Empirical Methods for the Analysis of the Energy Transition

Slide Set 6

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Roadmap

I. Entry, renewables, and transmission expansion

- Hausman (2025)
- Gonzales, Ito, and Reguant (2023)

II. Modelling transmission

III. Practicum: The grid and reshuffling in California

The transmission grid is a key aspect of the energy transition

- It enables to transmit renewable power from supply-rich areas to demand centers.
  - Example 1: CREZ project to bring wind from West to East Texas.
  - Example 2: Transmission projects to bring wind from West to East China.
  - Example 3: Grid expansion in Chile to harvest solar power in Atacama.
  - Example 4: DC line to connect Spain and France (under construction).

- Transmission can deliver gains from trade, market power mitigation benefits (Cicala, 2021; Ryan, 2021), and environmental benefits (Fell, Kaffine, and Novan, 2021).

Several innovations make the transmission grid a key enabler

- DC cables that can go underwater and underground, with smaller losses (lost power due to travelled distance).
- Capacitors that enable to more flexibly change the topology of the grid.
- Reconductoring of existing transmission lines with improved materials/technologies.
- Smart meters helping control voltage at the distribution network.

The absence of transmission can be a bottleneck

- In the absence of good integration, power prices can go to zero or even negative:
  - At that point, "curtailment" (throwing renewable power away) is likely to occur.
  - It also makes future investment in renewable power uncertain and less valuable $\rightarrow$ investment effect.

The difficulty in allocating costs and getting permitting

- Dynamic benefits from transmission expansion can be substantial.
- However, transmission projects are difficult to implement (see Davis, Hausman, and Rose (2023)).
  - They often require public intervention to be successful (e.g., to obtain right of way, coordinate across countries or states).
  - Its cost is difficult to allocate: who benefits? who pays? Losing and winning regions?
  - Oftentimes decisions implemented in a centralized manner by a regulated operator.

Related literature

1. Economic theory of electricity transmission
   - Bushnell (1999), Joskow and Tirole (2000,2005), Borenstein, Bushnell and Stoft, (2000)
2. Efficiency gains from market-based dispatch and enhanced transmission in electricity markets
   - Mansur and White (2012), Cicala (2022), Hausman (2025)
3. Environmental impacts of transmission expansion and/or bottlenecks
   - Fell, Kaffine, and Novan (2021), Lamp and Samano (2022), Gonzales et al. (2023).
4. Market power and transmission
   - Wolak (2015), Davis & Hausman (2016), Ryan (2021)

We will review two papers

- Hausman (2025): A BBW-style calculation of the benefits of transmission (MISO/SPP).
- Gonzales et al. (2023): An event-study + structural model to assess the benefits of transmission (Chile).

Hausman (2025)

- Hausman (2025) quantifies the inefficiencies from the lack of perfect transmission.
- Question: How much would generation costs change if transmission constraints were relaxed? Who are the winners and losers?
- Tools: counterfactual merit order + regressions/descriptives.
- Some key findings:
  - Transmission inefficiencies in MISO/SPP of around 2 billion.
  - Transmission inefficiencies are large, growing, and **create opposition despite overall gains**.

Data

- **Unit-level hourly generation** for fossil plants:
    - Individual units within plants (coal, gas, oil)
    - Technology type (boiler, combined cycle, combustion turbine)
    - Location and ownership (IOU vs. IPP)
- **System-level hourly generation**:
    - Renewables and nuclear at the ISO level
    - Reported curtailments by ISO

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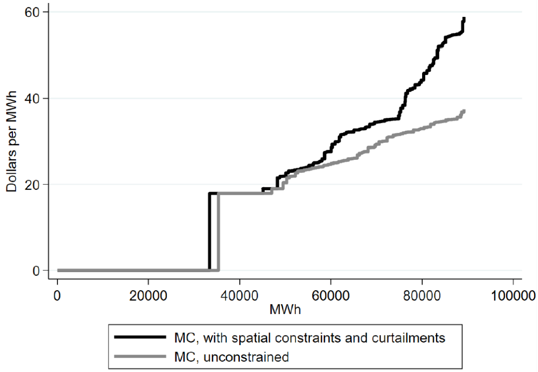
Empirical strategy

- Construct hourly counterfactual supply curves by ranking generators by marginal cost.
- Compare:
  - Least-cost dispatch without transmission constraints
  - Observed dispatch with within- and across-ISO constraints and curtailment
- The difference identifies excess generation costs from transmission frictions.



