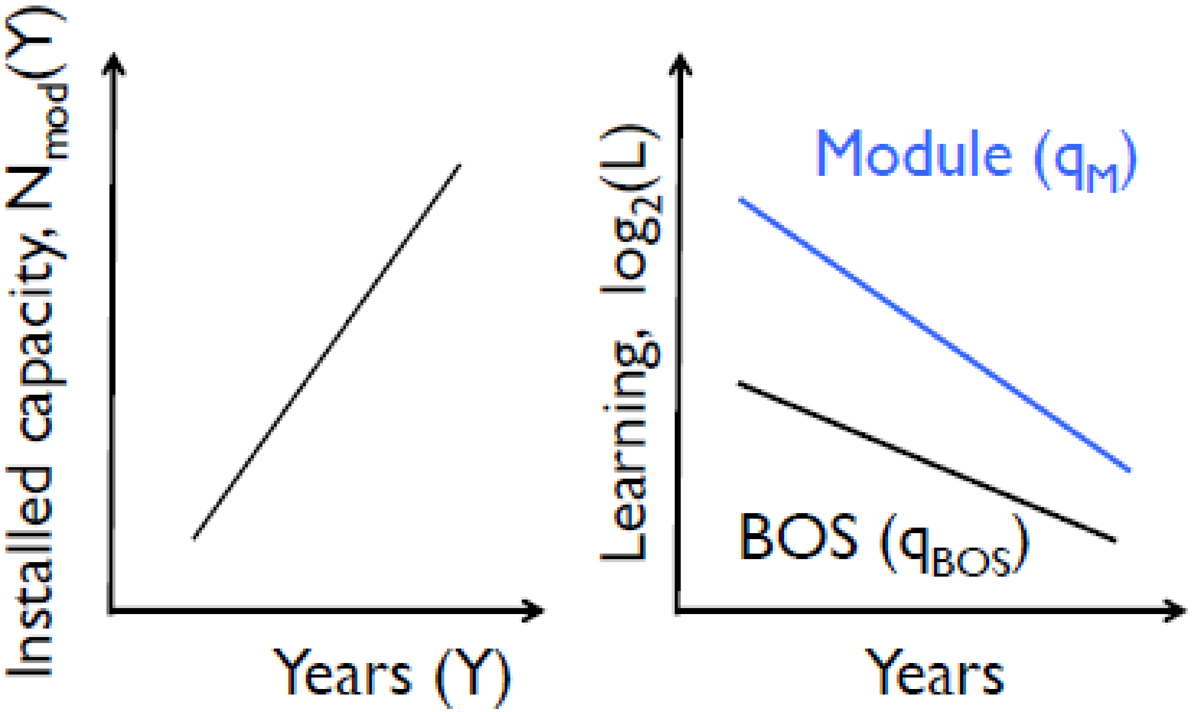
Costs at time t and 0
Production at time t and 0
b is the learning coefficient

Learning curves for each technology

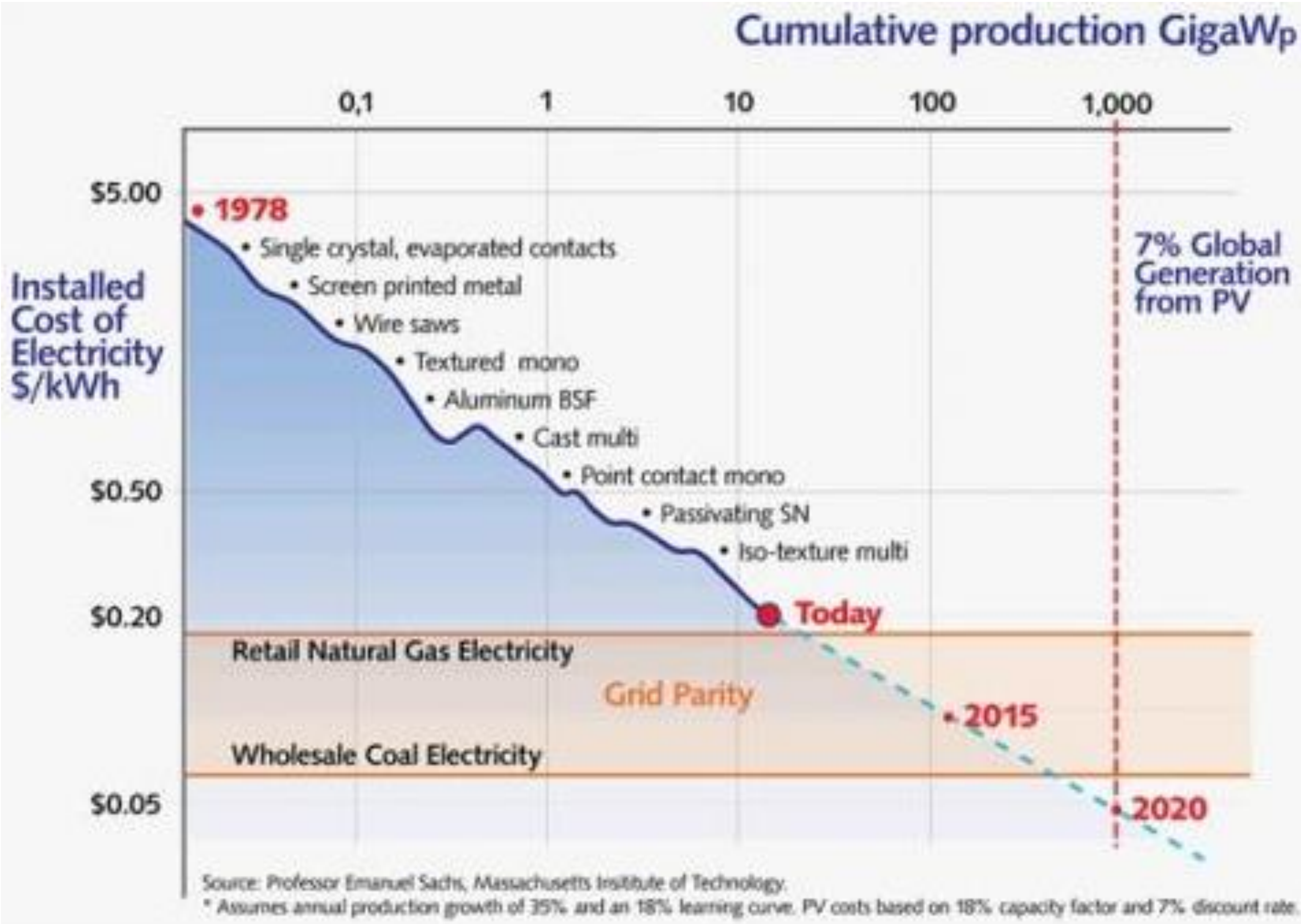
$$N_R \equiv \frac{N_{mod}(X)}{N_{mod}(0)} = 1 + f_0 \sum_{k=1}^{X} (1+g)^k$$

