Empirical Methods for the Analysis of the Energy Transition

Slide Set 1

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2025/2026

Outline

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0. Introduction and Organizational Issues

Organization

- We will work with the materials mostly at the classroom website.
- I will post slides, readings, and code in the website.
- We will use the website also to submit assignments.
- Class will be focused on policy context, theoretical background, and hands-on practice with electricity market data.

Goal

- The goal of the class is to provide you with:
  - Knowledge of how electricity markets work and how they are evolving with the energy transition.
  - Familiarity with different kinds of datasets that are used in the electricity sector (technology, time series, smart meter data, etc.).
  - Ability to perform analysis using a range of **tools**: regression, model building, machine learning,...

Plan for the ten sessions

1. Intro. Practicum: regression analysis.
2. Supply I. Practicum: k-means clustering.
3. Supply I. Practicum: building a first model.
4. Supply II. Practicum: adding climate policies.
5. Supply II. Practicum: adding transmission.
6. Demand I. Practicum: modeling demand.
7. Demand I. Practicum: treatment effects/elasticities.
8. Demand II. Practicum: smart meter data and k-means.
9. Demand II. Practicum: demand policy simulations.
10. Project presentations.

Requirements

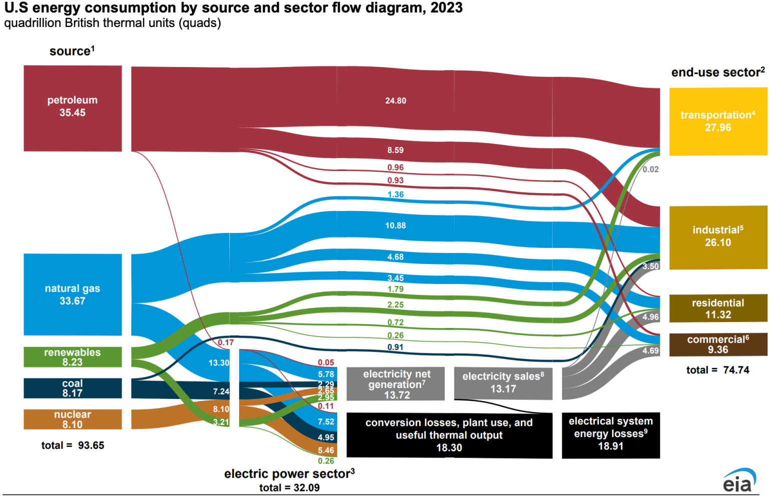
- There will be a group project and presentation (50%).
- There will be small assignments and in-class presentation (50%).
  - We will be using Jupyter notebooks and Python.

I. Overview of major topics in the energy transition

Big push in the electricity sector to decarbonize and electrify

- Need to reduce Green House Gas emissions (GHGs).
- Electricity sector (≈35-40% of CO_2 emissions) has been **most active** and has the greatest potential in making the transition.
- Ambition to move towards **carbon-free electricity** by 2050.
- **Limits to decarbonization**:
  - **Renewables' intermittency** might lead to a potential mismatch between supply and demand, increasing need for flexibility.
  - **Need to improve complementary infrastructure** in high and low voltage.
  - **Vulnerabilities** due to climate shocks.
  - **Growing pressures** due to decarbonization of other sectors (cars, heating, etc.).

Electricity is a Key Input in the Economy



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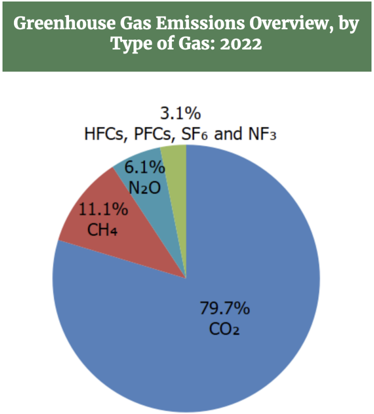
Why Energy?

- Energy is a key factor for almost all economic activities:
  - Production of goods
  - Transportation of goods and services
- World energy consumption growth, but natural resources are scarce
- Uneven distribution of natural resources leads to energy security issues
- Energy-related CO2 emissions
  - large share of GHG emissions (over 70%)



Total U.S. Emissions in 2022 = 6,343 Million Metric Tons of CO_2 equivalent (excludes land sector). Percentages may not add up to 100% due to independent rounding. Land Use, Land-Use Change, and Forestry in the United States is a net sink and offsets 13% of these greenhouse gas emissions. This net sink is not shown in the above diagram. All emission estimates are sourced from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*.

