Power Flows: Transmission Lines, Allocative Efficiency, and Corporate Profits

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Motivation

- Market integration lowers aggregate production costs and brings gains from trade.
- Grid integration critical to decarbonization
- Renewable sources often located far from demand centers, power is often dumped
- Wholesale electricity prices often low in renewable-rich regions while high in other regions, $\downarrow$ incentives for renewable investment

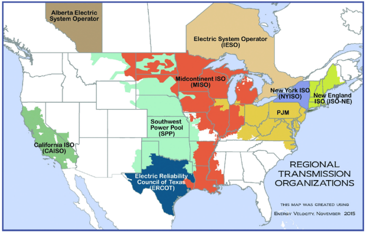
Question

1. **What is the magnitude of allocative ineffeciencies from transmission congestion in Midcontinent Independent System Operator (MISO) and Southwestern Power Pool (SPP)?**

2. **What are the firm-level gains and losses from market integration?**

Background

- Midcontinent Independent System Operator (MISO) and Southwestern Power Pool (SPP) are non-profit entities responsible for matching supply and demand and ensuring grid reliability within their footprint.



Data

- U.S. Environmental Protection Agency's CEMS provides hourly generation and fuel use, fuel type, location
- From this, calculate a heat rate, measure of how efficient a plant is at converting fuel to electricity
- Calculate each unit's capacity as the 99th percentile of observed generation.
- Energy Information Administration (EIA) provides fuel price data

Allocative Inefficiencies

Marginal Cost Curves

$$mc_{i,t} = fp_t \cdot hr_i + om_i + ec_{i,t} \tag{1}$$

where,

$$\begin{aligned} fp &= \text{fuel price in each hour (\$ per mmBTU)} \\ hr &= \text{heat rate of each unit (mmBTU per MWh)} \\ om &= \text{unit's variable operating and maintenance cost (\$ per MWh)} \\ ec &= \text{environmental compliance cost (\$ per MWh)} \end{aligned}$$

Allocative Inefficiencies cont'd

Least-cost Dispatch

$$\min_{g_{i,t}} \left(\sum_{i \in (1,2,\ldots,I)} mc_{i,t} g_{i,t} \right) \quad s.t. \quad \sum_{i \in (1,2,\ldots,I)} g_{i,t} = demand_t; \qquad (2)$$
$$g_{i,t} \leq C_{i,t} \quad \forall i;$$

where,

$g_{i,t}$ = generation for unit i for each hour t

$C_{i,t}$ = capacity constraint at each unit

$demand_t$ = total quantity generated in the real world in hour t across all generators

1. Rank units by marginal cost
2. Dispatch units until demand is met

Allocative Inefficiencies cont'd

Modeling Transmission Constraints

$$\min_{g_{i,t}} \left(\sum_{i \in (1,2,\ldots,I)} mc_{i,t} g_{i,t} \right) \quad s.t. \quad \sum_{i \in (1,2,\ldots,I)} g_{i,t} = obs\_gen_{r,t} \quad \forall r \in R; \qquad g_{i,t} \leq C_{i,t} \quad \forall i; \tag{3}$$

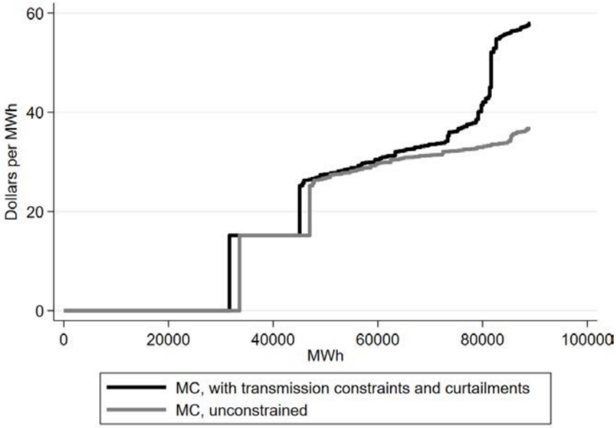
where,

$$obs\_gen = \sum_{i \in (1,2,\ldots,I_r)} g_{i,t}^{observed}$$

- Each subregion can generate no more than what was actually generated in the real world.
- Total generation constraint must be met *within* region

Marginal Cost Curves

Figure 1: Example Marginal Cost Curves, With and Without Transmission Constraints and Wind Curtailments



Calculating Allocative Inefficiencies

- Calculate the area between the two curves in each hour and construct time series of allocative inefficiencies
- For each hour t calculate $\sum_i mc_{i,t} g^{\dagger}_{i,t} - \sum_i mc_{i,t} g^{*}_{i,t}$ where $g^{\dagger}_{i,t}$ are equilibrium quantities from equation (3) and $g^{*}_{i,t}$ from equation (2)

Figure 2: Additional Generation Costs From Transmission Constraints and Wind Curtailments

