Strategic Entry on the Electric Grid

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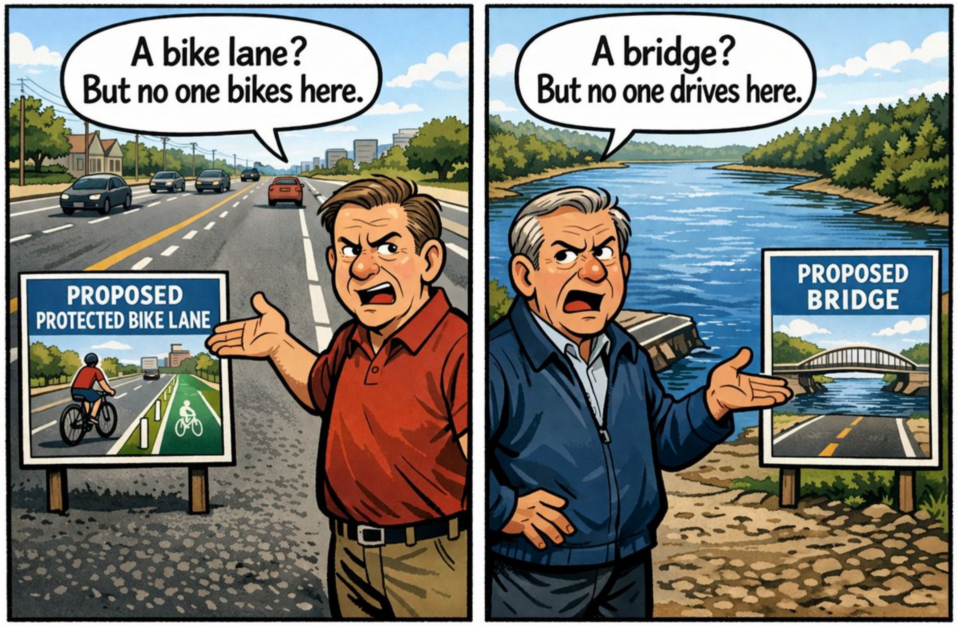


Options:

1. Build | enough accidents?
2. Developer builds their own bridge
3. Bridges to nowhere

What is the best way to provide infrastructure with endogenous entry?

- Uncertain utilization
- Markets difficult or impossible to set up, large fixed costs
- 'Best' depends on setting: welfare/reliability/prices all can matter

Setting: Texas electric grid

Evaluate how congestion prices and entry fees shift spatial allocation of entry on the grid

1. Stylized facts
2. Structural model of spatial location decision, grid congestion, and grid upgrades
3. Counterfactuals: test two main policy regimes, alternative infrastructure funding

Background, Stylized Facts

Congestion prices:

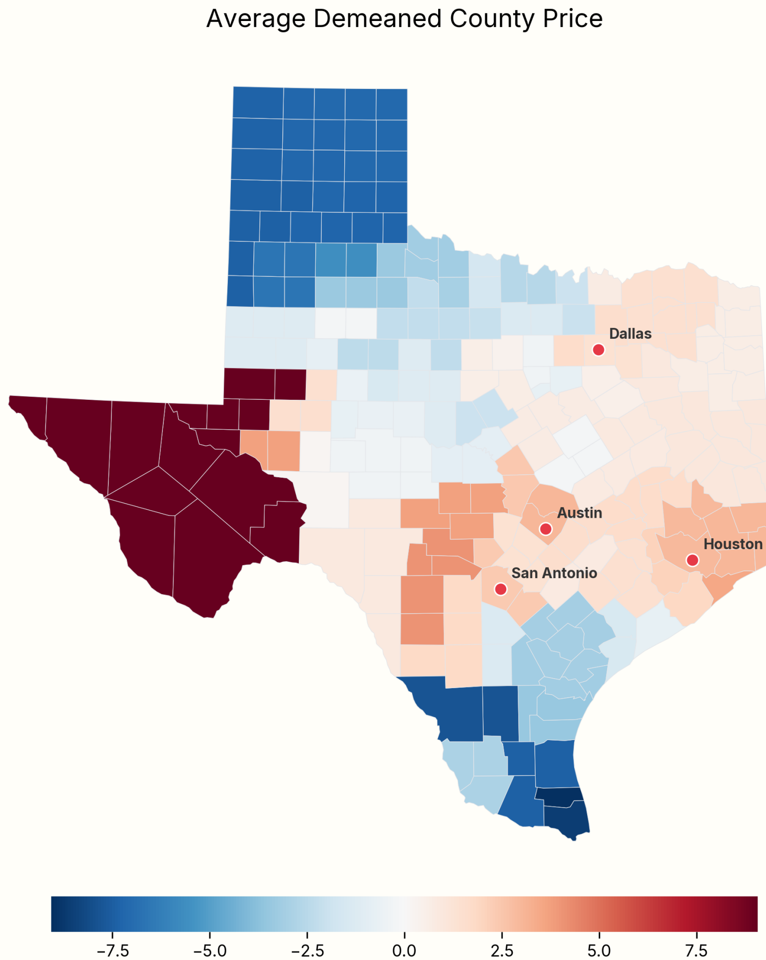
- Lower above congestion
- Higher below congestion

Entry Fees:

- In TX, none
- Elsewhere, high

Upgrades:

- Centrally planned
- Paid for by ratepayers



Visualizations

Lots of data. From 2018-2024:

- Demand, hourly
- County-generator level marginal cost curves, 15-minutes
- Line-level Congestion, 15-minutes
- Generator Entry, monthly
- Line-level upgrade data, monthly
- Grid topography (2024 only)

Missing: Grid capacity, reactance

QUERY	RESULT	
Do upgrade rules work?	Underweight PS	1
How rare are upgrades?	128 upgrades total	2
Do they respond to congestion?	Loosely	3
Does entry respond to upgrades?	Yes	4
Does entry respond to congestion?	Loosely	5
Are upgrades path-dependent?	*in-progress*	

Entry Model

Goal price-minimizing infrastructure provision

- What infrastructure to build? → Spatial entry model
- Spatial entry model? → Expected profits
- Expected profits? → Congestion, fixed costs, upgrades

1. N_τ entrants appear. Choose county and enter or die.
2. Operator views last period congestion, quantity of generation in counties, makes upgrade decisions
3. Production occurs for $h = 4,380$ hours in half-year t

Details

Each h, generator reports marginal costs $c_\tau(q_{r\tau th})$ and quantities $q_{r\tau th}$.

Period profits:

$$\pi(q_{r\tau th}) = (p_r - c_\tau(q_{r\tau th}))f_{r\tau}q_{r\tau th}$$

To find $q_{r\tau th}$, grid operator solves **least-cost dispatch** :

- Generators submit offer curves
- Demand forecasted
- Grid topology
- Selects $q_{r\tau th}$

Graph Representation

Recovering prices p_r:

- Prices reflect marginal cost of production for the grid
- For grid capacity $k^l = \infty$, location doesn't matter
- Binding $k^l \longrightarrow$ spatial variation in prices
- **Physically realistic dispatch model** to capture spatial price variation
- I need offer curves, demand, *grid capacity* $\longrightarrow$ need a panel k^l_t

Details

I fit a dispatch model on observed **prices, dispatch, offer curves, demand**

- Initialize $\boldsymbol{k}^l$ based on voltage alone

- Run penalized-GMM to recover panel of grid capacities that fits data

- Moments: prices, distribution of prices, congestion frequency, congestion costs

- Classify upgrades into 3 buckets, find average capacity increase due to each upgrade type

Fit is improving:

- Price level works overall, struggles in high-stress situations
- Reproduces spatial variation

Penalized-GMM:

- Avg capacity difference: 82MW
- Avg conditional on capacity being different: 200MW
- Ex: Chambers ↔ Harris - updated capacity 2133MW, initial guess 1200MW

Upgrades a function of line stress, line characteristics, FEs

- line stress is endogenous
- Potential shifters: {forecast errors (load, renewable supply), unexpected outages} $\times$ line exposure to shock

Consider a firm choosing to enter the grid in location r:

- Let $x_{r\tau t}$ be state variables:

$$x_{r\tau t} = \{q_{r\tau t}, \sum_{l_r} k_t^l, Q_{\tau t}\}$$

- Entry incurs fixed costs $\nu_{r\tau t} + \varepsilon_{r\tau t}$.

- Let

$$v_{r\tau t}^{enter}(x_{r\tau t}) = \sum_{z=0} \delta^z \mathbb{E}_x[\pi_{r\tau t+z} | x_{r\tau t}] - \nu_{r\tau t}.$$

- The value of entering is $v_{r\tau t}^{enter} + \varepsilon_{r\tau t}$.