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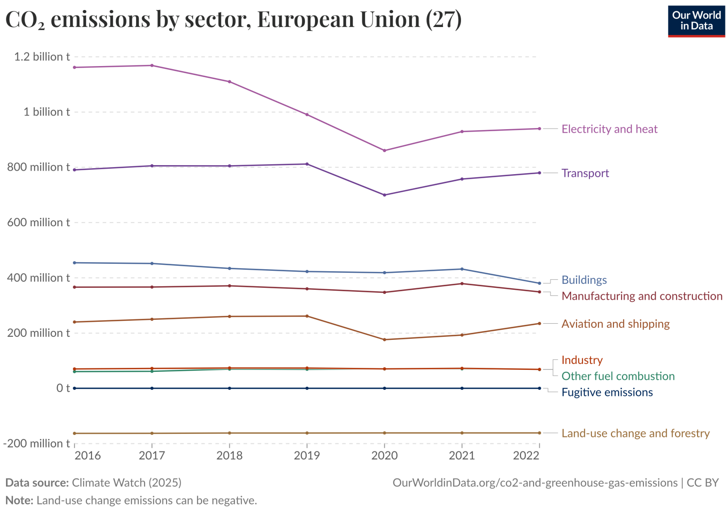
Why Electricity?



Why in an Economics master's?

- Economics is the study of the allocation of scarce resources.
- Economists seek to understand how households and firms interact in markets defined by scarcity and government regulation.
- Economics helps to explain market outcomes we have observed in the past, and to predict how future outcomes would respond to changes in the operating environment.

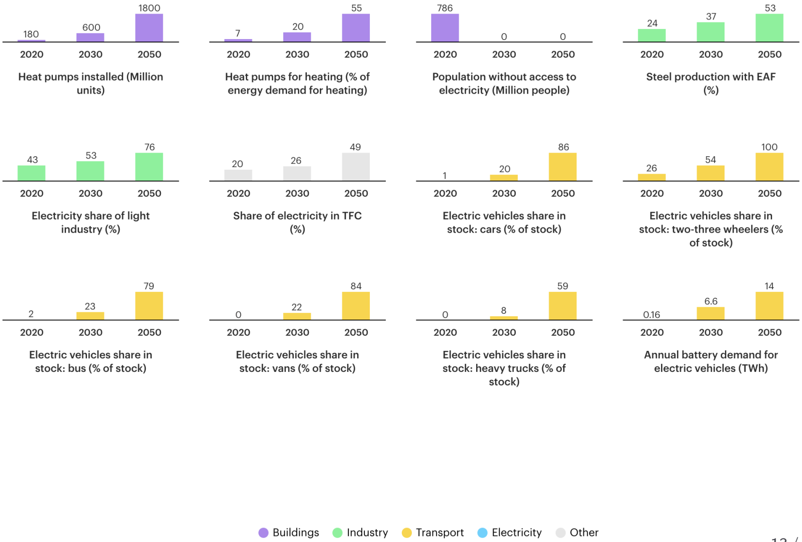
While many studies and tools come from engineering, economics can help understand market forces and incentives, while accounting for the regulatory environment.

A crucial element of the solution

Electrification

As electricity generation becomes progressively cleaner, electrification of areas previously dominated by fossil fuels emerges as a crucial economy-wide tool for reducing emissions.

This takes place through technologies like electric cars, buses and trucks on the roads, heat pumps in buildings, and electric furnaces for steel production.

