Investment and the Transfer of Power: Dynamic Effects of Transmission in Electricity Markets

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Presentation Outline

Motivating Observations

- Renewable generation is **intermittent** and geographically **dispersed**
- Electricity storage remains **costly and limited** in short-run
- Renewable potential is **uneven across regions**
- **Long-range transmission** is emerging as a key solution
- Investment in long-range transmission has been **minimal to date**

Potential for Renewable Generation by County

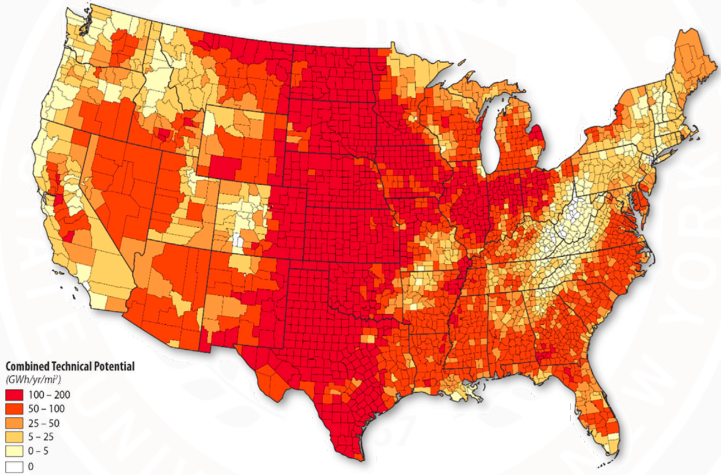


Figure 1: Potential for Wind and Solar Generation by County. Source: DoE

Existing and Planned High-voltage Direct Current Lines

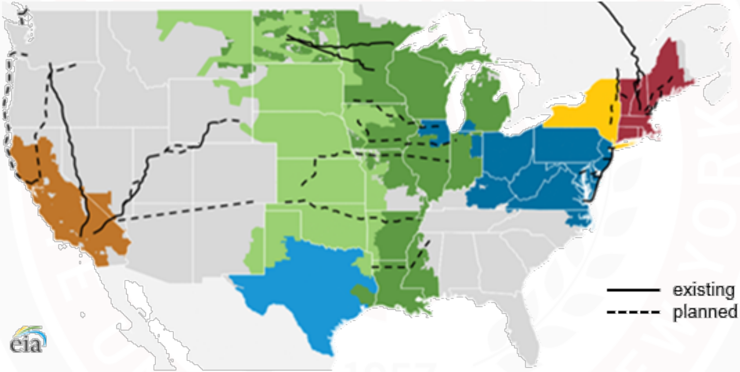
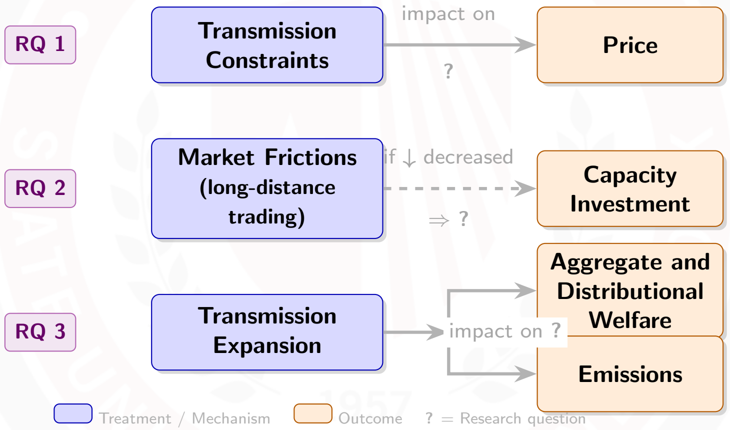


Figure 2: Proposed Expansions Electricity Transmission. Source: EIA

Research Questions



Contribution: Framework

New Framework

Model of how *transmission constraints* shape prices and quantities in multi-node grids

↓

Unique Dataset

Time-varying transmission capacity + hourly firm-level generation (ISO, EIA, EPA)

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Comprehensive Short Run

Marginal costs estimated across *all* resources.