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

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



… will drop cost of energy produced

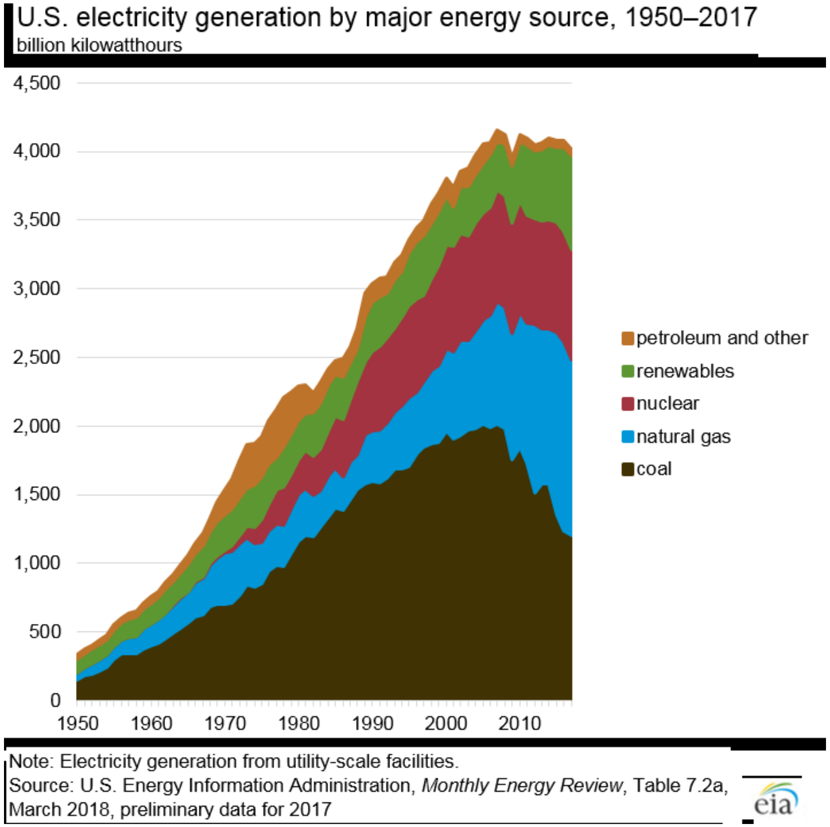


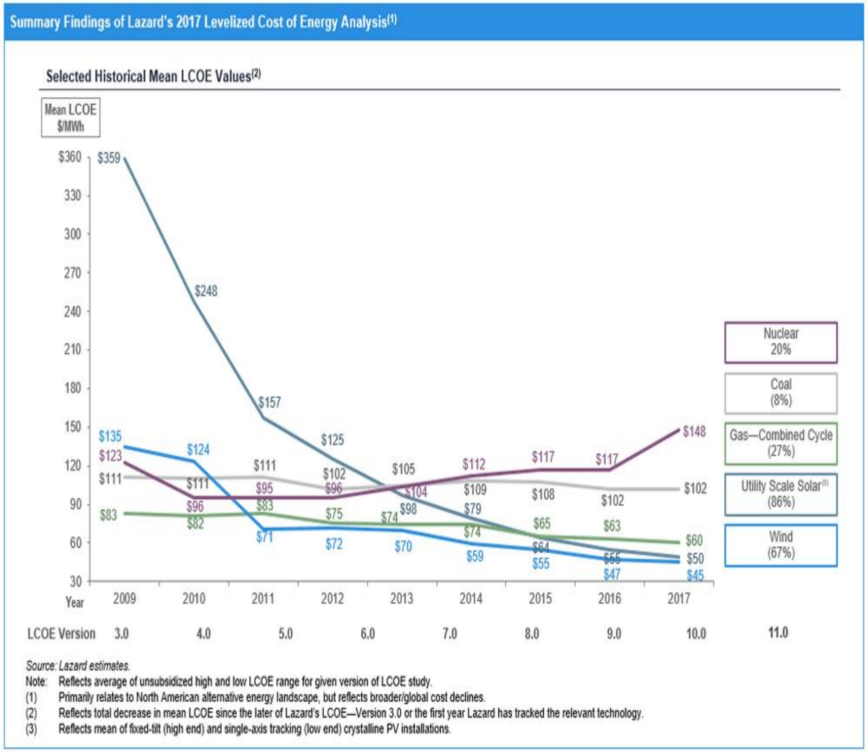
Acwa Power
5.84 cents!

Taqnia
5 cents!

LCOE compared

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





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?