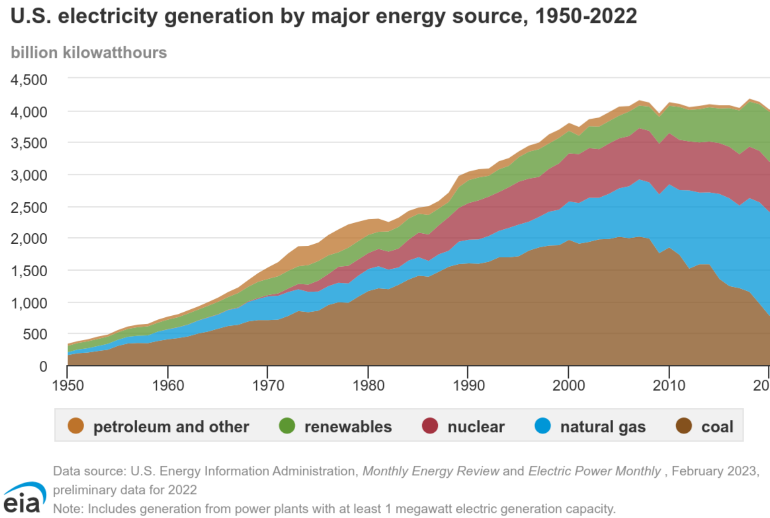


Implications for energy use and GHG

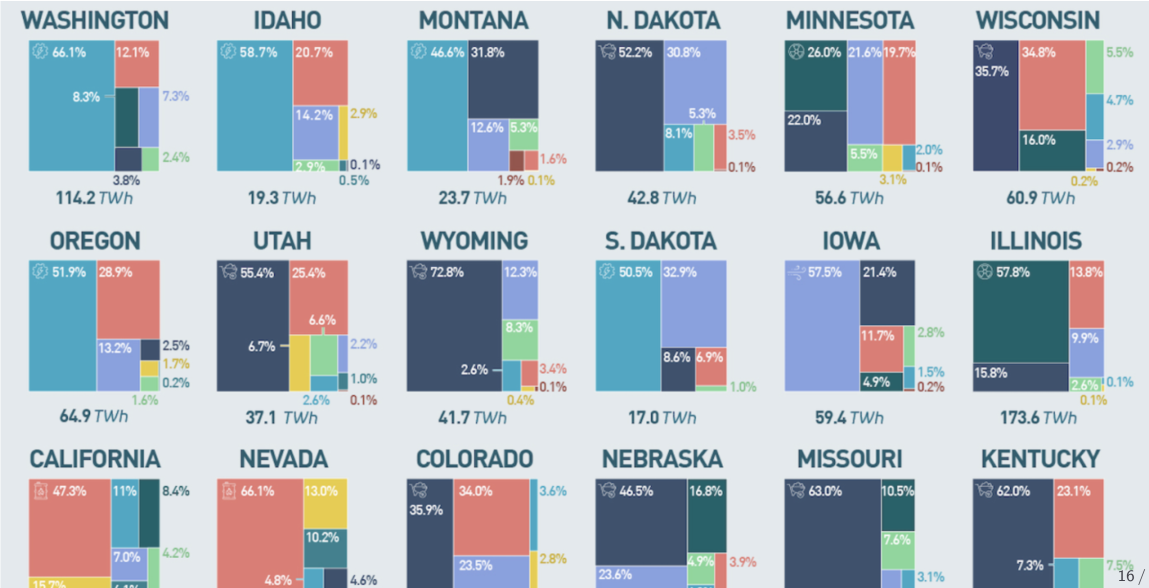
- Electricity generation contribution to GHGs has been steadily declining (both in % and even in levels).
- More attention shifting towards transportation and heating.

- These markets are becoming more and more **interrelated**: a low-carbon solution for transportation involves electric vehicles.
  - Need to figure out how to accommodate a growing need for electricity while shifting towards **zero-carbon technologies**.

Generation by energy source, US

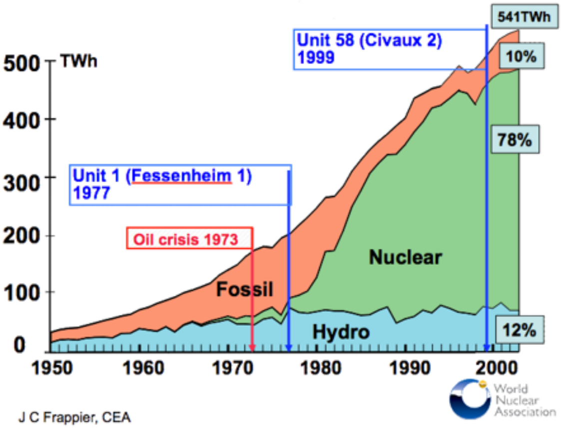


Large variations across regions and countries!

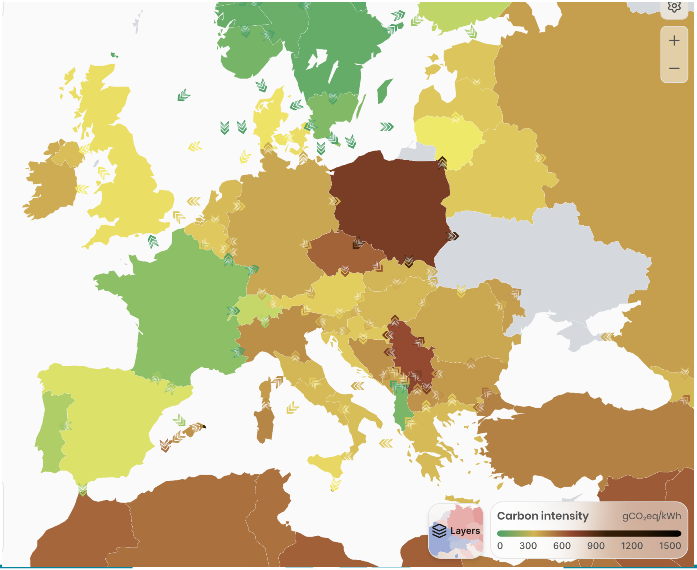


Generation by energy source, France

- Policy choices and resource availability can substantially impact the mix over many decades.
- Example: France opted for nuclear during the oil crisis (1970's) and it has long lasting impacts to today's mix.

