Empirical Methods for the Analysis of the Energy Transition

Slide Set 6

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Roadmap

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 → 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

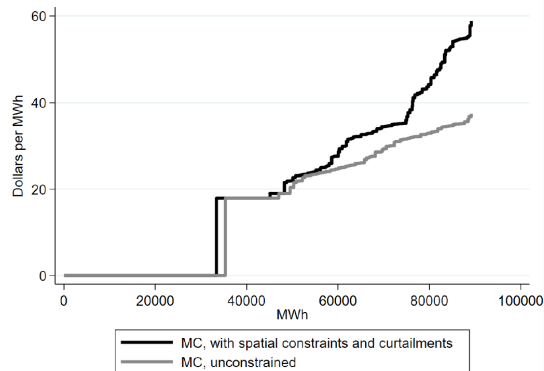- **Unit-level hourly generation** for fossil plants:
  - ▶ Individual units within plants (coal, gas, oil)
  - ▶ Technology type (boiler, combined cycle, combustion turbine)
  - ▶ Location and ownership (IOU vs. IPP)

- **System-level hourly generation**:
  - ▶ Renewables and nuclear at the ISO level
  - ▶ Reported curtailments by ISO

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.
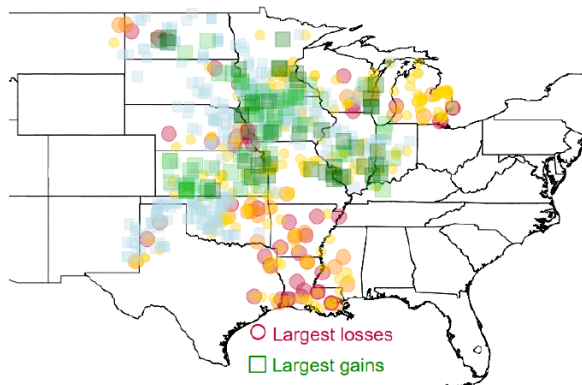
Key findings: aggregate effects

- Transmission constraints generate large and growing inefficiencies.

- Excess generation costs reach:
  - ▶ ~ $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.
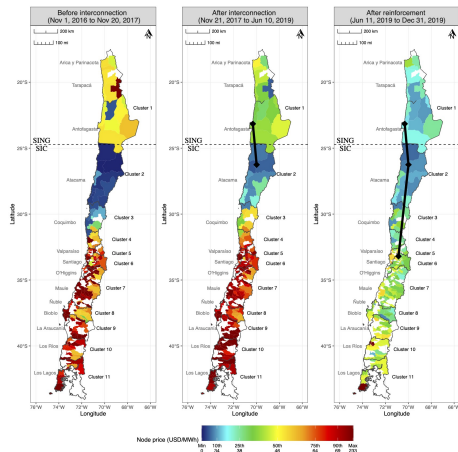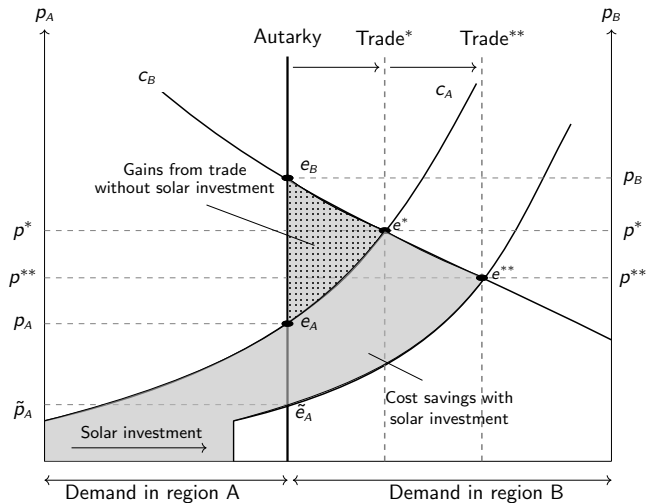
Political economy implications and takeaway