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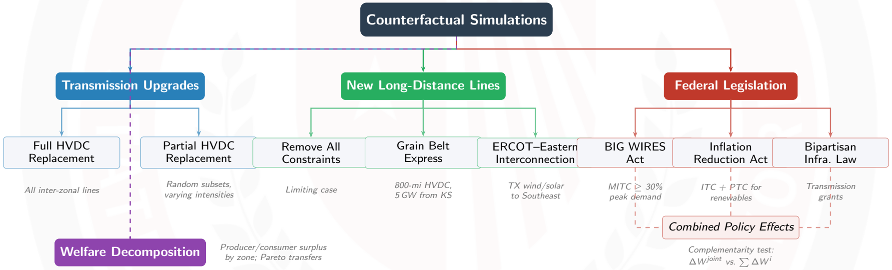
Dynamic Perspective

Integration of transmission into long-run electricity market models

Counterfactual Policy Experiments



Contribution: Preliminary Results

- **Short-run Results:**
  - Full Upgrade (2018–2023): average prices fall by **6%**.
  - Welfare gains: **$4 billion per year**, equal to about one-third of all congestion costs (Grid Strategies).
  - Partial replacement (50% of lines): still delivers **5%+ price reduction**.
  - Regional effects: largest price drops in the Northeast; modest price increases in the Midwest.
- **Long-run Results:**
  - With Grain-belt express, **10%+ increase** in solar and wind adoption in Eastern Interconnection by 2050

Locational Marginal Price (LMP)

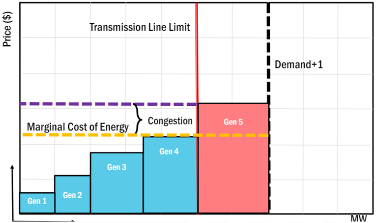


Figure 3: Congestion visualized (Source: NYISO)

Market Dynamics

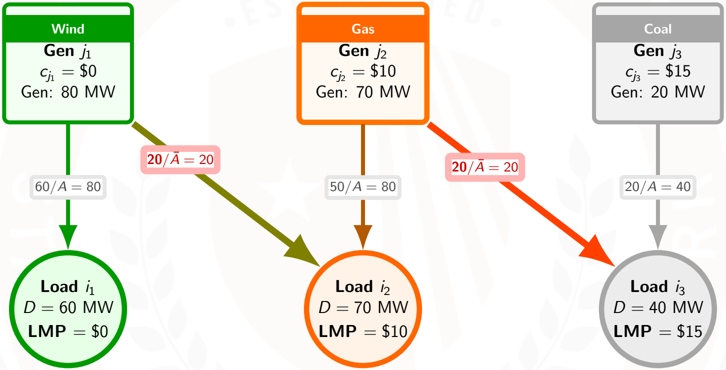
- **No Constraints:** Prices are uniform (λ).
- **Binding Constraints:** Congestion causes local price separation.

