Intermittency and the Value of Renewable Energy

Gowrisankaran et.al. (2016), JPE

Enviromental Reading Group session 6

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Motivation and Research Question

- To quantify the economic value of large-scale solar PV, besides investment cost:
    - how solar correlates with demand.
    - predictability of solar generation.
    - cost of backup generation.
- Comparative statics: how does the cost vary under different policy environments.

Contribution

- Joskow and Tirole (2007): unexpected failure of conventional generators.
- This paper:
  - renewable intermittency
  - stochastic demand
  - quantification of renewable cost
  - **Endogenize investment decision**

Set-up

- Given
  - exogenous level of solar generation capacity and retail price.
  - joint distribution of demand and renewable output computed by weather forecast.
- Decision variables:
  - Long-term
    - capacity of new backup generators.
    - Demand curtailment price.
  - Short-term:
    - for each period (1-hour), energy and reserves quantity.
    - the quantity of curtailment
- Real-time, demand, renewable output, plants breakdown realized.

Demand

$$Q^D(p, \bar{D}) = \begin{cases} 0 & p > v \\ \bar{D}p^{-\eta} & p \leq v \end{cases} \tag{1}$$

- $\bar{D} \sim F^D(\cdot|\overrightarrow{w})$ is a scale of demand. VOLL $= \frac{\partial S/\partial d}{\partial D/\partial d}$.
- curtailment price p_c, payment $= p_c - \bar{p}$.

Supply

- J incumbent conventional generators, each is indexed by $j = 1, 2, \ldots J$:
  - capacity k_j
  - marginal cost c_j (reserve costs fraction of)
  - $m_j \in \{0, 1\}, on_j = 0 \Leftarrow m_j = 1$
  - probability of failure P_j^{fail}
- n^{FF} new conventional generators,
  - each has capacity k^{FF}
  - capacity cost FC^{FF}
  - marginal cost c^{FF}
- **Fixed** solar PV capacity n^{SL}:
  - capacity cost FC^{SL}/MW
  - state-contingent distribution $n^{SL}\bar{S}, \bar{S} \sim F^S(\cdot|\overrightarrow{w})$
  - fraction d^{SL} of total solar capacity is distributed, which lowers transmission

Operator's problem: short-term

$$W(\overrightarrow{w}, \overrightarrow{m} | n^{FF}, p_c) = \max_{\overrightarrow{on}, z} E[[1 - d^{\text{outage}} \text{outage}(\overrightarrow{on}, z, \overrightarrow{w})]$$

$$\times [\overline{D}\overline{p}^{-\eta}\text{VOLL} - \text{WLC}(z, p_c)]$$

$$- PC(\overline{D}\overline{p}^{-\eta} - z - n^{SL}\overline{S} + LL(\cdot), \overrightarrow{x}(\overrightarrow{on}))|\overrightarrow{w}, \overrightarrow{m}] \tag{6}$$

$$\text{such that } m_j = 1 \Rightarrow on_j = 0,$$

- which conventional generators to be dispatched $\overrightarrow{on}$.
- The amount of demand to be curtailed z.

Operator's problem: long-term I

$$V(n^{FF}) = \max_{p_c} E[H \cdot W(\overrightarrow{w}, \overrightarrow{m} | n^{FF}, p_c)], \tag{7}$$

- price for curtailment contract p_c.

Operator's problem: long-term II

$$V^* = \max_{n^{FF}} \left\{ \frac{1-\beta^T}{1-\beta} V(n^{FF}) - n^{SL} FC^{SL} - n^{FF} FC^{FF} - \text{TFC}(n^{SL}) \right\}. \quad (8)$$

- new conventional generators investment decision n^{FF}.

Data

May 2011-April 2012: 58 sites in Tucson, Arizona

- Cost and failure information.
- Day-ahead weather forecast data.
- hourly load.
- emission rates for CO_2, SO_2, NO_x.
- ancillary service auction price.

Parameters: demand

TABLE 1
DEMAND PARAMETERS

Parameter	Interpretation	Value	Source
η	Demand elasticity	.1	Espey and Espey (2004)
$\bar{p}$	Retail price per MWh	\$98.10	EIA
g	Demand growth factor	1.20	Based on historical rate of demand growth
VOLL	Value of lost load	\$8,000/MWh	Cramton and Lien (2000)
$F \equiv (F^D, F^S)$	Forecastable distribution of demand and solar output		Estimated

Parameters: supply I

TABLE 2
SUMMARY STATISTICS FOR TEP GENERATORS, 2011–12

Unit Type	Number of Units	Mean Size	Mean MC	Mean NO_x	Mean SO_2	Mean CO_2
Solar PV	2	6.5 (.5)	0 (0)	0 (0)	0 (0)	0 (0)
Coal	6	263 (133)	23 (10)	3.0 (1.7)	1.6 (1.3)	1.0 (.06)
Natural gas combined cycle	1	185 (0)	35 (0)	.09 (0)	.01 (0)	.4 (0)
Natural gas steam turbine	3	89 (13)	54 (0)	1.5 (0)	.03 (0)	.5 (0)
Natural gas turbine	6	39 (20)	71 (13)	3.5 (2.0)	.05 (.01)	.8 (.2)
Potential new natural gas combined cycle	. . .	191	32.60	.05	.01	.4
Potential new natural gas turbine	. . .	91	47.60	.31	.01	.5

