Empirical Methods for the Analysis of the Energy Transition

Day 3

Prof. Mar Reguant

Summer School 2024

Barcelona School of Economics

Outline

I. 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.

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. 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).

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.

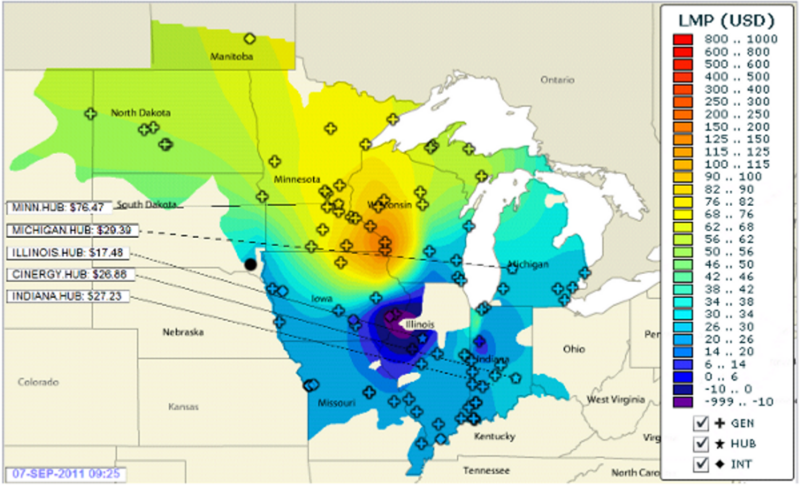
Electricity network externalities

- 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.



Barcelona School of Economics

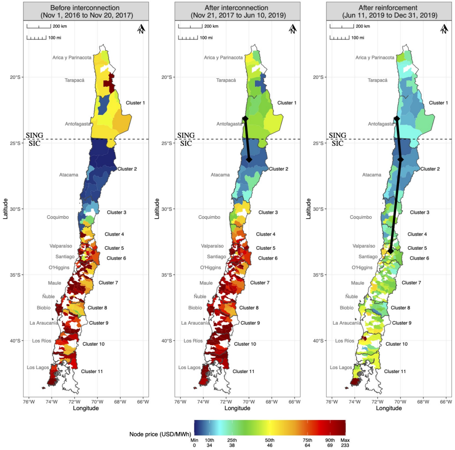
Simplifying networks in electricity models

- 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!

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.



Expressing the line constraints

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

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

Note: Computationally, this is a simple linear constraint.

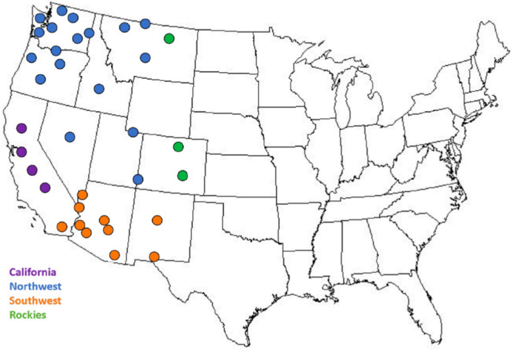
Fowlie, Petersen, and Reguant (2021)

- We adapt a model of the western electricity market eveloped by Bushnell et al. (2017, see website and bonus) 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.



Barcelona School of Economics

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.

III. Climate and Renewable Policies in Electricity Markets

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*

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

- Renewable portfolio standards (quantity) are quite 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.

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

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).

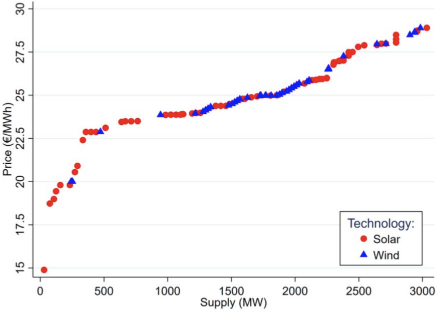
What are the details of auctions in practice?

