Empirical Methods for the Analysis of the Energy Transition

Day 3

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Outline

I. Climate and Renewable Policies in Electricity Markets

- a. Carrots
- b. Sticks
- c. Empirical assessments

II. Investment in electricity

III. Transmission

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I. Climate and Renewable Policies in Electricity Markets

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Climate policies in the electricity sector

- The electricity sector is among those with the most active climate policies.
- It is a sector "relatively easy" to decarbonize and it tends to be isolated (no competition concerns).
- Emphasis has been on both "carrots" and "sticks" strategies.

- Today we focus on **supply side** policies.
  - What are they?
  - Do they work?

Supply-side responses to climate policies

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 to improve efficiency.
- **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**, work on investment with a *simulation model*

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A battery of policies

Carrots

- Renewable subsidies
- R&D subsidies
- Centralized tenders (auctions)

Sticks

- Carbon tax
- Cap-and-trade
- Renewable portfolio standards (RPS)

a. Carrots

Example: Feed-In tariffs and premiums

- In Europe, subsidies to renewable power have been common.
- As a known fixed price (tariff).
- As an adder to the market price (premium)

- Advantages:
  - Predictable.
- Disadvantages:
  - Target quantity often unclear
  - Some experiences of "too much" entry (e.g., early solar investment in Spain and Portugal at high subsidy levels), now often include a cap.
  - They can lower electricity prices and incentivize consumption.

Example: Renewable Portfolio Standards

- Renewable portfolio standards (quantity) are more popular in the US as they trigger investment.
- States choose a certain goal for renewable energy penetration (in fuel standards, that was the percent of ethanol in gasoline).
- Generators (or suppliers) need to show that they have enough "renewable energy credits" (RECs).
- Either produced by themselves or purchased in the market: rewards clean technologies, penalizes dirty ones.

- Contested items: are they about renewables? Or about zero carbon (nuclear, hydro)?

Example: Renewable Portfolio Standards

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Are carrots really needed?

- Current renewable policy focused on centralized procurement.
- Auctions to coordinate investment, but no longer at subsidized prices.
- Many potential benefits:
  - Cheaper than gas.
  - Can help ensure steady progress towards net-zero goals.
  - Can keep prices low if well designed.
- Remaining "carrots":
  - Subsidies or tax credits for more expensive technologies at the distributed level (rooftop solar) or less mature technologies (batteries).
  - (Implicit subsidy) Payment of the expansion of the grid (to enable new locations of solar and wind generation).

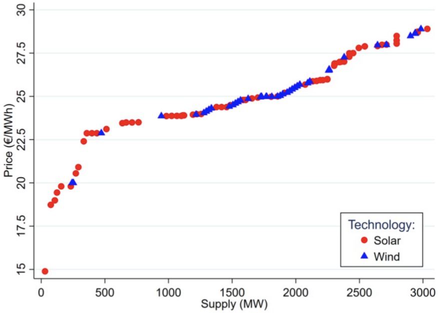
What are the details of auctions in practice?

Auctions can be tailored to affect particular technologies or plants:

- Technology-specific: different instruments/levels of support depending on technology, scale, location, etc.
- Technology neutral: all technologies treated equally
- Hybrid schemes: corrected technology-neutral approaches
- Banding:
  - Bids of some technologies are deflated
  - Minimum quantities for certain technologies

Example: Spanish renewable auction

- It took place last January 26, 2021
- Technology Neutral Auction of 3000MW
- Minimum quantity of 1000MW for solar PV and Wind
- Pay-as-bid
- Contract duration: 12 years
  - Once the contract is over, investors are paid at market prices



b. Sticks

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Cap and trade mechanisms

Permit markets have been used in electricity markets to internalize pollution in several settings, not just climate policy:

- **CO2:** ETS (Europe, Australia, New Zeland), RGGI, AB32 (EEUU)
- **SO2:** Acid Rain Program (EEUU)
- **NOx:** Budget Trading Program, RECLAIM

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

What is cap-and-trade?

- The regulator chooses the amount of pollution that is allowed (cap).
  - Limits apply to totals, not emissions by a specific source.
- The regulator distributes permits (or allowances) to emit pollution that amount to the total of the cap.
  - Allocates property rights to each power plant for a certain amount of tonnes.
  - Firms are then allowed to trade these permits to achieve an efficient allocation.
- Firms with highest added value are willing to buy the permits, others sell them.

A simple example

Imagine there are three power plants:

- Old coal power plant
- Old gas power plant
- New gas power plant

The regulator gives pollution permits to the old plants (typically called "grandfathering"). However, the new gas plant is much cleaner.