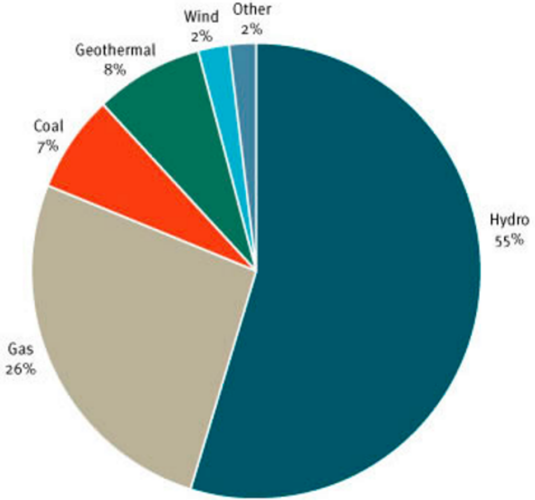


Europe mix, a snapshot



Generation by energy source, New Zealand

- Water availability is also a big driver of adoption.
- Example: Brazil, New Zealand, or Nordic countries have a large reliance on hydro.
- Decarbonized energy source but not available everywhere.



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Costs vary by resource

- Different sources might be better suited depending on utilization.
  - Some of them have very large fixed costs (e.g., nuclear), but low marginal cost ⇒ run always.
  - Some of them have much smaller fixed costs, but higher marginal costs (natural gas) ⇒ run only when demand is high
  - Some are only available in limited quantities (hydro) or at times (solar)
- Several technologies can co-exist!

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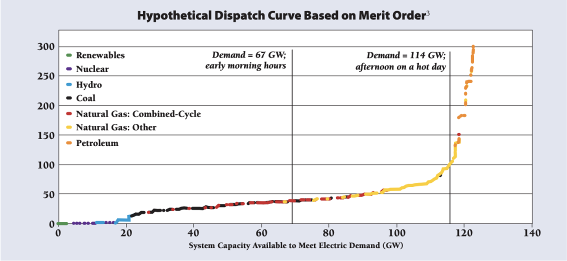
How to optimize the electricity market?

- Electricity markets are highly complex, but they follow an Econ 101 intuition: crossing demand and supply at each period.
- Supply units are stacked from cheapest to most expensive, called the "merit order".
- A central planner looks at the best combination of plants to produce at any given point.

Figure 21-1



Source: `https://www.4cleanair.org/event_meeting_notes/implementing-epas-clean-power-plan-a-menu-of-options/`