Regions vary in expected profits and fixed costs

Entrants choose

$$r \in \operatorname{arg\,max} \rho \cdot \mathbb{E}_{\varepsilon}[v_{r\tau t}^{enter}]$$

Letting $\varepsilon_{r\tau t}$ be distributed T1EV yields logsum probability of r:

$$p(r; \tau, x_t) = \frac{exp(v)}{1 + \sum_{r' \in R} exp(v_{r'})}$$

- Entrants track own region state vars $q_{r\tau t}, k^{l}_{rt}$. Assume k evolves according to own region quantity and aggregate quantities only
- Entrants assume aggregate quantities evolve according to AR-1 process
- Entry forms Moment-Based Markov Equilibrium (MME) (**Ifrach and Weintraub, 2017**)

Dynamic competitive equilibrium:

- Expectations about evolution of k and Q are correct
- Entry probabilities given by logsum prob.
- Upgrades given by upgrade policy function
- Dispatch satisfies least-cost optimization conditional on grid topology

- MME helps with curse of dimensionality
- Still ~80 counties with substantial generation, 300 transmission corridors
- Proposal: using most frequently congestion lines, condense generation into ~40 regions, connected by X transmission lines, let grid evolve for each region
- Problem parallelizable

Appendix

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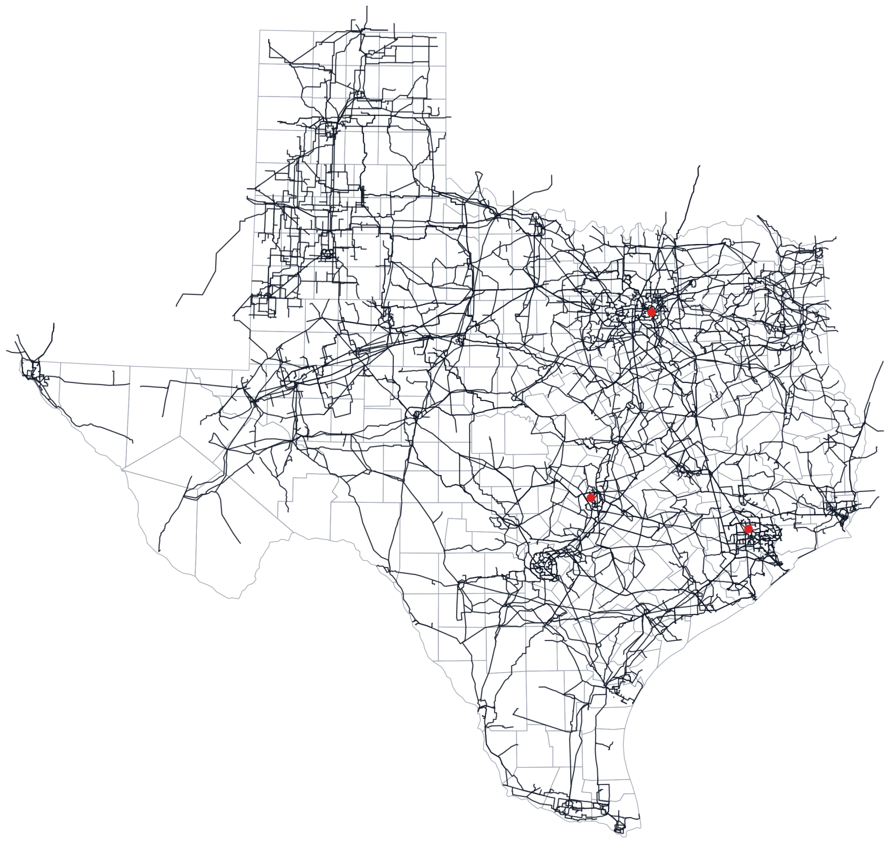

The Grid

The Backbone

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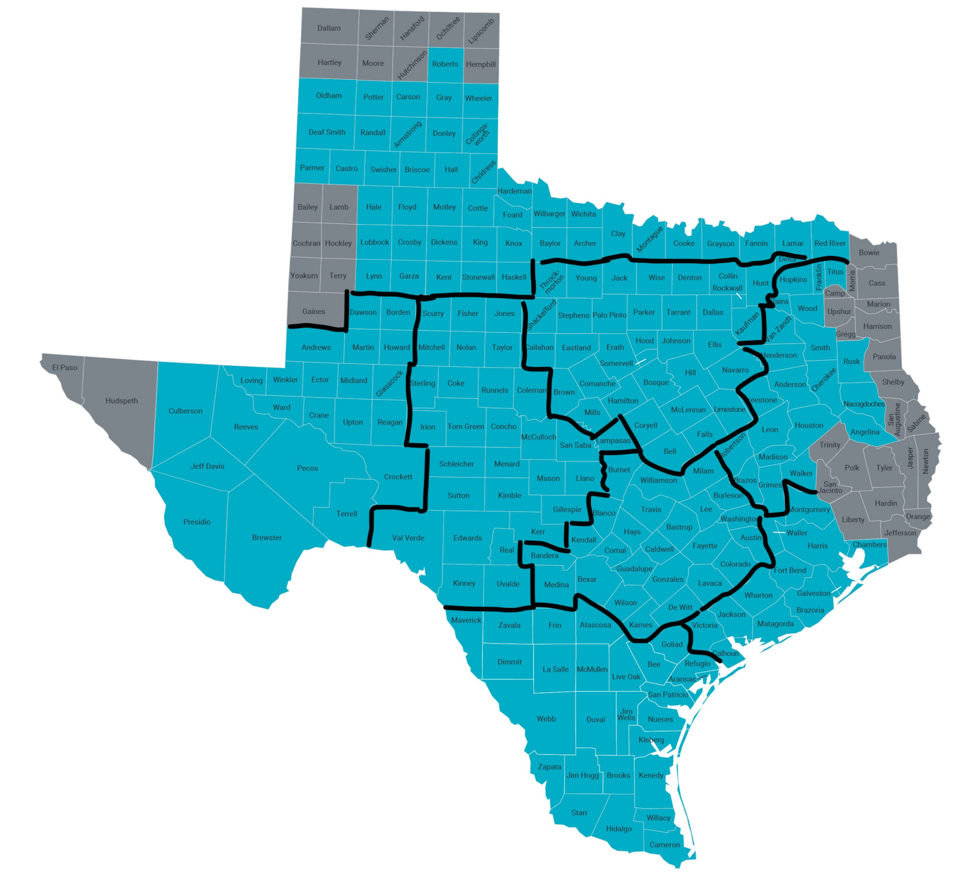

Black lines indicate each wz

+ Yearly utility sales data for 88 utilities
- 207/213 counties covered
- $D_r = w_r * D_{wz}$
- w_r calculated as share of wz sales attributable to utilities serving r

