Empirical Methods for the Analysis of the Energy Transition

Slide Set 5

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Econ 498-1

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I. Dynamics in the electricity sector

Modeling of dynamics

In any sector, important to decide how dynamics are modeled:

- One-shot vs. multiple periods?
- Stationary infinite horizon vs. finite horizon?
- Relevant dynamic variables vs. those that can be simplified?
- Strategic vs. competitive vs. social planner? When are the last two equivalent?
- Level of aggregation: hourly, monthly, annual?

Note: For the IO students, you will cover computational and theoretical general aspects of dynamics in Igal's class.

Dynamics in electricity

Several dimensions involve dynamics:

- Startup of power plants (Reguant 2014; Cullen, 2015).
- Allocation of hydro resources (Crampes and Moreaux, 2001; Bushnell, 2003).
- Batteries (Karaduman, 2021; Butters, Dorsey and Gowrisankaran, 2022).
- Divestitures (Linn and MacCormack, 2019).
- Renewable entry (Gonzales, Ito, and Reguant, 2023).

Implementation in each of the papers can be widely different from a technical perspective!

Competitive equilibrium definition

- In energy markets, firms need to recover their capital investment, which are often very sizeable:
  - Nuclear plant, gas power plant, wind mill...
- Firms make profits in day-to-day operations.
- In the long-run definition of equilibrium, profits cover the long run fixed costs of the marginal unit.

Competitive investment

- From "day 3", we have a zero profit condition for the marginal entrant in a technology:

$$K_i \geq 0 \perp F_i - \sum_t \psi_{it} \leq 0 \quad \forall i$$

- Remember ψ_{it} is the infra-marginal rent of the technology (for the last unit).
- Other firms / technologies that are not marginal could be making profits.
- Positive entry requires the technology to not always be marginal (i.e., $P > MC$ for some hours).

Note: In the presence of short-run market power, ψ could still distort entry even if entry is competitive, see problem set (about to go live!).

Empirical interpretation

- Firms look forward to forecast industry supply, possible demand, and possible profits, then decide how much to invest.
- A firm invests if the expected net present value of short-run profits exceeds the investment cost.
- Different beliefs about future demand and costs are one cause of differentiated firm investments.
- Additionally, this is a completely changing environment (costs, demand due to electrification, regulation,....!).
- Some investments will end up being profitable, while others will not. In practice, almost no firms exactly break even.

The peak-load pricing model

If the price is equal to the marginal cost of each unit, they will also recover the fixed cost. (Boiteaux, 1960).

- Building a market with short-run efficiency guarantees the optimal amount of entry of each technology.

Short-run efficiency

- The market clears where demand crosses supply.
- During peak periods this may be where supply is vertical.
- The extent to which price exceeds marginal cost at peak output represents the "shadow value" of more capacity.
- Marginal cost pricing essential for short-run efficiency.

Long-run efficiency

- The shadow value of capacity represents the net revenue that a new entrant could earn if it has costs equal to the marginal producer.

- If shadow value is greater than fixed cost of capacity, new entry will occur and drive down prices.
- If shadow value is less than fixed cost of capacity, exit will occur and prices will rise.

Limitations to the peak-load pricing model

- The Boiteux result:
  - If P=MC, we will get the right kind and amount of power plants
- Regulators worry that there will not be enough investment.
  - Boiteaux model is too stylized in practice.
  - Constant market and non-market interventions to guarantee security of supply.

Some of the limitations of the Boiteaux model

- Volatility
  - The market is too volatile, power plants rely on very few hours of the day when electricity is very expensive.
- "Missing money" problem (e.g., see work by Joskow)
  - The "energy only" market is not enough to compensate the power plants, regulators limit prices.
  - Electricity markets often complemented with capacity payments/markets that pay existing investments to "stick around".
- Hold up
  - Rules in the market change too often, and especially when prices raise.

Hold-up

- Concerns about opportunistic behavior by the regulator.
  - For peaking plants, most revenues come from days of extremely high prices.
  - Investors could be concerned about discretionary behavior in those instances.

- More broadly, changes in policy goals can have important impacts on firms revenue.
- Regulatory intervention can also impact rents (e.g., clawback of carbon price rents).
- Unfortunately, credibility in ability to pay can also lead to hold up even in fixed-price auctions!!! (Spanish experience, Ryan, 2023).

