The Performance of U.S. Wind and Solar Generating Plants

Richard Schmalensee

EPRG/CEEPR International Conference

June 11, 2013

MIT CEEPR

Motivation

- Much talk about wind & solar focuses on “grid parity” – cost per kwh v. cost per kwh for fossil, nuclear – and deals with averages
  - But fossil & nukes generate when called; wind & solar generate when they want to:
  - Average **value** of wind & solar output may be different than average price;
  - **Variability** of wind & solar output may impose costs on the rest of the system, which geographic averaging may mitigate;
  - And location & weather matter, so may have great **diversity** in facility performance.
- No novelty above, but no(?) prior studies of these issues using actual, plant-specific U.S. generation and spot price data
  - Many facilities are unregulated, so fine-grained generation data are confidential
  - Many studies use wind speed or insolation data, infer output from engineering information – assumes away sources of variance (v. studies of fossil units)
  - To model integration costs, need a system model and assumptions about wind & solar operating characteristics – would be good to base on actual experience

Approach

- Basic approach: Use hourly price/output data to compute *summary statistics*, *compare* over time & space, and examine *patterns*
  - Descriptive **but with implications for subsidy policies**
- Want summary statistics to reflect value of wind & solar output, interesting dimensions of variability, performance diversity
  - Would welcome any suggestions for additional statistics, analysis…
- Request: *2x8760 hours of output & nodal spot price data including all of 2011 for geographically dispersed wind & solar PV units*
  - Need for prices limited focus to ISO/RTO regions – 2/3 of load, customers
  - Confidentiality issues eliminated solar in regions with few units, most information on location, capacity, etc. No information on vintages.
  - Worked with personal contacts, their contacts, etc.