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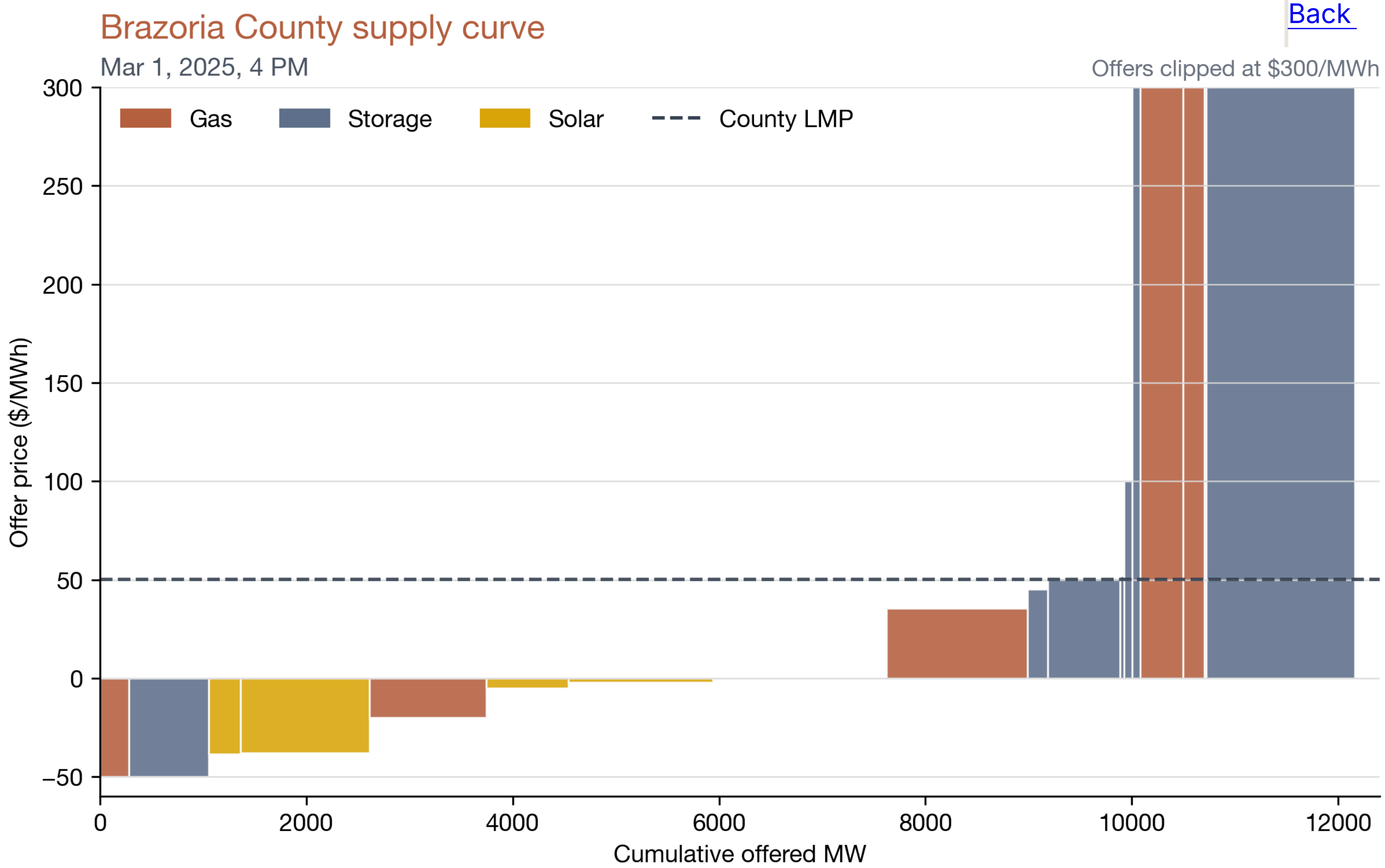

Brazoria County supply curve
Mar 1, 2025, 4 PM
Offers clipped at $300/MWh
Gas
Storage
Solar
County LMP
Offer price ($/MWh)
300
250
200
150
100
50
0
−50
0
2000
4000
6000
8000
10000
12000
Cumulative offered MW

ENTRY PANELS

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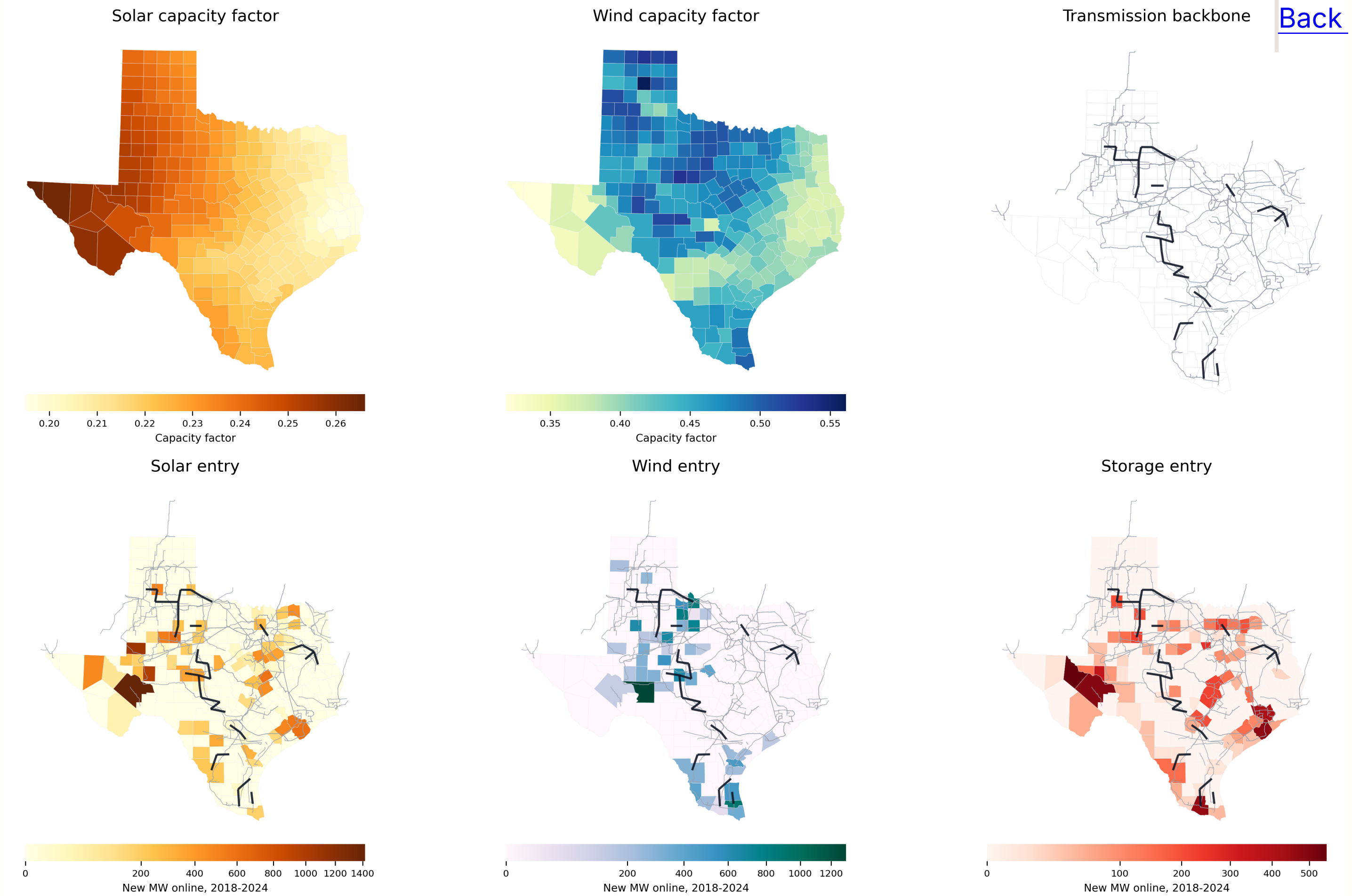
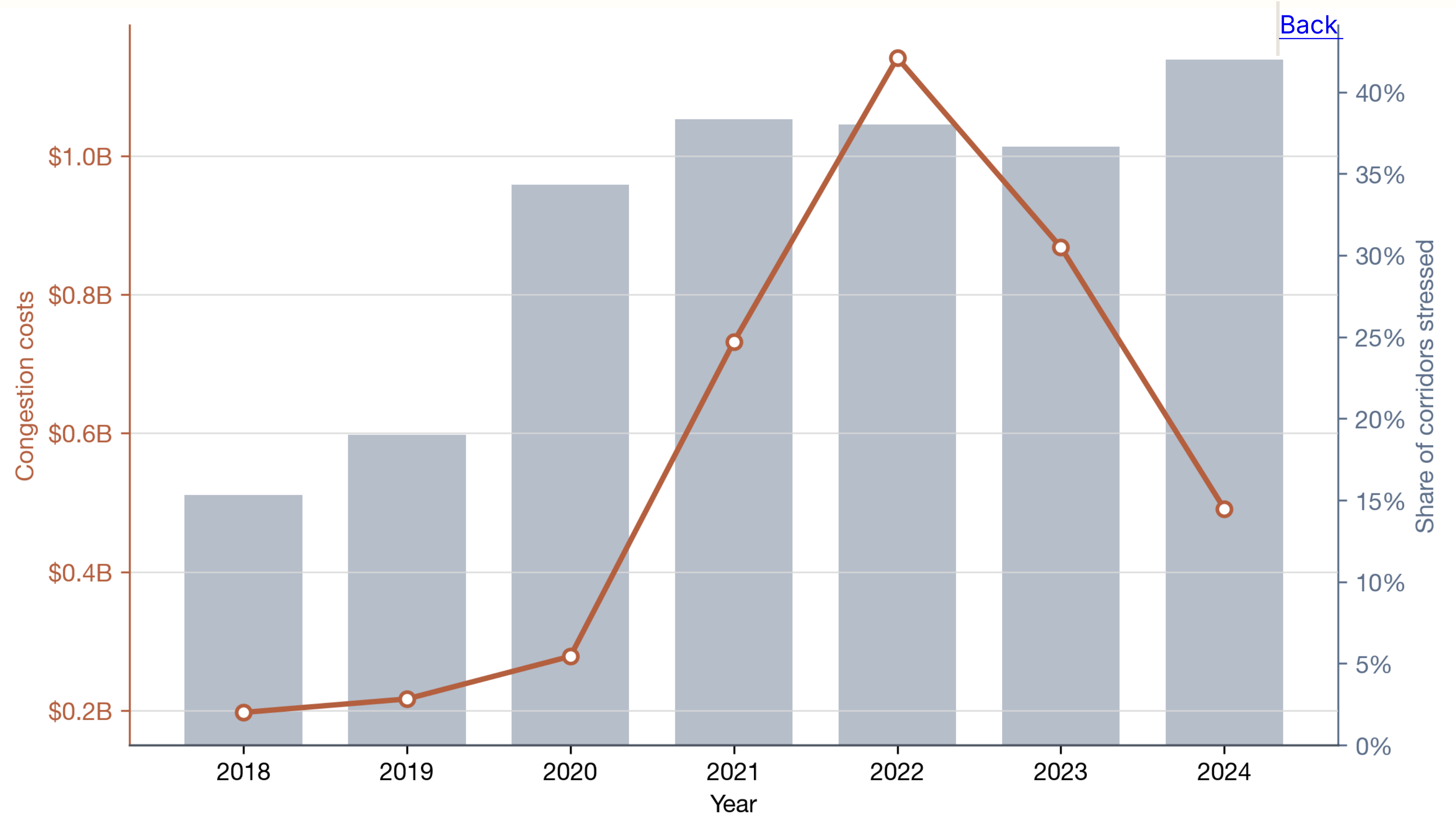