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

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.

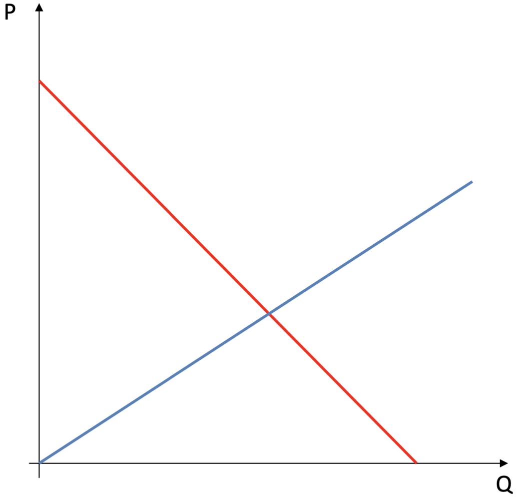
- The dirtiest plants sell their right to pollute to the cleaner plants.
- Accordingly, it produces less or stops production.

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

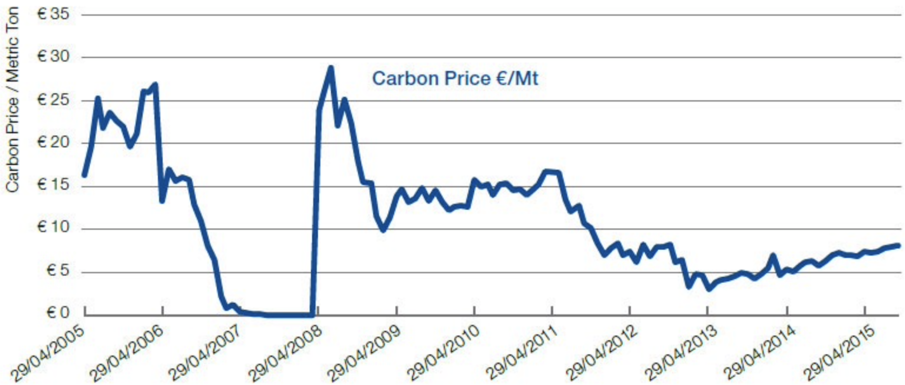
- $CO2$ allowance markets are the largest emissions markets in the world:
  - European Union Emissions Trading Scheme (Phase I) valued at between \$30 to \$60 billion per year, lately much more.
  - U.S. national market would be about 3 times the size of ETS.
  - AB32 in California already covering emissions 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

European Union Emission Trading Scheme Prices

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



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, CO2 price goes up to penalize coal.
- Introduction of carbon border adjustment mechanisms (CBAMs).

c. Empirical assessments

Barcelona School of Economics

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)

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)

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

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

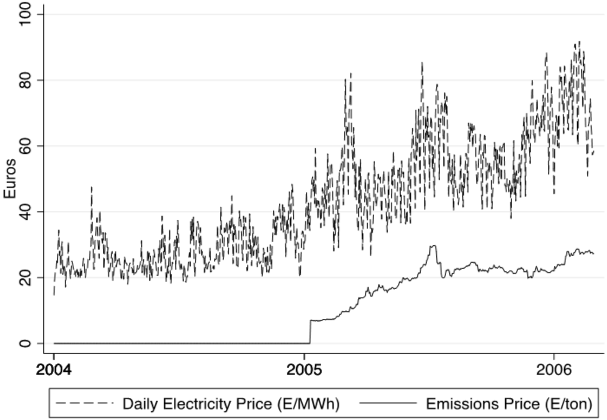
Information at the power plant level

Marginal cost
= input cost + emission cost

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

emissions rate
× permit price

Electricity and Carbon Prices



Barcelona School of Economics

Measuring Pass-through

- Use reduced form representation of equilibrium prices:

