Production Network, Wind Penetration and Environmental Impact: The Case of Texas Wholesale Electricity Market

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Motivation

- Majorities of renewable subsidies do not consider the locations of newly entering renewable generators and existing fossil fuel generators.
- The profiles and production substitution patterns of neighbors matter for considering emission reductions of fossil fuel generators.
- The conventional wisdom of understanding the benefits of renewable generators on emissions reductions generally neglects the locational and interconnection effects as well as the changing network structure.

Research Question

- We aim to understand how newly entering renewable generators affect existing fossil fuel generators at the generator level after accounting for locations and connections along the transmission network;
- We aim to quantify the effect of growing renewable on emissions for each generator.

Data

We generator a generator-level hourly data from 2011 to 2018 by combining:

- ERCOT: the real-time net productions data and the hourly regional load demand data;
- Power System Simulator for Engineering (PSS/E): production network structure used by ERCOT for transmission planning. PSS/E fully captures electrical connectivity between generators and reflects unique features of the network;
- EPA's Continuous Emissions Monitoring System (CEMS): generator-level hourly emissions data;
- EIA-923: generators fuel cost data.

Conceptual Framework

Generator's profit maximization problem under Cournot competition:

$$\begin{aligned}\pi_{it} &= \max_{q_{it}} \mathbf{E}_{p_{-jt}}[p * g(q_{jt}|p_{-jt}, \mathcal{L}_t)q_{it} - C_i(q_{it})] \\ &= \max_{q_{it}} \mathbf{E}_{p_{-jt}}[(a_i + b_i(D_t^g + T_{it}^g) - \lambda_i)q_{it} - \theta_i \sum_{j\in N, j\neq i} g_{ij}q_{jt}q_{it}|q_{-jt}, \mathcal{L}_t] \\ &= \max_{q_{it}} \mathbf{E}_{\sigma_{-it}}\alpha_i q_{it} - \theta_i \sum_{j\in N, j\neq i} g_{ij}q_{jt}q_{it}|q_{-jt}, \mathcal{L}_t],\end{aligned} \tag{1}$$

where i is the objective generator, j is all other generators connected in the network, g is the constrained local market, D_t^g is the local demand, T_{it}^g is the electricity exported by i to other constraint market, λ_i is the marginal cost, $\mathcal{L}_t$ is the transmission constraint, and g_{ij} is the network matrix.

Empirical Strategy

We investigate the heterogeneous neighbourhood effects on the productions and emissions of existing generators. We adopt a generalized fixed effects model with generator specific slopes (FEIS) by [2]:

$$\begin{aligned} y_{i,t} = \alpha_i + \beta y_{i,t-1} + \delta_i^R y_{-i,t}^R + \delta_i^N y_{-i,t}^N + \delta_i^C y_{-i,t}^C + \delta_i^O y_{-i,t}^O \\ + \sum_b (\rho_{b,i} \cdot 1\{system - widedemand_t = b\}) + \theta \mathbf{X}_{i,t} + \epsilon_{i,t}\end{aligned} \tag{2}$$

- i represents generator $i, i \in \{1, 2, \cdots, N\}$ and t stands for hour $t, t \in \{1, 2, \cdots, T\}$;
- $y_{i,t}$ is the electricity production or emission of generator, including CO_2, SO_2, and NO_x;
- $y_{i,t-1}$ is the outcome variable with one period lagged;
- $y_{-i,t}$ is the weighted average of electricity output of all neighboring generator of generator i calculated based on the PSS/E matrix;
- generators are categorized into four groups, R renewable generators, N natural gas generators, C conventional generators, and O other generators;
- following [1]'s way of describing the relationship between system-wide demand and individual generation, we divide system-wide demand into bins based on 5 percentile, indexed by b. $\rho_{b,i}$ is the average generation for generator i when system demand is in bin b and generator's response to demand;
- $\mathbf{X}_{it}$ are the control variables such as fuel prices, weekend dummies, monthly dummies;
- α_i is generator fixed effects;
- δ_i^R are individual-specific slopes of our interest, which capture the neighbor effects for each generator from renewable neighbours.

Based on the estimates of Eq (2), we conduct counterfactual analysis by removing newly entering renewable neighbours from network, which enables us to estimate the resulting production patterns for a given demand/hour and environmental values of these newly entered renewable. Finally, based on the prediction of emission reduction, we investigate the influence of production network structures and location characteristics on emission abatement. The estimating equation is

$$\Delta\hat{E}_{i,t} = \alpha_i + \mathbf{S}_{i,t}\beta + \mathbf{L}_{i,t}\gamma + \theta\mathbf{X}_{i,t} + \varepsilon_{i,t} \tag{3}$$

- $\Delta\hat{E}_{i,t}$ is the predicted emission avoided;
- $\mathbf{S}_{i,t}$ is a vector of network characteristics such as betweenness centrality;
- $\mathbf{L}_{i,t}$ is location characteristics such as distance to neighbor generators

Some Results and Remarks

Our preliminary results suggest that neighbor effects play an important role in the electricity production. That is, a rising production of directly interconnected generators increases the production of the generator itself on average. We further investigate the heterogeneity of the neighbor effects for each generator. See the individual slopes of each generator below. This figure shows that: a rise production of the "synthetic" neighbor generally decreases the production of fossil fuel generators but increases the production of renewable generators, meaning that newly entering renewable generators substitute the existing fossil fule generators but supplement the existing renewable generators. In the future, we will further estimate Eq (3).