CONGESTION COSTS AND SPREAD RISING



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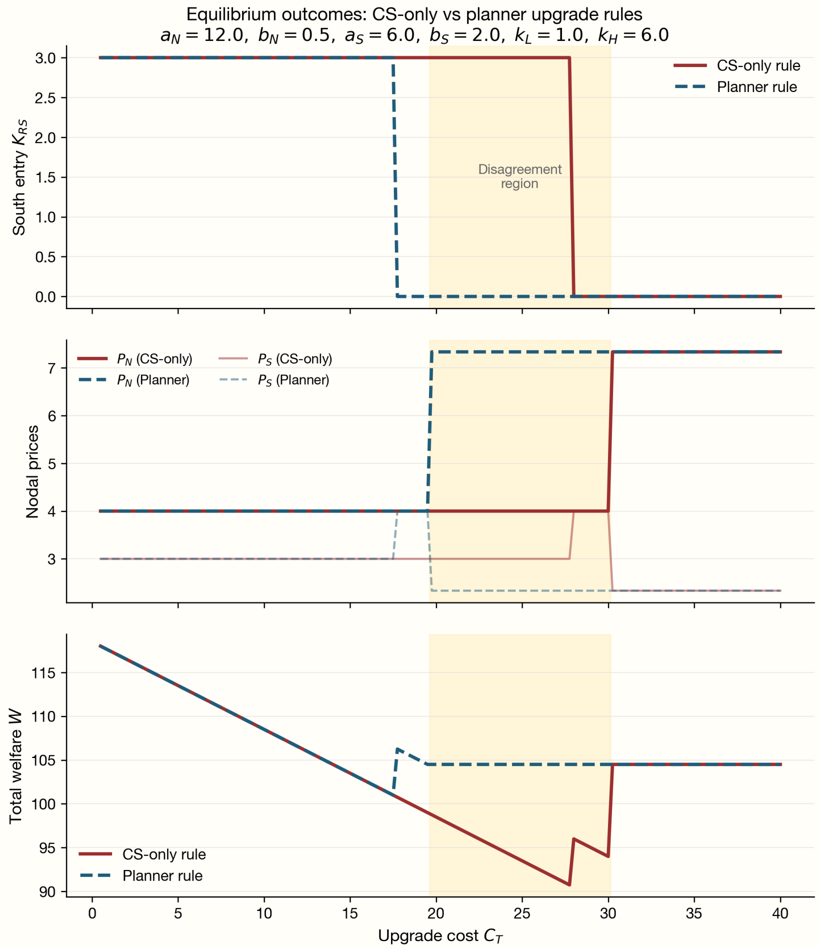
Equilibrium outcomes: CS-only vs planner upgrade rules
$a_N = 12.0,\ b_N = 0.5,\ a_S = 6.0,\ b_S = 2.0,\ k_L = 1.0,\ k_H = 6.0$
South entry K_{RS}
CS-only rule
Planner rule
Disagreement region
Nodal prices
P_N (CS-only)
P_N (Planner)
P_S (CS-only)
P_S (Planner)
Total welfare W
CS-only rule
Planner rule
Upgrade cost C_T

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2019-2024:

- 185 backbone projects initiated
- Initiated $t-1$ congestion: 11.0%
- 119 backbone projects completed
- Completed $t-1$ congestion: 10.3%
- All lines $t-1$ congestion: 11.2%

I use completion in this paper

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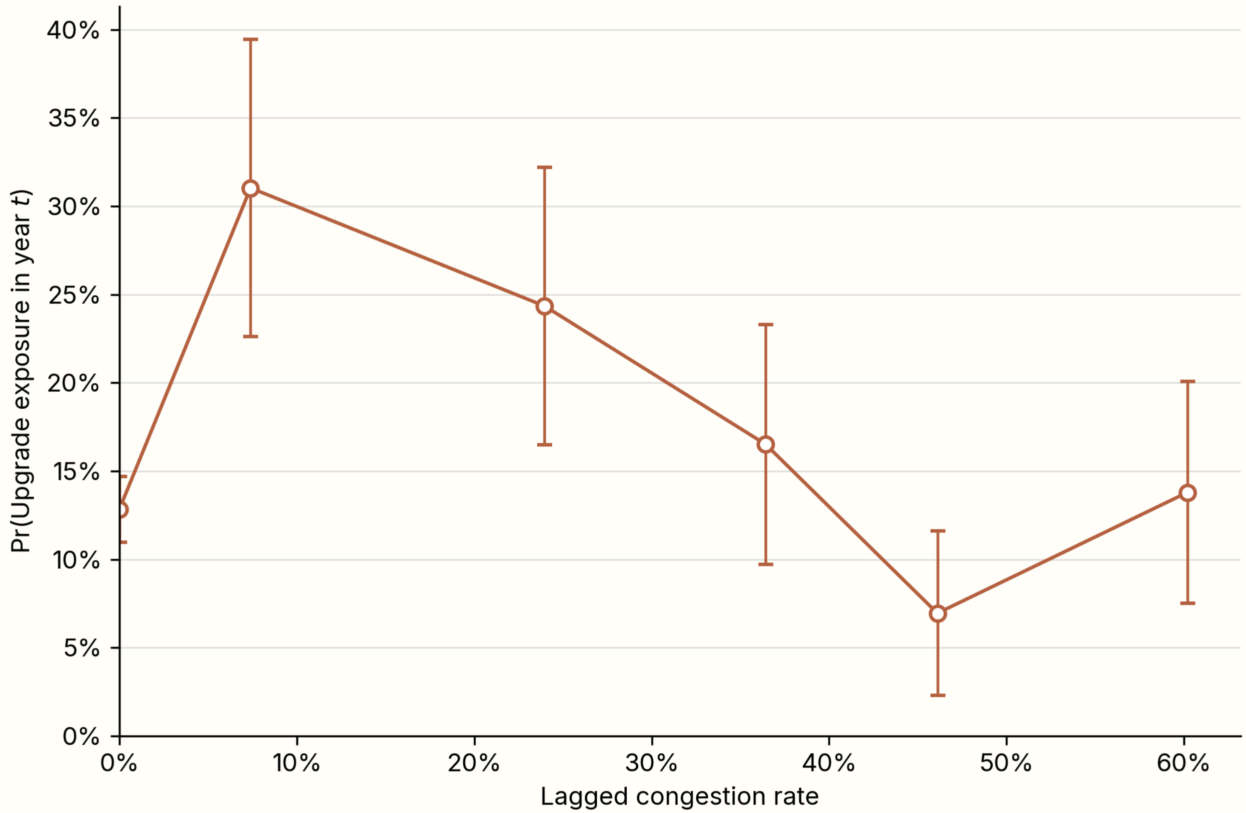