LMP Calculation

$$\text{LMP} = \text{Energy} + \text{Loss} + \textbf{Congestion}$$

**Congestion component is non-zero only when transmission constraints bind.*

Network Topology: Prices and Constraints

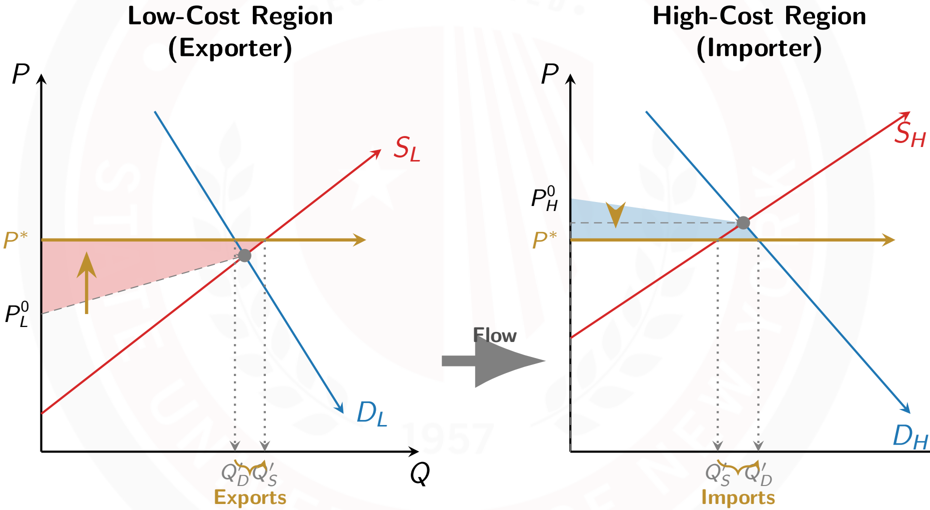


Market Clearing with Congestion:
Binding export constraints limit cheap power.
Each zone's LMP = local marginal cost:
$\text{LMP}_{i_1} = c_{j_1}, \quad \text{LMP}_{i_2} = c_{j_2}, \quad \text{LMP}_{i_3} = c_{j_3}$

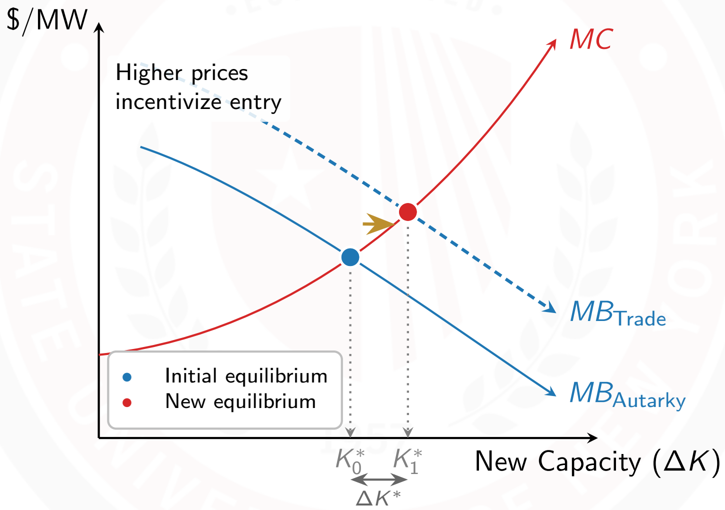
Legend:
- Wind zone (LMP = \$0)
- Gas zone (LMP = \$10)
- Coal zone (LMP = \$15)
- Binding constraint ($\bar{A}$)

Figure 4: Binding export constraints create price separation.

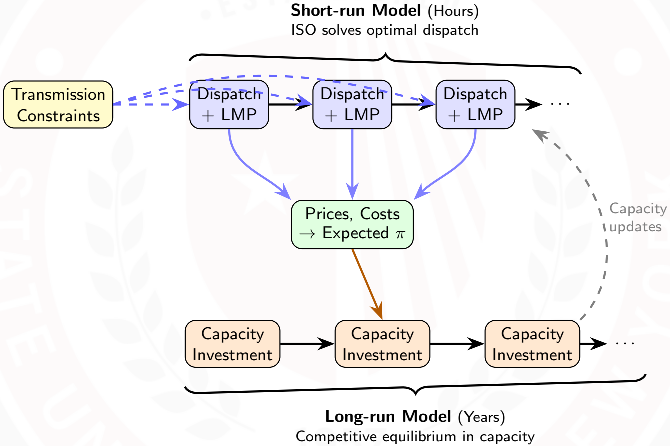
Static Effects: Price Convergence & Arbitrage



Dynamic Effects: The Investment Signal



Timeline of Short-run and Long-run Models



Short-run: A combined ISO minimizes dispatch costs subject to transmission constraints (engineering problem).

Long-run: Generators choose capacity to maximize profits given expected prices (equilibrium).