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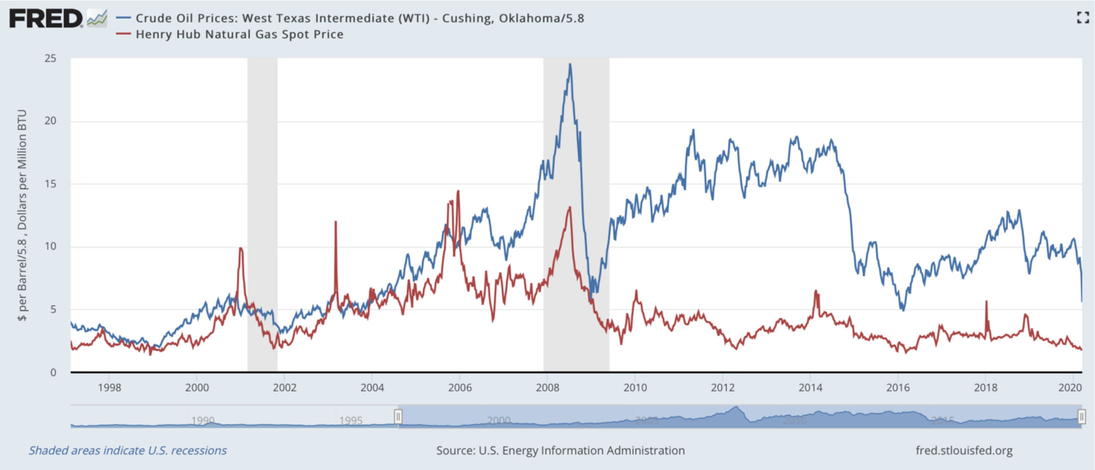
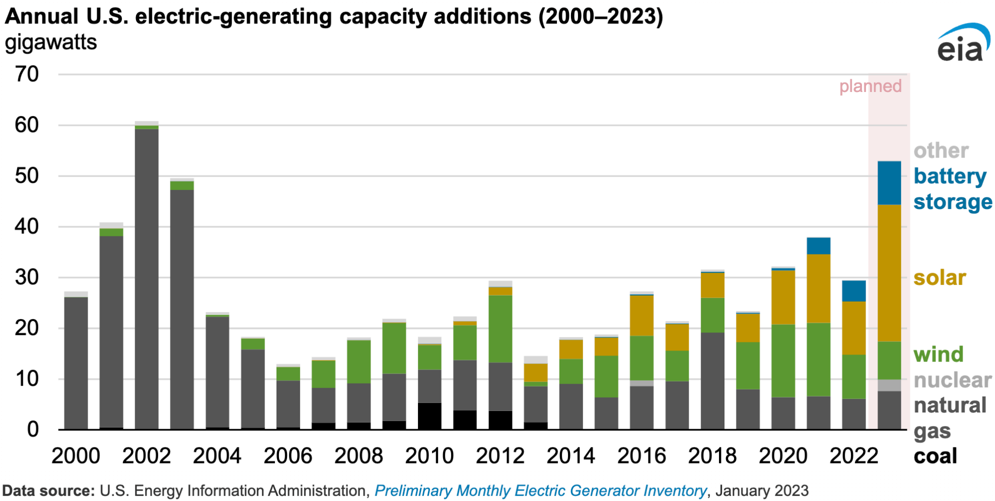
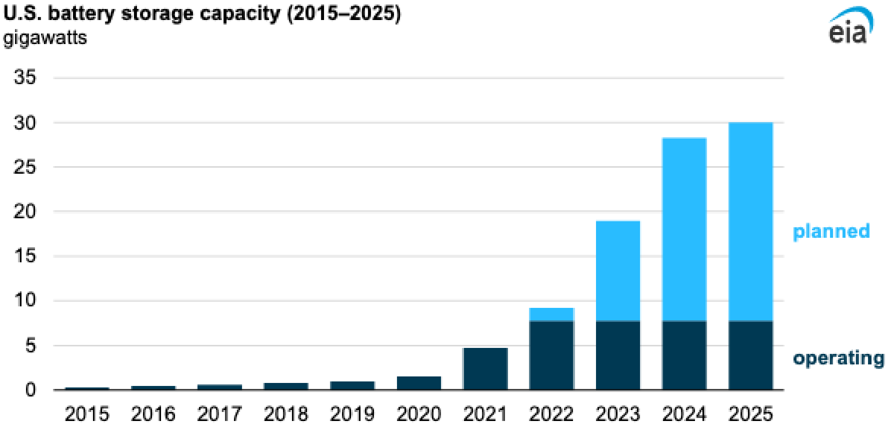
Important changes recently: shale gas



Important changes recently: Renewables



Important changes recently: Batteries

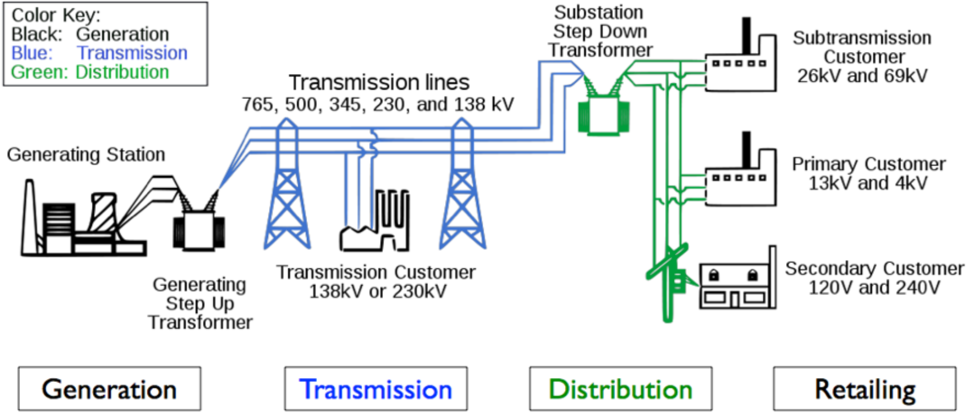


Data source: U.S. Energy Information Administration, Preliminary Monthly Electric Generator Inventory, October 2022

Let's get some more basics about electricity

(before we take a deeper dive on renewable power!)