Upgrades sort of respond to congestion, surprising shape

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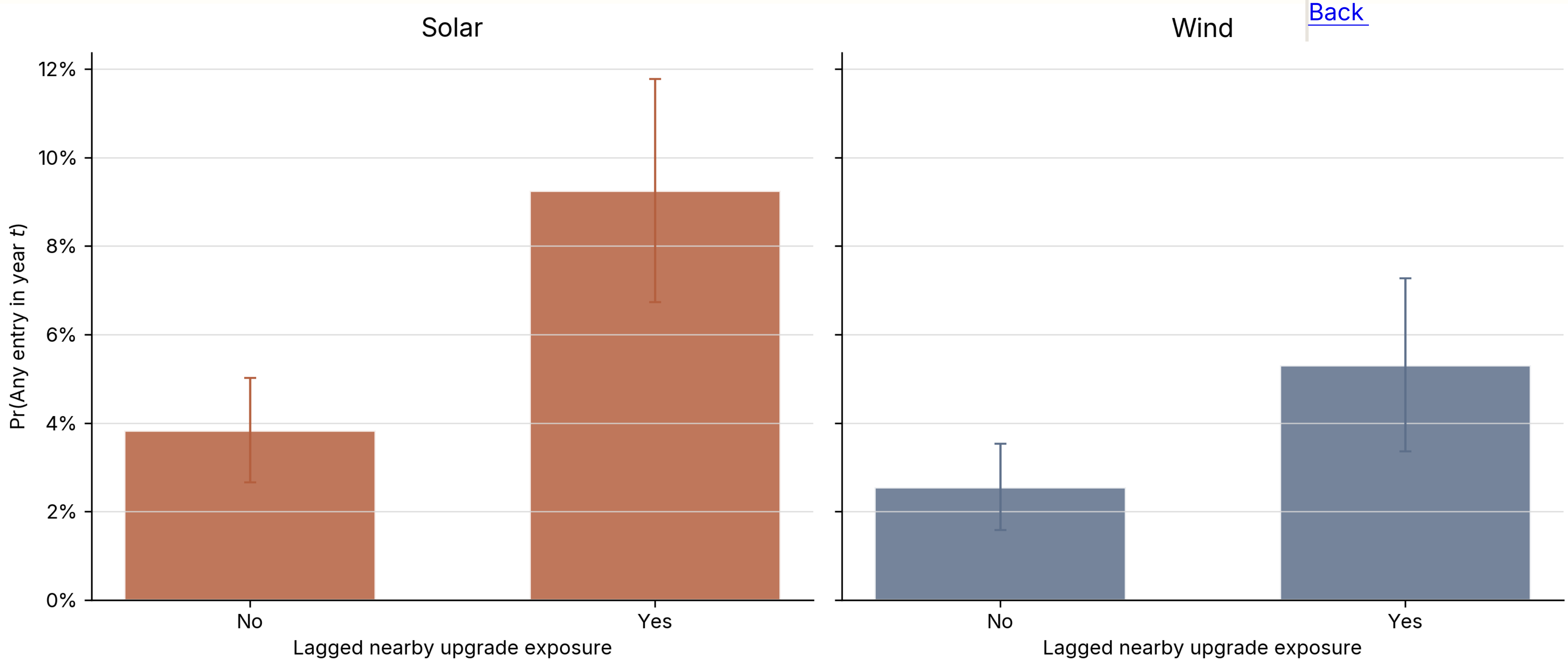

Entry is probably a function of upgrades

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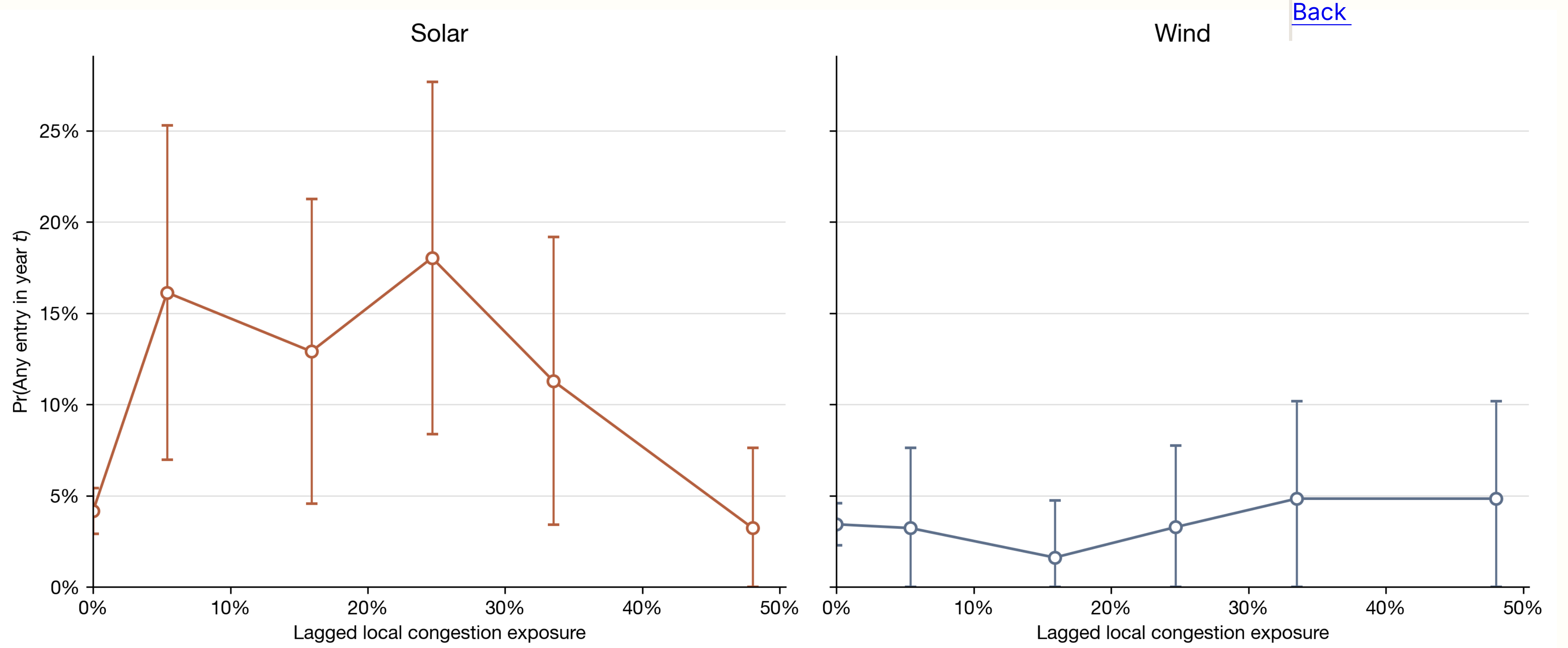

Entry not really a function of congestion, though counterfactual unclear

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$$\mathcal{L} = \sum_r \int_0^{q_{r\tau th}} c_\tau(x)dx + \lambda_{th}(\sum_r (D_{rth} - q_{rth}))+$$
$$\sum_l \mu_{th}^l (k_t^l - \sum_r (q_{rth} - D_{rth}) SF_r^l)$$

- $c_\tau \longrightarrow$ Data
- $D_{rth} \longrightarrow$ Data

- $q_{r\tau th} \longrightarrow$ Choice Var.
- $\lambda_{th} \longrightarrow$ Model Output
- $\mu_{th}^l \longrightarrow$ Model Output†

- $k_{th}^l \longrightarrow$ Parameter
- $SF_r^l \longrightarrow$ Parameter

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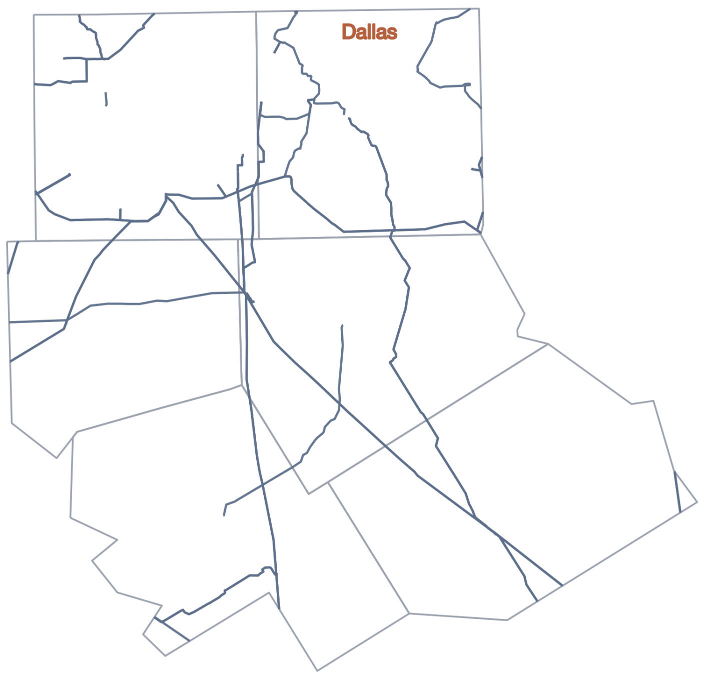
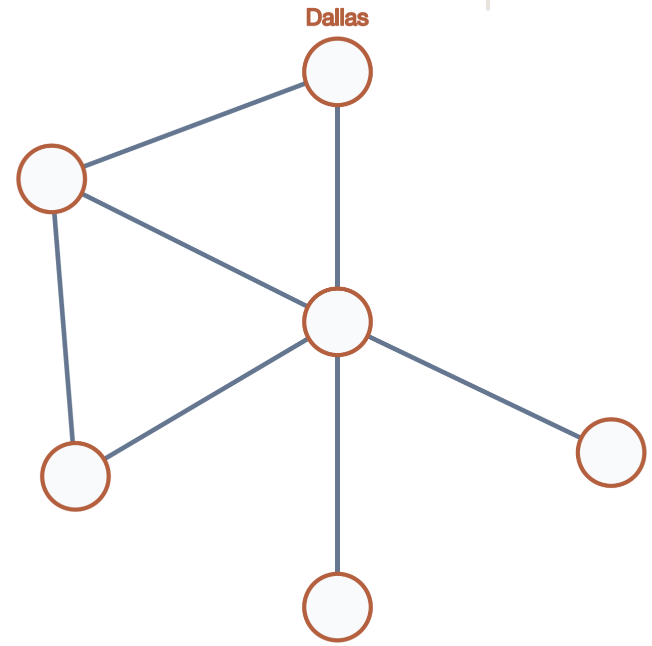