Short-run Model: ISO Problem

Objective: Minimize Cost of Generation

$$\pi_t = \min_q \sum_{i,j,k,g} c_{jkgt}(\ldots, \mathbf{q}_{ijkgt}, \ldots)$$

Subject to:

1. Balance

Supply = Demand

$$\sum (1 - B_{ij}) q_{ijkgt} = L_{it}$$

(at each node)

2. Grid Limits

Flow ≤ Line Limit

$$\sum_k \sum_g q_{ijkgt} \leq A_{ij}$$

(per line and timestep)

3. Capacity

Gen ≤ Max Output, Exogenous for Renewable

$$0 \leq \sum q_{jkgt} \leq O^{MAX}_{jkgt}$$

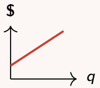
(per generation unit)

Short-run Model: Cost Structure

General Form: Costs depend on cost shifters x, output q, and shock ϵ:
$c_{jkgt}(x, q, \epsilon)$

Fossil Fuels (Positive MC)

$$MC = \underbrace{x\beta}_{\text{Base}} + \underbrace{q\nu}_{\text{Slope}} + \epsilon$$

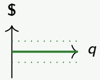


$\epsilon \sim N(0, \Omega)$

Renewables (Zero/Stochastic)

$$MC = \epsilon_{ijkgt}$$

(No fuel cost)



Identification Strategy:

- We observe the market price P, fuel mix across time, and cost shifters.
- For the **marginal resource**, $MC = LMP$.
- *Result:* We recover exact cost data for the price-setting unit and use constraints to estimate cost differences with other dispatched resources.

Long-run GenCo Problem

Bellman Equation

$$v_{gt}(\Theta) = \max_{\Delta O_g} \left[\sum_j \Pi_{jg}(\Theta) + \varepsilon_{jg}(\Delta O) + \beta \mathbb{E} v_{jgt+1}(\Theta') \right]$$

Period Profit Π_{jg} (Revenue - Cost)

$$\Pi_{jg} = \sum_k \left[\underbrace{D_{jkg} P_{jkg}}_{\text{Revenue}} - \underbrace{C_{jkg} D_{jkg}}_{\text{Op. Cost}} - \underbrace{F_k O_{jgk}}_{\text{Fixed}} - \underbrace{E_k \max(\Delta O_{jgk}, 0)}_{\text{Entry Cost}} \right]$$

Capacity

Endogenous Evolution:

$$O' = O + \Delta O$$

Cost Shocks (Integrated AR1)

Exogenous $x \in \{F, E\}$:

$$x'_k = \psi_x + \rho_x x_k + \zeta'_x, \quad \zeta \sim N(0, \sigma^2)$$

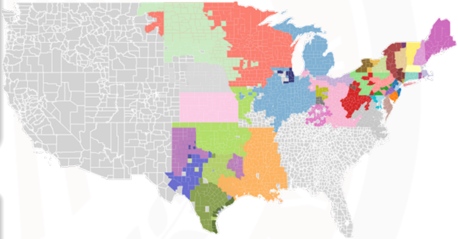
Dataset Overview

Spatial Granularity

- **54 Discrete Zones**
- Captured attributes: Load, Price, Gen, Capacity, cost shifters