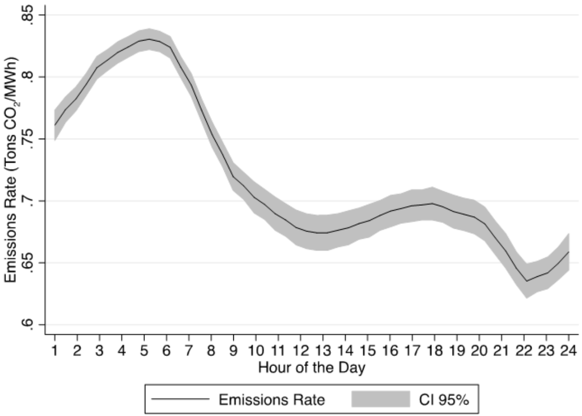
$$p^*_{th} = P_t(e_{th}\tau_t, X_{th}, X^S_{th}, X^D_{th})$$

- Pass-through regression:

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

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 80% 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		-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)	

Barcelona School of Economics

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**.

Barcelona School of Economics

Structural framework

- Profit maximization:

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

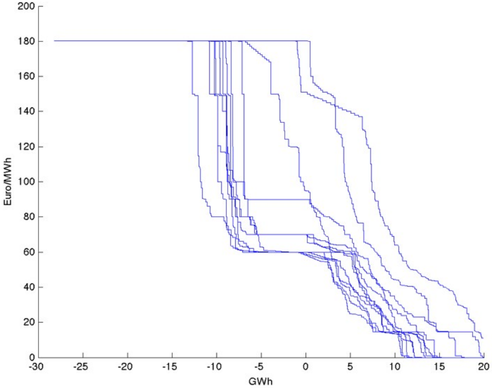
- Empirical bidding equation:

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

Barcelona School of Economics

Constructing Markup Term

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



Barcelona School of Economics

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:

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

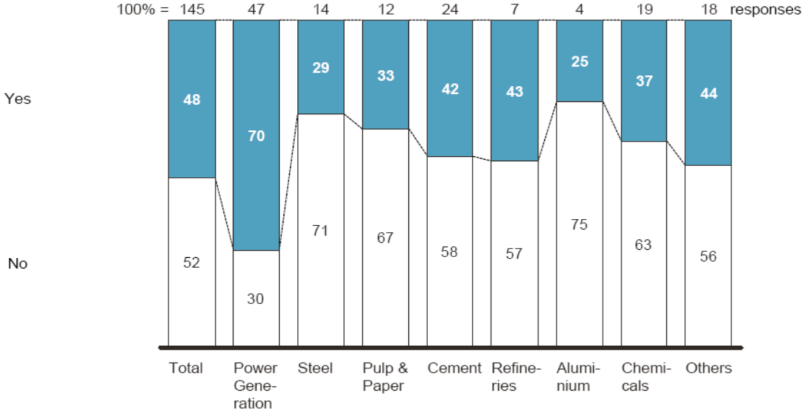
Barcelona School of Economics

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?



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 the 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.

Reguant (2019)

The Efficiency and Sectoral Distributional Impacts of Large-Scale Renewable Energy Policies

Mar Reguant

Abstract: Renewable energy policies have grown in popularity. Given that renewable energy costs are mostly nonmarginal, due to the large presence of fixed costs, there are many different ways to implement these policies in both the environmental design and retail pricing margins. I show that the efficiency and distributional implications of large-scale policies crucially depend not only on the design of wholesale policies to incentivize renewables but also on how the costs of such policies are passed-through to consumers. Using data from the California electricity market, I develop a model to illustrate the interaction between large-scale renewable energy policies (carbon taxes, feed-in tariffs, and renewable portfolio standards) and their pricing to final consumers under alternative retail pricing schemes (no pass-through, marginal fees, fixed flat tariffs, and Ramsey pricing). I focus on the trade-off between charging residential versus industrial consumers to highlight tensions between efficiency, distributional, and environmental goals.