The European energy crisis and the peak-load pricing model

- The natural gas crisis in Europe led to extreme prices that made all produced electricity more expensive (via the short-run marginal price in the peak-load pricing mechanisms, set typically by gas plants).
- Many governments gradually put regulations in place to limit infra-marginal rents.
- Policy and academic debates have emerged on whether these policies have efficiency implications via short and long-run distortions.
- *Do they affect efficiency? In which instances?*

Renewables and the peak-load pricing model

- This is an active area of research *and* policy-making: theory and empirics quite open.
- How should be markets designed in the presence of renewable energy (high fixed cost, almost zero marginal cost)?
- What is the role for centralized auctions for new and existing investments?
- Are renewables cannibalizing themselves and deterring future investments?
- See two references as potential “higher-level” readings (Botterud and Auer, 2018, Fabra, Motta, and Petiz, 2022).

II. Entry, renewables, and transmission expansion

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.

- 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
- 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

- Dynamic benefits from transmission expansion can be substantial.
- However, transmission projects are difficult to implement.
  - 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.

Modeling the grid: why?

- Modeling different regions can be relevant under several circumstances:
  - To account for resource heterogeneity.
  - To account for environmental policy heterogeneity.

- The grid itself is important to model when congestion is an issue–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

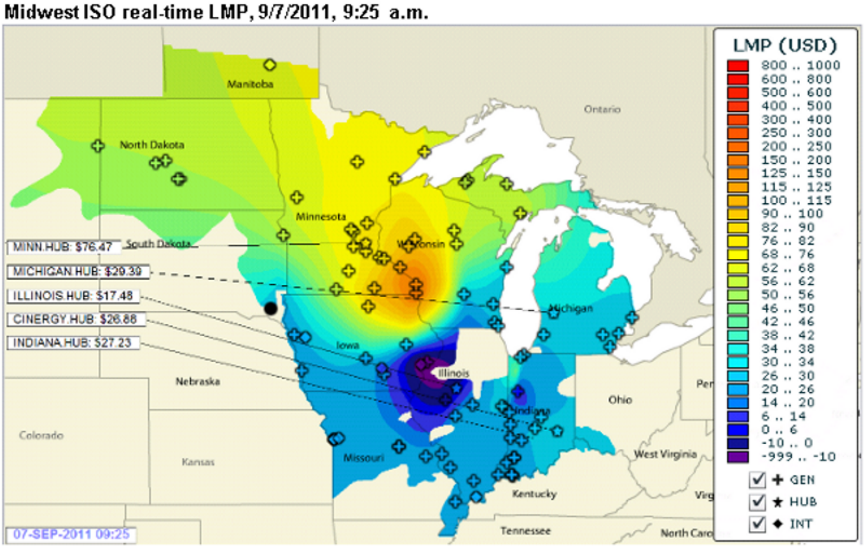
- More generally, electric energy is injected into the grid by all generators and withdrawn by all end users
- To maintain frequency, the quantity injected must always equal the quantity withdrawn
- Contrast this with other commodity markets
- Power flows in inverse proportion to the resistance it faces (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!



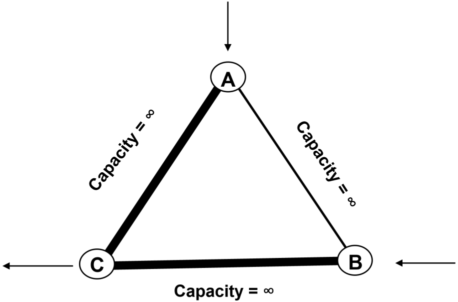
Simplifying networks in electricity models

- 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!

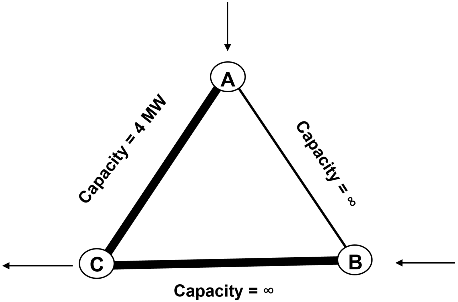
Loop flow example

- 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.