Time Horizon

- **Historical:** 2018–2024 (Hourly)
- **Projection:** Extends to **2050**



Map of Prices by Zone

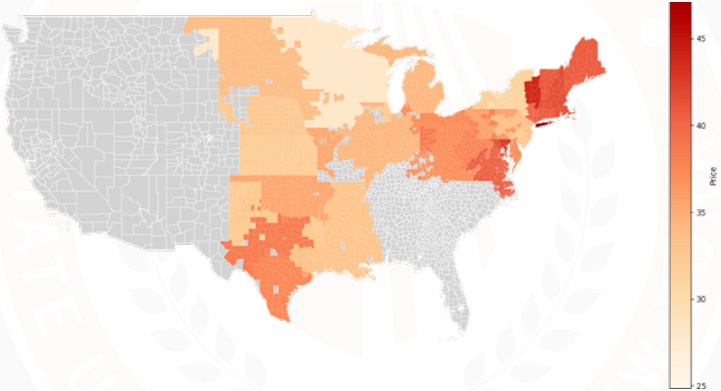
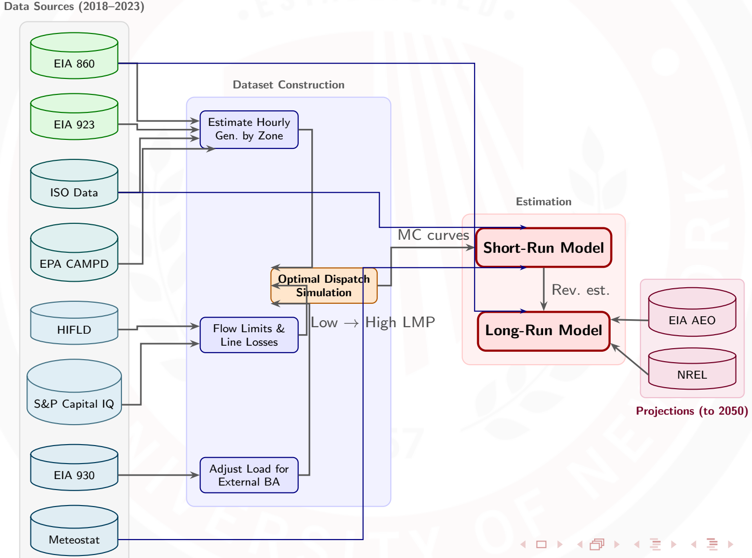


Figure 5: Prices by Zone.

Dataset Construction Process



Short-Run Estimation: Model Construction

1. Composite Error

Difference out Transmission Constraint (λ) and Capacity Constraint (θ):

$$\tilde{\epsilon}_{ijkt} = \epsilon_{ijkt} - \epsilon_{i'jkt} - \epsilon_{ijk't}$$

2. Deterministic Component $\tilde{V}_{ijkt}$

$$\tilde{V}_{ijkt} = \underbrace{x_{jkt}\beta + q_{ijkt}\nu_k}_{\text{MC of resource } jk} - \underbrace{\frac{1-B_{ij}}{1-B_{ij''}} LMP_{it}}_{\text{MC of central resource}}$$

$$+ \underbrace{q_{i'jkt}\nu_k - q_{ijkt}\nu_k + \frac{LMP_{i't}}{1-B_{i'j''}}(1-B_{i'j}) - \frac{LMP_{it}}{1-B_{ij'''}}(1-B_{ij})}_{\text{cost of transmission constraint}}$$

$$+ \underbrace{(x_{jk't}\beta + q_{ijk't}\nu_{k'}) - (x_{jkt}\beta + q_{ijkt}\nu_k)}_{\text{cost of capacity constraint}}$$

Short-Run Estimation: Likelihood & Parameters

3. Likelihood Function

Multivariate normal, variance–covariance Ω:

$$\mathcal{L} = \prod_{t=1}^{T} P_t(\tilde{V}_{111t}, \ldots, \tilde{V}_{IJKt})$$

MLE Recovers

$$\hat{\beta}, \quad \hat{\nu}_k$$

β : Observable cost shifters

ν_k : Resource-type marginal cost

Variance–Covariance

$$\hat{\Omega}$$

Captures correlations across zones, resources, and time within generator portfolios

Long-Run Equilibrium Computation: Nested Fixed Point

Outer Loop: Iterate on Beliefs about Rival Investment

1. Initialize beliefs over aggregate rival capacity changes
2. Solve each firm's DP via backward induction (inner loop)
3. Update beliefs using implied investment distributions
4. Check convergence: $\max|\sigma^{(n+1)} - \sigma^{(n)}| < \epsilon$

Equilibrium Concept: Oblivious

Firms condition on own state + aggregate rival capacity (not full joint distribution).

Reduces dimensionality while preserving the strategic investment channel.

Selection Rule

Sequential moves in descending order of installed capacity.