[*Assumption*] reactance only varies by voltage, line length, number of lines between counties

- Initial $\bar{k}^l$: voltage

- Capacity mapping:

$$k_t^l(\theta) = k_0^l + \sum_{p=1}^{P} A_{lp} 1\{t \geq t_p\} \delta_{g(p)}$$

- Parameters:

$$\theta = (\{k_0^l\}_{l=1}^{L}, \{\delta_g\}_{g=1}^{G}) \; \Theta = \{k_0^l \geq 0 \forall l, \delta_g \geq 0 \forall g\}$$

Objective:

$$\hat{\theta} = \arg\min_{\theta \in \Theta} (m - \hat{m}(\theta))' W (m - \hat{m}(\theta)) + \lambda_0 \sum_{l=1}^{L} ((k_0^l - \bar{k}^l)/\bar{k}^l)^2 + \lambda_1 \sum_g \delta_g^2$$

Moments

1. Binding frequency
2. Mean shadow price
3. Mean/tail price spreads
4. Pre/post changes around upgrades

Upgrade Groups

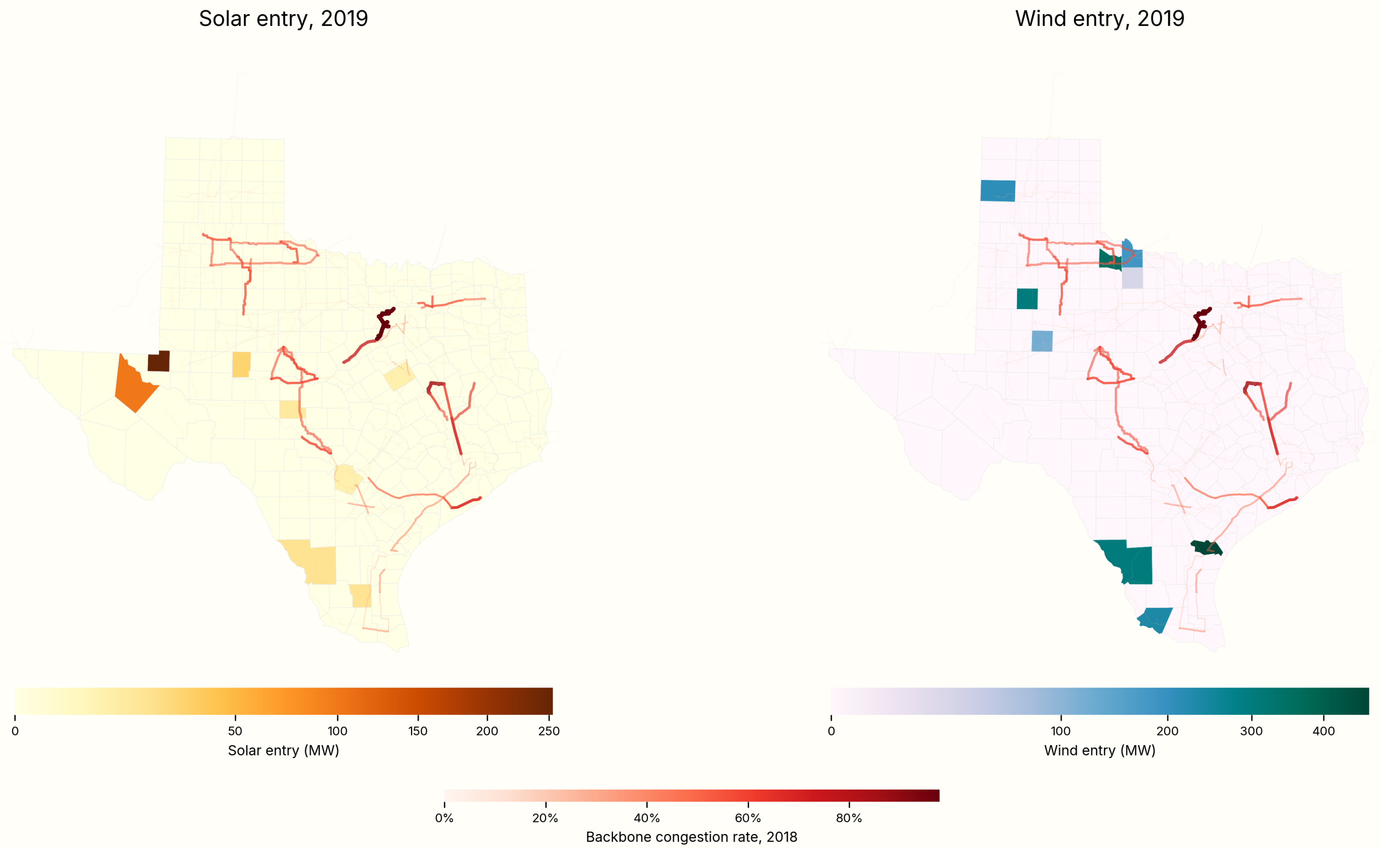
1. New corridor
2. Existing corridor expansion
3. Station expansion

Moments

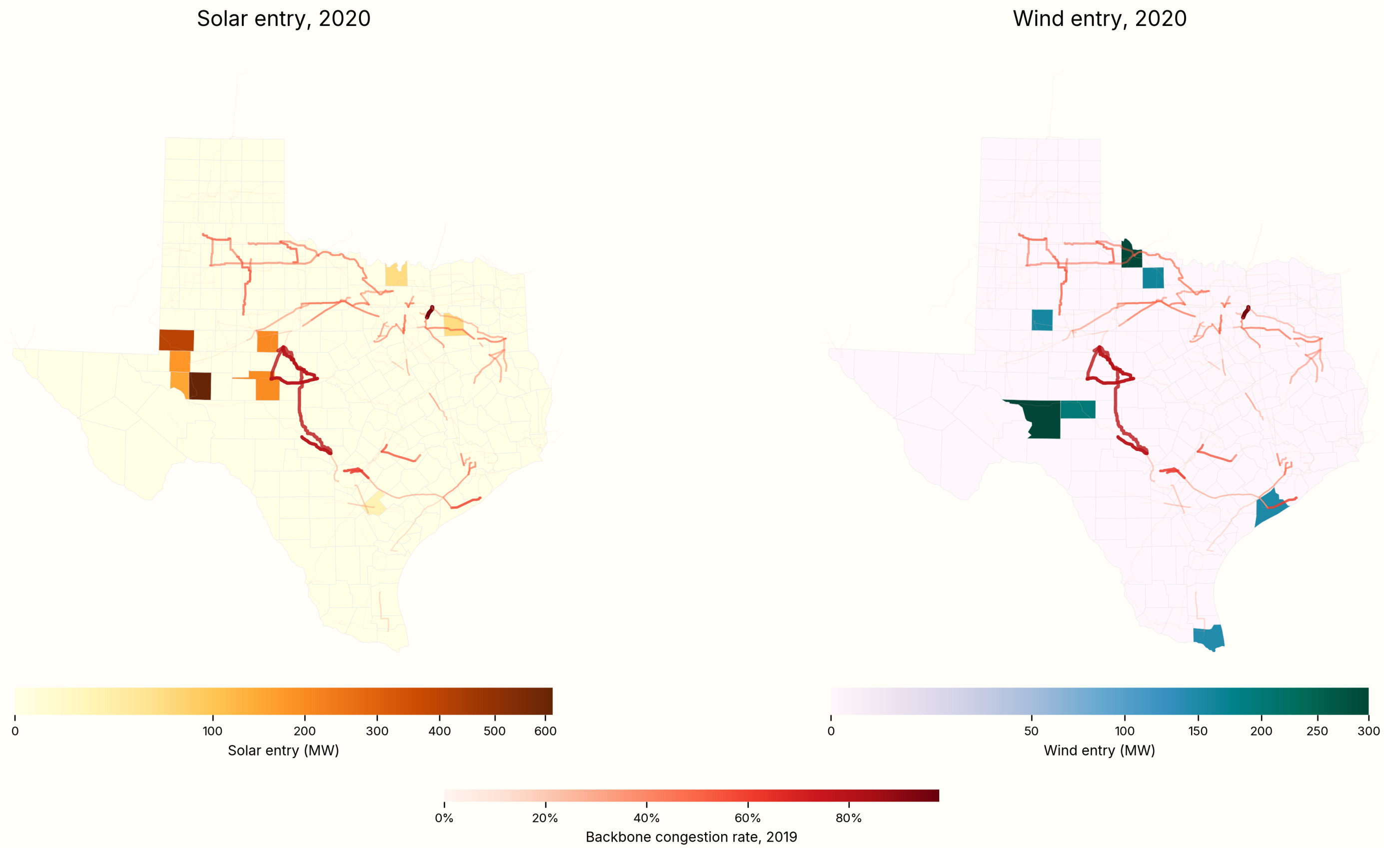
Let μ_{lt}^{obs} denote observed shadow prices for l.