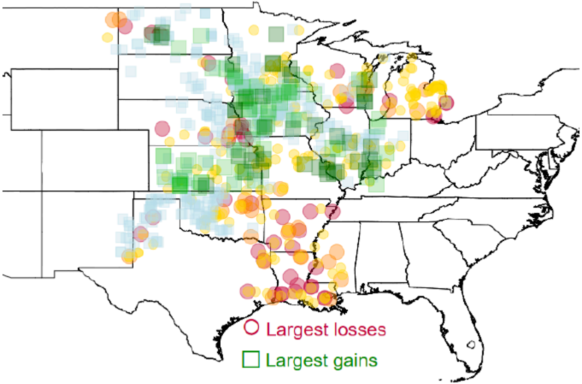
Key findings: aggregate effects

- Transmission constraints generate large and growing inefficiencies.
- Excess generation costs reach:
  - $\sim$ \$2 billion in 2022 for MISO/SPP
  - Several billions annually when extended to the full U.S. grid
- Costs rise sharply with renewable penetration and curtailment.

Annual cost, billion dollars	2016-2020	2021	2022
Total	0.39 to 0.50	1.19	2.30
Across-ISO constraints	0.07	0.16	0.24
Within-ISO constraints	0.28	0.70	1.39
Curtailments	0.03 to 0.14	0.33	0.66
Within-SPP constraints	0.10	0.23	0.30
Within-MISO constraints	0.19	0.47	1.09

Spatial and firm-level effects

- Inefficiencies are spatially structured:
  - Load pockets benefit from congestion
  - Renewable-rich regions are constrained
- Relaxing constraints creates clear winners and losers.
- Some firms experience losses of hundreds of millions of dollars per year.

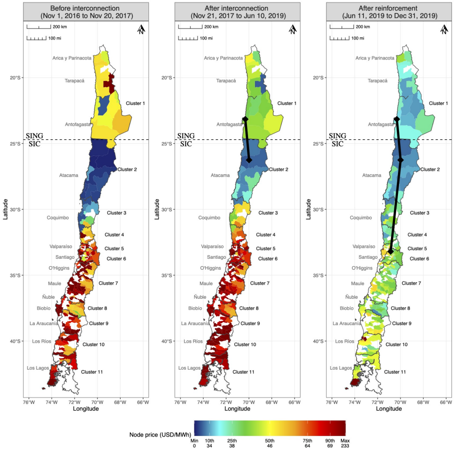


Political economy implications and takeaway

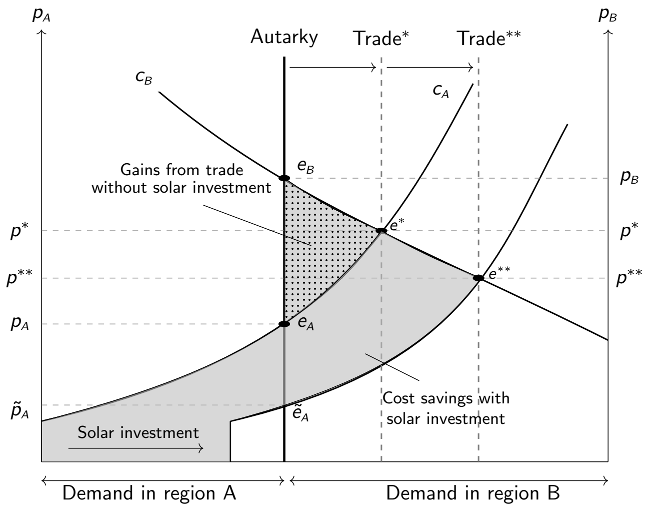
- Firms that lose from integration may have incentives to block new transmission.
- Transmission planning may not adequately internalize these strategic incentives.
- Distributional conflict helps explain why transmission expansion is politically difficult.
- These distributional effects are central to understanding barriers to grid expansion in the energy transition.

