Empirical Methods for the Analysis of the Energy Transition: Day 3

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Today's outline

1) Environmental regulations in electricity markets
2) Transmission constraints and climate policy
3) Case study: Leakage in the California electricity market
   - Overview of paper
   - Code (afternoon)

Pollution and climate change policies

Permit markets have been used in electricity to internalize pollution in several settings:

- **SO_2**: Acid Rain Program (EEUU)
- **NO_x**: Budget Trading Program, RECLAIM
- **CO_2**: ETS (Europe, Australia, New Zeland), RGGI, AB32 (EEUU)

Pollution permits **interact with the existing institutional features of electricity markets** (regulation, market power, technology mix, profitability).

Responses to environmental regulation

Electricity firms can respond to pollutions costs in several ways:

- **Short-run:** shift production to cleaner inputs or different technologies
- **Medium-run:** perform plant refurbishing and install scrubbers
- **Long-run:** change investment plans to a cleaner mix

Depending on the pollutant, some abatement options are more feasible than others.

Today focus on *evidence of response* in the **short** and **medium term**.

Analyzing responses to pollution permits

Several **empirical strategies** have been used to identify the importance of **emissions permits** in electricity markets.

Some examples:

- Impacts on prices/short-run outcomes and compliance
  - Bushnell et al. (2013) (regression discontinuitiy), Fabra and Reguant (2014) (IV pass-through), Fowlie (2010) (random effects)
- Endowment effect
  - Fowlie and Perloff (2012), Reguant and Ellerman (2008)
- Counterfactual simulations (case study)
  - Fowlie, Reguant and Ryan (2014), Fowlie and Mueller (2013), Toyama (2020)

Bushnell, Chong and Mansur (2013)

Profiting from Regulation: Evidence from the European Carbon Market

By James B. Bushnell, Howard Chong, and Erin T. Mansur*

We investigate how cap-and-trade regulation affects profits. In late April 2006, the EU CO_2 allowance price dropped 50%, equating to a €28 billion reduction in the value of aggregate annual allowances. We examine daily returns for 552 stocks from the EUROSTOXX index. Despite reductions in environmental costs, we find that stock prices fell for firms in both carbon- and electricity-intensive industries, particularly for firms selling primarily within the EU. Our results imply that investors focus on product price impacts, rather than just compliance costs and the nominal value of pollution permits.

JEL: G14, Q50, H23, Q54, H22
Keywords: Climate Regulation, Incidence, Event Study

Summary of BCM (2013)

What does the paper do?

1) Explore the impacts of carbon prices on firms' stock value
2) Exploit an exogenous discontinuity in carbon prices due to information updating

What does the paper find?

- Responses of firms to the change in prices in line with predictions
- Cleaner firms suffered relatively more from the drop in carbon prices
- Importantly, firms can be *worse off* from reduced environmental compliance

Context and Data

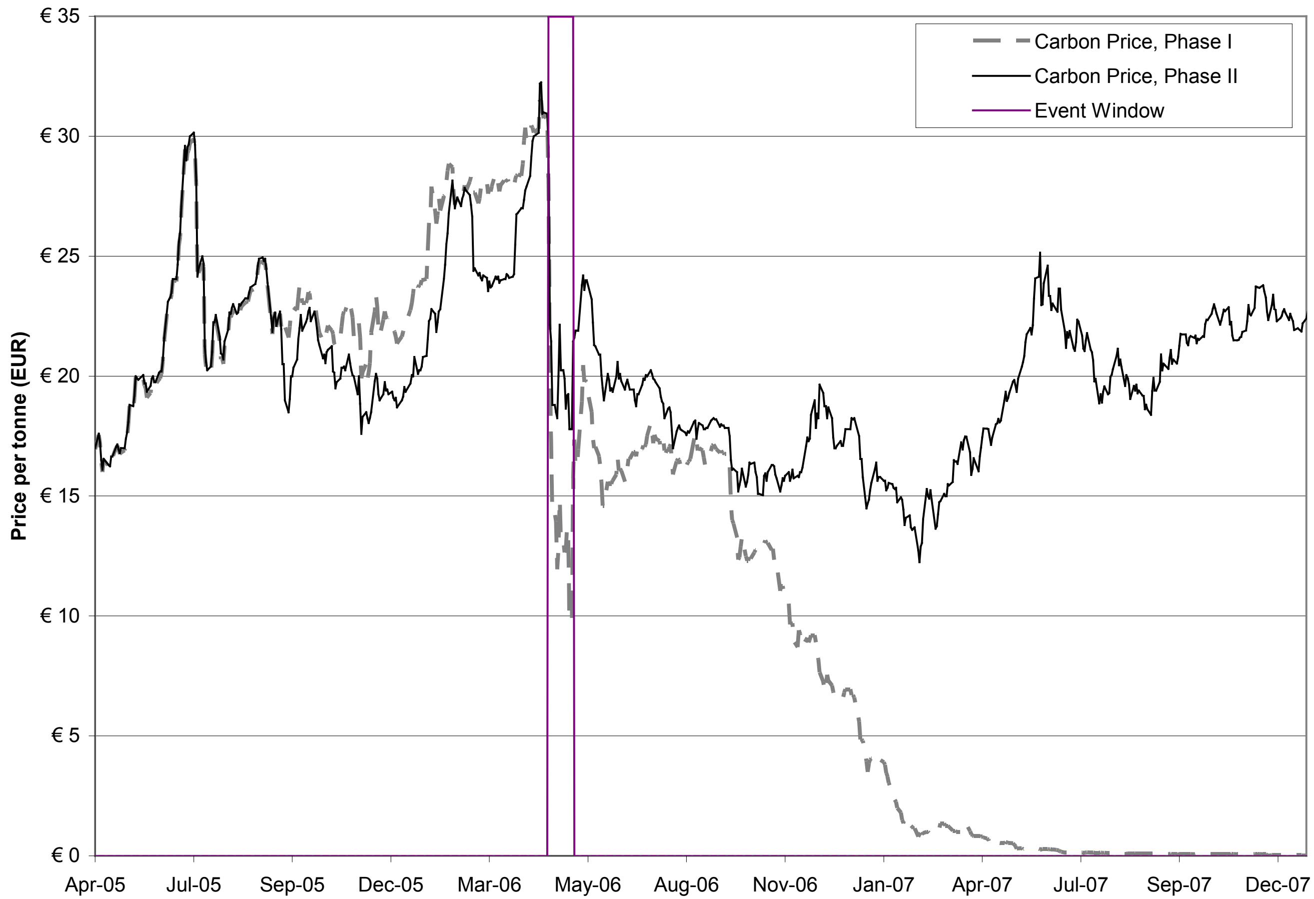
- Study effects of cap-and-trade regulation on firm profits during EU ETS trial period (2005-2007).
- Focus on sudden drop in prices in late April, 2006.
- Updated information in the stringency of the cap induced prices to collapse rapidly. M
    - atch firms to their publicly traded stocks and examine daily returns around price jump.
    - Match some to their emissions.

Goal: Study market response to changes in regulatory costs.

