An Empirical Analysis of the Interconnection Queue

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August 2024

Decarbonizing electricity production is central to climate policy

Electricity production accounts for over 25% of both U.S. and global CO_2 emissions

Widespread policy goal: decarbonize electricity production + electrify transportation

Will require massive investment in wind and solar powered electricity generators

These new generators will have to connect to the grid

New generators must complete an interconnection process before starting operation

Steps:

1. Join a waitlist called the interconnection queue
2. Have studies done to identify whether the new generator will overload the grid
   - If so, what new equipment is necessary to resolve the overload? what is its cost?
     - e.g., rebuild a transmission line for $5 million
   - **Connecting generators must pay** for necessary grid upgrades
3. Pay the interconnection cost and connect to the grid

Roughly, **first-come, first-served**: priority for studies based on queue entry date

Grid connection is a major bottleneck

The interconnection process is slow and costly

- Usually takes several years from entering the queue to beginning operation
- Costs can be comparable to construction costs

Especially problematic for renewable energy

- 85% that enter queues never begin operation, compared to 68% for fossil fuel
- Recent survey: interconnection the single largest barrier to solar development

FERC and individual grid operators are in the process of making reforms

- FERC Order 2023

This paper

1. Use new data to describe the queue
   - The necessary studies are often delayed
   - Interconnection costs can be high, are hard to predict, and lead to withdrawals
2. Quantify the externalities in the queue
   - Find a sizable **congestion externality**
3. Develop a dynamic model of the queue and use it to simulate reforms
   - Approximate the optimal mechanism
   - Increasing fees to enter and stay in the queue

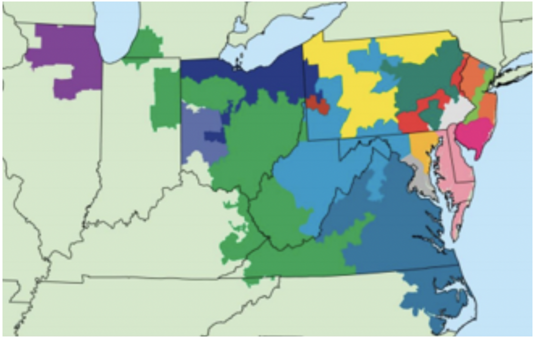
We study the PJM interconnection process

PJM is the largest regional grid operator

Similar process to many U.S. regional grid operators

Queue dominated by solar, wind, and natural gas

Unconcentrated: 100s of firms, none with a large share of generators



It is inexpensive to enter the queue

Generators can enter the queue twice a year

- Those that enter at the same time form a cohort; priority is by cohort

To enter, must demonstrate site control, pay a small fee for first study

- Inexpensive to enter and we see lots of entry

Up to 3 engineering studies are done sequentially

- Each study provides a cost estimate; generators update expectations

Subsequent studies also require small fees, generators can leave at any time

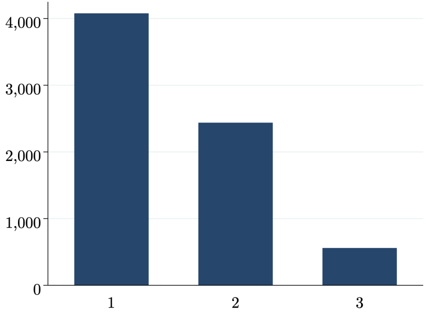
We collect data from pdfs of these studies

We've collected data for all requests from 2008-2020

- costs, tests, study issue dates

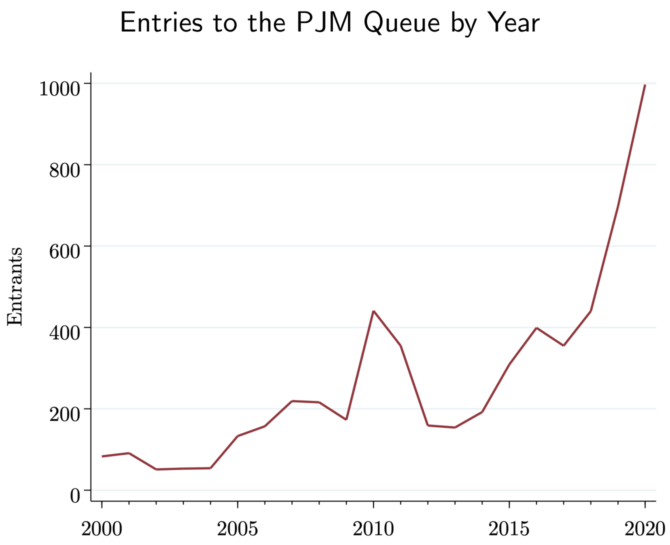
For all requests from 1997-2022:

- queue date, in-service and withdrawal dates
- location, generator type, size



N for each study

PJM has seen a dramatic increase in requests



Complaint 1: The necessary studies are often delayed

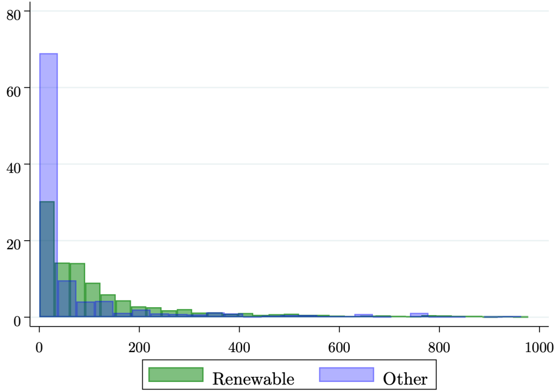
Study	Official	Median	90^{th} percentile
1	3	4	9
2	4	7	30
3	6	16	35

Times in months to final version of study.