JEL Codes: L51, Q42, Q58

Keywords: renewable policies, efficiency, distributional impacts

Motivation: how to pay for renewables?

- Renewable policies have grown in popularity across states in the US, and also worldwide.
- The costs and benefits from renewable policies are unevenly distributed across several margins.
  - Stakeholders.
  - Regional heterogeneity in resources (and correlation of resources with demand).
  - Heterogeneity across consumer types, e.g. residential vs commercial.
  - Heterogeneity in consumption, e.g., across income groups.

Goal: Quantify (some of) these distributional impacts under alternative policy assumptions, focusing on redistribution across sectors (customer classes). *Who to charge?*

- Carbon tax, feed-in tariff, production subsidy and renewable portfolio standards (RPS).
- We will do much more about distributional effects later in the course.

How to pay for renewables affects demand

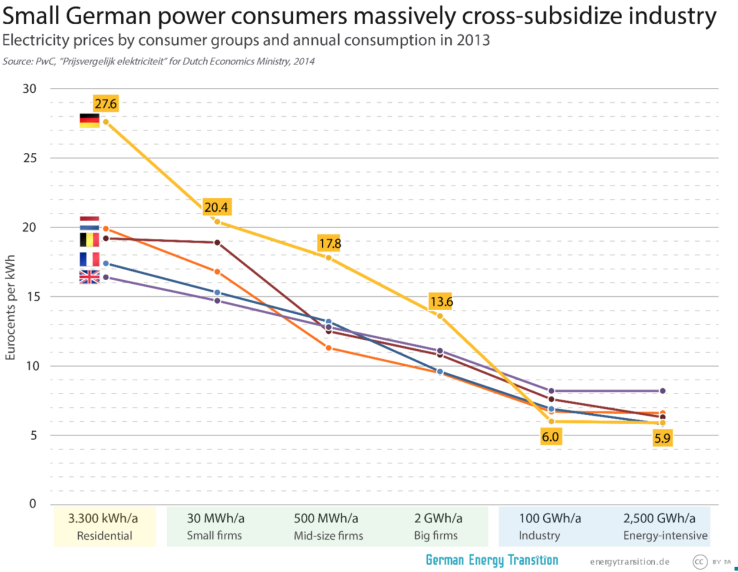
- Subsidies to renewable can be considered a subsidy to consumers if they do not pay for them at the margin.
- Here, different experiences:
  - Europe: usually charged to residential/commercial consumers.
  - US: some of the subsidies are federal tax credits (FTCs), not reflected in price. State-initiatives usually as RPS (partially reflected).

Policy and Tariff Design

- Previous work on large-scale renewable policies tends to model wholesale demand for electricity (Fell 2013, Wibulpolprasert, 2014).
- Implementation of wholesale renewable policies can have impacts to electricity consumption also through its impacts on retail tariffs.

- Example:
  - If RPS, how do consumers pay for it through retail rates?
  - If production subsidies are used, how is the revenue raised?

Feed-in tariffs do not necessarily depress *all* prices



Also in the US

Table 4: RPS impact by retail sector

Effect of Renewable Portfolio Standards on Electricity Prices, by Sector

	Total (1)	Total (2)	Residential (3)	Commerical (4)	Industrial (5)
δ_1: 1(RPS)	0.714**				
	(0.298)				
$\delta_1 + 5\delta_3$		1.119**	1.499***	0.827	0.681
p-value		0.022	0.003	0.109	0.107
State FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
N	1224	1224	1224	1224	1224

Notes:
1) Coefficient estimates for states with data seven years before and five years after RPS effective date.
2) Standard errors clustered at the state level.
3) Asterisks denote significance at the 90% (*), 95% (**), and 99% (***) levels

Source: Greenstone and McDowell, 2016.