ISO/RTO Coverage

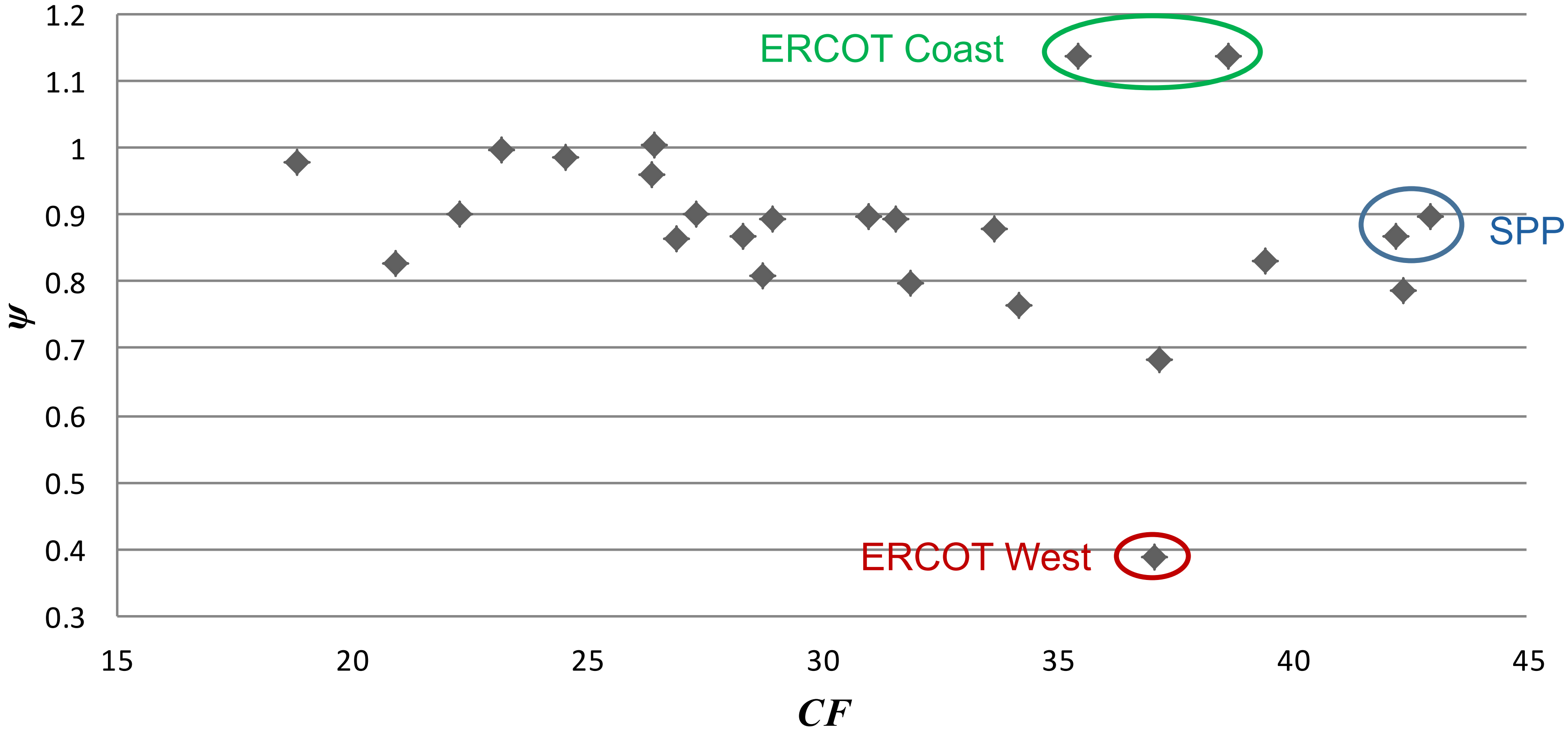
The Dataset

- 2x8760 = 17,520 hours [*except as noted below*] including all of 2011 of plant-specific P,Q data for:
  - ERCOT: 5 wind [*13,247 hours*], *3 western & 2 coastal*
  - ISONE: 3 wind, 3 solar [*one solar 13,128 hours*]
  - NYISO: 3 wind
  - MISO: 5 wind
  - PJM: 3 wind, 3 solar [two solar 15,864 hours]
  - SPP: 3 wind units
  - CAISO: 3 wind [16,797 hours], 3 solar [16,749 hours]
- Total: 25 wind units from all 7 ISOs, 9 solar units from 3
- Results more reliable for wind; solar statistics suggestive