- 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

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

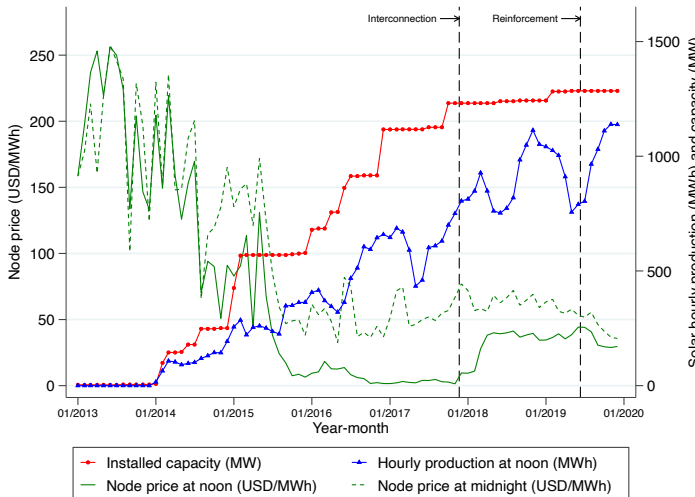- Our method uses insights from Cicala (2022)
  - c_t is the observed cost
  - c_t^* is the nationwide merit-order cost (least-possible dispatch cost under full trade in Chile)
  - $I_t = 1$ after the interconnection; $R_t = 1$ after the reinforcement
  - X_t is a set of control variables; θ_t is month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

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
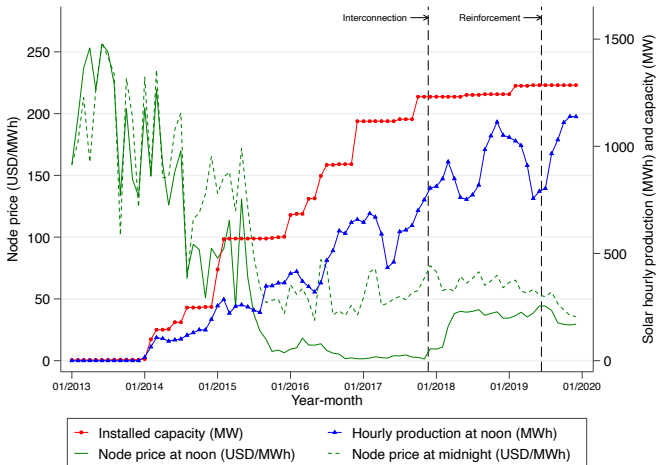
Solar investment occurred in anticipation of integration

- 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**
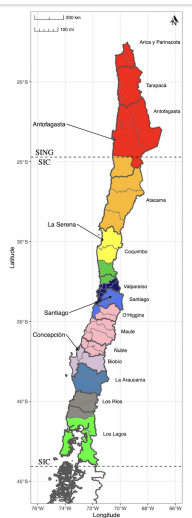
Buidling a model to get at the full effect)

- 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.

$$(1) \quad \sum_j q_{ztj} + \sum_l \Big((1 - \delta_1) \, imp_{lzt} - exp_{lzt} \Big) \geq \frac{D_{zt}}{1 - \delta_2}, \quad \forall z, t,$$

$$(2) \quad 0 \leq imp_{lzt} \leq f_{lz}, \quad 0 \leq exp_{lzt} \leq f_{lz}, \quad \forall l, z, t,$$

$$(3) \quad \sum_z (imp_{lzt} - exp_{lzt}) = 0, \quad \forall l, t,$$

Note: Computationally, this is a simple linear constraint.

Dynamic responses are solved as a zero-profit condition

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

- 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
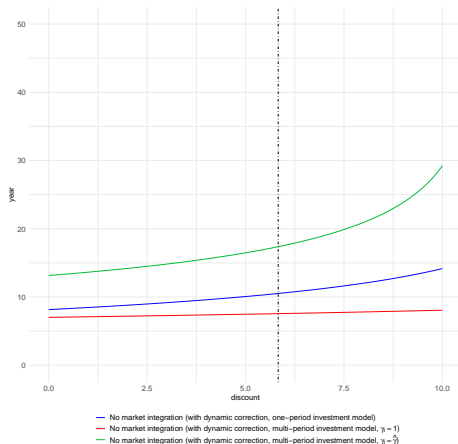
- Cost of the interconnection and reinforcement

  - ▶ $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?