- Delays can be costly: options to lease expire, power sales negotiations break down

Complaint 2: Interconnection costs can be very high

Study 2 interconnection cost estimates $ per kW



- Median cost estimate is $50/kW, 90$^{\text{th}}$ percentile is $400/kW
  - Installation costs for wind and solar $\approx$ $1,500/kW

High interconnection costs lead to withdrawals

Effect of high Study 2 cost on withdrawal

High cost (>\$100/kW)	0.22***	0.22***	0.22***
	(0.03)	(0.03)	(0.06)
Permitting controls		X	
Cost Difference IV			X

Dep. variable indicates withdrawing before Study 3

At the mean: a high interconnection cost $\Rightarrow$ 49% increase in probability of withdrawal

Specifications in columns (2) and (3) address

- Permitting: Control for distance to grid; ordinance restricting renew. development
- Selection: Instrument with the cost difference between studies

There are three potential externalities

1. Congestion externality: Another generator in the queue slows down study delivery for other generators
2. Cost externality: A costly interconnection lowers costs for next generator in the same location
3. Output-market externality: Another generator starting operation reduces electricity prices and thus profits

We focus on the congestion externality in this paper

1. Congestion externality: Another generator in the queue slows down study delivery for other generators

   $\Rightarrow$ Empirical evidence that this externality is the most important

2. Cost externality: A costly interconnection lowers costs for next generator in the same location

3. Output-market externality: Another generator starting operation reduces electricity prices and thus profits

We find a significant congestion externality

Estimate a flexible probit model of study delivery

- Assume delivery is random conditional on queue position, controls for complexity

Congestion slows down the delivery of 3rd study

- 10% increase in generators ahead reduces 3rd study arrival prob. by 5%

Model Features

We next develop a dynamic model of the queue. Its key features are

- Non-stationary
- Finite Horizon
- A continuum of heterogeneous generators
  - Akin to non-stationary oblivious equilibrium
  - Queue status has deterministic transitions
  - Generators still face uncertainty about their own shocks
- Rich observed heterogeneity

Generators solve an optimal stopping problem

We focus on the waiting decision after receiving the first study

Model

A discrete time, finite horizon problem

- $(\tau, \tilde{\tau}, t)$: time in the queue, time since last study, calendar time
- c: cost from most recent study
- x: generator characteristics
- z: content from past studies, e.g., which tests were conducted

Timing within a Period t

1. Wait or withdraw
2. New studies issued
3. Potential generators decide whether to enter the queue

New period starts

Bellman equations give the value of waiting

Let $r \equiv r(c'; c, z, \tau, \tilde{\tau}, t, x)$ be the probability a study arrives with cost c'

The expected value of waiting for the third and final study:

$$W(c, z, \tau, \tilde{\tau}, t, x) = \mathbb{E}\Bigg[\max\{\underbrace{\xi_t}_{\text{outside option}}, \sum_{c'} r \cdot \Pi(c', t, x)$$

$$+ (1 - \sum_{c'} r) \cdot W(c, z, \tau + 1, \tilde{\tau} + 1, t + 1, x) - \underbrace{o(\tau, \tilde{\tau}, x)}_{\text{waiting cost}}\}\Bigg]$$

where:

Π is the value of receiving the final study

$$\Pi(t, \tau, x, c) = \max\left\{\pi(t, \tau, x) - c + \epsilon_t, \xi_t\right\}$$

The Bellman equation for waiting for the second study is similar

Queueing Equilibrium

Equilibrium objects: for $t = 1, \ldots, T$

1. Withdrawal and entry probabilities
2. Beliefs
3. Queue size N_t
4. Queue composition m_t based on current costs, study contents, time, and generator characteristics

Equilibrium conditions:

- Optimality condition
- Consistent beliefs
- Balance conditions

Identification and Estimation

Identification:

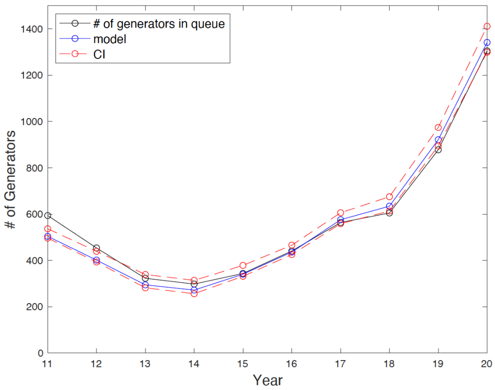
- Profit function: Last period decision, variation in final interconnection cost
- Waiting cost: Withdrawal decisions, variation in current interconnection costs
- Entry cost: Free entry assumption