EU Emissions Trading Scheme

- Cap-and-trade market for tons of CO_2
- Covers mostly static polluting installations in power generation and manufacturing
- First phase: 2005-2007, self-contained
- Emissions allowances given for free to most installations
- Firms can trade permits across countries/ industries:
  - Permits have an opportunity cost

Drop in ETS prices



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Methodology

- Look at returns of firms affected by the regulation around the discontinuity.
- Stock market data (firm-level and Dow Jones).
- Emissions data from Community Independent Transaction Log (CITL).
- Basic event study regression:

$$S_{ijt} = \alpha_i + \beta_i M_t + \gamma_j EVENT_t + \epsilon_{ijt}$$

Event results

TABLE 1— STOCK MARKET THREE-BUSINESS DAY CUMULATIVE ABNORMAL RETURNS BY INDUSTRY

NACE	Industry Description	Observations	-44% Permit Price Drop April 26, 2006 Main Event		+16% Permit Price Rise January 13, 2006 Event	
10	Coal and lignite mining	2	-0.032	(0.021)	0.045	(0.034)
11	Crude petroleum extraction	20	-0.032	(0.017)*	0.038	(0.017)**
27	Basic metals	15	-0.031	(0.011)***	0.055	(0.027)**
90	Sewage and refuse	1	-0.027	(0.012)**	0.037	(0.033)
61	Water transport	2	-0.027	(0.020)	0.001	(0.023)
23	Refining and coke	2	-0.027	(0.015)*	0.037	(0.016)**
30	Computer manufacturing	2	-0.023	(0.007)***	-0.056	(0.055)
13	Metal ores mining	7	-0.023	(0.023)	0.096	(0.034)***
16	Tobacco manufacturing	3	-0.019	(0.005)***	0.019	(0.016)
40	Electricity and gas	26	-0.017	(0.014)	0.049	(0.026)*
70	Real estate	16	-0.016	(0.003)***	0.023	(0.010)**
41	Water	4	-0.016	(0.008)*	0.035	(0.027)

If regulation costs go down, how can profits go down?

Negative impact of price drop

Additional Effects

- In the EU-ETS, and similar to other cap-and-trade programs, most permits were allocated for free.
- Consider the profits of a firm:

$$\pi_i = P(q_i + q_{\neq i})q_i - C_i(q_i, \omega) + \tau A_i - \tau r_i(q_i, I_i)q_i - k(I_i)$$

ω: input costs

A_i: free allocation; τ : emissions price

r_i : emissions rate; I_i : abatement investments

Effect (local):

$$\frac{d\pi_i^*}{d\tau} = P'\frac{\partial q_{\neq i}^*}{\partial \tau}q_i^* + \left[P'\frac{\partial q_{\neq i}^*}{\partial \omega}q_i^* - \frac{\partial C}{\partial \omega}\right]\frac{\partial \omega}{\partial \tau} + [A_i - r_i q_i^*]$$

Revenue increase due to reduced output

Indirect impact on costs

Net position

Focus on Electricity Firms

- Exploit heterogeneity in technology mix.
- Cleaner firms have small effects on marginal costs but benefit from high electricity market prices.
- Dirtier firms can have ambiguous effects:
  - Higher costs from higher carbon prices
  - Reduced revenues from permits if long
  - Reduced profits for clean share of mix

- Authors find that stock value decreased more for cleaner firms in response to lower carbon prices.

Results for electricity companies

Table 3—Stock Market Cumulative Abnormal Returns for Firms in the Electricity Sector

Stock name	Main event (1)		January counter event (2)		Carbon per MWh (3)	Carbon per equity (4)	Allowances per equity (5)	Net allowances per equity (6)
Fortum	−0.088	(0.075)	0.086	(0.060)	0.214	142.8	157.1	14.3
Verbundgesellschaft	−0.086	(0.061)	0.099	(0.063)	0.252	610.5	535.5	−75.0
British Energy Group	−0.071*	(0.043)	0.076**	(0.032)	0.108	1236.2	779.2	−457.0
EDF	−0.050*	(0.028)	0.093**	(0.044)	0.104	459.1	402.6	−56.4
RWE (XET)	−0.045**	(0.023)	0.054	(0.052)	0.909	3587.1	3436.8	−150.3
Vestas Wind	−0.026	(0.033)	0.086*	(0.049)				
A2A	−0.024***	(0.004)	0.066**	(0.027)	0.287	812.1	1029.8	217.8
Atel Holding 'R'	−0.022	(0.015)	0.046*	(0.025)	718.1	821.6		
DRAX Group	−0.019	(0.047)	0.110***	(0.012)	1.046	4384.0	3071.8	−1312.2
United Utilities Group	−0.018***	(0.005)	0.030*	(0.016)	0.1	0.1		
EDP Energias de Portugal	−0.015	(0.011)	−0.018	(0.025)	0.712	1283.8	1221.2	−62.6
Solarworld	−0.013	(0.024)	0.077***	(0.026)				
International Power	−0.012**	(0.005)	0.091	(0.067)	0.611	1203.1	1098.4	−104.7
E.ON	−0.007	(0.015)	0.003	(0.028)	0.525	1196.0	1090.8	−105.2
Red Electrica de Espana	−0.005	(0.012)	0.055*	(0.03)				
Scot. & Southern Energy	−0.004	(0.010)	0.045*	(0.027)	0.819	1626.7	1178.7	−447.9
ENEL	−0.003	(0.006)	0.037	(0.037)	0.501	1320.2	1133.3	−186.8
National Grid	−0.001	(0.007)	0.022	(0.040)				
Terna	−0.001	(0.010)	0.021	(0.037)				
Sofina	−0.006	(0.013)	0.026*	(0.016)				
Union Fenosa	0.004	(0.005)	0.024	(0.015)	0.972	1740.3	1382.7	−357.6
Schneider Electric	0.011	(0.020)	0.003	(0.013)				
Iberdrola	0.015***	(0.002)	0.010	(0.013)	0.349	608.2	529.7	−78.6
Public Power	0.052***	(0.012)	0.014	(0.010)	0.982	11659.6	11550.4	−109.2
Coefficient estimates					0.071**	7.445***	7.175***	−5.937
					(0.033)	(1.924)	(2.098)	(31.510)

Conclusions BCM (2013)

- Paper presents evidence that stock market responded to the event in the EU ETS.
- The stock market valuation captured the effects of carbon on firms' portfolios, not just compliance costs.
- Evidence is somewhat mixed in its quantification, unclear whether the impacts are as large as "theory would predict", or just suggestive.

Fabra and Reguant (2014)

Pass-Through of Emissions Costs in Electricity Markets†

By Natalia Fabra and Mar Reguant*

We measure the pass-through of emissions costs to electricity prices. We perform both reduced-form and structural estimations based on optimal bidding in this market. Using rich micro-level data, we estimate the channels affecting pass-through in a flexible manner, with minimal functional form assumptions. Contrary to many studies in the general pass-through literature, we find that emissions costs are almost fully passed through to electricity prices. Since electricity is traded through high-frequency auctions for highly inelastic demand, firms have weak incentives to adjust markups after the cost shock. Furthermore, the costs of price adjustment are small. (*JEL* D44, L11, L94, L98, Q52, Q54)

Pass-through in economics

- Pass-through: price change after a cost shock.
  - Industrial Organization: merger assessment
  - International Economics: exchange rates
  - Public Economics: tax incidence

- Empirical measurement of pass-through, challenging in most markets.
  - Marginal costs non-observable and/or endogenous
  - Reliance on structural forms
  - Implications for pass-through?