The electricity industry consists of four segments



The electricity industry consists of four segments

- **Generation**
  - Many different technologies, all produce homogeneous good (ignoring location)
- **Transmission**
  - Long-distance, high-voltage
- **Distribution**
  - Local, low-voltage (natural monopoly)
- **Retailing**
  - primarily a financial business

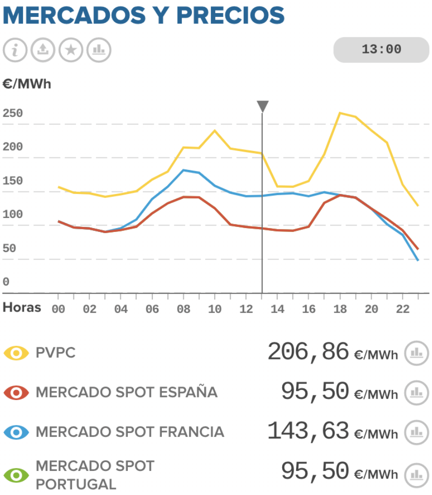
Key features of electricity

- Electricity cannot be easily stored. Recent developments in battery technologies, but still limited in quantity and price.
  - Otherwise, blackouts can occur.
- Demand and supply need to balance each other in real-time
  - The whole system is connected.
- Transportation of electricity follows very particular laws of physics

$\Rightarrow$ All these **features** affect how we think about electricity using *economics*.

Electricity cannot easily be stored!

- In markets with short-run capacity constraints, costly storage, and variable demand one should expect to see **large price fluctuations**.
  - In addition to electricity other examples include air travel and ski resorts
- These price swings are *efficient*, and provide efficient incentives for investments in capacity.
- In electricity this is called *peak-load pricing* or *real-time pricing (RTP)* or *dynamic pricing*.



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Transmission constraints

- Physical characteristics of the transmission grid create externalities across grid "users"
  - The transmission grid has limited capacity, especially at times of peak demand
  - One plant's production can affect another plant's ability to supply power if they're both on one side of a transmission constraint
  - Defining prices that vary by location is both theoretically and practically challenging

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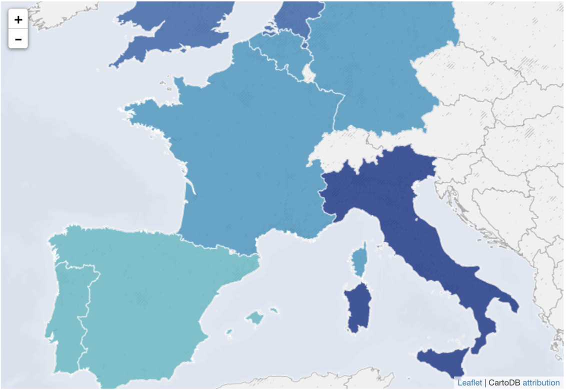

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Grid must stay within frequency band

- One unique characteristic of electricity markets is that the $S = D$ condition has little margin for error.
- Small differences between the two change the frequency of the electricity in the grid
  - Large changes in the frequency damage electric equipment
- Capacity to respond quickly and cost-effectively to variations in demand will depend on the flexibility of the power plants.
- Note: the fine level adjustments happen automatically.

Modeling the energy transition

- Modeling the energy transition in the electricity sector can be **complicated**.
- Amount of engineering detail can be overwhelming but at the same time important.
- Detailed realistic models can be *computationally burdensome*.
- Purely engineering models might have a hard time getting at *economic incentives*.

A bit like physics, depending on the question, one needs a different model

Most important!

1. Understand the tools that are used by both economists and engineers to model these markets.
2. Be familiar with strengths and weaknesses of a given model.
3. Listen to engineers if important aspects are missing and investigate computational tricks if worth incorporating.

II. The value of renewable power

Expansion of Renewables

Renewables represent a change in paradigm for how electricity markets operate, as they are "non-dispatchable".

- **Before:** supply follows demand.
- **Now:** demand follows supply?

There have been some discussions on the value of renewables in the presence of technical constraints.

- Renewables fluctuate substantially and/or cannot produce at night (e.g., solar).
- See recommended reading Joskow (2019) for a discussion.

