Spatial, Temporal, and Technological Variation in the Value of Solar Power across the U.S.

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PV value (not just cost) declines with penetration

Azevedo, I.L. et al. 2017 (https://cedm.shinyapps.io/MarginalFactors/)

→ “Grid parity” is a moving target

- What is the value of solar today across the U.S.?
- What cost target is required for solar to stay competitive?
- How can PV system design be optimized for solar value?
Our approach: Nodal exploration of solar value

**Model variables:**
- Tracking strategy (fixed or 1-ax track) [1-ax track]
  - Max angle [60°]
  - Ground coverage ratio [0.33]
  - Backtracking [True]
- Axis tilt, azimuth [0°, 180°]
- DC/AC ratio [1.3]
- System losses [14%]
- Inverter losses [4%]
- AR coating index [1.3]
- Temperature coefficient [-0.4%/°C]
- Ground albedo [0.2]
- Diffuse sky model [Reindl]

**Revenue** = \( \sum_t (P_{AC}(t) \times \text{value}(t)) \) [\$/kW\textsubscript{AC}-yr]
Outline

1. PV model validation
   - Monthly (vs. EIA)
   - Hourly (vs. NREL PVDAQ)

2. PV value across U.S. markets
   - Energy (locational marginal price)
   - Capacity (resource adequacy)
   - Public health (SO$_2$, NO$_x$, PM$_{2.5}$) and climate (CO$_2$)

3. PV breakeven costs

4. Temporal shaping of PV output for energy value
Model validation: Monthly simulated output vs EIA 860/923

- **EIA Form 860:**
  - Plant latitude & longitude
  - Module technology (c-Si, CdTe, CIGS)
  - Tilt angle
  - Tracking
  - DC & AC capacity

- **EIA Form 923:**
  - Monthly generation

- **Hundreds of plants:**
  - 2014: 542 plants
  - 2015: 800 plants
  - 2016: 1170 plants
Monthly validation: Plant size

Lower bias in summer than winter

Lower bias for large (≥10 MW) plants

Better match for fixed-tilt than 1-axis tracking

Error rates comparable to NSRDB (rMBE ±5% for GHI, ±10% for DNI)

Model validation: Hourly simulated output vs. PVDAQ

1.14 MWac, 16.8° tilt
1.02 DC/AC ratio

NREL PVDAQ (https://developer.nrel.gov/docs/solar/pvdaq-v3/)

2016 measured and simulated output: Site 1332 (NREL Parking Garage)
Spatial & temporal variation in energy revenue

2016
1-axis track
Day-ahead
Market clearing prices for capacity by ISO capacity zone

\[ \times \]

Calculated PV capacity credit

- Net load = (ISO load) – (wind generation) – (simulated utility-scale PV generation)
- Capacity credit = CF during peak net load hours (top 7%) or ISO-defined hours

\[ = \]

Calculated PV historical capacity revenue
Marginal emissions data: Azevedo, I.L. et al. 2017 (https://cedm.shinyapps.io/MarginalFactors/)
EASIUR: Heo, J. et al. Atmospheric Environment 2016, 137, 80; (https://barney.ce.cmu.edu/~jinhyok/easiur/)

Air pollution damages
- Historical marginal emissions factors
- EASIUR model for monetized health impacts by eGRID region

$\text{CO}_2$ offset
- Multiply by chosen carbon price (subtract cap & trade clearing price if applicable)

- Marginal public health benefits from PV are declining as emissions-control measures are adopted, but are still substantial in 2017
- $\text{CO}_2$ offset has not changed substantially
PV breakeven cost with full value stack, 2017

NPV = \sum_{t=1}^{L} \frac{\left( R + C_{CO2} M_{CO2} \right) (1 - d)^t - C_{OM} \right) (1 - T) + \frac{D_t}{(1 + i)^t} C_{PV} T}{(1 + \rho)^t} - C_{PV}

NPV = net present value [$/kWac]
L = system lifetime [yr]
R = yearly revenue [$/kWac-yr]
C_{CO2} = CO_2 price [$/ton]
M_{CO2} = CO_2 offset [ton/kWac-yr]
d = degradation rate [%/yr]
C_{OM} = O&M cost [$/kWac-yr]
T = corporate tax rate [%]
D_t = 5-yr MACRS depreciation [%]
i = inflation rate [%]
\rho = weighted ave. cost of capital [%]
C_{PV} = upfront cost [$/kWac]