Gonzales, Ito, and Reguant (2023)

- Gonzales, Ito, and Reguant (2023) quantify the value of transmission infrastructure in Chile.
- Question: What is the cost benefit of the expansion project?
- Tools: regression analysis + structural model of the Chilean electricity market.
- Some key findings:
    - We highlight the dynamic benefits of grid expansion, enabling increased renewable expansion.
    - The cost of transmission can be quickly recovered, even when ignoring the added climate change benefits.



Summary of the paper in a picture



Static impacts: Event study effects of the line

$$c_t = \alpha_1 I_t + \alpha_2 R_t + \alpha_3 c_t^* + \alpha_4 X_t + \theta_m + u_t$$

- Our method uses insights from Cicala (2022)
  - c_t is the observed cost
  - c_t^* is the nationwide merit-order cost (least-possible dispatch cost under full trade in Chile)
  - $I_t = 1$ after the interconnection; $R_t = 1$ after the reinforcement
  - X_t is a set of control variables; θ_t is month fixed effects
  - α_1 and α_2 are the impacts of interconnection and reinforcement

Static impacts: Event study effects of the line

	Hour 12		All hours	
1(After the interconnection)	-2.42	(0.26)	-2.07	(0.17)
1(After the reinforcement)	-0.96	(0.58)	-0.61	(0.37)
Nationwide merit-order cost	1.12	(0.03)	1.03	(0.01)
Coal price [USD/ton]	-0.03	(0.01)	-0.01	(0.01)
Natural gas price [USD/m^3]	-10.36	(4.33)	-0.65	(3.09)
Hydro availability	0.43	(0.14)	0.00	(0.00)
Scheduled demand (GWh)	-0.51	(0.13)	-0.01	(0.00)
Sum of effects	-3.38		-2.68	
Mean of dependent variable	35.44		38.63	
Month FE	Yes		Yes	
Sample size	1033		1033	
R^2	0.94		0.97	

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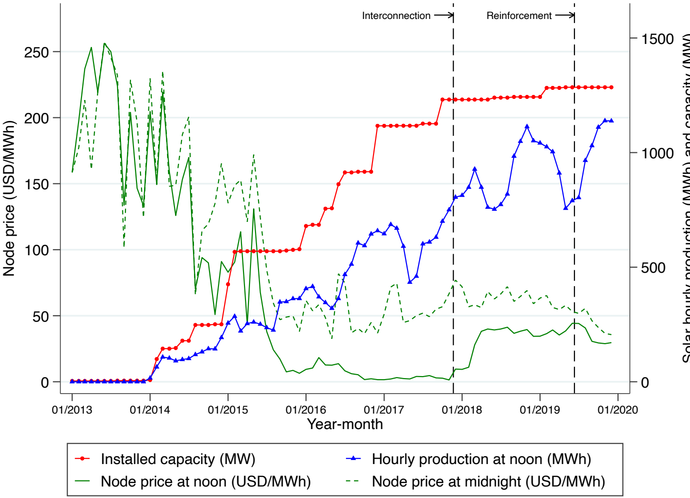
Does this static event study analysis get the full impact?