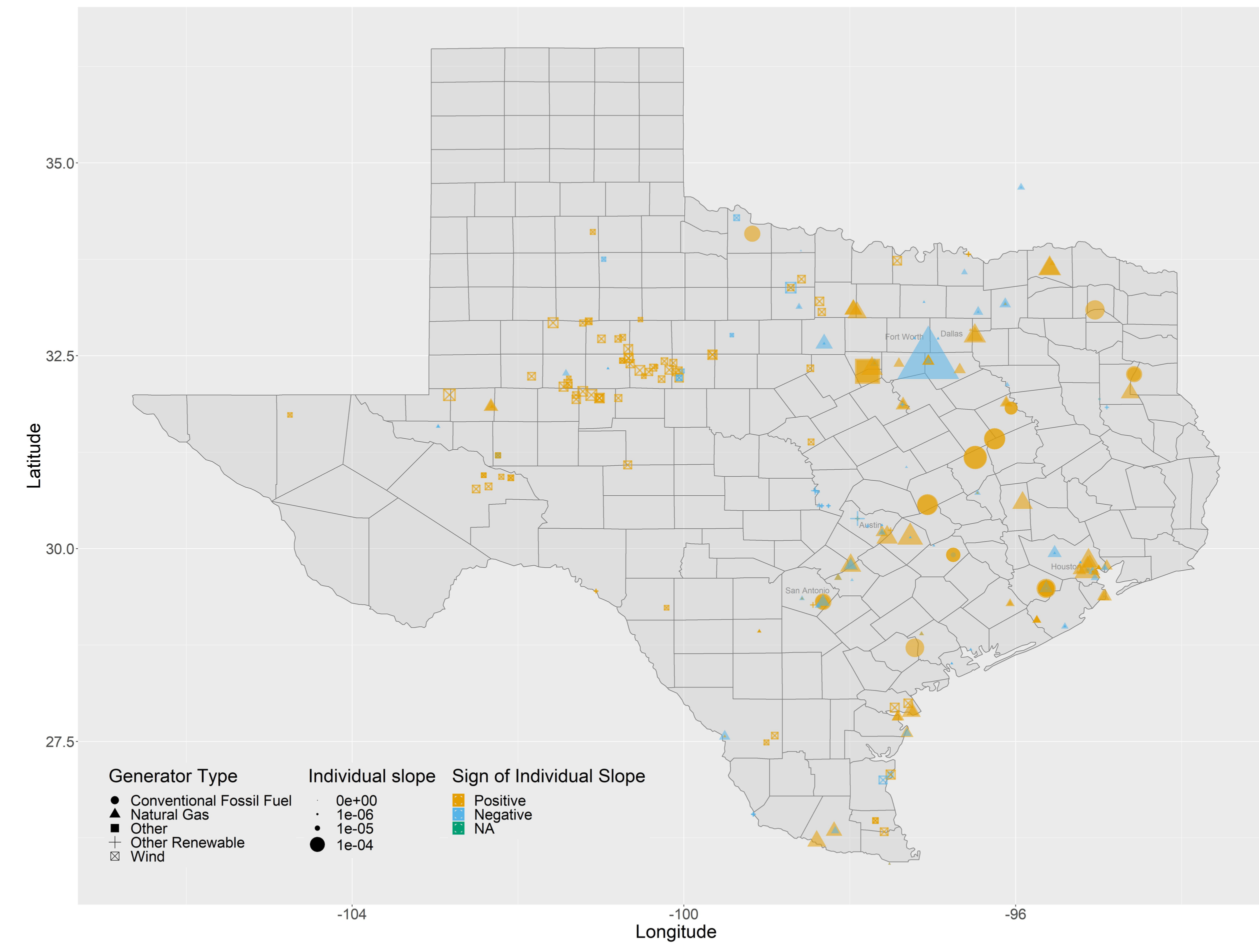

Fig. 1: Individual Slope 2014

Discussion

This project contributes to three topics:

- how renewable have affected existing generators and emissions, with a focus on generator-level effects and network structure;
- how renewable crowding into a cluster of locations increase burden of transmission network;
- neighbor effects in energy economics by considering the neighbor effect as a determinant for production and emission at the generator level

References

[1] Lucas Davis and Catherine Hausman. "Market impacts of a nuclear power plant closure". In: *American Economic Journal: Applied Economics* 8.2 (2016), pp. 92–122.

[2] Tobias Rüttenauer and Volker Ludwig. "Fixed effects individual slopes: Accounting and testing for heterogeneous effects in panel data or other multilevel models". In: *Sociological Methods & Research* (2020), p. 0049124120926211.