Let $s_{lt}^{obs} = |\lambda_{r(l)t}^{obs} - \lambda_{r'(l)t}^{obs}|$ with corresponding model moments, r and r' connected counties. Let $\mathcal{T}_l = \{t : \mu_{lt}^{obs} \textbf{ in top 20\% >0 for corridor } l\}$

1. $m_l^{1,obs} = \frac{1}{T}\sum_{t\in\mathcal{T}_l} 1\{\mu_{lt} > 0\}$, for observed and model data
2. $m_l^{2,obs} = \frac{\sum_{t\in\mathcal{T}_l}\mu_{lt}1\{\mu_{lt}>0\}}{\sum_{t\in\mathcal{T}_l}1\{\mu_{lt}>0\}}$
3. $m_l^{3,obs} = \frac{1}{|\mathcal{T}_l|}\sum_{t\in\mathcal{T}_l} s_{lt}$, for observed and model data
4. $m_g^{4,obs} = \frac{1}{|P_g|}\sum_{p:g(p)=g}[\frac{1}{|\mathcal{T}_p^{\text{post}}|}\sum_{t\in\mathcal{T}_p^{\text{post}}}\mu_{l(p)t} - \frac{1}{|\mathcal{T}_p^{\text{pre}}|}\sum_{t\in\mathcal{T}_p^{\text{pre}}}\mu_{l(p)t}]$, for observed and model data Notes: Back



Backbone congestion is $t-1$



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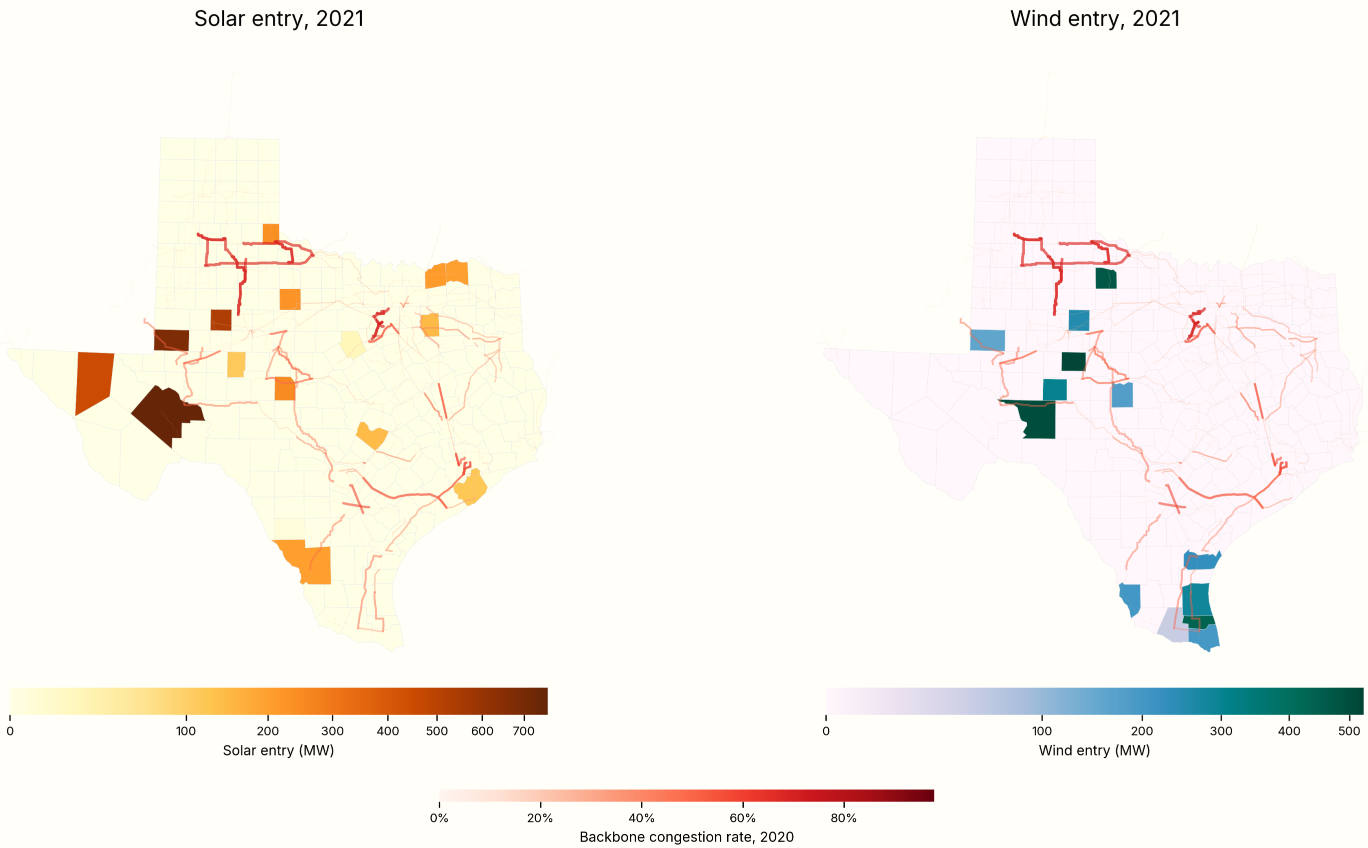