GMM Estimation: Moment Conditions

36 Moments (overidentified: 36 > 32 parameters)

Moments constructed from simulated vs. observed investment decisions.

Natural Gas, Solar, Wind (per type)

$\mathbb{1}(\Delta O_{jkg} > 0) \times \Delta O_{jkg}$	Positive inv. × qty
$(\Delta O_{jkg})^2$	Investment squared
$\mathbb{1}(\Delta O_{jkg} > 500)$	Large inv. indicator
$\Delta O_{jkg} \times \sum_j O_{jkg}$	Capacity interaction
$\text{Var}(\Delta O_{jkg})$	Investment variance
$\lvert \min(\Delta O_{jkg}, 0) \rvert$	Retirements

Coal

Moments focus on retirement behavior.

One investment moment included to anchor entry cost scale.

Estimated Cost Coefficients Short-Run

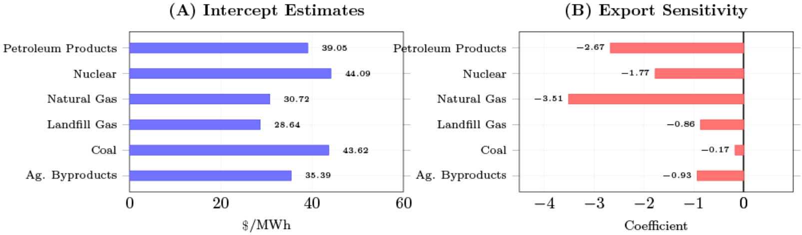
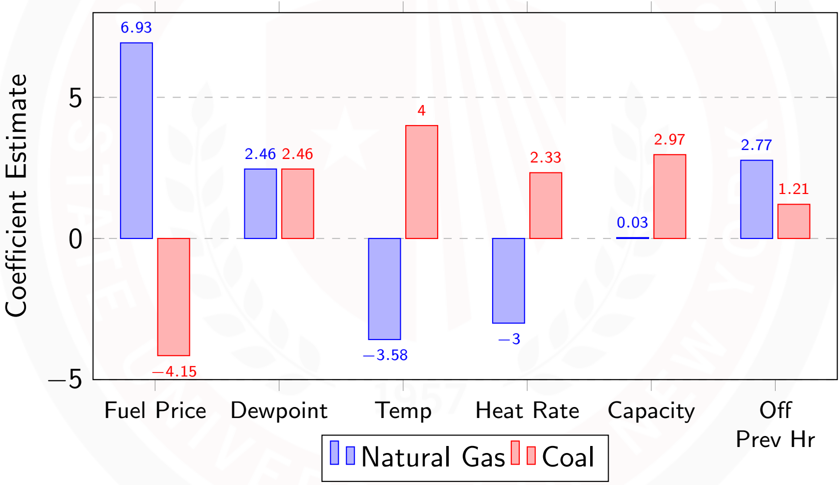


Figure 7: Intercept and Export Sensitivity Estimates by Resource.

Cost Function Shifter Estimates: Coal and Natural Gas



Preliminary Model Fit: Long-run

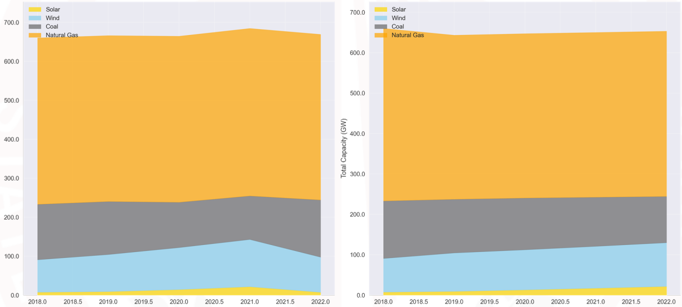


Figure 8: Actual vs. Simulated Capacity Mix Evolution over Time.