Proposed approach

- Integrate two elements:
  - Supply-side model with endogenous dispatch and capacity.
  - Demand-side model for residential, commercial and industry sectors, with tariff design.
- Use framework to simulate:
  - Carbon tax
  - Feed-in tariff/production subsidy
  - RPS/Standards

Key: Renewables mostly about fixed capital costs. How do we recover their costs?

$\rightarrow$ Affects *both* efficiency and distributional implications.

Stylized overview of the model

Demand

Demand Industrial:	$D^I_{rt}(P_{rt}, X_{rt}; \theta^I)$
Demand Commercial:	$D^C_{rt}(P_{rt}, X_{rt}; \theta^C)$
Demand Residential:	$D^R_{irt}(P_{irt}, X_{irt}; \theta^R)$

Supply

$$\min_{q,K} \quad \sum_g \left(F_g K_g + \sum_t C(q_{gt}, K_g, \tau) \right)$$

$$\text{s.t.} \quad \sum_g q_{gt} = \sum_r \left(D^I + D^C + \sum_i D^R \right)$$

Barcelona School of Economics

Renewable policies considered

1. **Carbon tax:** Puts a price τ on carbon. Not necessarily about large-scale renewables.
2. **Feed-in tariff/subsidies:** Gives a flat rate per MWh of renewable production. Often technology specific. Also common to have subsidies at the margin, on top of the market price.
3. **Renewable Portfolio Standard:** Sets a percent goal in renewable generation, typically at the utility level. Trading of certificates to induce compliance and reveal market price. Similar in spirit to subsidies, but utilities are directly responsible to charge these costs.

Today: We will add subsidies. The key is how to pay for them.

Ranking across policies: Demand

Policy	Wholesale prices	Retail prices
Carbon Tax	$\uparrow$	$\uparrow$
Feed-in tariff	$\downarrow$	?
Production subsidy	$\downarrow$	?
RPS	$\downarrow$	$\uparrow$

Distributional implications: Producers will tend to benefit most if wholesale prices increase (infra-marginal rents), although not for all technologies. Consumers will suffer most when retail prices increase at the margin.

Adding retail tariffs...

- Some of these policies generate revenues or policy costs that are not accounted for by the model.
- Typical partial equilibrium assumption is to treat them as lump-sum transfers, maybe with a multiplier (large body of work looking at how they might impact general equilibrium).
- In practice, some of them might be priced directly into electricity consumption, e.g., with environmental charges to the price of electricity.

- Two extreme cases:
  - lump-sum charges, no multiplier
  - full cost recovery at the margin within the electricity sector –¿ Need to solve for it in equilibrium as demand responds

Solution approach to find renewable charge in the code

- We will use a **loop** to search for the right level of renewable charge added to the electricity price.

- These solutions can also be implemented as "raising the water level" algorithms, as it is very clear that the solution will cross the optimal point at some point (also with carbon tax to get a certain level of emissions).
  - If renewable charge collects too little money, increase.
  - If renewable charge collects too much money, decrease.

Retail tariffs considered in the paper

1. **Flat or real-time plus lump-sum:** assumed to be allocated equally across sectors.
2. **Flat or real-time plus marginal fee:** assumed to be allocated equally across sectors.
3. **Ramsey:** potential reallocation of costs across sectors (only for environmental fixed costs).

Can Ramsey prices justify shifting the burden on residential consumers vs. industrial consumers?

Theory detour on Ramsey prices

Typical Ramsey formula:

$$\frac{p_s - c}{p_s} = \frac{\lambda}{1+\lambda}\frac{1}{\epsilon_s},$$

- Given that industrial consumers are more elastic, serves as a justification for the type of pricing that we see.
- Burdensome on consumers, but potentially still efficient.
- Importantly, these are optimal Ramsey prices ignoring the presence of an externality.