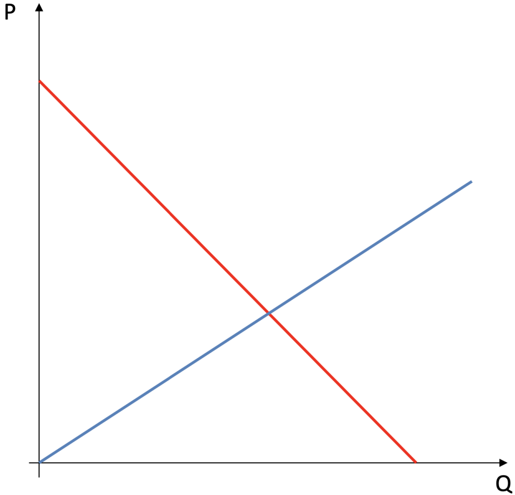
- The dirtiest plants sell their right to pollute to the cleaner plants.
- Accordingly, it produces less or stops production.

Theoretical ideal equilibrium

- All firms arbitrage their abatement decisions against the costs of emissions credits.
- Low cost firms do relatively more abatement, high-cost firms buy permits.
- In equilibrium, the emissions credi tprice becomes the marginal cost of abatement which is equilibrated across all regulated industries.

Sounds good in theory. But some concerns:

- price volatility, too low/high prices.



What cap-and-trade instead of a tax?

Taxes offer advantages:

- No price volatility, no very high price surprises
- Revenue generating (double-dividend)
- Potentially provide better incentives for breakthrough technologies
- Set it and forget about it

However:

- Political non-starter in many jurisdictions
- Opposition of industry, hard to put givebacks to certain sectors or power plants

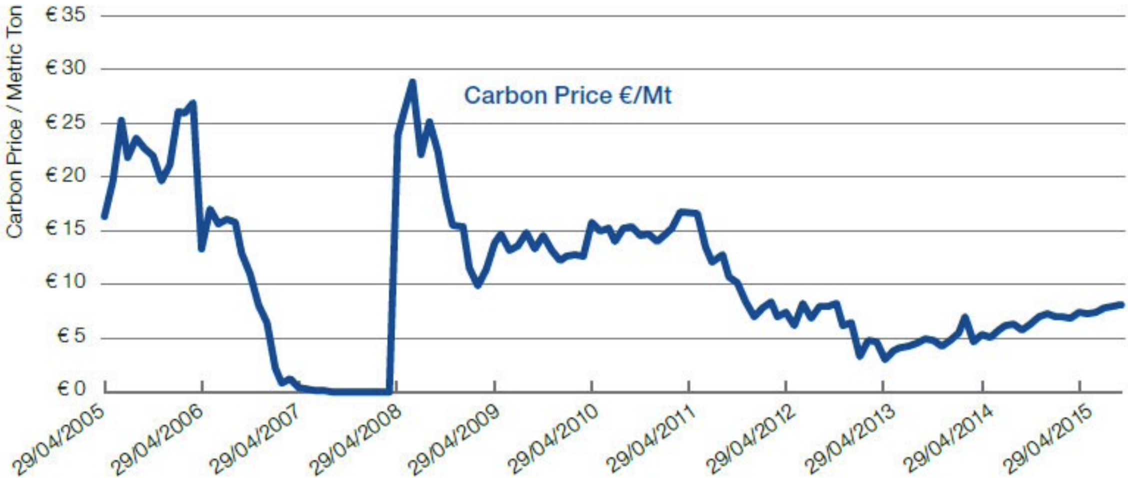
Cap-and-trade as a climate policy

- $CO2$ allowance markets are the largest emissions markets in the world:
  - European Union Emissions Trading Scheme (Phase I) valued at between $30 to $60 billion per year, lately much more.
  - U.S. national market would be about 3 times the size of ETS.
  - AB32 in California already covering emissions since 2013.
  - China also had several pilots, with market launched in 2021 ($27 billion in value, $1.3 billion in trade).

European Union Emission Trading Scheme

- Trading Periods
  - Phase I: 2005-2007 "trial period"
  - Phase II: 2008-2012
  - Phase III: 2013-2020
  - Phase IV: 2021-2030
- Multinational,multi-industry regulation
  - Applies to 10,000+ stationary sources
  - half of all carbon emissions in EU
- Allows unlimited banking and borrowing within trading periods
- Permits initially allocated for free, transition to auctioning over time
- Despite its flaws, system has performed well

Fig. 1: EU ETS, EUR price of carbon per metric ton



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Recent developments in the EU ETS

- EU ETS prices have been increasing significantly with the gas crisis.
- Their prices have moved from 30 Euros/ton to above 60-70 Euros/ton (record prices).
- This is a sign of the cap-and-trade market working.
- Big indicator of carbon prices: substitution between gas and coal.
- As gas becomes expensive, CO_2 price goes up to penalize coal.

c. Empirical assessments

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)

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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 Bushnell, Chong and Mansur (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.
  - Match 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 Emission Trading Scheme (ETS)

- Cap-and-trade market for tons of CO2
- 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.