This Paper

Pass-through of emissions costs to electricity prices

1. Measure pass-through
2. Decompose determinants of pass-through

Policy relevant topic:

- Cap&Trade programs for emissions control
- Efficiency vs distributional concerns
    - Cost internalization is necessary for efficiency
    - Distributional concerns of pass-through

Some advantages of electricity markets

- Electricity markets, unique setting for a pass-through analysis
  - Detailed bid data: supply and demand
  - Reliable cost data
  - Emissions costs well measured
  - Emissions costs relevant and heterogeneous
  - Plausibly exogenous to the firms in our market
  - Strategic behavior well understood

Spanish Electricity Market

- Liberalized electricity market since 1998
- Relatively insulated from the rest of Europe
- Daily auctions to sell and buy electricity
- Production based on thermal plants (coal, gas), nuclear, hydro and renewables
- High concentration: 2 large+2 small firms
- Retail prices mostly regulated

Bid Data

- Market clearing prices and quantities
- Hourly bidding data at the wholesale electricity market (demand and supply)
    - Step-wise bids at the unit-level (generators) or demand-unit level (retailers, pumped storage, industrial customers)
    - This allows us to construct supply functions, demand functions, residual demand functions and to identify the price-setting unit.

Cost Data

Marginal costs

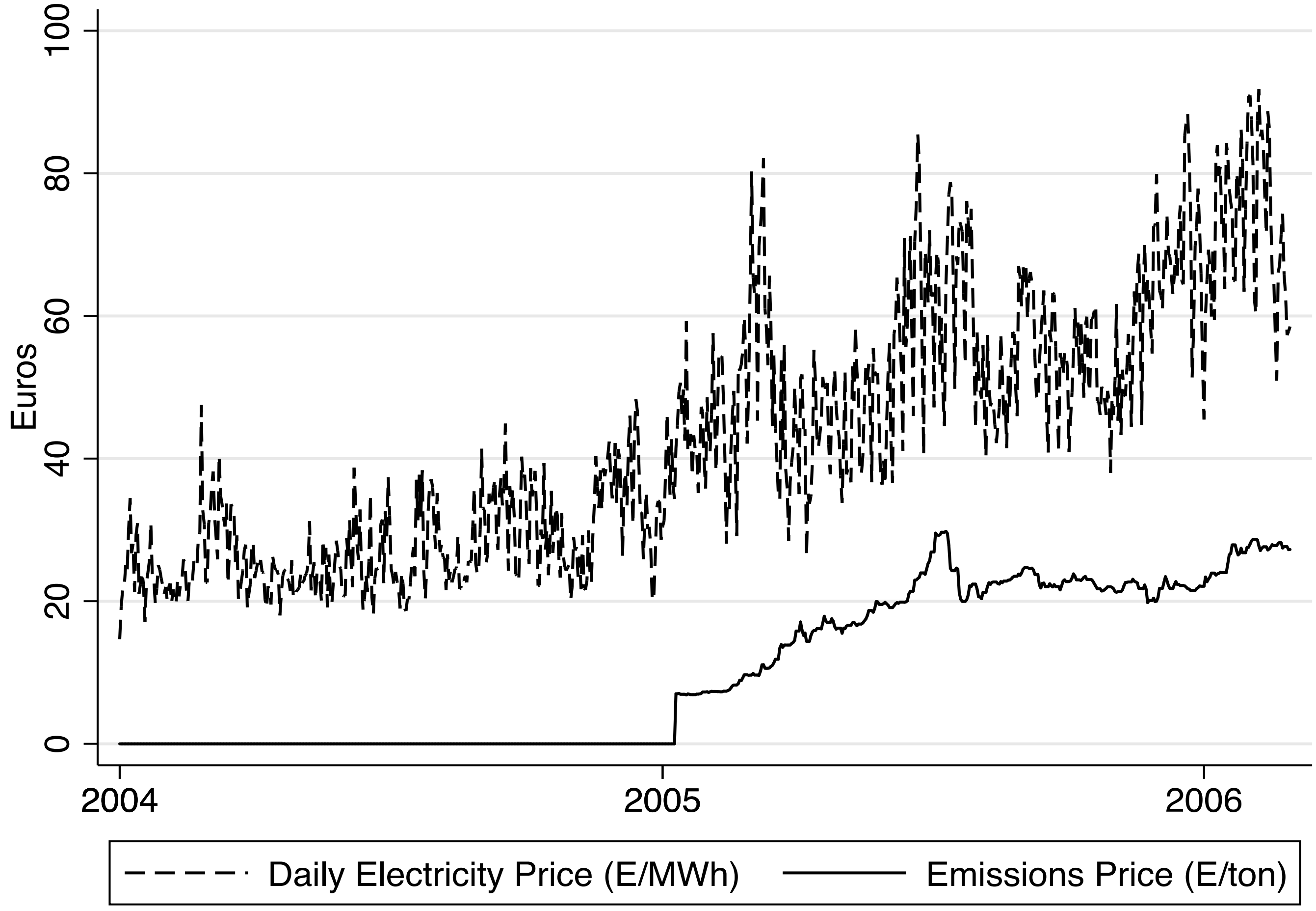
= input costs+ emissions costs

heat rates x
commodity prices
(coal, gas, oil)

emissions rate
x permit price

Information at the power plant level

Electricity and Carbon Prices



Measuring Pass-through

- Use reduced form representation of equilibrium prices:

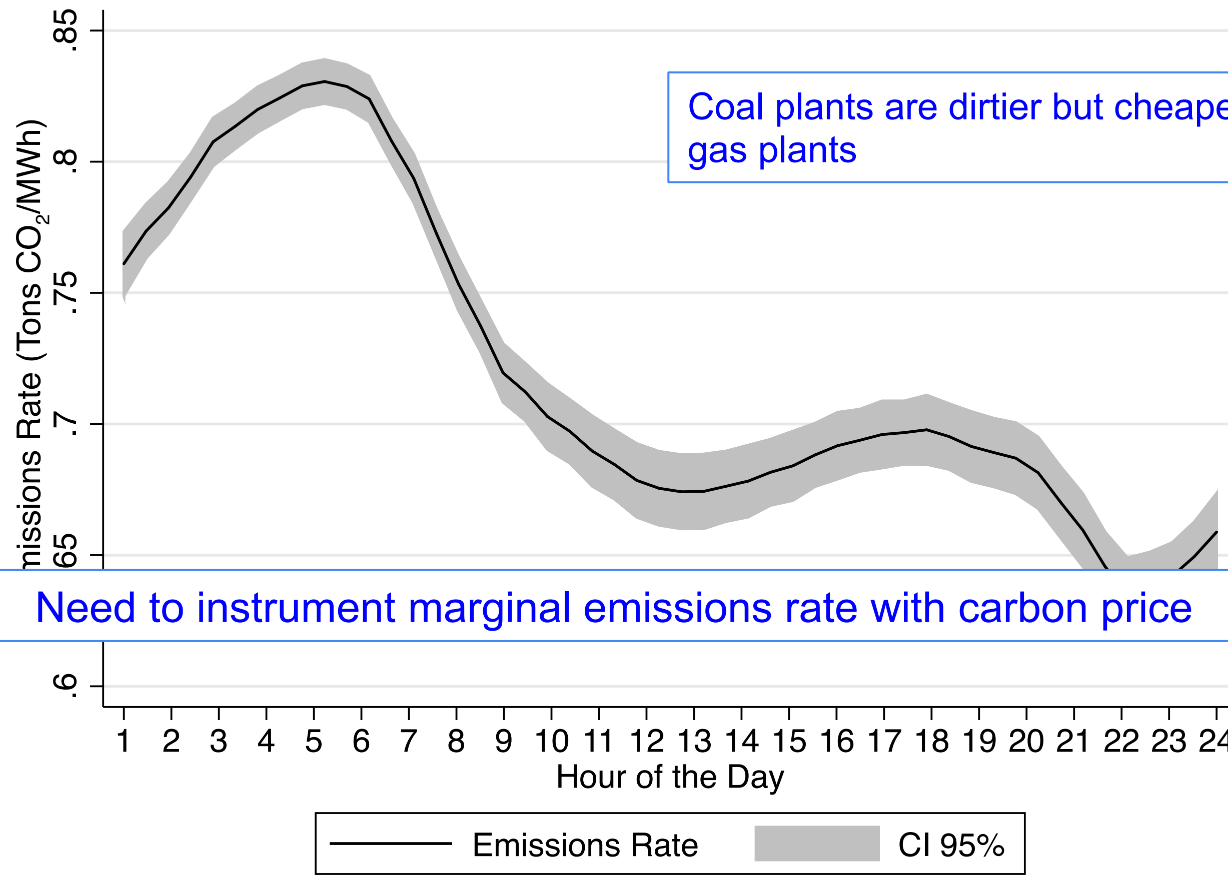
$$p^*_{th} = P_t(e_{th}\tau_t, X_{th}, X^S_{th}, X^D_{th})$$