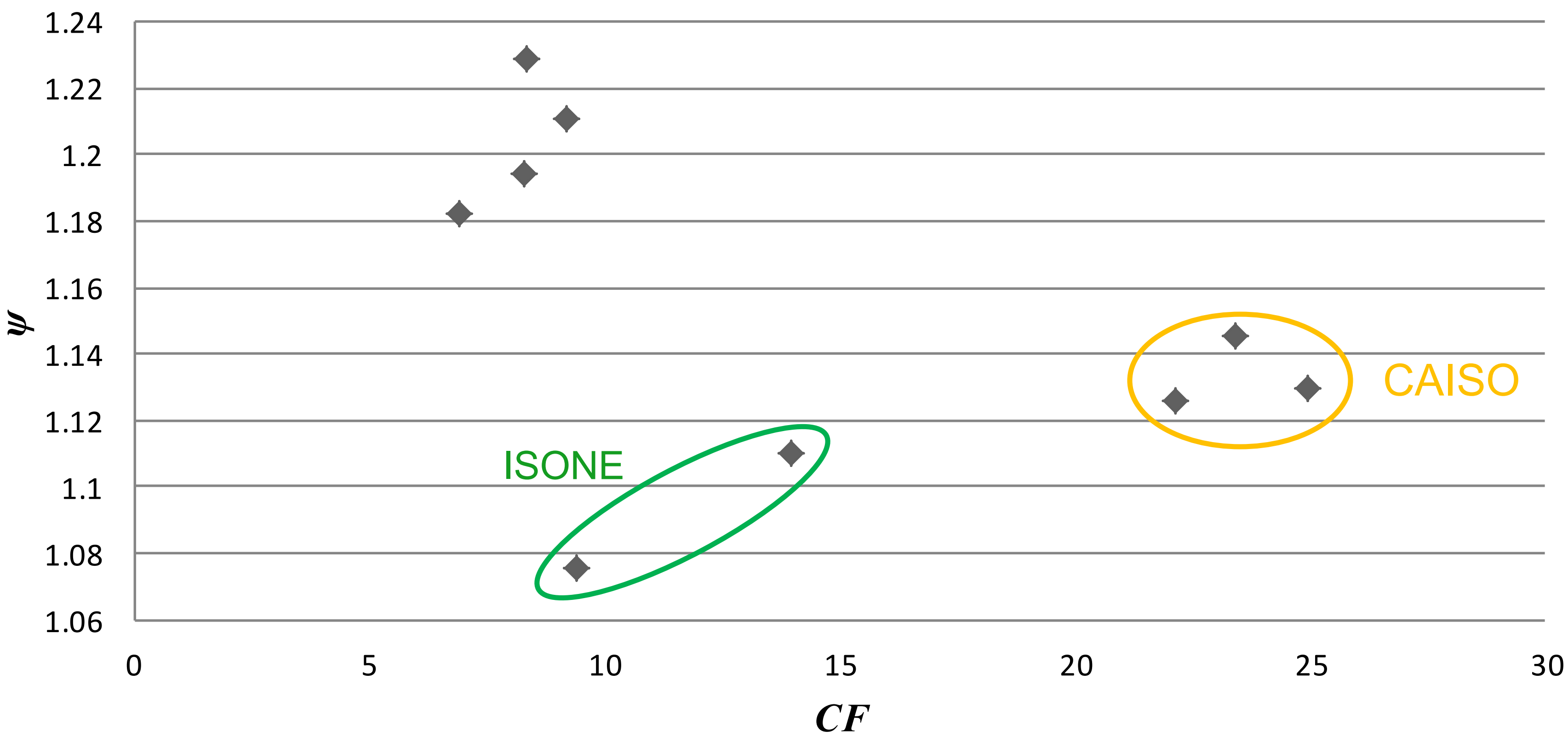
Output Quantity and Value

- **Quantity** – Capacity Factor is the usual figure of merit; approximate as CF ≡ average hourly Q (2011) divided by maximum observed Q:
  - Maximum Q is close to nameplate capacity for California facilities
  - σ/μ: $\Delta T = \sigma$ (early to late changes)/μ(2011); *will show only "large" σ/μ after this*
  - Wind: 0.19 (ISONE) – 0.43 (SPP), $\mu = 0.31$, σ/μ: 2011 = 0.22, $\Delta T = 0.13$
  - Solar: 0.07 (ISONE) – 0.25 (CAISO), $\mu = 0.14$, σ/μ: 2011 = 0.52, $\Delta T = 0.18$
- **Value** – Value Factor (Hirth (2013)), defined as ψ ≡ Q-weighted average spot price divided by unweighted average spot price (2011):
  - Wind: 0.39 (ERCOT) – 1.14 (ERCOT), $\mu = 0.88$, σ/μ: 2011 = 0.17, $\Delta T = 0.10$
  - Solar: 1.08 (ISONE) – 1.23 (CAISO), $\mu = 1.16$, σ/μ: 2011 = 0.04, $\Delta T = 0.07$
  - A solar kwh was worth 32% more on average than a wind kwh relative to average spot price – *but lots of variation, and distributions overlap*
- ψ*CF better than CF for site selection, but little difference here

Capacity Factors v. Value Factors: Wind



Capacity Factors v. Value Factors: Solar



Changes in ψ

- Would expect value factors to decline with increased (correlated) penetration – Hirth (2013)
- Have two years at most here; weather could mask this effect
- Decomposed changes to focus on price change impacts:

$$(10)\quad \psi(P^2,Q^2)-\psi(P^1,Q^1)=\frac{1}{2}\left\{\left[\psi(P^2,Q^2)-\psi(P^1,Q^2)\right]+\left[\psi(P^2,Q^1)-\psi(P^1,Q^1)\right]\right\}$$

$$+\frac{1}{2}\left\{\left[\psi(P^2,Q^2)-\psi(P^2,Q^1)\right]+\left[\psi(P^1,Q^2)-\psi(P^1,Q^1)\right]\right\}\equiv\Delta\psi_p+\Delta\psi_q.$$