Theory detour on Ramsey prices

Adding externality to the Ramsey formula:

$$\frac{p_s - c}{p_s} = \frac{\lambda}{1+\lambda}\frac{1}{\epsilon_s} + \frac{1}{1+\lambda}\frac{e_s \times \text{SCC}}{p_s},$$

- No longer as clear whether Ramsey formula is optimal or prescriptive in its standard form.
- Can depend substantially on marginal emissions rate, e_s.
- If consumers see to low prices due to renewable subsidies, possible to justify charging more to the *more* elastic.
- As long as they are also elastic *in terms of emissions*, i.e. no leakage.

Ramsey prices considered

1. **Ramsey:** Ramsey prices that recover costs of renewables and maximize welfare (ignoring externality).
2. **Ramsey enviro:** Ramsey prices that recover renewables costs and consider externalities.
3. **Ramsey enviro + leak:** Ramsey prices when emissions reductions in the industrial sector leak (decoupling between electricity response and emissions response).

Note: For all of them, additional markups exactly cover renewable costs. Of course, in practice, there are many other reasons why retail prices are above marginal cost.

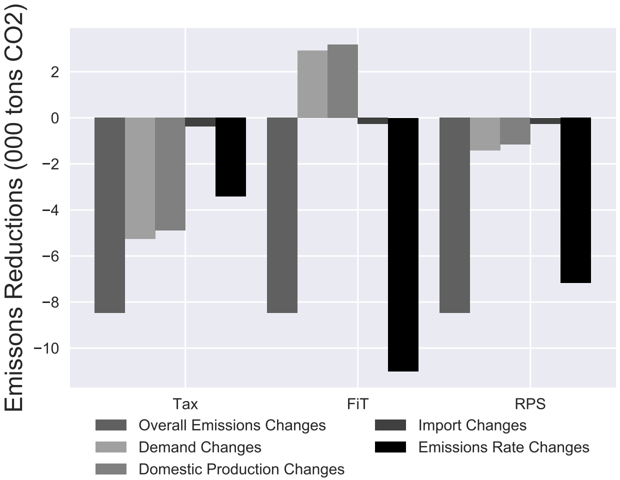
Efficiency and Distributional implications

- Do policies induce the right investment?
- How is this reflected in abatement?
- Who are the winners and losers?
- How much does it all change as the cost of renewables is passed through to consumers?

Efficiency decomposition

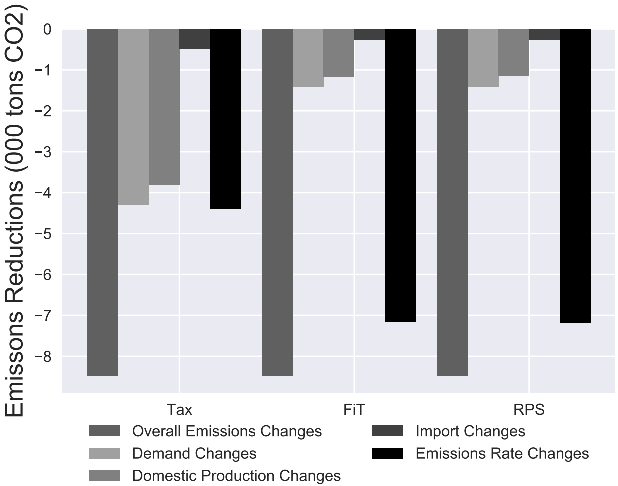
- Reduction of emissions held fixed across policies.
- Decompose source of reductions between:
  - Demand/supply changes
  - Emissions rate becoming cleaner
- Two sets of results:
  - Carbon tax, subsidies, and RPS
  - Carbon tax with marginal rebate, subsidies charged at the margin, and RPS