Counterfactual Simulation Scenarios

Scenario	Description	Modified Primitives: Line A_{ij}, B_{ij}	Modified Primitives: Entry E_k	Modified Primitives: Revenue P_k^{eff}
Panel A — Transmission Infrastructure Upgrades				
Full HVDC	All inter-zonal lines upgraded	✓		
Partial HVDC	Random subset at intensity $\alpha \in (0, 1)$	✓		
Panel B — New Long-Distance Transmission				
No constraints	All transmission limits removed	✓		
Grain Belt Express	5,000 MW HVDC, KS to IN	✓		
ERCOT–Eastern IC	HVDC link, ERCOT to Southeast	✓		
Panel C — Federal Legislation				
BIG WIRES Act	MITC $\geq$ 30% peak demand by 2035	✓		
IRA × BIL Factorial Design				
Baseline	Neither IRA nor BIL			
IRA only	IRA enacted, no BIL		✓	✓
BIL only	BIL enacted, no IRA	✓		
As enacted	Both IRA and BIL	✓	✓	✓
Panel D — Cross-Cutting Analysis				
Welfare decomposition	Producer/consumer surplus by zone	*Applied to all scenarios*		

Notes: Each scenario holds estimated structural parameters fixed and modifies only the indicated primitives. A_{ij}: inter-zonal transfer capacity; E_k: technology-specific entry cost; P_k^{eff}: effective per-MWh revenue inclusive of PTCs. All policy wedges phase in via $\rho(t;\, t_0, R)$. Panel C uses identical random seeds.

BIG WIRES ACT visual

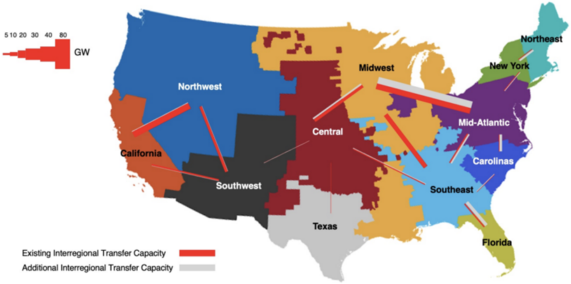


Figure 2: Map of existing and additional interregional transfer capacity between regions

Figure 9: Big Wires Act Visualized

Price Decrease by Percentage Grid Upgrade

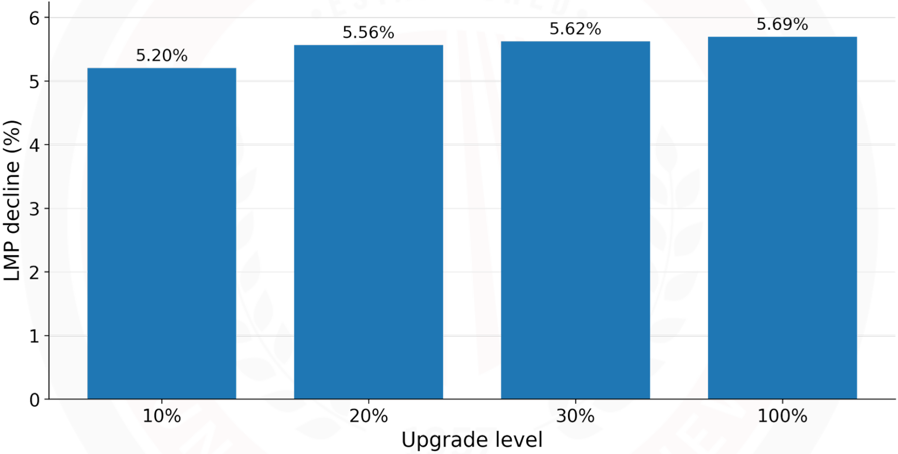


Figure 10: Price Decrease by Percentage Grid Upgrade.

Conclusion

- **Model transmission dynamics:** Develop a structural model capturing how grid constraints shape spatial price formation and congestion patterns
- **Short-run price effects:** Quantify how transmission capacity and network topology influence locational marginal prices and price volatility
- **Long-run investment implications:** Trace how transmission-induced price signals propagate to generation capacity decisions and resource adequacy outcomes

Thank You!