- Adverse price changes seem to be visible…

	Wind Facilities		Solar Facilities	
	Number < 0	Mean Change	Number < 0	Mean Change
$\Delta\psi$	13/25	-0.022	3/9	0.030
$\Delta\psi_p$	14/25	-0.024	7/9	-0.019
$\Delta\psi_q$	0/25	0.002	2/9	0.050

Possible Correlates of ψ

- Night (10-6)/day generation (2011): > 1 for all but three wind plants (2 Coastal ERCOT): $\mu(2011) = 1.15$
  - Correlation with $\psi = -.73$
- Summer/other generation (2011), no correlation with ψ:
  - > 1 for only 4 wind plants (3 CAISO); $\mu = 0.81$, $\sigma/\mu(2011) = 0.51$
  - > 1 for all solar plants; $\mu = 1.68$, $\sigma/\mu(2011) = 0.61$
- Peak-price periods/other generation (2011): Using $\cong$ 100 hours with highest plant-specific prices, positive correlations with ψ:
  - > 1 for only 4 wind plants (2 Coastal ERCOT); $\mu = 0.73$
  - > 1 for all solar plants; $\mu = 1.58$, σ/μ: $\Delta T = 0.50$

Negative Spot Prices and ψ

- All but 2 (ISONE wind) facilities faced negative spot prices in 2011, for 18 (SPP) to 1542 (ERCOT West) hours
  - 12/34 facilities (all 6 CAISO, all 3 ERCOT West) faced negative spot prices for at least 500 hours
- Solar facilities saw fewer negative prices, partly because P < 0 was more likely at night (2x for wind plants, 2.5x for solar plants)
- Wind: Pr(generation when P<0), μ = 0.91, $\sigma/\mu(2011)$ = 0.55
  - Output when P<0/other times, >1 for 19/22, μ = 1.48
- Solar: Pr(generation when P<0 in the day) = 0.66, but >0.90 for all CAISO & >0.70 for all PJM
  - Output when P<0/other times, <0.6 for all, μ = 0.27 – helps explain higher solar ψ
- **Why sell at negative prices?** Wind ptc subsidies, state RPS regimes operate on a per-kwh basis, regardless of timing or value

Variability: Measures

- Can't measure impact, esp. of increased penetration, without a system model (ideally reflecting imperfect forecasting)
- Intuitively, two dimensions of variability matter:
  - Changes in generation, esp. at the ISO level, that require ramping – standard deviations divided by mean generation (but can't capture intra-hour solar variation)
  - Low levels or zero generation, esp. at the ISO level, that require backup or the equivalent
- Wind and solar require different measures:
  - Variability: need to restrict solar sample to avoid under-stating because of night-time constancy
  - Low/zero: zero at night for solar is predictable; zeros between positive hours are very rare

Variability: Changes in Generation

- Consider intra-ISO plant averages of four measures of variability:
  - V1: σ(change from prior hour)/μ(2011)
  - V2: σ(change from same hour in prior day)/μ(2011)
  - V3: σ(difference from mean of adjacent hours)/μ(2011)
  - V4: σ(difference from mean of same hours in adjacent days)/μ(2011)
  - V3 & V4 take out short-term trends for wind & solar and diurnal, seasonal trends for solar if sample is restricted to hours with positive generation

- If N plants were identical and statistically independent, at the ISO level these variability measures would decline as $1/N^{1/2}$
  - Rescale plant outputs by μ(2011) to take out effects of scale differences; add to get rescaled total output; compute Ri ≡ variability of rescaled total output using measure i/variability if plants were uncorrelated
  - Expect R > 1 for wind because all intra-ISO output correlations are positive; larger values imply smaller gains from geographic averaging