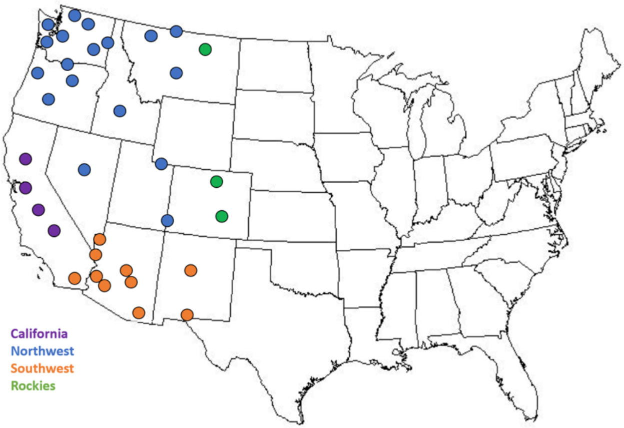
Loop flow example

- 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?



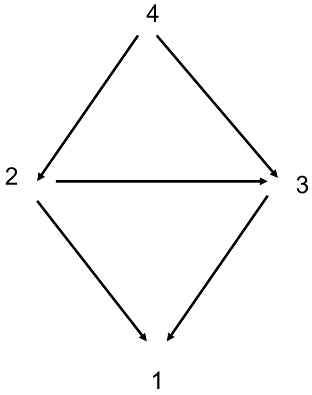
Preview from today's practice

Figure A.1: Illustration of balancing authority regional designations



The line conditions

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



The line conditions: 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

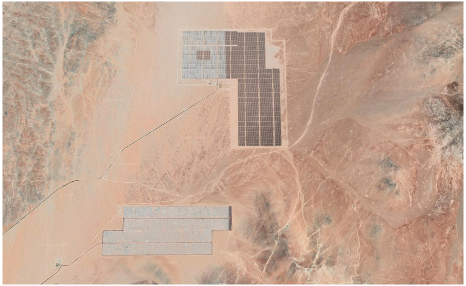
- Flows are part of the market clearing condition:
  - Demand $=$ Production in-state $+$ incoming flows
- Lines are limited by their capacity and the flows which circulate according to the factors:

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

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

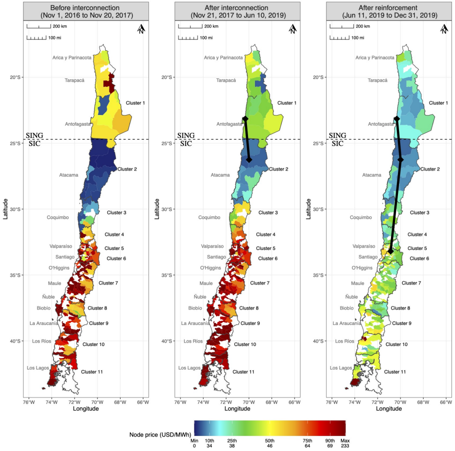
A case study from Chile

- The Chilean context provides a unique case study.
- Chile has large solar resources, but best spots disconnected from demand centers (Antofagasta and Atacama desert).
- Chile successfully connected these areas via ambitious grid projects in 2017 and 2019.



Gonzales, Ito, and Reguant (2022)

- Gonzales, Ito, and Reguant (2022) 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.



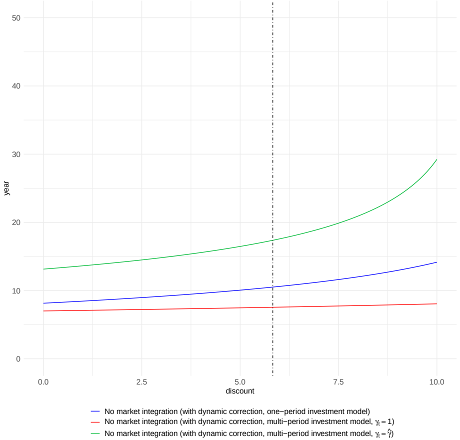
Buidling a model to get at the full effect (with JuMP!)