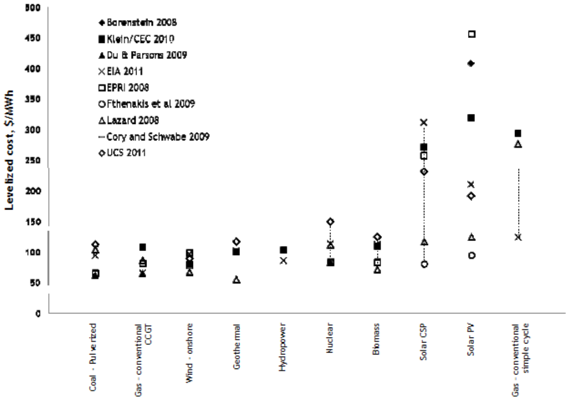
The economics of renewables

- How should we *start* thinking about the economics?
- People often talk about "levelized costs".

$$LCOE = \frac{\sum_{t=0}^{T} \frac{C_t(q_t)}{(1+r)^t}}{\sum_{t=0}^{T} \frac{q_t}{(1+r)^t}}$$

- They provide a sense of *average cost per MWh produced*.
- Units are typically \$/MWh.

Figure 1. Levelized cost estimates



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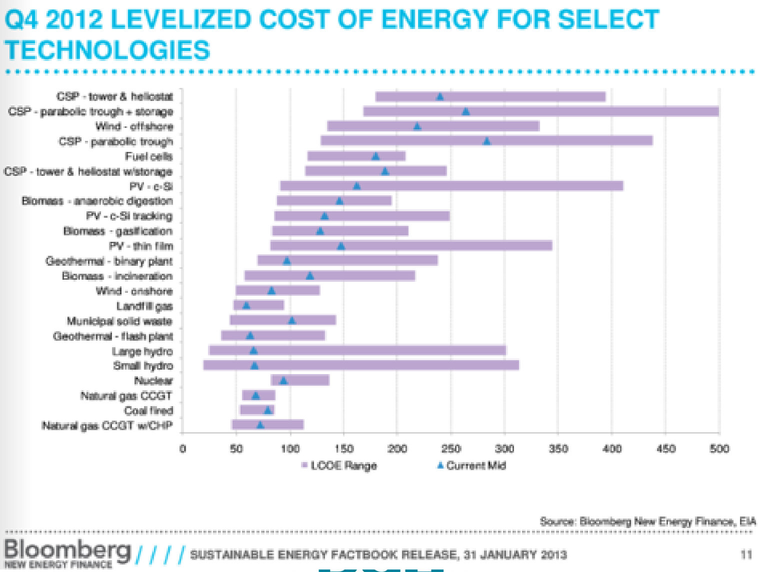
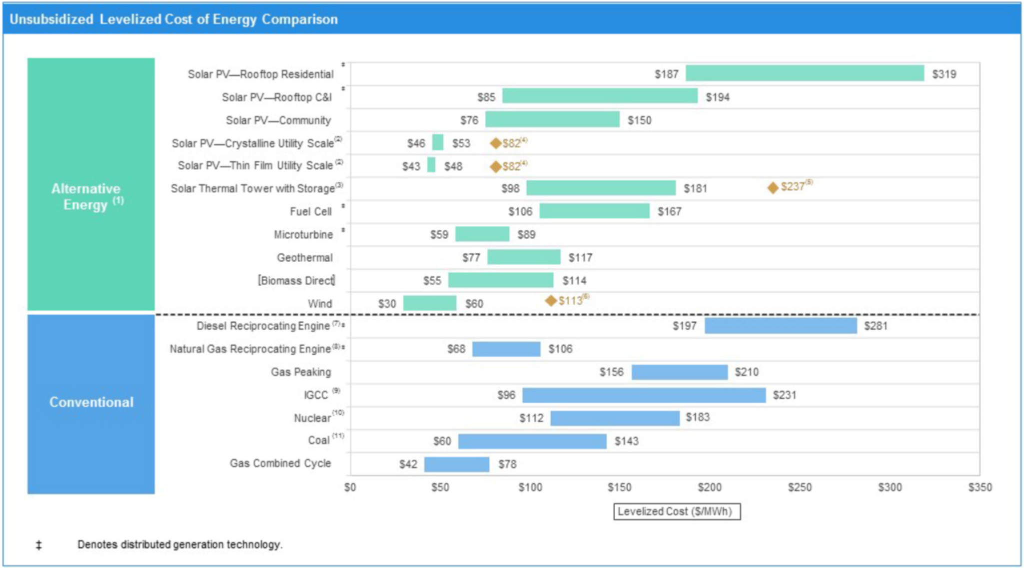
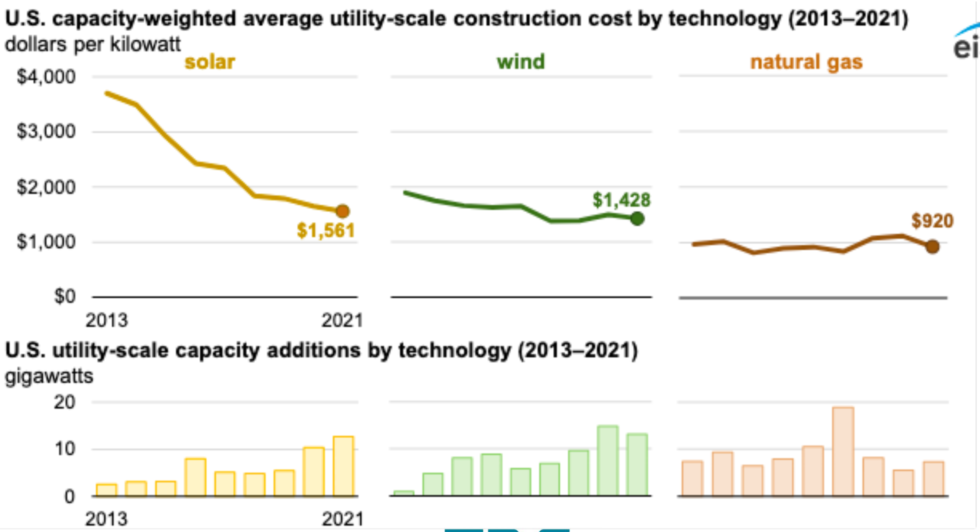
Variation in LCOEs (newer estimates)