Roadmap

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!
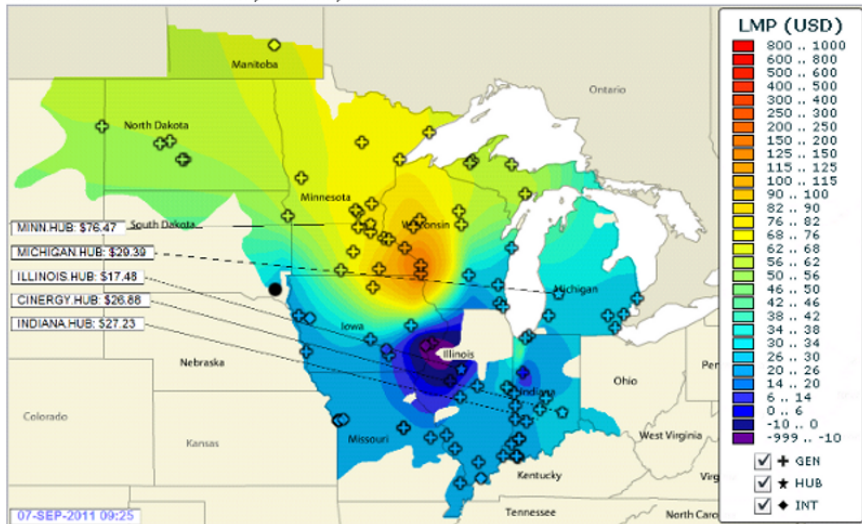
Electricity network externalities

- 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!

Midwest ISO real-time LMP, 9/7/2011, 9:25 a.m.

LMP (USD)

	800 .. 1000
	600 .. 800
	500 .. 600
	400 .. 500
	300 .. 400
	250 .. 300
	200 .. 250
	150 .. 200
	125 .. 150
	115 .. 125
	100 .. 115
	90 .. 100
	82 .. 90
	76 .. 82
	68 .. 76
	62 .. 68
	56 .. 62
	50 .. 56
	46 .. 50
	42 .. 46
	38 .. 42
	34 .. 38
	30 .. 34
	26 .. 30
	20 .. 26
	14 .. 20
	6 .. 14
	0 .. 6
	-10 .. 0
	-999 .. -10

MINN HUB: $76.47
MICHIGAN HUB: $20.39
ILLINOIS HUB: $17.48
CINERGY HUB: $26.88
INDIANA HUB: $27.23

✓ + GEN
✓ ★ HUB
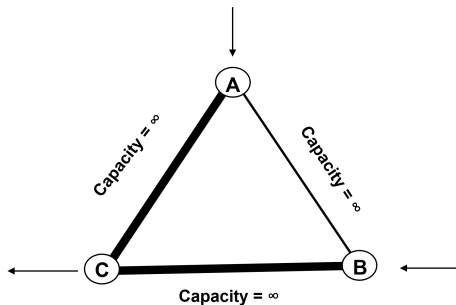✓ ◆ INT

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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!
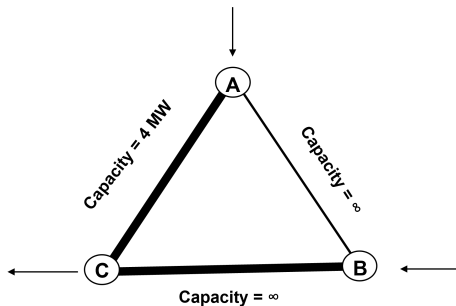
Loop flow example