- Pass-through regression:

$$p_{th} = \boxed{\rho^c \tau_t e_{th}} + X_{th}\beta_0 + X^S_{th}\beta_1 + X^D_{th}\beta_2 + \omega_{th}\delta + \epsilon_{th}$$

Endogeneity of Emissions Costs

Figure 2.2: Average Marginal Emissions Rate across the Day



Coal plants are dirtier but cheaper than gas plants

Need to instrument marginal emissions rate with carbon price

Instrumental Variables Approach

- We use emissions prices at the European level as an instrument for emissions costs
- Supply side/structural model:
  - Emissions price freely traded across participating states, several sectors and many firms
- Demand side:
  - Emissions price could reflect macroeconomic trends
  - Within month variation, control for commodity prices and other demand shifters

Measuring Pass-through

	(1)	(2)	(3)	(4)	(5)
Mg. Emissions Costs (ρ)	0.862	0.860	0.835	0.829	0.848
	(0.181)	(0.182)	(0.173)	(0.172)	(0.168)
Temperature	-0.231		[illegible]		
	(0.060)		[illegible]		
Maximum Temperature	0.137		0.112		
	(0.050)		(0.047)		
Wind Speed	-2.086	-2.171	-2.089	-2.191	-2.238
	(0.354)	(0.361)	(0.333)	(0.337)	(0.329)
Wind Speed Squared	0.055	0.066	0.054	0.067	0.068
	(0.025)	(0.025)	(0.023)	(0.023)	(0.023)
Coal	57.477	45.548	57.496	45.469	
	(4.035)	(4.364)	(3.885)	(4.164)	
Gas	5.638	3.589	5.604	3.563	
	(0.407)	(0.405)	(0.391)	(0.387)	
Brent	-2.896	-1.685	-2.938	-1.778	
	(0.881)	(0.985)	(0.834)	(0.930)	

Estimates indicate 80% pass-through

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Dynamic Effects: Peak vs Off-peak

	(1)	(2)	(3)	(4)	(5)
Mg. Emissions Costs - Peak	1.085	1.083	1.055	1.051	1.107
	(0.185)	(0.185)	(0.178)	(0.177)	(0.175)
Mg. Emissions Costs - Off Peak	0.635	0.633	0.608	0.603	0.496
	(0.170)	(0.170)	(0.164)	(0.163)	(0.164)
MonthXTemp,MaxTemp	N	Y	N	Y	Y
MonthXHour FE	N	N	Y	Y	Y
HourXInput	N	N	N	N	Y

Full pass-through at peak times

Lower pass-through when dynamic constrains present

Understanding Pass-through

- The finding of a complete pass-through is an exception in the broader pass-through literature.
  - Electricity markets exhibit very quick and perfect pass-through at the wholesale market.
- Exchange-rate pass-through: <50% or less

- We also can test more directly if aggregate (time-series) pass-through is consistent with **individual firm behavior.**

Structural framework

- Profit maximization:

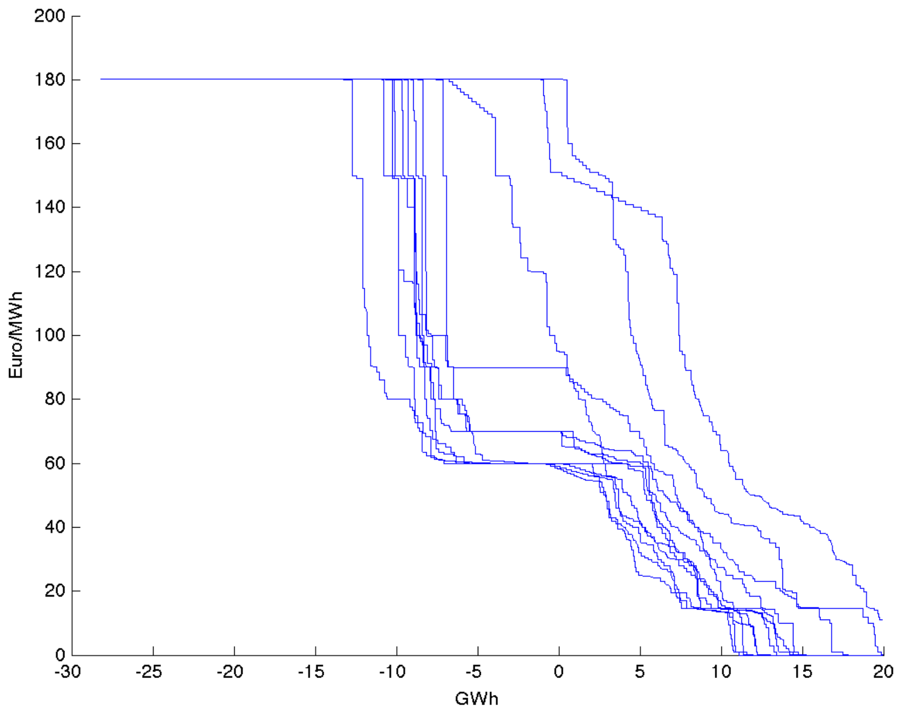
$$p = \underbrace{c_i + \tau e_i}_{\text{mg. cost}} + \underbrace{\left|\frac{\partial D_i^R}{\partial p}\right|^{-1} Q_i}_{\text{markup}}$$

- Empirical bidding equation:

$$b_{ijth} = \underbrace{\alpha_{ij} + \beta_i c_{jt} + \gamma_i \tau_t e_{ij}}_{\text{mg. cost}} + \underbrace{\theta_i \left|\frac{\widehat{\partial D^R}_{ijth}}{\partial p_{th}}\right|^{-1} Q_{ijth} + \epsilon_{ijth}}_{\text{markup}}$$

Constructing Markup Term

- Terms in FOC can be approximated thanks to the richness in the bidding data.