Variability: Changes in Generation II

- Differences among measures in means across ISOs:
  - Wind Vs: V2 = 1.14 > V4 = 0.96 > V1 = 0.32 > V3 = 0.20
  - Wind Rs: R3 = 1.07 < R1 = 1.12 < R4 = 1.32 < R2 = 1.35
  - Solar Vs: V4 = 0.57 > V3 = 0.24
  - Solar Rs: R3 = 1.25 < R4 = 1.30
  - Much plant-level variability, even for solar; more at the daily time-scale (2 & 4)
  - Considerable gain from aggregation; more at the hourly time-scale (1& 3)
- Extreme ISO means across measures:
  - Wind V's: NYISO, ISONE ≅ 0.76 > CAISO = 0.55
  - Wind R's: PJM =1.08 < ISONE =1.45
  - Solar V3 & V4: PJM = 0.52 > CAISO = 0.22
  - Solar R3 & R4: ISONE = 1.16 < PJM = 1.46
  - Moderate, comparable differences in wind Vs and Rs; ISONE has the short straw
  - Moderate differences in solar Rs; bigger differences in Vs; PJM has the short straw

Variability: Zero Wind Generation

- Every wind plant had ≥ 100 hours with zero generation in 2011; μ = 948 hours, 83% in spells of 3 or more hours
  - Plant averages within ISOs varied from 532 (ERCOT) to 1424 (ISONE)
- All ISOs but ERCOT had 16 (CAISO) to 178 (NYISO) hours with no wind generation from sample units in 2011
  - At least 76% of those hours were in the day for all ISOs
  - Except for CAISO (22%), at least 47% were in spells of 3 or more hours
- Looked for departures from independence of zero-output events:
  - Statistically significant (normal approx, exact test),
  - Substantial (all probability ratios > 4; 5/7 > 11)

Variability: Low Solar Generation

- Zero solar generation when generation is + in adjacent hours (same hours in adjacent days) is very rare: 0.3% (3.4%) of relevant hours
- Instead looked at **low** generation ≡ < half the mean of output in adjacent hours or in same hours in adjacent days
- Low generation relative to adjacent hours (cloudy hours?), rare:
  - Plant average = 133 hours in 2011; ISONE = 97 to PJM = 188
  - All plants low is even rarer; CAISO = 0 hours in 2011 to PJM = 14 hours
  - Independence rejected, probability ratios > 40, but too rare to get excited?
- Low v. same hours in adjacent days (cloudy days?), more common:
  - Plant average = 583 hours in 2011; CAISO = 349 to PJM 870
  - All plants low: CAISO = 18 hours in 2011 to PJM 473 hours
  - Independence rejected, probability ratios > 50, worth some worry?
- ISO-wide cloudy days more common than ISO-wide cloudy hours but probably easier to forecast…?

Concluding Observations

- A unique dataset has produced both new results & confirmations of prior literature, but all must be qualified by limitations of sample.
- **On average** a solar kwh was worth 32% more than a wind kwh in 2011, wind blows more at night & less in the summer, solar generates more than wind in peak-price periods… **But averages can mislead!**
- **Wide distributions** of capacity factors, value factors, measures of variability, etc. among plants & ISOs – *even within Texas* -- and wind & solar distributions often overlap.
- Increased wind & solar penetration may have reduced value factors of both, even within our short two-year sample period.

Concluding Observations II

- Considerable wind & solar **output variation**, especially day-to-day; considerable gains from aggregation despite positive correlations, especially hour-to-hour.
  - Moderate differences among ISOs on all dimensions
- **Zero wind generation** is common for plants, fairly common for ISOs; **low solar generation** is less common, seems mainly to reflect cloudy days, not cloudy hours; plant-level zero/low events not independent
- **Kwh-based subsidies give perverse (& effective) incentives to generate when spot price is negative; subsidies should be proportional to spot price (or system λ).**

Despite <u>profound</u> Excel fatigue, I welcome suggestions for further analysis of these data…