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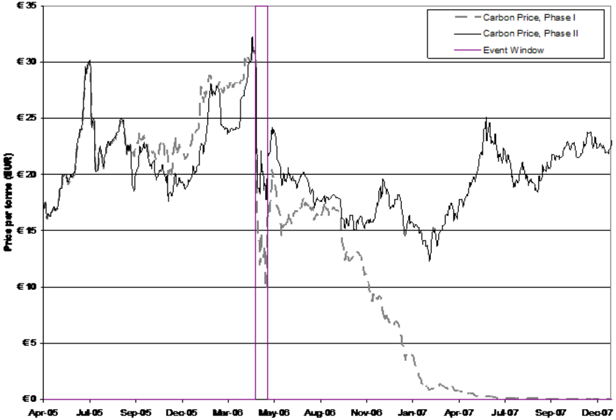
Bushnell, Chong and Mansur (2013)



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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:

$$S_{ijt} = \alpha_i + \beta_i M_t + \gamma_j Event_t + \varepsilon_{ijt}$$

Event results

Negative impact of price drop

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?

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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:

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

where ω: input costs; A_i: free allocation; τ: emission price; r_i: emission rate; I_i: abatement investments

- Effect (local):

$$\frac{\partial \pi_i^*}{\partial \tau} = \underbrace{P' \frac{\partial q_{-i}^*}{\partial \tau} q_i^*}_{\text{Revenue increase due to reduced output}} + \underbrace{\left[P' \frac{\partial q_{-i}^*}{\partial \omega} q_i^* - \frac{\partial C}{\partial \omega} \right] \frac{\partial \omega}{\partial \tau}}_{\text{Indirect impact on costs}} + \underbrace{[A_i - r_i q_i^*]}_{\text{Net position}}$$

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.

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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** (0.033)	7.445*** (1.924)	7.175*** (2.098)	−5.937 (31.510)

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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.

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Fabr

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)

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This paper

- Pass-through of emissions costs to electricity prices
  1. Measure pass-through
  2. Decompose determinants of pass-through

- Policy relevant topic:
  - Cap-and-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

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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.

Bid data

Information at the power plant level

Marginal cost

$=$ input cost $+$ emission cost

heat rates $\times$
commodity prices
(coal, gas, oil)

emissions rate
$\times$ permit price

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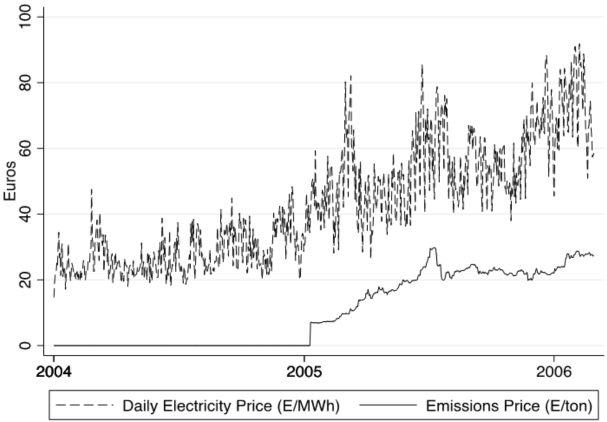
Electricity and Carbon Prices



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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:

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

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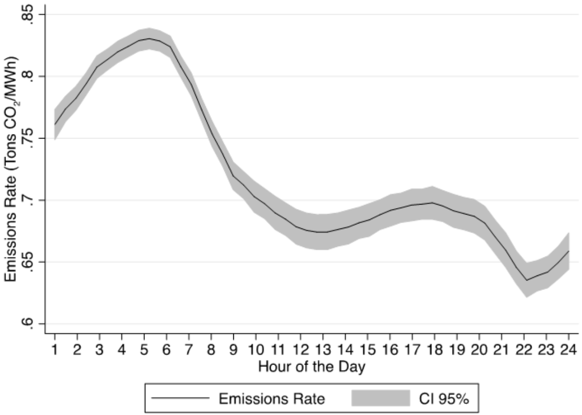
Endogeneity of Emissions Costs

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

Estimates indicate 8

	(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		-0.204		
	(0.060)		(0.057)		
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)	

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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

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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**.