We use MLE to estimate the model

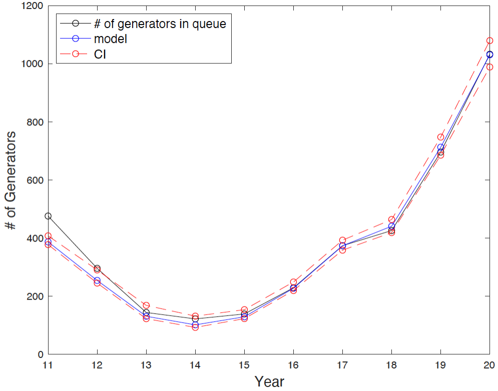
1. Estimate study arrival process (beliefs)
2. Solve optimal waiting problem via backward induction

The model fits the data

Number of Generators Waiting in the Queue



All generators



Renewables

We simulate counterfactual effects on in-service capacity

Quantifying the congestion externality:

1. Decreasing wait times: Increasing the rate at which PJM processes studies
2. Alternative queuing mechanism: Change priority to maximize completion
    - Provides a benchmark for policy counterfactuals

Policy-relevant counterfactuals:

3. Adding Fees: Entry fees and study fees; flat and per MW fees

Key outcome: new capacity in service relative to the status quo

We first quantify the effects of faster studies

- We simulate increases in the arrival probability of the 2$^{\text{nd}}$ and 3$^{\text{rd}}$ studies
- Find faster delivery leads to large increases in in-service capacity

	Added Capacity (GW)	
Speed up (%)	Total	Renewable
5	2.1	0.8
10	4.0	1.6
20	7.4	2.8

Status quo: 71 GW total, 32 GW renewable

An alternative queuing mechanism that changes priority

Fixing PJM's processing capacity, we consider an alternative to first-come, first-served

Why might it help?

- Suppose a generator at the back of the queue is likely to complete if given a study
- De-prioritize generators ahead to fast track it

Implementation

- Exclude some generators from the study process to effectively get a smaller queue
- Choose which generators to exclude to **maximize total capacity in-service**

Selectively prioritizing larger generators can increase capacity

If we value renewable and non-renewable capacity equally:

- Total capacity increases by 8 GW (11%); renewable capacity by 1.5 GW (5%)
- Smaller generators are more likely to be screened out

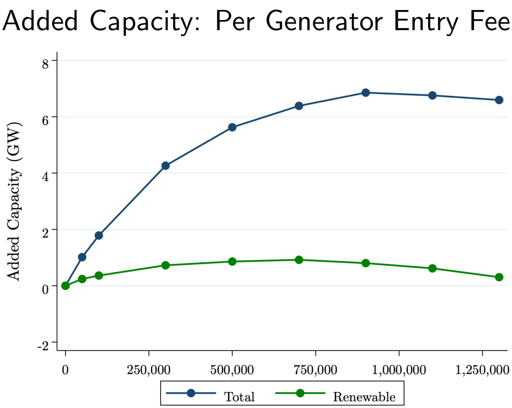
Percentage of generators removed by category

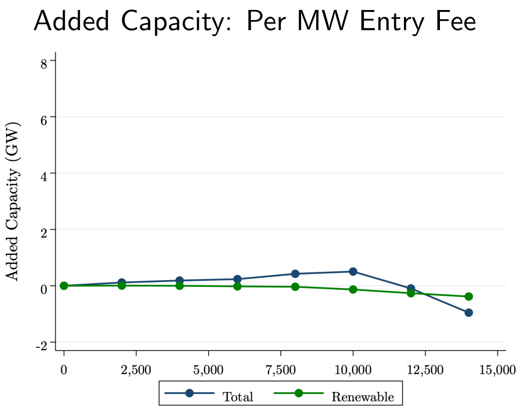
	Small	Medium	Large
Size (MW)	$<$20	20-100	$>$100
Renewable	72	52	2
Non-renewable	56	57	0

If we value renewable capacity three times as much as non-renewable capacity:

- Total capacity increases by 4.1 GW; renewable capacity by 2.7 GW

Increasing fees can increase capacity, with flat entry fee most effective





- At $900,000 fee to enter adds 6.85 GW total capacity, 0.8 GW renewable capacity
- A per MW entry fee can slightly increase capacity, but not for renewables
- Increased fees for later studies are less effective

Conclusion

- Interconnection costs can be very high, are a key factor in withdrawal decisions
- More higher-queued generators $\Rightarrow$ a generator receives its final study more slowly
- There are large gains from speeding up the queue
  - Policy reforms that increase cost to enter the queue partially realize these gains
- Large climate benefits from reforms that increase renewable capacity

Thank you!