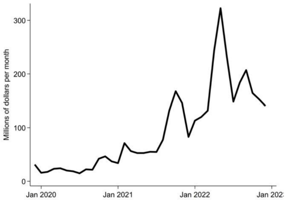


Table 1: Annual Allocative Inefficiencies

Annual cost, billion dollars	2016-2020	2021	2022
Total	0.32 to 0.43	0.98	2.16
Across-ISO constraints	0.03	0.10	0.21
Within-ISO constraints	0.25	0.57	1.31
Curtailments	0.03 to 0.14	0.31	0.64
Within-SPP constraints	0.08	0.12	0.19
Within-MISO constraints	0.18	0.45	1.12

Drivers of Allocative Inefficiencies

$$\ln c_t = \beta_1 \ln d_t + \beta_2 \ln w_t + \beta_3 \ln n_t + \beta_4 \ln o_t + X_t \Theta + \epsilon_t \quad (4)$$

$c_t =$ hourly inefficiency i.e. additional costs

$d_t =$ total demand

$w_t =$ potential wind generation

$n_t =$ natural gas price

$0_t =$ oil price

$X =$ controls for weather and time effects

	(1)	(2)
Demand	2.13***	2.13***
	(0.11)	(0.10)
Natural gas price	1.26***	1.28***
	(0.10)	(0.09)
Oil price	0.02	0.09
	(0.16)	(0.10)
Wind generation + curtailments	0.17***	
	(0.02)	
Wind generation		-0.16***
		(0.01)
Wind curtailments		0.27***
		(0.01)
Observations	61,242	61,008
R^2	0.73	0.80

Note: The unit of observation is an hour. The dependent variable is the log of the hourly allocative inefficiency induced by transmission congestion. The independent variables of interest are total demand, total wind potential (generation plus curtailments), and fuel prices. Additional controls are heating and cooling degree days and time effects (month of sample, day of week, hour of day). Standard errors are clustered by sample month and by sample week.

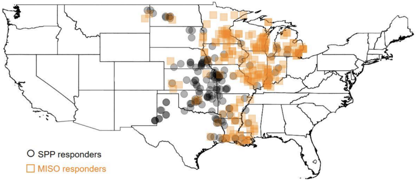
Source of Transmission Constraints

- To which load is generator dispatch most likely to respond?
- Assume demand shocks are exogenous
- Run separate regressions for each power plant,

$$g_{i,t} = \beta_1 d_{SPP,t} + \beta_2 d_{MISO,t} + \beta_3 d_{EI,t} + X_t \Theta + \epsilon_{i,t} \quad (5)$$

- If the grid were unconstrained, generators would be expected to respond equally to a demand shcok regardless of region.

Figure 3: Power Plants Are Dispatched For Own-ISO Load

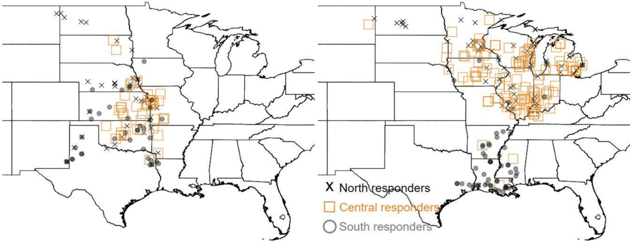


Within-ISO Constraints

- Extend those horse-race regressions
- For a SPP-located unit, for example, the regression is:

$$g_{i,t} = \beta_1 d_{NorthSPP,t} + \beta_2 d_{CentralSPP,t} + \beta_3 d_{SouthSPP,t} + \beta_4 d_{MISO,t} + \beta_3 d_{EI,t} + X_t\Theta + \epsilon_{i,t} \quad (6)$$

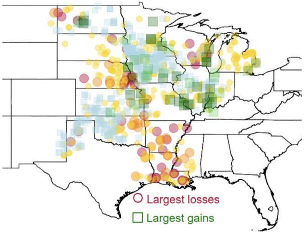
Figure 4: Some Power Plants Are Dispatched More For Own-Region Load



Barriers - Winners and Losers

- Producers in constrained regions stand to lose if constraints are alleviated
- For example, MISO-South, has no wind generation. For every 1 GWh of additional wind, net revenues as fossil and nuclear plants combined drop $1,200
- However, had that market been integrated, that same increase would imply a drop in hourly net revenues of $4,800
- The four firms that stand to lose the most collectively would have experienced a combined drop in net revenues of **$1.6 billion** in 2022 alone

Figure 5: Power Plants That Gain Versus Lose Are Located in Different Regions



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Conclusion

- Allocative inefficiencies in U.S. electricity markets stemming from congestion limits the ability of low-cost generators to participate
- Allocative ineficiencies rose sharply 2020-2022 in part from wind generation and curtailments that have resulted from transmission lines not keeping pace
- As new wind enters, the incentive for some fossil incumbents to block new transmission rises $\uparrow$