Efficiency implications



Barcelona School of Economics

Efficiency implications

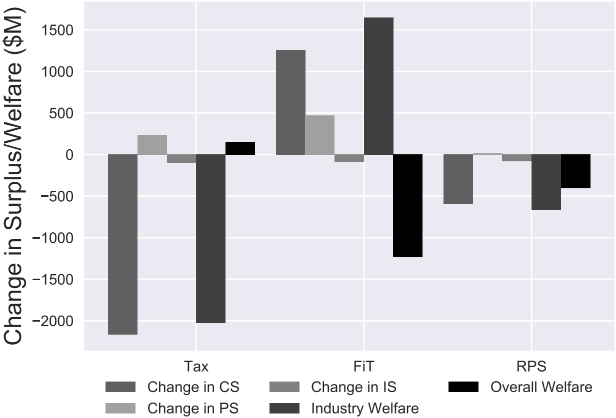


Distributional implications

- Who are the winners and losers?
- How does it depend on retail pass-through?

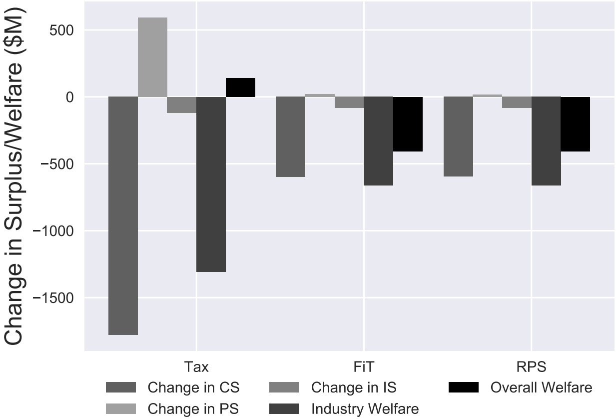
- For now, look at producers vs consumers:
  - Consumer surplus
  - Producers surplus
  - Import surplus

Distributional impacts



Barcelona School of Economics

Distributional impacts



Getting at sectoral redistribution

- I consider three different Ramsey scenarios:
  1. Standard Ramsey formula (ignores externality).
  2. Optimal Ramsey taking into account externality for welfare.
  3. Optimal Ramsey when industrial emissions leak.

- Also important to consider different levels of renewables subsidies.
- Helps consider situations far from first best, as Ramsey pricing can be used as corrective tool.

Results for Ramsey pricing

Low renewable target – FiT $107

	Prices			Δ Surplus			
	Res.	Com.	Ind.	Res.	Com.	Ind.	Δ W
Flat	40.84	40.84	40.84	-0.05	-0.09	-0.14	-1028.86
Ramsey	45.19	38.72	36.92	-0.08	-0.06	-0.05	-1047.02
Ramsey Enviro	39.51	41.14	43.14	-0.04	-0.09	-0.19	-1026.54
Ramsey Enviro Leak	40.86	43.14	34.65	-0.05	-0.12	-0.00	-1044.23

Ramsey prices are not welfare improving

High renewable target – FiT $148

	Prices			Δ Surplus			
	Res.	Com.	Ind.	Res.	Com.	Ind.	Δ W
Flat	59.19	59.19	59.19	-0.18	-0.33	-0.51	-3702.68
Ramsey	76.48	47.50	47.19	-0.29	-0.18	-0.28	-3641.29
Ramsey Enviro	69.78	52.42	47.80	-0.25	-0.25	-0.29	-3611.35
Ramsey Enviro Leak	72.36	52.47	41.73	-0.26	-0.25	-0.16	-3622.08

Barcelona School of Economics

Results for Ramsey pricing

Low renewable target – FiT $107

	Prices			Δ Surplus			
	Res.	Com.	Ind.	Res.	Com.	Ind.	Δ W
Flat	40.84	40.84	40.84	-0.05	-0.09	-0.14	-1028.86
Ramsey	45.19	38.72	36.92	-0.08	-0.06	-0.05	-1047.02
Ramsey Enviro	39.51	41.14	43.14	-0.04	-0.09	-0.19	-1026.54
Ramsey Enviro Leak	40.86	43.14	34.65	-0.05	-0.12	-0.00	-1044.23

Ramsey prices with externality reverse!