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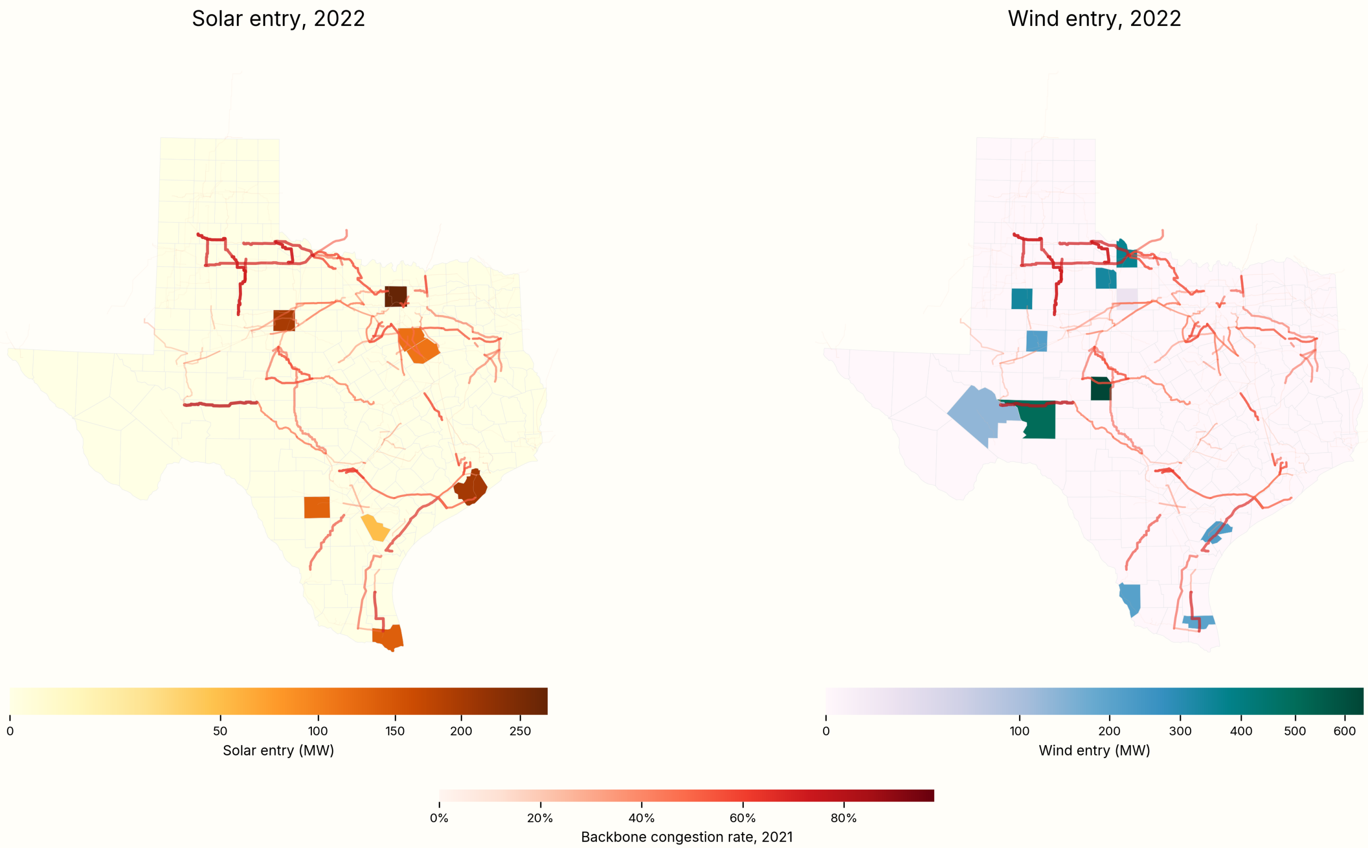

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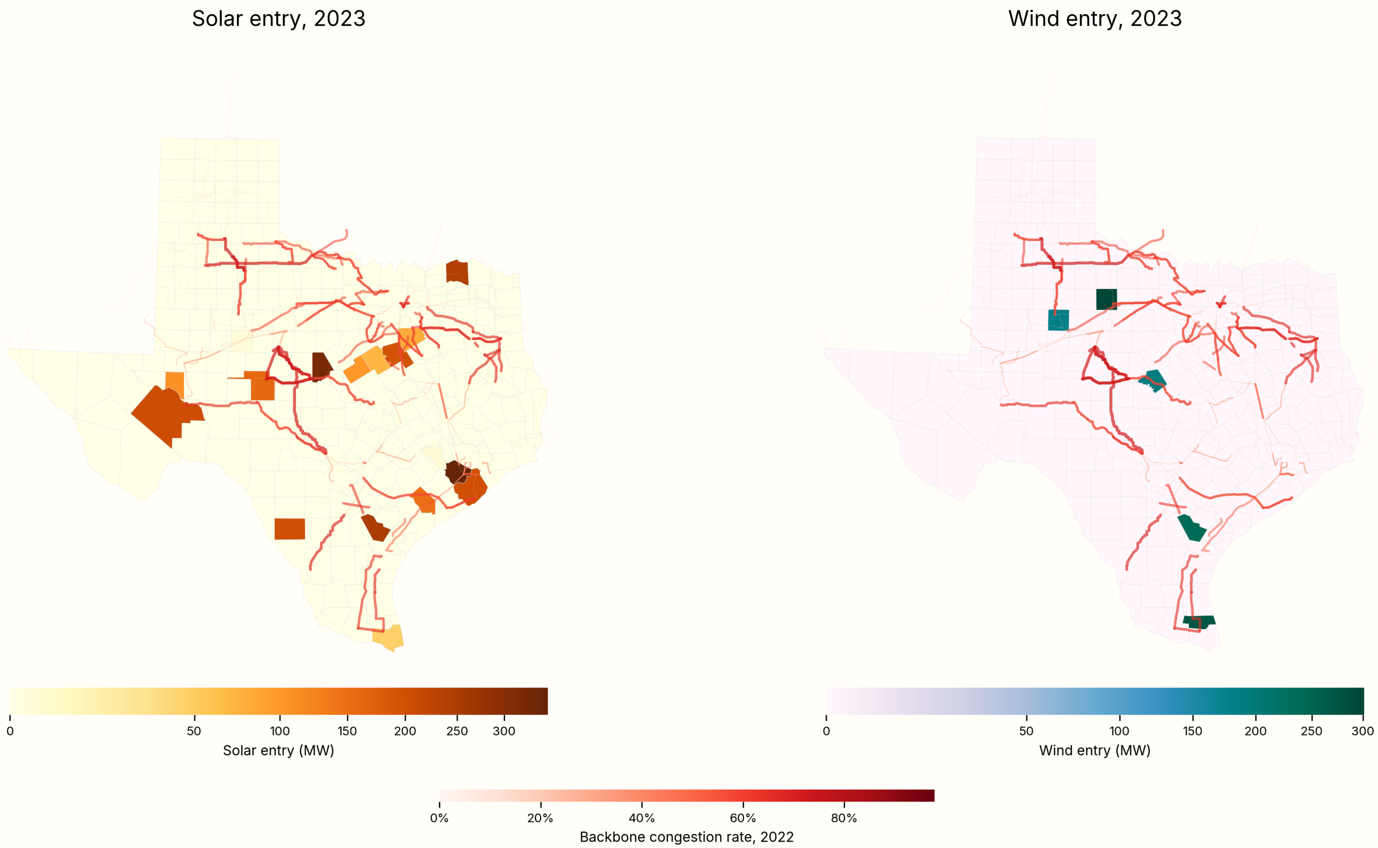

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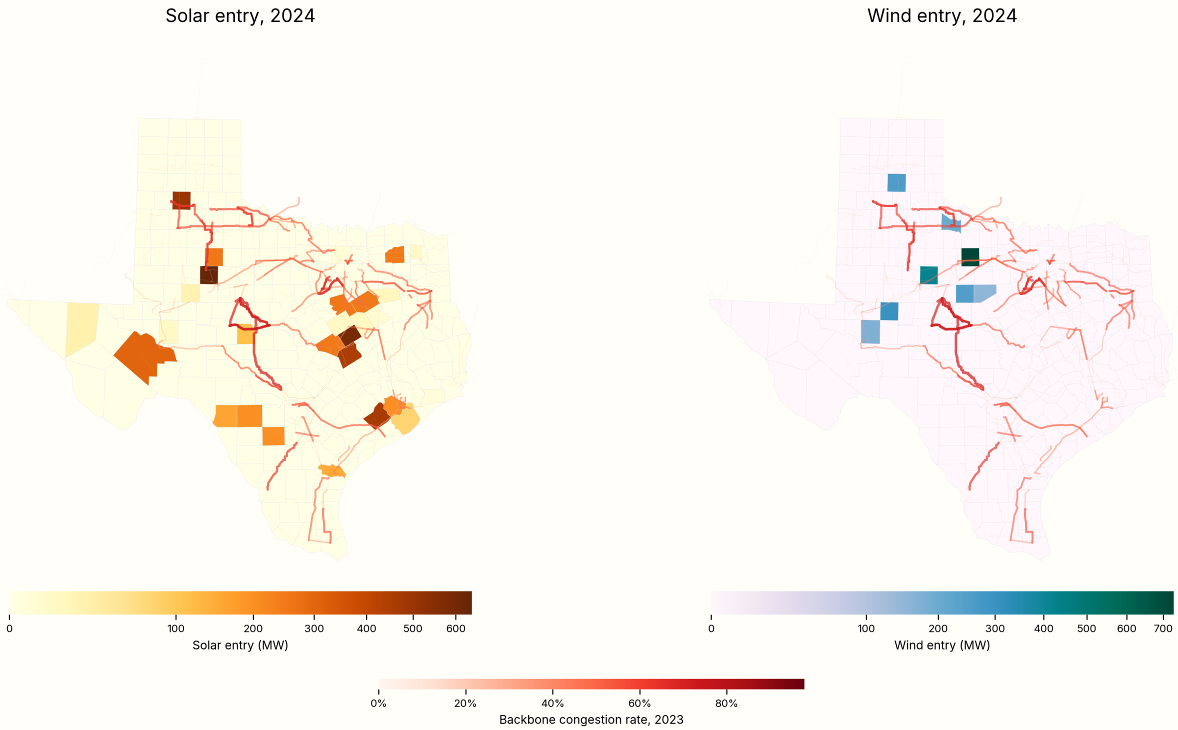

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