Demand, supply and markups

Profit maximization:

$$p = \underbrace{c_i + \tau e_i}_{\text{mg. cost}} + \underbrace{\left| \frac{\partial D_i^R}{\partial p} \right|^{-1} Q_i}_{\text{markup}}$$

Empirical bidding equation:

$$b_{ijth} = \underbrace{\alpha_{ij} + \beta_i c_{jt} + \boxed{\gamma_i} \tau_t e_{ij}}_{\text{mg. cost}} + \underbrace{\theta_i \left| \frac{\widehat{\partial D^R}_{ijth}}{\partial p_{th}} \right|^{-1} Q_{ijth}}_{\text{markup}} + \epsilon_{ijth}$$

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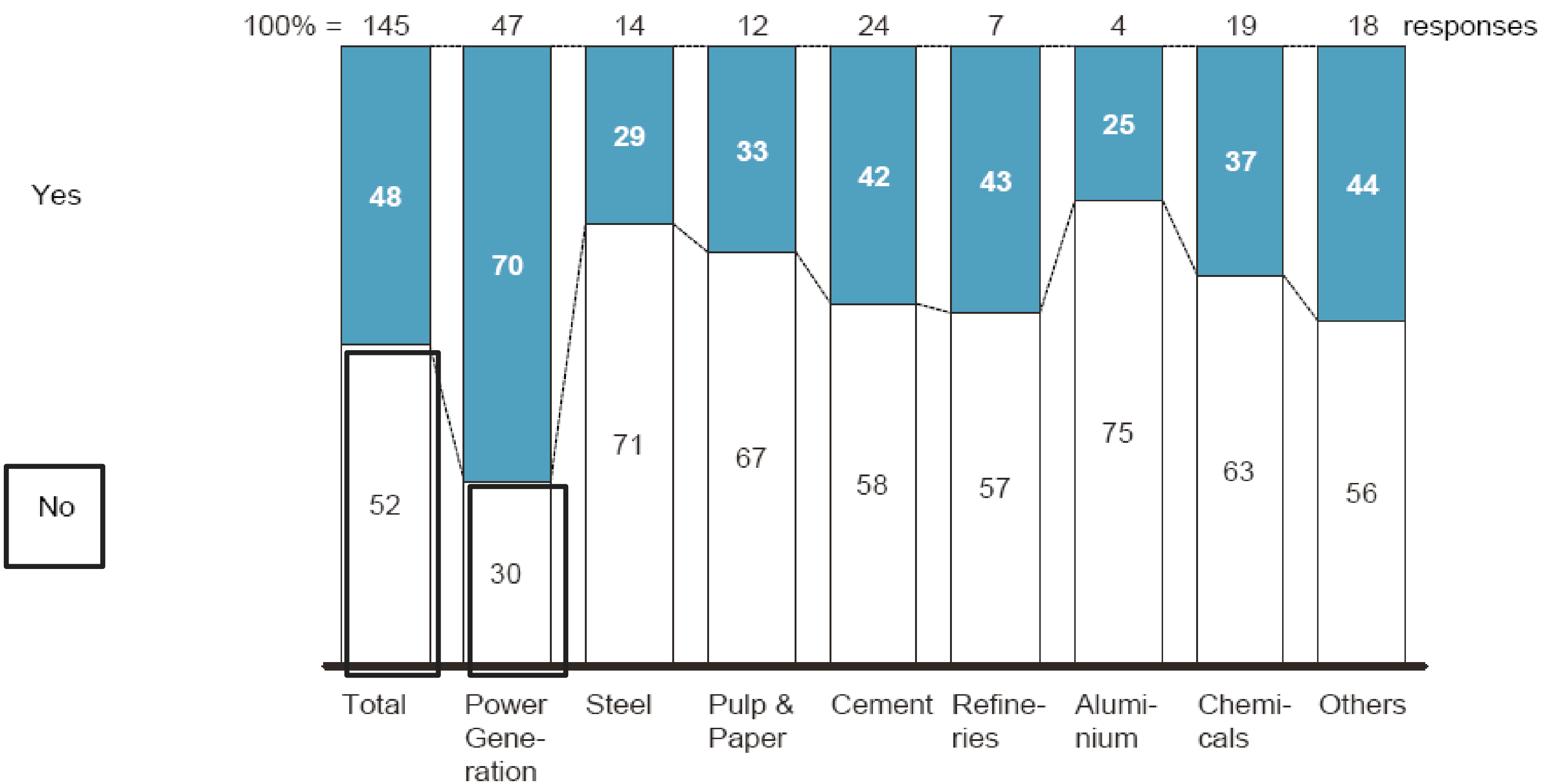
Which costs do firms internalize?

- Permits have an opportunity cost even if received for free, as they can be sold in the emissions market, but…
  - Are there transaction costs?
  - What if firms expect to receive more free allocations in the future if they increase their current emissions?
  - What if firms believe that permits cost nothing because they were free?

EU Survey (June-September 2005)

Are you already **now** "pricing in" the value of CO2 allowances into your daily operations?



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Opportunity Costs: Emissions

	All	Firm 1	Firm 2	Firm 3	Firm 4
Emissions cost (γ)					
(1) No FE	0.939	0.925	0.998	1.117	0.806
	(0.070)	(0.039)	(0.032)	(0.039)	(0.073)
(2) Unit FE	0.971	0.947	0.963	1.062	0.803
	(0.034)	(0.031)	(0.039)	(0.046)	(0.102)
(3) Unit FE + Season	0.957	0.959	0.963	1.008	0.784
	(0.034)	(0.028)	(0.027)	(0.053)	(0.085)
(4) Spec.3 + Markup (IV)	0.959	1.036	0.962	1.013	0.834
	(0.062)	(0.058)	(0.024)	(0.197)	(0.101)

Estimates close to one, implying full internalization of permit prices

Opportunity Costs: Inputs

Input cost (β)					
(1) No FE	0.812	0.476	0.892	0.952	1.037
	(0.047)	(0.029)	(0.021)	(0.021)	(0.014)
(2) Unit FE	0.598	0.494	0.303	0.821	0.643
	(0.064)	(0.057)	(0.055)	(0.037)	(0.053)
(3) Unit FE + Season	0.601	0.497	0.348	0.769	0.640
	(0.058)	(0.047)	(0.039)	(0.043)	(0.027)
(4) Spec.3 + Markup (IV)	0.604	0.487	0.335	0.773	0.683
	(0.069)	(0.038)	(0.060)	(0.172)	(0.114)

More noisy estimates :
input costs not measured as accurately as emissions prices

Conclusions FR (2014)

- We explore impact of emissions costs on firms' decisions and market outcomes
- We find pass-through around 80-100%
- Firms fully internalize permit prices
- Institutional framework in electricity markets (frequent auctions for very inelastic demand):
  - Weak incentives to adjust markups
  - Small price rigidities

Day-ahead auctions very efficient mechanism in inducing full pass-through.
It also applies to cost of inputs, as we have seen.

Fowlie (2010)

Emissions Trading, Electricity Restructuring, and Investment in Pollution Abatement

By Meredith Fowlie*

This paper analyzes an emissions trading program that was introduced to reduce smog-causing pollution from large stationary sources. Using variation in state level electricity industry restructuring activity, I identify the effect of economic regulation on pollution permit market outcomes. There are two main findings. First, deregulated plants in restructured electricity markets were less likely to adopt more capital intensive environmental compliance options as compared to regulated or publicly owned plants. Second, as a consequence of heterogeneity in electricity market regulations, a larger share of the permitted pollution is being emitted in states where air quality problems tend to be more severe. (*JEL* L51, L94, L98, Q53, Q58)

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Firm incentives and cap-and-trade

- Basic economics model assumes all firms have equivalent incentives to reduce emissions costs.
- Firms can face differing incentives.
    - Regulatory treatment of firms
        - Rate of return regulation vs market
- Allocation mechanisms can distort incentives.
    - The problem with endogenous allocations

NO_x Markets

- Large cap-and-trade program for NOx among eastern utilities---"NOx Budget Trading Program"
  - Began in 2003
- Cap-and-trade program for NOx in Southern California---"RECLAIM"
  - REgional CLean Air Incentives Market
  - Began in 1994
  - Also covers SO2

- **Important**: NO_x is a local pollutant.