2017 data

2017 data

2017 data

2017 data
PV breakeven cost with full value stack, 2017

Observed NREL 2017

CAISO  ERCOT  MISO  Breakeven  PJM  NYISO  ISONE

Year

Percent of nodes [%]

PV system cost [$/Wac]

SunShot 2030 target

2017 data
Utility-scale PV is competitive in 2017 at today’s upfront cost…

- based on energy, capacity, and health benefits alone in ~60% of PJM, 50% of NYISO
Utility-scale PV is competitive in 2017 at today’s upfront cost...

- based on energy, capacity, and health benefits alone in ~60% of PJM, 50% of NYISO
- including a $50/ton-CO₂ price in 100% of ERCOT, MISO, PJM; ~60% of NYISO; 85% of ISONE
Utility-scale PV is competitive in 2017 at today’s upfront cost...

- based on energy, capacity, and health benefits alone in ~60% of PJM, 50% of NYISO
- including a $50/ton-CO₂ price in 100% of ERCOT, MISO, PJM; ~60% of NYISO; 85% of ISONE
- including a $100/ton-CO₂ price at 100% of nodes in all ISOs
Significant interannual variability (primarily driven by natural gas price variation)

Based on market revenues alone, median unsubsidized breakeven costs over 2010–2017 range from ~$0.70/Wac in MISO to ~$1/Wac in NYISO, CAISO

Long Island and parts of ERCOT and PJM demonstrate highest profitability
Optimizing for solar value: Orientation

Is the observed change in price profile in California enough to change the way a PV system should be designed and operated?
PV orientation: CF-optimized vs. Revenue-optimized

CAISO:STCKTNAR_6_N001 (Real-time, non-curtailable)

Capacity factor [%]

0° 15° 30° 45° 60° 75° 90°

(TMY) 24°

270° 240° 210° West

180° East

Revenue [$/kWac-yr]

0° 15° 30° 45° 60° 75° 90°

270° 240° 210° 180°

2010 PV capacity ~ 1.7% of peak demand

2017 PV capacity ~ 28% of peak demand
Optimal azimuth tending west in CAISO

CAISO system:

Azimuth°, CF-opt.

240
210
180
183° (TMY)

Azimuth°, revenue-opt.

235°
226°

Revenue ratio, revenue-opt. / CF-opt.

1.13
1.04

Revenue ratio, revenue-opt. / CF-opt.

1.20
1.05
Optimal azimuth tending west in CAISO

CAISO system:

Azimuth°, CF-opt.

Azimuth°, revenue-opt.

Revenue ratio, revenue-opt. / CF-opt.

Revenue ratio, revenue-opt. / CF-opt.

Effect is most pronounced in CAISO real-time market:

Revenue ratio, revenue-opt. / CF-opt. (curtailable)
1-axis tracking: Revenue benefit outweighs CF benefit in CAISO

CAISO system:

**Revenue benefit is ≤ CF benefit in other ISOs:**

- Revenue benefit from tracking is increasing with PV penetration in CAISO, beyond the CF benefit.
- With curtailment, CF benefit is erased but revenue benefit is increased.
Conclusions

- Spatial variation in the value of PV, even at transmission level, can be significant
  - LCOE and capacity factor give an incomplete picture

- Utility-scale PV breaks even on the basis of market, public health, and climate benefits at the majority of nodes at today’s cost
  - Cost declines have outrun value declines (so far)

- The optimal PV system design changes as solar penetration increases
  - Appropriate system design and siting choices can mitigate some of the decline in solar value


Brown, P.R.; O'Sullivan, F.M. “Shaping photovoltaic array output to align with changing wholesale electricity price profiles”. Applied Energy 2019, in press
Spatial & temporal variation in PV value factor

2016 1-axis track Day-ahead
Sensitivity: PV capacity factor

- Axis tilt [°]
- Axis azimuth [°]
- DC/AC ratio [·]
- System DC loss [%]
- Inverter AC loss [%]
- Temp. coef. [%/°C]
- Max tracker angle [°]
- GCR [·]
- Ground albedo [·]
- AR coating index [·]
PV breaks even at most nodes with a moderate carbon price

Energy + Capacity + CO₂ ($50/ton)