- 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.

```julia
### MODEL                ##################################################
# ----------------------------------------------------------------------- #
# Set basic model
model = Model(optimizer_with_attributes(Gurobi.Optimizer, "NonConvex"=>2, "OutputFlag"=>1, "MIPGap"=>1e-5));
# model = Model(NLopt.Optimizer);
# set_optimizer_attribute(model, "algorithm", :LD_MMA)
set_silent(model);

# quantity produced and flows between clusters
@variable(model, D_hold[c=1:C, h=1:H] >= demand[c,h]); # demand variable, weakly larger than scheduled demar

# unit-level non-gas generation
@variable(model, dfs.thermal_lb[i] <= q[i=1:I] <= dfs.capacity[i]);

# CONSTRAINT on ramping (only for coal units)
@variable(model, q_last[i=1:I] >= 0); # last hour's coal production
@constraint(model, [i = list_coal_hr1], -0.01 <= q_last[i] -  dfs.last_coal[i]  <= 0.01); # for hours == 1
@constraint(model, [i = list_coal_incomplete], q_last[i] <= 0.01);
@constraint(model, [i = list_coal_index], - 0.01 <= q_last[i] - q[dfs.last_index[i]] <= 0.01); # for hours >
@constraint(model, [i = 1:I], - dfs.change_bound[i] <= q[i] - q_last[i] <= dfs.change_bound[i])

# hydro generation
@variable(model, dfd.min_hydro[j] <= qh[j=1:CH] <= dfd.max_hydro[j]);  # hydro generation (must be less thar
@variable(model, 0.999 * cluster_hydro.period_hydro_cluster[c]/1000.0 <= qhydro_period[c = 1:C] <=
        1.001 * cluster_hydro.period_hydro_cluster[c]/1000.0); # cluster-level weekly hydro production

# gas generation
@variable(model, dfd.min_ng[j] <= qg[j=1:CH] <= dfd.max_ng[j]);  # natural gas generation (must be less thar
@variable(model, 0 <= qg_part1[j=1:CH] <= dfd.p75_gen[j]);
@variable(model, 0 <= qg_part2[j=1:CH] <= dfd.p90_gen[j] - dfd.p75_gen[j]);
@variable(model, 0 <= qg_part3[j=1:CH]);
@constraint(model, [j=1:CH], qg[j] == qg_part1[j] + qg_part2[j] + qg_part3[j]);

@variable(model, 0 <= q_solar[j= 1:CH] <= dfd.prod_solar_cluster_adjusted[j]); # solar generation
@variable(model, 0 <= q_wind[j= 1:CH] <= dfd.prod_wind_cluster[j]); # wind generation
```

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?



II. The grid and reshuffling in California

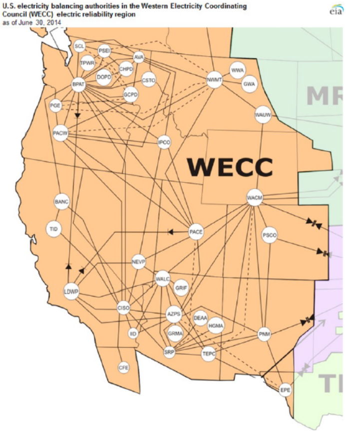
Today's application

- 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

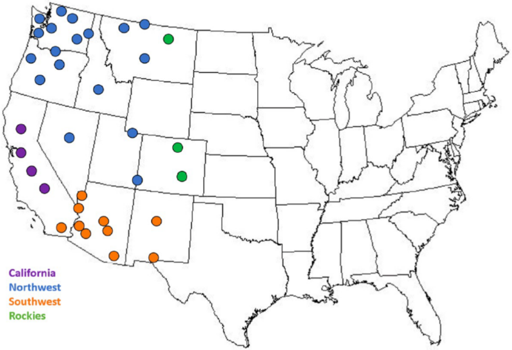
- Phenomenon by which products that were already clean are claimed by the regulated jurisdiction.
- One can think of it as a form of creative accounting or avoidance.
- It can reduce effectiveness of CBAMs.
- Particularly risky when sources are heterogeneous but final product is homogeneous $\rightarrow$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

Modeling: policy – two BCA designs

- **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

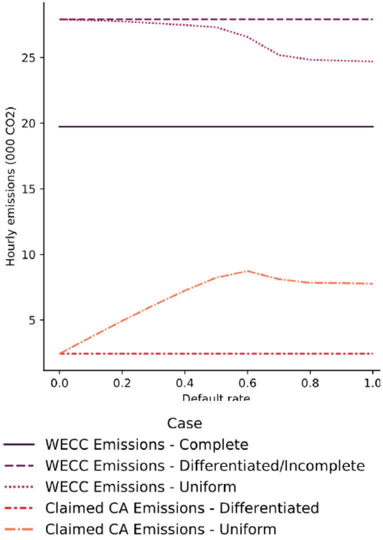
- We consider several cases.
  1. No regulation, tax is 0.
  2. Uniform tax, every region.
  3. CA tax only.
  4. Tax of imports at default rate, with opt-out. Uniform BCA
  5. Tax of imports at default rate, no opt-out.

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.



Next class

- **Supply II.**
  - 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?

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