The Impacts of Renewable Energy on Electricity Markets: Emissions, Prices, Investment and Market Equilibrium

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Abstract

This paper studies how to design the electricity market to meet demand efficiently and reliably, while achieving environmental objectives.

I built a dynamic equilibrium model of production decisions across generators of different energy sources. Using data from the market in California, I estimate this model and use it to simulate production under counterfactual policies.

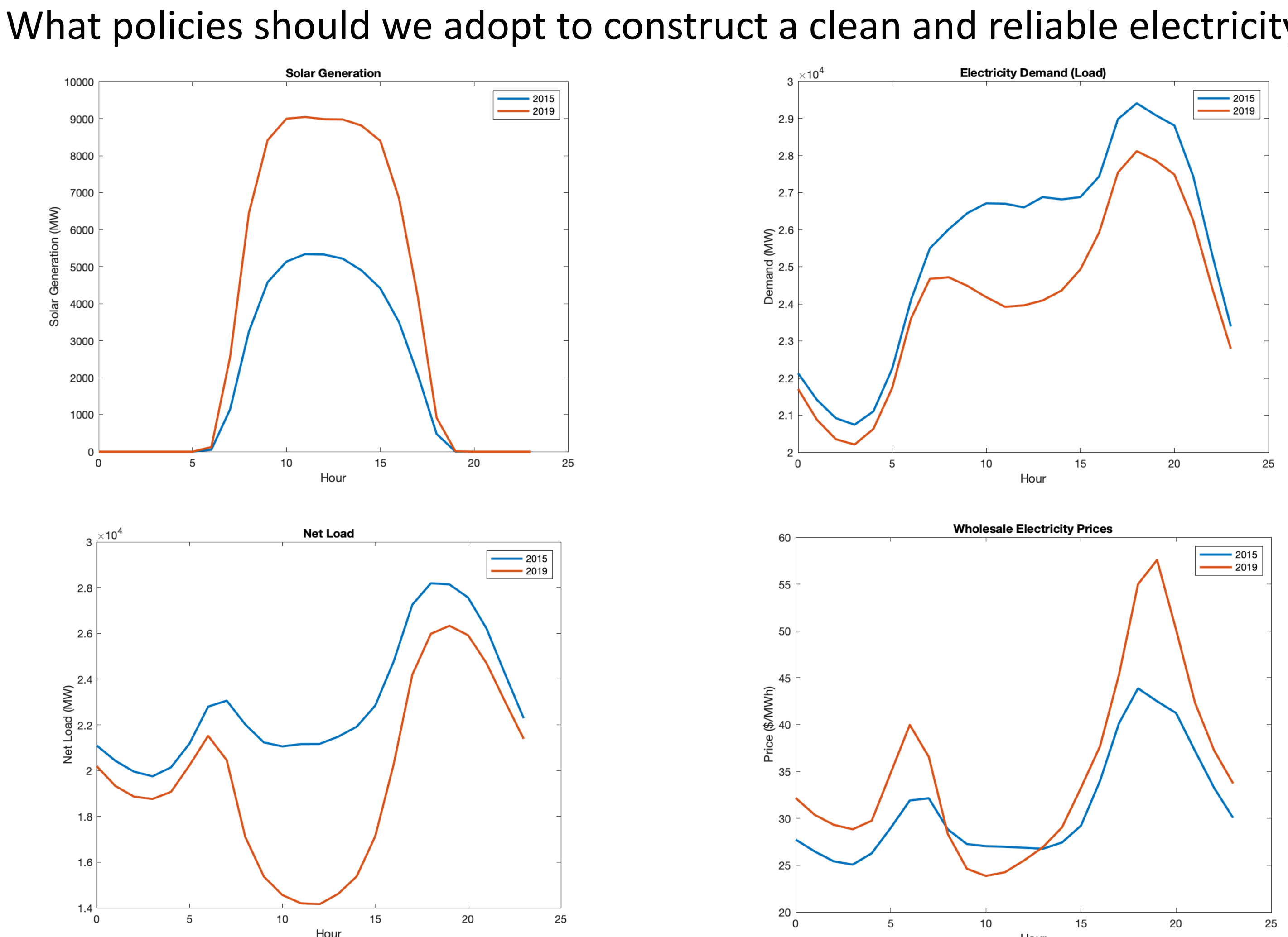
Both carbon taxes and Renewables Portfolio Standard (RPS) reduce emissions but, can result in higher market prices, and loss in profits of fossil fuel generators.

Subsidizing capacity can help lower the prices, but at the expense of higher emissions.

Combining both policies together, keeps reliable, emissions-intensive generators profitable in the market and prevents them from being used unless necessary.

Introduction

Zero-emission renewable energy sources, such as wind and solar, are intermittent. Grid operators are facing an increasing challenge to keep the electricity market in constant equilibrium.
1. How does renewable energy integration impact market prices, emissions, production decisions across generators of all sources, and profitability?
2. What policies should we adopt to construct a clean and reliable electricity grid?