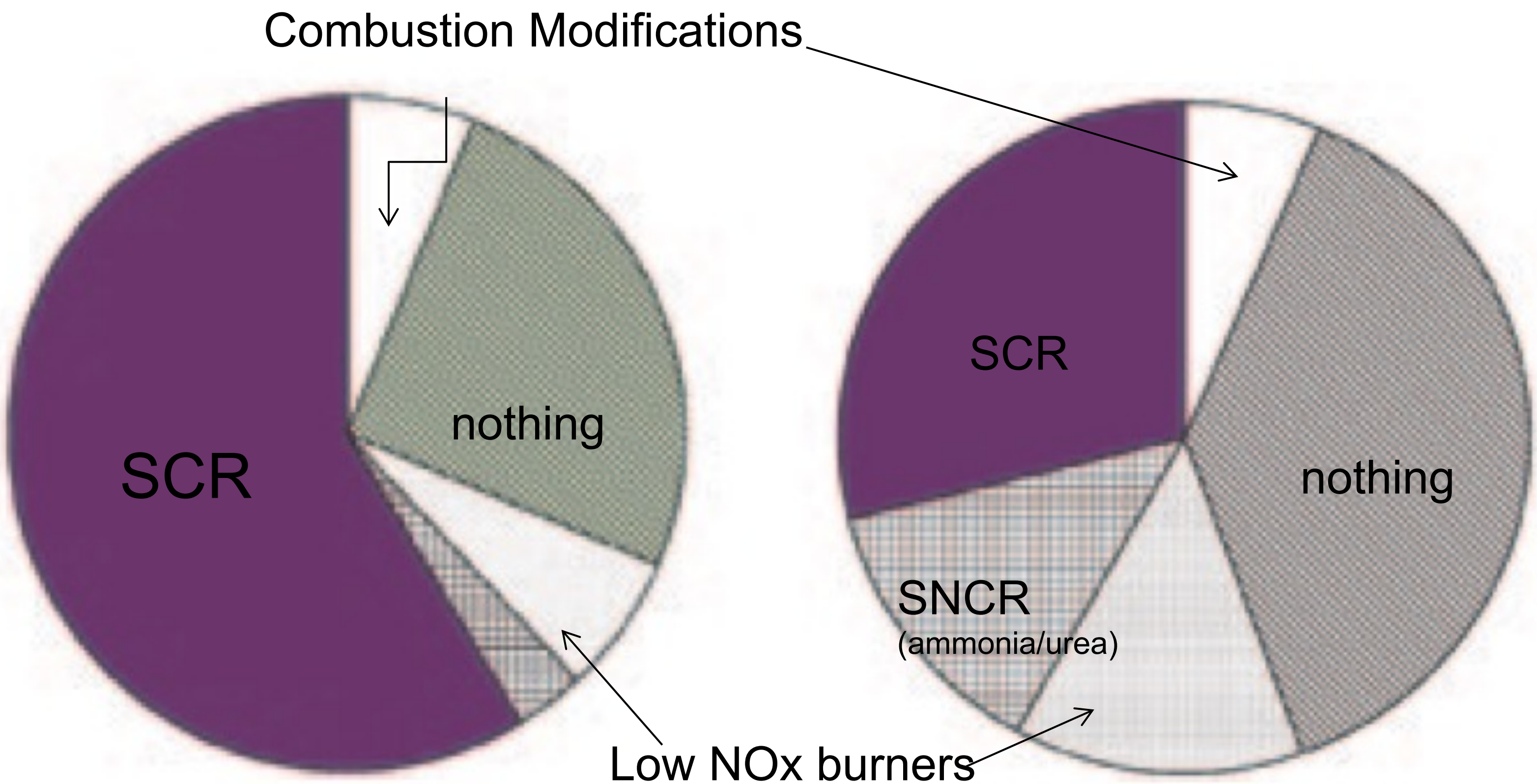
NO_x abatement options

- Selective Catalytic Reduction
  - Reduce NO_x emissions up to 90%
- Selective Non-Catalytic Reduction
  - Reduce NO_x emissions up to 35%
- Low NO_x burners (LNB) or combustion modifications (CM)
  - Reduce NO_x emissions up by 15-50%
- Produce less

This paper: Fowlie (2010)

- Develops a model of abatement choice (random coefficient logit).
- Shows that firms in deregulated vs. regulated states faced made very different choices.
- Damages ended up being larger due to this difference in compliance choices.

Regulated vs. non-regulated choices



Compliance choices of regulated units

Compliance choices of unregulated units

Meredith Fowlie. "Emissions Trading, Electricity Industry Restructuring, and Investment in Pollution Control". American Economic Review, 2010.

Main take away Fowlie (2010)

- The response to environmental and climate policies can depend substantially on how firms are regulated.
- This can be an important factor affecting the energy transition:
  - Are there regulatory structures that can delay the transition?
  - Are there regulatory structures that can facilitate it?

Example: In ongoing work with Gautam Gowrisankaran and Ashley Langer, we explore how the regulatory structure can affect the phase out of coal.

Today's outline

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2) Transmission constraints and climate policy
3) Case study: Leakage in the California electricity market
   - Overview of paper
   - Code (afternoon)

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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 <u>environmental policy + transmission</u>.

Leakage / reshuffling policies

- California has implemented a border tax adjustments
  - **Similar to the CBAMs being discussed in Europe.**
- Electricity is a good candidate for CBAMs because consumption is easy to track.
- The California operator puts the regulatory burden on utilities (demand side), and therefore it can tax imports without getting into too much legal trouble.
  - Technically, it is taxing consumption in-state.
- However, how to tax imports is a big question.
  - What is being imported?
  - Can firms claim a lot of emissions reductions without much real change (”reshuffling”)?

Modeling: policy

- 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 main findings

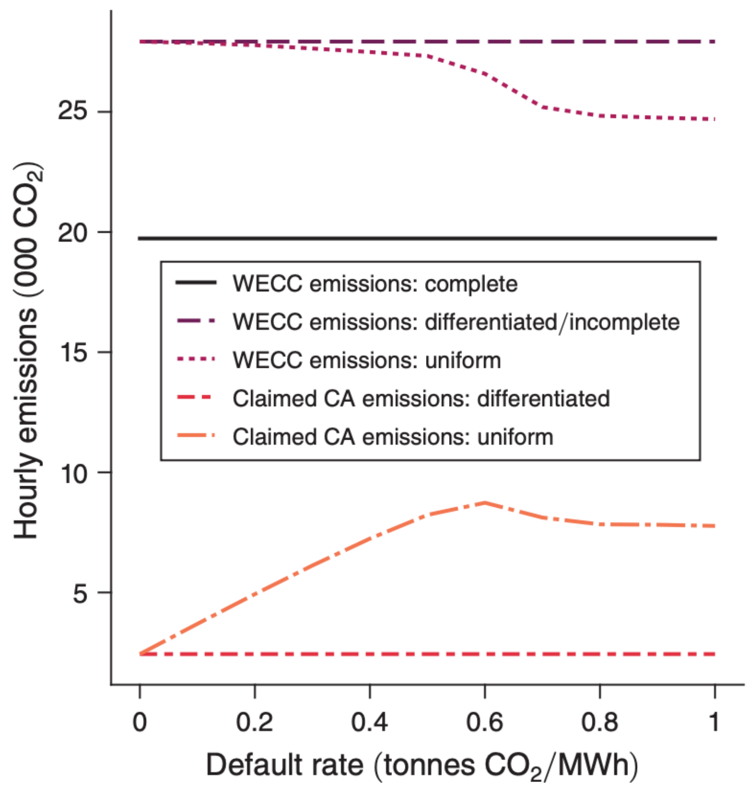


FIGURE 1. CLAIMED EMISSIONS VERSUS EMISSIONS IN CALIFORNIA

- Mechanism to mitigate resource shuffling is not working if firms are allowed to chose their source (case 4).
- CA emissions in total are the same no matter the default rate.
- Observed outcomes a bit less negative but suggest high level of leakage.