- Our theory suggested:
  - Yes if solar investment occurs simultaneously with integration
  - No if solar investment occurs in anticipation of integration

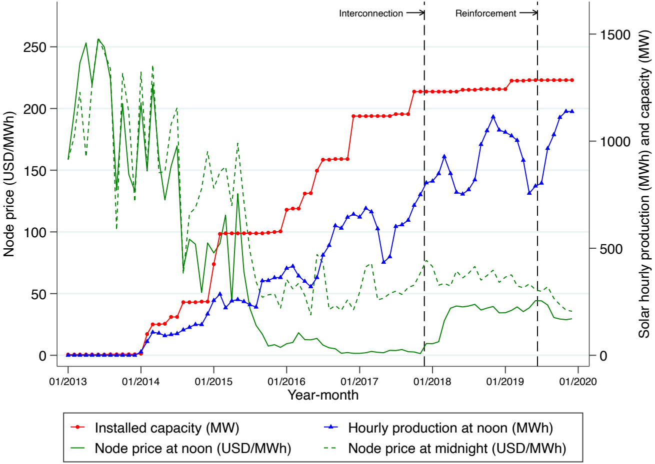
Solar investment occurred in anticipation of integration

- Solar investment began after the announcement of integration in 2014
- These solar entries depressed the local price to near zero in 2015-2017



Solar investment occurred in anticipation of integration

- Solar investment began after the announcement of integration in 2014
- These solar entries depressed the local price to near zero in 2015-2017
  - Investment occurred in the anticipation of the profitable environment
  - [→] **Event-study does not capture the full impact of market integration**



Buidling a model to get at the full effect)

- Impacts of the grid can be static and dynamic:
  - Production benefits: more solar can be sent to the demand centers, prices in solar regions go up.
  - Investment benefits: more solar power is built.

- We highlight that an event study is likely to capture only the first kind of effects (e.g., around time of expansion).
- We build a model of the Chilean electricity market to quantify the benefits of market integration including its investment effects.

A structural model to study a dynamic effect on investment

- We divide the Chilean market to five regional markets with interconnections between regions (now expanding to 11)
- Model solves constrained optimization to find optimal dispatch that minimizes generation cost
- Constraints:
  1. Hourly demand = (hourly supply - transmission loss)
  2. Supply function is based on plant-level hourly cost data
  3. Demand is based on node-level hourly demand data
  4. Transmission capacity between regions:
     - Actual transmission capacity in each time period
     - Counterfactual: As if Chile did not integrate markets

The structural model solves this constrained optimization (as in our practicums)

$$\underset{q_{it}\geq 0}{\text{Min}} \quad C_t = \sum_{i\in I} c_{it} q_{it},$$

$$\text{s.t.} \quad \sum_{i\in I} q_{it} - L_t = D_t, \quad q_{it} \leq k_i, \quad f_r \leq F_r. \tag{1}$$

- Variables:
  - C_t: total system-wise generation cost at time $t \in T$
  - c_{it}: marginal cost of generation for plant $i \in I$ at time t
  - q_{it}: dispatched quantify of generation at plant i
  - L_t: Transmission loss of electricity
  - D_t: total demand
  - k_i: the plant's capacity of generation
  - f_r: inter-regional trade flow with transmission capacity F_r

Expressing the line constraints

- Line allows for relatively simple grid representation.
- Each line has a maximum capacity defined by how much power flows through it (in practice, a matrix showing connected zones and allowed trade between them).
- The flow direction determines which region receives the power together.

$$
\begin{aligned}
&(1) \quad \sum_j q_{ztj} + \sum_l \Big((1-\delta_1)\ imp_{lzt} - exp_{lzt} \Big) \geq \frac{D_{zt}}{1-\delta_2}, \quad \forall z, t, \\
&(2) \quad 0 \leq imp_{lzt} \leq f_{lz}, \quad 0 \leq exp_{lzt} \leq f_{lz}, \quad \forall l, z, t, \\
&(3) \quad \sum_z (imp_{lzt} - exp_{lzt}) = 0, \quad \forall l, t,
\end{aligned}
$$

Note: Computationally, this is a simple linear constraint.