Industry Background

Beginning in the 1990s, many US states decided to deregulate their electricity systems to create competition and lower costs:
Generation is owned by independent firms.
Transmission is owned by grid operator.
Distribution is owned by utility companies (independent retailers).

Wholesale Electricity Market: Regional transmission organizations (RTOs) act as grid operators, which run two energy markets - auction:
Day-ahead market (DAM): schedules which generators to operate for each hour of the next day and levels of output.
Real-time market (RTM): serves to settle any last minute adjustments due to demand shocks and unforeseen supply outages on day of delivery.

RTOs dispatch the lowest cost generators to meet demand:
In each time interval, generators submit bids to RTOs. RTOs take all bids in ascending order and stops with the last incremental bid needed to supply power.
The price in that time interval is based on the last bid accepted, known as a single clearing price market.

Retail Electricity Market (highly regulated market): utility companies (retailers) sell electricity to end-users.
The price is set by the government every year, which covers cost and a reasonable capital return.

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Data

Generator and Hourly Level Descriptive Statistics:

Capacity (MW)	148.84 (133.71)
Heat Rate (MMBtu/MWh)	10.12(5.27)
Gas Fuel Price ($/MMBtu)	3.52 (0.78)
Marginal Fuel Costs ($/MWh)	31.17(20.86)
Generation (MWh)	37.25 (82.77)
Generation at Peak Hours (MWh)	47.71 (88.18)
Generation at Low Demand Hours (MWh)	28.75 (69.43)
Share of Hours at Zero Generation	0.68%(0.31)
Electricity Price ($/MWh)	33.49 (22.50)
Net Load (GWh)	21.67(5.18)
Generators	230
num.obs.	over 10 million

Note: Peak hours are between 17:00pm-20:00pm.
Low demand hours are between 2:00am-4:00am and 9:00am-10:00am.

Model - Wholesale Market Operations

Hourly Level:
Demand is unresponsive to wholesale electricity prices.
Generators submit generator-level step function bids (US$/MWh).

Generators produce and sell electricity in a competitive market in every one-hour time interval to maximize the sum of expected discounted profits.
I model generator i, as solving an infinite-horizon dynamic problem.
Generators are price takers: sufficiently small capacity.
State variables: last period output, current market price and the expected future market prices, own private cost shocks.

The Bellman Equation for each generator i:

$$V_{it}(p_t, \tilde{q}_{it}, \epsilon_{it}) = \max_{q_{it}} \left\{ p_t q_{it} - c_{it}(\tilde{q}_{it}, q_{it}, \epsilon_{it}) + \beta \mathbf{E}\left[V_{it'}(p_{t'}, q_{it}, \epsilon_{it'}) | p_t, \tilde{q}_{it}, \epsilon_{it} \right] \right\},$$
$$s.t. \quad q_{it} \in \{0\} \cup [\underline{K}_i, \overline{K}_i] \qquad (1)$$

The variable cost function:

$$c_{it}(\tilde{q}_{it}, q_{it}, \epsilon_{it}) = \zeta_{1it} q_{it} + \zeta_{2k} \left(\frac{q_{it}}{\overline{K}_i} \right)^2 + \zeta_{3k} \mathbb{1}\{\tilde{q}_{it} = 0, q_{it} > 0\} \qquad (2)$$

where k is for each generator type, and ζ_{1it} is recovered using hourly heat input data.

Estimation

1. Estimate electricity demand distribution.
2. Estimate the distribution of generators' production costs.

Value Function Representation:
To facilitate computation, I solve for a finite approximation of the infinite horizon model: compute Value Function using backwards induction.

Three Types of generators in each hour:
1. Unconstrained generators 2. Constrained from above 3. Constrained from below

General Idea: 1. use FOCs to recover distribution of production costs, taking into account capacity constraints; 2. use shocks to bound shocks for constrained generators; 3. Use MLE.

Results and Conclusions

Based on current generator portfolios, generators incur an additional cost of $20 each time they initiate a startup, which is around 2 times more than the marginal generation cost.

Both Carbon taxes reduce emissions, but at the same time increases wholesale market prices and reduce profits of fossil fuel generators.

Regulatory mandate of electricity production from renewable energy sources of 52% will increase wholesale market prices by 5% and reduced emissions by 10%, compared to 2019 data.

References

1. Butters, R. A., Dorsey, J., & Gowrisankaran, G. (2021). Soaking up the sun: Battery investment, renewable energy, and market equilibrium (No. w29133). National Bureau of Economic Research.
2. Elliott, J. T. (2022). Investment, emissions, and reliability in electricity markets. Working Paper.
3. Gowrisankaran, G., Langer, A., & Zhang, W. (2022). Policy uncertainty in the market for coal electricity: The case of air toxics standards (No. w30297). National Bureau of Economic Research.
4. Mar Reguant. Complementary bidding mechanisms and startup costs in elec- tricity markets. The Review of Economic Studies, 81(4):1708–1742, 2014.