Parameters: supply II

TABLE 3
REMAINING SUPPLY PARAMETERS

Parameter	Interpretation	Value	Source
d^{outage}	System outage hours times % of affected customers	.98	EIA
d^{SL}	Fraction of solar generation that is distributed	.3	Arizona Renewable Portfolio Standard
FC^{FF}	New combined cycle gas generator capital cost per MW	\$1,095,458	EIA
FC^{FF}	New gas turbine gas generator capital cost per MW	\$921,927	EIA
FC^{solar}	Solar capital cost per MW of DC	\$4,410,000	Baker et al. (2013), Barbose et al. (2013)
c^{r}	Ratio of MC for operating reserves to production MC	.41	Calculated from ERCOT data
α	Line loss constant	.000035	Calculated fromTEP Form 10K
AFC^{T}	Average transmission fixed cost per MW	\$1,259,000	Baughman and Bottaro (1976), Borenstein and Holland (2005), and TEP line loss cost
β	Discount factor	.94	
T	Lifetime of generators in years	25	

Parameter: failure and maintenance prob

TABLE 4
MEAN HOURLY MAINTENANCE AND FAILURE PROBABILITIES

	Failure Probability, P^{fail} (%)	Maintenance Probability, P^{maint} (%)	Mean Number of Units per Hour
Natural gas generator	.0492	.0382	342
	(.01)	(.008)	
Coal generator	.099	.047	859
	(.027)	(.010)	

Social costs of solar

TABLE 5
THE SOCIAL COSTS OF LARGE-SCALE SOLAR (Base Specification)

	Fraction of Generation from Solar			
	0%	10%	15%	20%
Forgone new gas generators (N)	0	2	2	3
Mean system outage probability	4.76e−5	5.82e−5	5.81e−5	8.4e−5
Reserves (as % of energy consumed)	30.5	32.1	33.6	35.2
Curtailment quantity (as % of total load)	.11	.19	.14	.24
Curtailment price p_c ($/MWh)	661	469	431	804
Production costs	437.20	380.00	355.20	332.20
Reserve costs	78.10	81.50	82.80	84.80
Gas generator investment costs	2,090	1,672	1,672	1,463
Solar capacity investment costs	0	4,148	6,221	8,295
Transmission fixed costs	331.40	319.40	317.40	316.20
Loss in $ surplus per MWh solar produced	. . .	126.70	133.70	138.40
Loss in $ surplus per ton CO_2 reduced	. . .	293.10	283.50	279.10

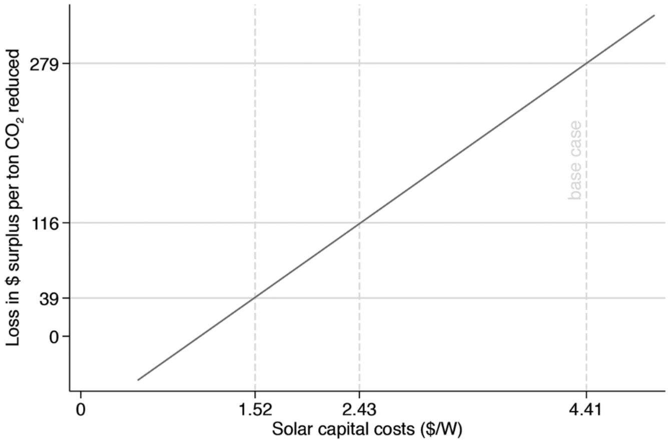
Social costs of solar: decomposition

TABLE 6
DECOMPOSITION OF SOCIAL COSTS OF 20 PERCENT SOLAR

Experiment	Loss in $ Surplus per MWh Solar	Number of New Gas Generators	Curtailment Price p_c ($/MWh)
Base case—feasible solar	138.40	7	804
No unforecastable intermittency	132.30	7	792
Fully dispatchable	92.40	1	300
Equal generation profile	133.80	7	783
Eliminate distributed generation: $d^{SL} = 0$	118.70	7	834
Fixed costs FC^{SL} drop from $4.41/W to $2/W	39.40	7	804
Same policies as without solar	281.60	10	661
Rule-of-thumb policy with 10% solar capacity credit	154.80	10	661
Rule-of-thumb policy with 12.5% solar capacity credit	153.20	9	661

Non-dispatchable, high capacity cost

Social costs of solar: welfare-neutral



Capital cost $= \$ \ 1.52/\text{W}$.

Robustness: policy environment

- curtail contracts
- imports/exports
- additional generator type
- different forecasts
- different VOLL

are all trivial.

Conclusion

- Re-optimization reduces the social cost of large-scale solar PV.
- With solar capital cost = \$4.41/W, social benefit of 20% renewable penetration is negative = -\$138.4.(not accounting for emission reduction.)
- Social welfare neturality when solar capital cost = \$1.51/W.
- Two main ways to increase value of solar energy: lower capital cost, better storage.

Reference

Gowrisankaran, G., Reynolds, S. S., & Samano, M. (2016). Intermittency and the value of renewable energy. Journal of Political Economy, 124(4), 1187-1234.