Dynamic responses are solved as a zero-profit condition

$$E\left[\sum_{t\in T}\left(\frac{p_{it}(k_i)q_{it}(k_i)}{(1+r)^t}\right)\right]=\rho k_i \tag{2}$$

- where:
  - NPV of profit (left hand side) = Investment cost (right hand side)
  - ρ: solar investment cost per generation capacity (USD/MW)
  - k_i: generation capacity (MW) for plant i
  - p_{it}: market clearing price at time t
  - q_{it}: dispatched quantify of generation at plant i
  - r: discount rate
- This allows us to solve for the profitable level of entry for each scenario

We calibrate the model with detailed market data

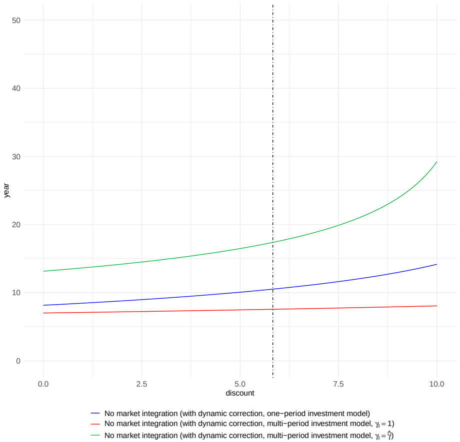
- Network model
  - k-means clustering of province prices into 5 zones, observed flows between clusters to set transmission.
- Supply curve:
  - based on observed production and/or observed reported costs.
- Demand:
  - based on nodal level data, aggregated to clusters.
- Solar potential:
  - based on days without transmission congestion.
- Cost of solar:
  - based on zero profit condition.

The cost and benefit of the transmission investments

- Cost of the interconnection and reinforcement
  - \$860 million and \$1,000 million (Raby, 2016; Isa-Interchile, 2022)
- Benefit—we focus on three benefit measures
  - Changes in consumer surplus
  - Changes in net solar revenue (= revenue − investment cost)
  - Changes in environmental externalities

Assessing the cost-benefit

- With the model, we can compute the benefits of the line, with and without investment effects.
- We find that investment effects are key to justify the cost of the line.
- The line was also very attractive from a consumer welfare perspective, even at 5.83% discount rate (Chile's official rate).
- Political economy makes renewable expansion "easy" in Chile.
- How to reduce political economy challenges in other jurisdictions?



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Modeling the grid: why?

- As we have seen, modeling different regions can be relevant under several circumstances:
  - To account for resource heterogeneity.
  - To capture relevant constraints and inefficiencies.
  - To account for environmental policy heterogeneity.

- Note: We do not always need to model the grid. While transmission losses can be economically relevant (e.g., 3-5%), probably not worth the trouble in markets without bottlenecks.

Modeling: the network in the wild

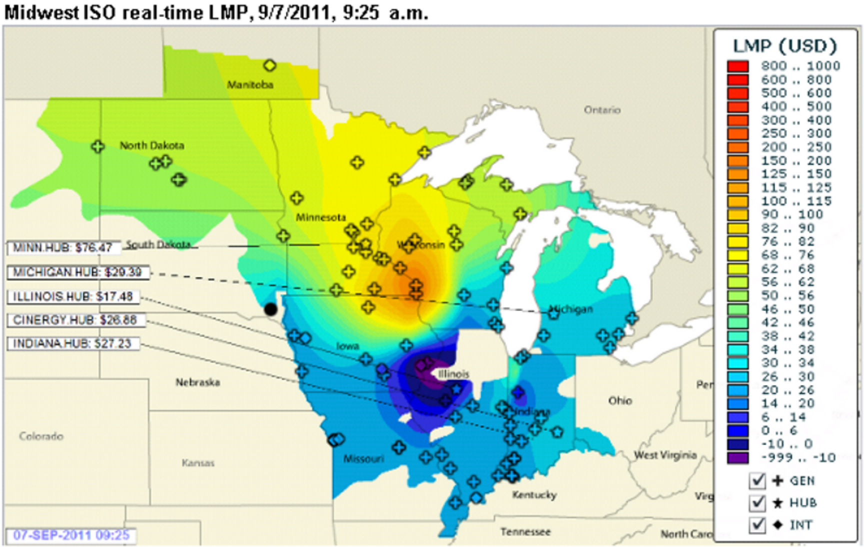
- More generally, electric energy is injected into the grid by all generators and withdrawn by all end users
- To maintain frequency, the quantity injected must always equal the quantity withdrawn
- Contrast this with other commodity markets
- Power flows in inverse proportion to the resistance it faces (Kirchhoff's laws), so that an injection or withdrawal anywhere affects the system everywhere else!