High renewable target – FiT $148

	Prices			Δ Surplus			
	Res.	Com.	Ind.	Res.	Com.	Ind.	Δ W
Flat	59.19	59.19	59.19	-0.18	-0.33	-0.51	-3702.68
Ramsey	76.48	47.50	47.19	-0.29	-0.18	-0.28	-3641.29
Ramsey Enviro	69.78	52.42	47.80	-0.25	-0.25	-0.29	-3611.35
Ramsey Enviro Leak	72.36	52.47	41.73	-0.26	-0.25	-0.16	-3622.08

Results for Ramsey pricing

Low renewable target – FiT $107

	Prices			Δ Surplus			
	Res.	Com.	Ind.	Res.	Com.	Ind.	Δ W
Flat	40.84	40.84	40.84	-0.05	-0.09	-0.14	-1028.86
Ramsey	45.19	38.72	36.92	-0.08	-0.06	-0.05	-1047.02
Ramsey Enviro	39.51	41.14	43.14	-0.04	-0.09	-0.19	-1026.54
Ramsey Enviro Leak	40.86	43.14	34.65	-0.05	-0.12	-0.00	-1044.23

Subject to no leakage assumption

High renewable target – FiT $148

	Prices			Δ Surplus			
	Res.	Com.	Ind.	Res.	Com.	Ind.	Δ W
Flat	59.19	59.19	59.19	-0.18	-0.33	-0.51	-3702.68
Ramsey	76.48	47.50	47.19	-0.29	-0.18	-0.28	-3641.29
Ramsey Enviro	69.78	52.42	47.80	-0.25	-0.25	-0.29	-3611.35
Ramsey Enviro Leak	72.36	52.47	41.73	-0.26	-0.25	-0.16	-3622.08

Barcelona School of Economics

Results for Ramsey pricing

Low renewable target – FiT \$107

	Prices			Δ Surplus			
	Res.	Com.	Ind.	Res.	Com.	Ind.	Δ W
Flat	40.84	40.84	40.84	-0.05	-0.09	-0.14	-1028.86
Ramsey	45.19	38.72	36.92	-0.08	-0.06	-0.05	-1047.02
Ramsey Enviro	39.51	41.14	43.14	-0.04	-0.09	-0.19	-1026.54
Ramsey Enviro Leak	40.86	43.14	34.65	-0.05	-0.12	-0.00	-1044.23

High renewable target – FiT \$148

	Prices			Δ Surplus			
	Res.	Com.	Ind.	Res.	Com.	Ind.	Δ W
Flat	59.19	59.19	59.19	-0.18	-0.33	-0.51	-3702.68
Ramsey	76.48	47.50	47.19	-0.29	-0.18	-0.28	-3641.29
Ramsey Enviro	69.78	52.42	47.80	-0.25	-0.25	-0.29	-3611.35
Ramsey Enviro Leak	72.36	52.47	41.73	-0.26	-0.25	-0.16	-3622.08

If prices above first best, then traditional qualitative result holds

Barcelona School of Economics

Getting at sectoral redistribution - insights

- Ramsey pricing can be detrimental to the extent that it prevents reductions from most elastic sectors.
- Ramsey pricing accounting for externalities prescribes prices that are closer together (if renewable goal large enough), or even reversed in the presence of too modest targets (increase reductions of electricity instead of avoiding them).

- All of this crucially depends on whether elasticity of electricity is correlated with elasticity of emissions:
  - If electricity-elastic sectors are not truly reducing emissions, then a further motive to strengthen Ramsey result.

Conclusions

- Paper builds a model to understand the trade-offs between charging different types of customers.
- I find it is key to understand whether elasticity is for electricity or for emissions.
  - If elasticity is for emissions, Ramsey undoes potential environmental goal.
- Model is silent about distributed generation as it doesn't have household granularity, but also a big part of the discussions on equity.

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