Modeling: the network

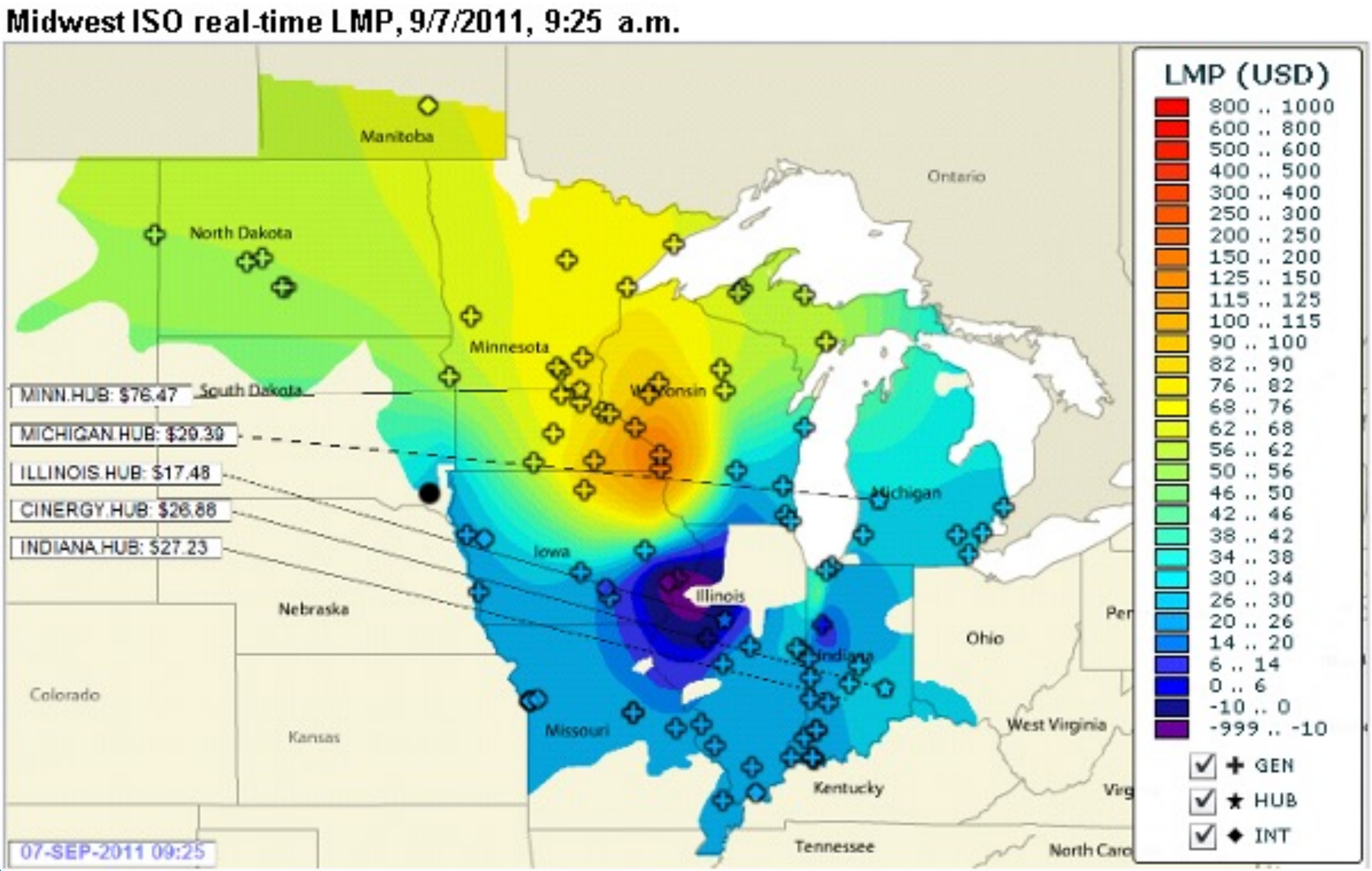
- Electric energy is injected into the grid by all generators and withdrawn by all end users
- To maintain frequency, the quantity injected must always equal the quantity withdrawn
- Contrast this with other commodity markets
- Power flows in inverse proportion to the resistance it faces (Kirchhoff's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

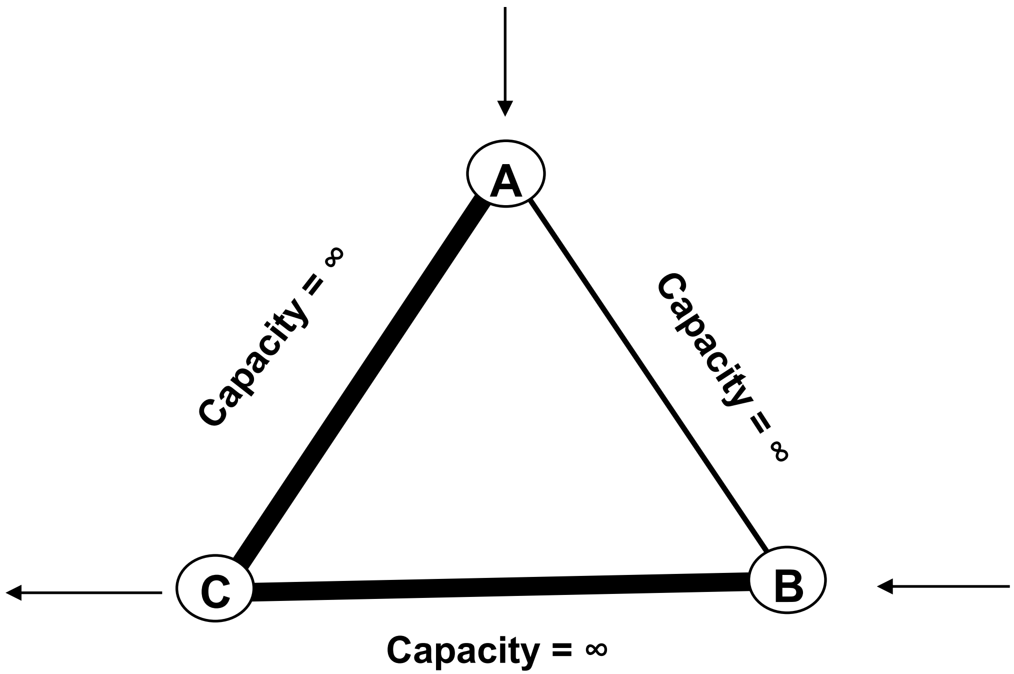
An *externality* is present whenever one agent's actions impact the utility or production of another agent through a non-price mechanism.

Nodal prices in markets are complicated!