Electricity network externalities

- The key economic idea here is that there are externalities in electricity transmission networks.
  - Both positive and negative.
  - You are *hurt* if someone else's actions cause congestion.
  - You are *helped* if someone else's actions reduce congestion.

An *externality* is present whenever one agent's actions impact the utility or production of another agent through a non-price mechanism.

Nodal prices in markets are complicated!



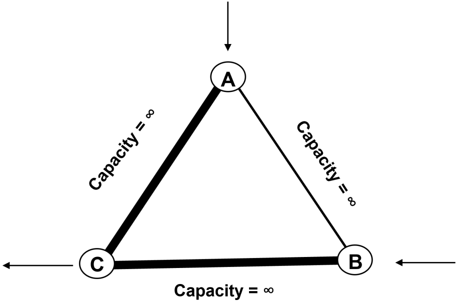
Simplifying networks in electricity models

- Electricity networks are a non-linear object that depends on the topological features as well as voltage, resistance, reactive power.
- An active research area in electrical engineering looks for formulations of the grid that are good enough but linear.
- Optimal power flow (OPF) models tend to work with a linearized direct current (DC) version of the grid.
- In Economics, we tend to use the simplest possible models.

Maybe a more useful take-away: if you want to build a simplified network model, electrical engineers might have a comparative advantage and it is best to borrow from them!

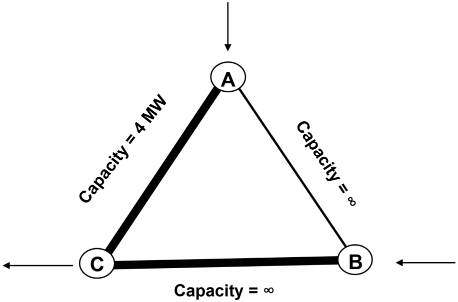
Loop flow example

- Consider this simple 3 node example.
- Nodes A and B are generators (supply only) and node C is a customer center (demand only). Imagine A is cheaper. Demand at C is 10 MWh.



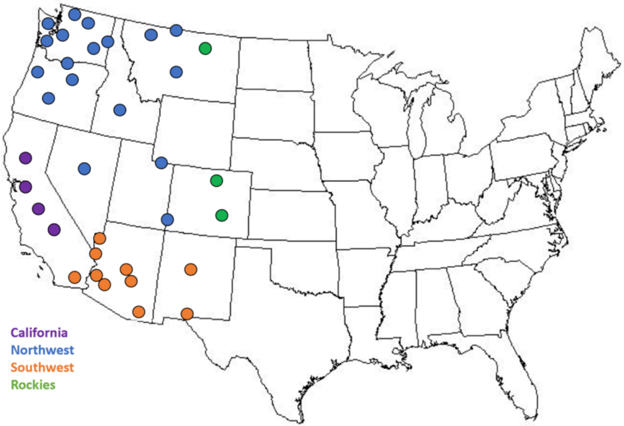
Loop flow example

- Now suppose capacity A→C is only 4MW.
- Let total demand in C be equal to 10MWh.
- Can A produce all 10MWh? Can B?
- How much can each produce?