- 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.
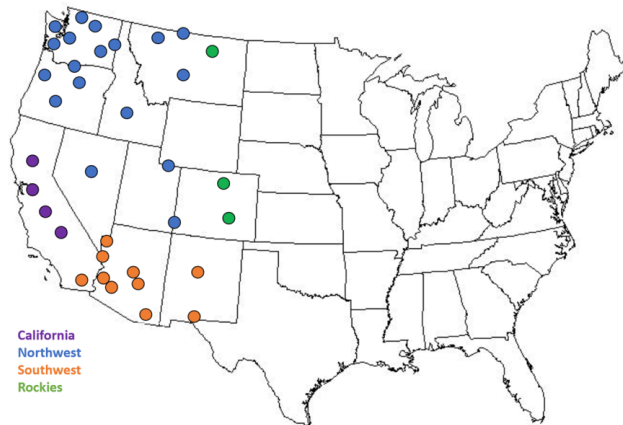
Loop flow example

- 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

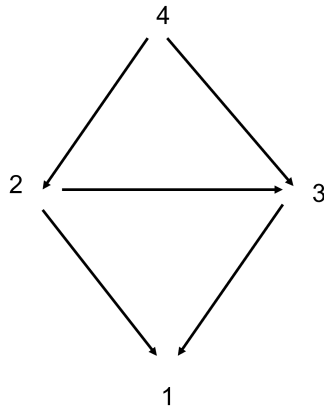Figure A.1: Illustration of balancing authority regional designations

California
Northwest
Southwest
Rockies

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.
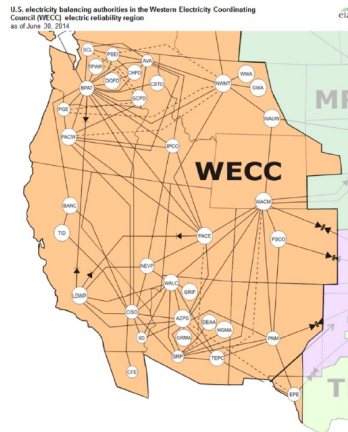
Roadmap

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 CO_2/MWh.

- Imposing this default on all imports would discriminate against low- carbon, out-ofstate resources.
    - Qualifying importers can thus specify a lower carbon intensity
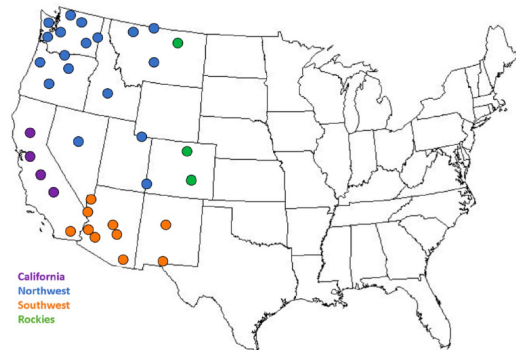
Resource "shuffling" 101

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.

California
Northwest
Southwest
Rockies

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

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:	$\min c_i + \tau.d, c_i + \tau.e_i$

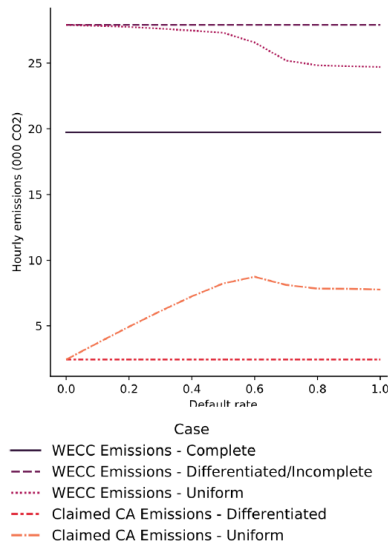# Modeling: policy – summary

- 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.

Case
— WECC Emissions - Complete
-- WECC Emissions - Differentiated/Incomplete
⋯ WECC Emissions - Uniform
-·- Claimed CA Emissions - Differentiated
-·- Claimed CA Emissions - Uniform

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?