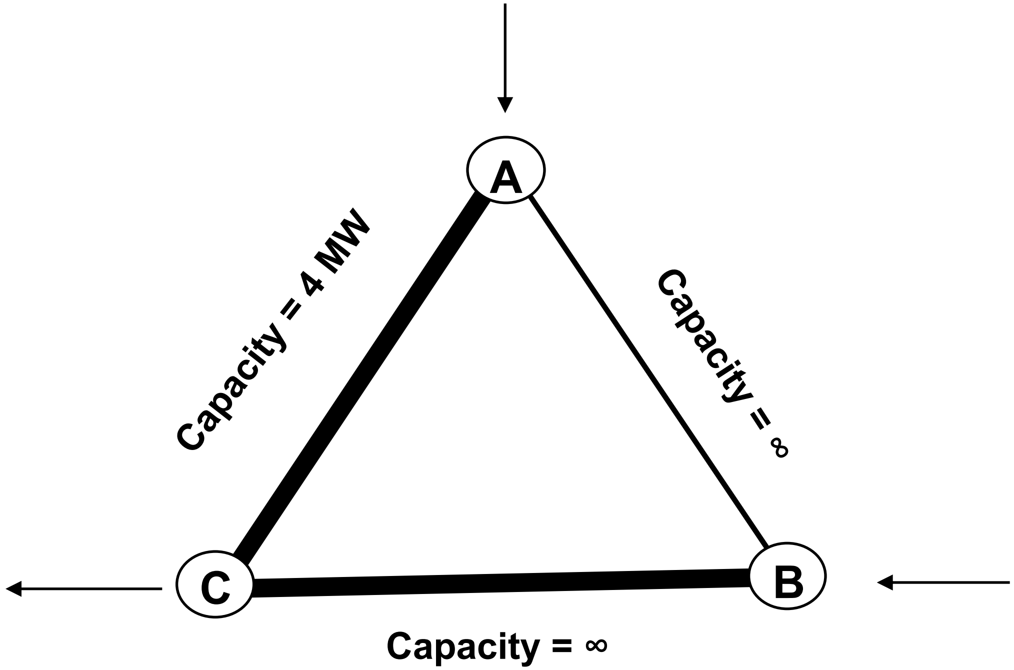
Loop flow example

- 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?



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.

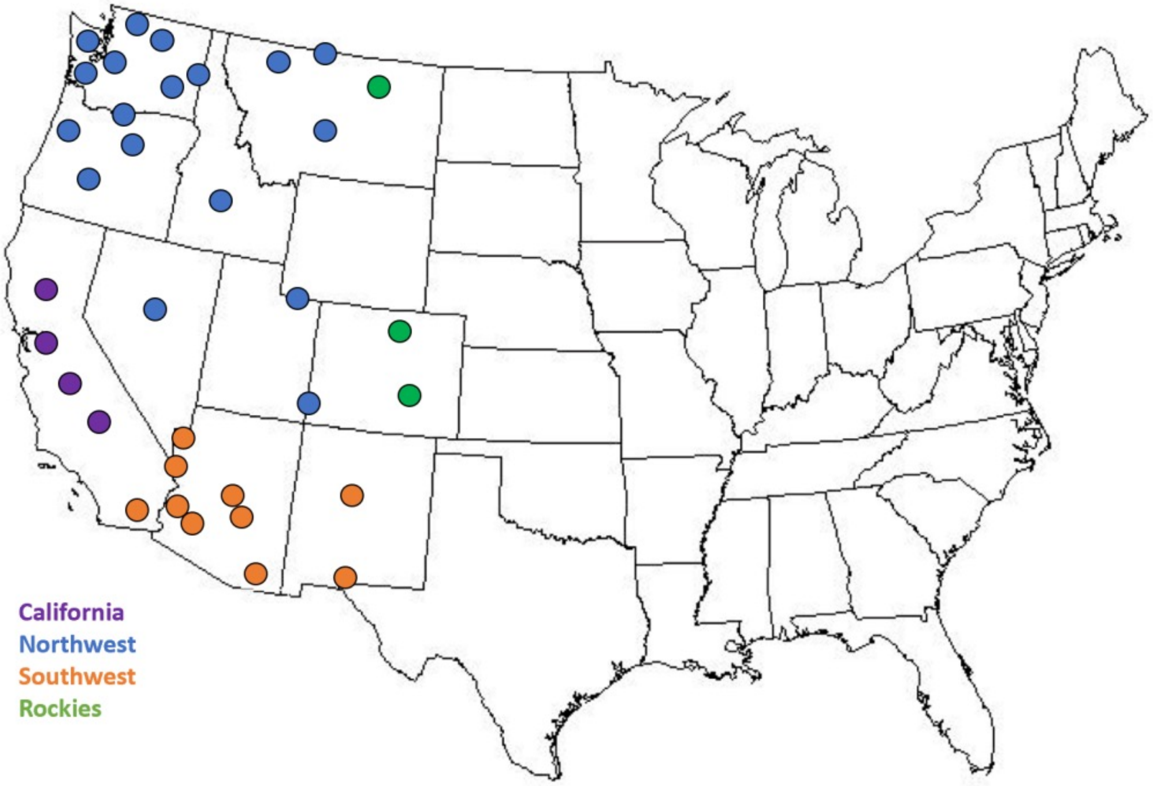
Maybe a more useful take-away: if you want to build a simplified network model, electrical engineers might have a comparative advantage and it is best to borrow from them! ☺

In our application

- We take a very simplified version of the network from Bushnell et al., 2017, that separates the Western interconnection in 4 areas.
- In practice, machine learning tools can be used to decide how narrow the network can be (see Mercadal, 2021).
    - Combination of k-means clustering with market fit to tune the number of clusters.
- **Intuition**: areas that are not congested should exhibit highly similar prices.

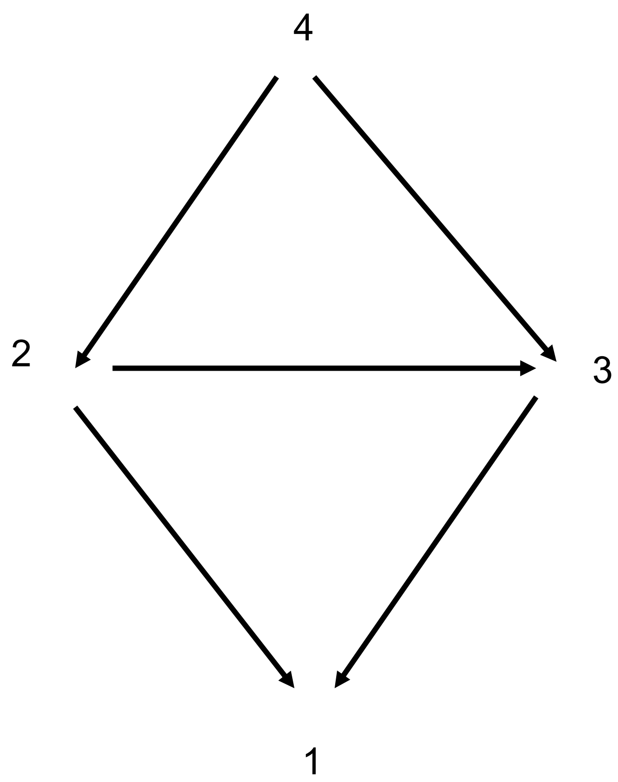
Our four markets

Figure A.1: Illustration of balancing authority regional designations



The line conditions

- Two inputs:
  - Line size
  - 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:

$$-lines_l \leq \sum_{r \notin CA} fct_l * yflow_{rt} \leq \text{lines}_l$$

We will look at these in the afternoon!

- If you are interested in this kind of modeling, please check the online appendix of the short paper for guidance – the conference paper is very short.

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?

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