Preview from today's practice

Figure A.1: Illustration of balancing authority regional designations

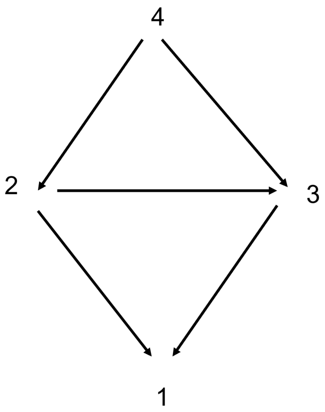


The line conditions

- Two inputs:
  1. Line size
  2. Flow factors

factors

region	12	13	42	43	23
2	0.623	0.378	-0.144	0.144	0.234
3	0.378	0.623	0.144	-0.144	-0.234
4	0.5	0.5	0.5	0.5	0



The flows can be expressed as constraints

- Flows are part of the market clearing condition:
  - Demand = Production in-state + incoming flows
- Lines are limited by their capacity and the flows which circulate according to the factors:

$$-lines_l \leq \sum_{r \notin CA} fct_l \times yflow_{rt} \leq lines_l$$

Challenge: Difficult to modify with grid changes, as factors need to be re-computed.

Practical implications for modeling transmission

- We can use electricity market software to build models of transmission (e.g., pyPSA).
- Unless we have a simple model with a few zones and a relatively simple topology, this is the way to go.
- If we use specialized software, we still want to keep the grid as simple as possible for our application.
- The grid is a complex object and it can clutter our understanding of the economics behind the model.

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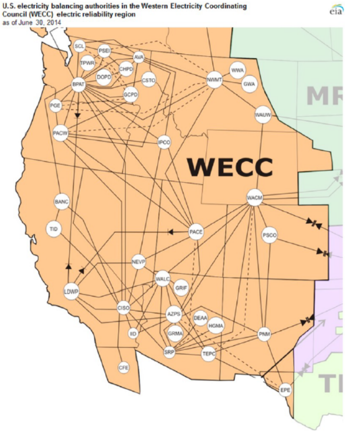
Today's application

- We will review a short paper examining the role of carbon border regulations to reduce "leakage" and "resource shuffling".
- **Concern:** electricity imports into California will claim that they are very clean and reduce the ambition and effectiveness of the policy.
  - This is a particular concern because California would like to claim that they have helped reduce emissions.
  - However, lots of emissions reductions can be achieved by just claiming that imports are cleaner, without much change in operations outside of California.
- To get at this: build a **model** with environmental policy + transmission.

California's experiment. . .

- A rich literature analyzes how border carbon adjustments (BCAs) can work in theory.
- California offers a rare opportunity to investigate a BCA in practice.

Since 2013, **electricity imports** have been taxed on the basis of assessed GHG emissions intensity.



California's BCA design

- California's GHG cap-and-trade program (AB23) regulates in-state power producers and importers.
  - Note: it also includes many other products, but BCA only applied to electricity.
  - This is because electricity consumption is much easier to monitor.
- Importers must hold permits to offset assessed GHG emissions. A 'default' GHG emissions intensity is set at 0.428 tonnes $CO2/MWh$.
- Imposing this default on all imports would discriminate against low- carbon, out-ofstate resources.
  - Qualifying importers can thus specify a lower carbon intensity

Resource “shuffling” 101

Reshuffling

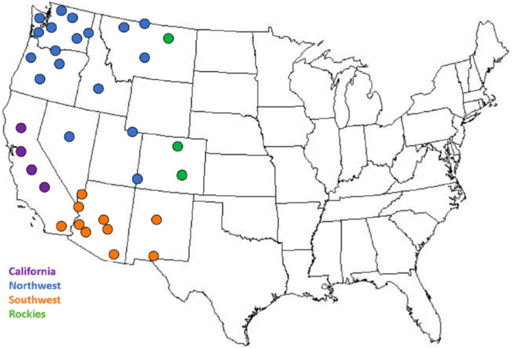
- Phenomenon by which products that were already clean are claimed by the regulated jurisdiction.
- One can think of it as a form of creative accounting or avoidance.
- It can reduce effectiveness of CBAMs.
- Particularly risky when sources are heterogeneous but final product is homogeneous $\rightarrow$ electricity!