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Structural framework

- Profit maximization:

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

- Empirical bidding equation:

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

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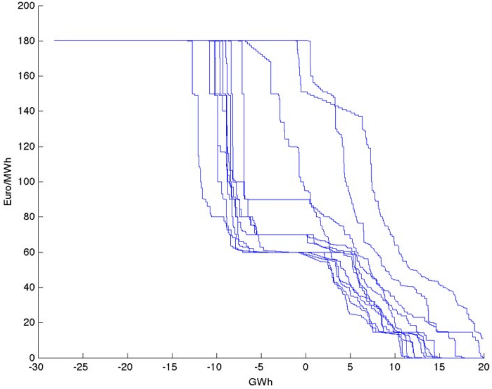
Constructing Markup Term

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



Demand, supply and markups

- Profit maximization:

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

- Empirical bidding equation:

$$b_{ijth} = \underbrace{\alpha_{ij} + \beta_i c_{jt} + \color{red}{\gamma_i}\tau_t e_{ij}}_{\text{marginal cost}} + \underbrace{\theta_i \left| \frac{\partial \widehat{D_{ijth}^R}}{\partial p_{th}} \right|^{-1} Q_{ijth}}_{\text{markup}} + \varepsilon_{ijth}$$

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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?

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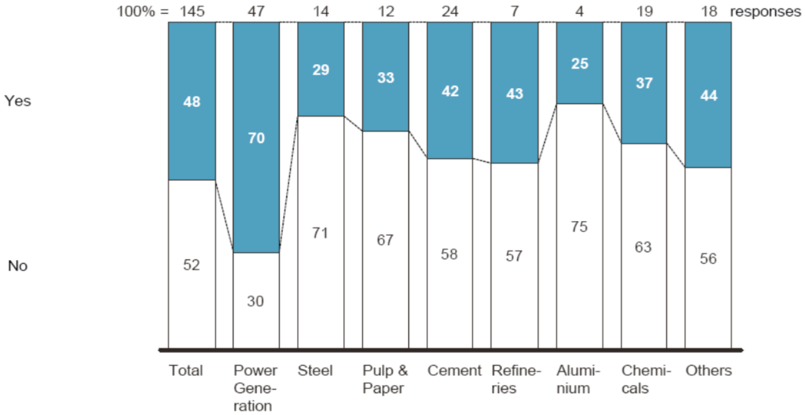
EU Survey (June-September 2005)

Are you already now "pricing in" the value of CO_2 allowances into your daily operations?



Opportunity Costs: Emissions

Estimates close to one, implying full internalization of permit prices

	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)

Opportunity Costs: Inputs

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

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)

Conclusions Fabra and Reguant (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.

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II. Investment in electricity

Dynamics and Investment 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.

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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).

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III. Transmission

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).

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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

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The absence of transmission can be a bottleneck

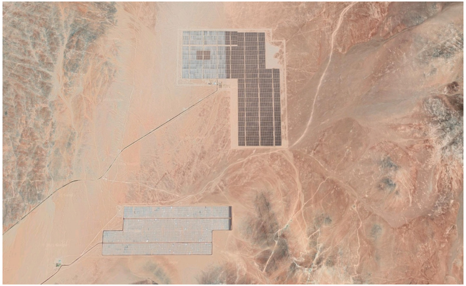
- In the absence of good integration, power prices can go to zero or even negative:
  - At that point, "curtailment" (throwing renewable power away) is likely to occur.
  - It also makes future investment in renewable power uncertain and less valuable $\rightarrow$ investment effect.

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.

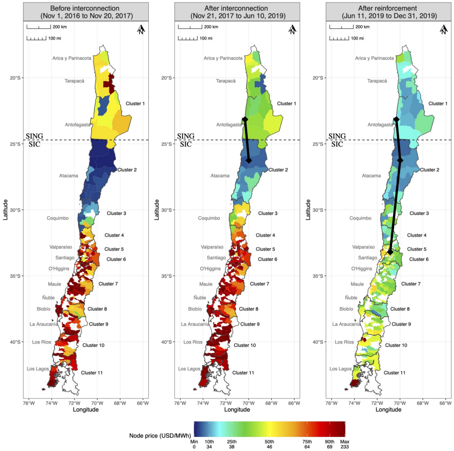
A case study from Chile

- 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.
- See bonus slides.



Next class

- **Demand I**
  - What demand-side policies are used during the energy transition?
  - How do households respond to these policies?

  - **Practicum**: add retail tariffs