Fowlie, Petersen, and Reguant (2021)

- We adapt a model of the western electricity market eveloped by Bushnell et al. to simulate hourly (static) equilibrium outcomes in 2019.
  - Hourly data from hydro, nuclear, wind, solar, and other renewable energy production are directly incorporated.
  - Operating costs and emissions intensities for thermal power plants are calibrated using eGRID.
  - Transmission grid is modelled using a DC flow approximation that link four WECC sub-regions.
  - Region-specific hourly demand functions calibrated using a constant elaticity of 0.1.
  - We assume an exogenous carbon price of \$17/ton.
  - To account for local resource adequacy considerations, impose must-run constraints on some in-state resources.

Reshuffling concerns in the map

- Only the purple area can be regulated.
- All areas participate in the electricity market.
- Wind/solar farms in other parts can claim to be exporting to California.
- This makes it very easy for California to "reduce" its emissions and achieve its carbon target, while not much is happening.



Modeling: policy

- **Complete regulation**: All western electricity producers are regulated under the same carbon pricing regime.

Variable operating costs	
Inside California:	$c_i + \tau.e_i$
Out-of-state:	$c_i + \tau.e_i$

- **Incomplete regulation**: Only producers in California are subject to the carbon tax.

Variable operating costs	
Inside California:	$c_i + \tau.e_i$
Out-of-state:	c_i

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Modeling: policy – two BCA designs (in paper)

- **Uniform BCA regulation**: All imports into California are assigned the same default emissions intensity d.

Variable operating costs	
Inside California:	$c_i + \tau.e_i$
Out-of-state:	$c_i + d$

- **Differentiated BCA regulation**: Importers can opt-out of the default and specify the carbon intensity of their out-of-state generation sources.

Variable operating costs	
Inside California:	$c_i + \tau.e_i$
Out-of-state:	$\min c_i + \tau.d, c_i + \tau.e_i$

Modeling: policy – summary

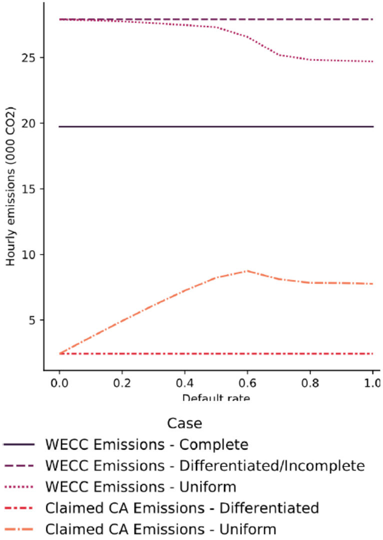
- We consider several cases.
  1. No regulation, tax is 0.
  2. Uniform tax, every region.
  3. CA tax only.
  4. Tax of imports at default rate, with opt-out. Uniform BCA
  5. Tax of imports at default rate, no opt-out.

Table D.1: Taxed Emissions Rates by Case

Case	**Taxed Emissions Rate (er_tax) Definition**
Complete Regulation	$\text{er\_tax}_{u,r} = \text{er}_{u,r}$
Incomplete Regulation	$\text{er\_tax}_{u,r} = \text{er}_{u,r} * \text{istax}_{u,r}$
Uniform BCA	$\text{er\_tax}_{u,r} = \text{er}_{u,r} * \text{istax}_{u,r} + \text{default} * (1 - \text{istax}_{u,r})$
Differentiated BCA	$\text{er\_tax}_{u,r} = \text{er}_{u,r} * \text{istax}_{u,r} + MIN(\text{default}, \text{er}_{u,r}) * (1 - \text{istax}_{u,r})$

Preview of findings: Large reshuffling risk

- We estimate very large risk.
- Extreme case: with differentiated BCA, WECC emissions do not decrease, even if California can claim to be cleaner.
- In practice, regulators put oversight in place to avoid this kind of overclaiming.
- Comparing simulations to data, Realized GHG emissions outcomes in 2019 suggest leakage and underaccounting not as bad as we might expect.



Let's practice.

Next class

- **Demand I.**
  - How do consumers respond to feedback in the residential market?
  - What does the experimental data say?
  - Can we test behavior in a non-experimental setting?