Variation in LCOEs (even newer estimates)



LCOEs for renewables are rapidly changing!



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Why so much variation in LCOEs?

- **Engineering assumptions**
  - Costs
  - Output
  - Transmission/curtailment
  - Operation and maintenance

- **Economic assumptions**
  - Discount rate
  - Time horizon
  - Future input costs
  - Private v. social costs (subsidies, taxes, regulation)
  - Opportunity/less-salient costs

Some limitations of LCOEs

- Depending on the assumptions, some aspects might be overlooked:
  1. Intermittency (costs of reliability)
  2. Output and price (market equilibrium effects, cannibalization)
  3. Location (limits on ability to site optimally)
  4. Externality benefits (sometimes) not included

- These limitations in LCOEs have been used as a motivation to compute also measures of the **costs and benefits of wind and solar power using an ex-post assessment.**

Examples in the (economics) literature

- Cullen (2013) and Novan (2015) measure the emissions reductions benefits from wind production.
- Bushnell and Novan (2021) measure the price impacts of solar in California.
- Abrell, Kosch, & Rausch (2019) assess impacts of wind and solar in Germany and Spain.
- Liski, M., & Vehviläinen (2020) assess impacts of wind in Nordic market.
- Gowrisankaran, Reynolds, & Samano (2016) build a structural model to analyze optimal reliability policies.

- **Note 1:** Modeling the impacts of renewables is a huge topic also in engineering.
- **Note 2:** This is not meant to be a comprehensive list, huge literature!

Reduced form approach (today)

- **Main approach** consists in regressing an outcomes of interest (emissions, prices, etc.) onto wind or solar output.
- Collection of data from markets with substantial renewable generation (Texas, California, Germany, Spain).
- *Key:* Wind and solar mostly exogenous.
- Concerns and variations:
  - Endogeneity as renewable output increases
  - Confounders (solar very related to demand)
  - Short vs. long-run impacts
- Note: some papers complement regressions with quantification framework (e.g., Abrell et al., Liski).

Case Study: Wind Power in Spain

Measuring the Impact of Wind Power and Intermittency*

Claire Petersen† Mar Reguant‡ Lola Segura§

October 2, 2023

Abstract

Wind power is crucial to decarbonizing electricity markets but is intermittent, which complicates operational management. We assess the welfare impact of wind power on the Spanish electricity market during the years 2009-2018, with a focus on how wind impacts congestion and reliability costs. In the baseline results, for an additional GWh of forecasted wind generation, we estimate that operational costs go up by about 0.19 EUR/MWh compared to an average of 3.85 EUR/MWh. We find no evidence of these marginal impacts significantly increasing with wind availability. Using detailed bidding data for congestion and reliability markets, we highlight how changes in market design can reduce the negative impacts of wind power on the operation of the grid.

KEYWORDS: electricity markets, energy transition, intermittency, wind power.

JEL classification codes: Q40, Q42, Q52.

Paper overview

- **Question**
  - What have been the impacts of wind generation in the last decade?
- **Methodology**
  - Regression analysis of hourly operational data (prices, congestion costs, emissions benefits, etc.).
- **Finding**
  - Consumers have been better off, even after accounting for the cost of the subsidies.
  - Market design can impact these benefits.
- **Co-authors**
  - Claire Petersen and Lola Segura-Varo

Data

- We get hourly data from the **Spanish electricity market** (2009-2018). Data from REE and OMIE.
  - Time series data, hourly level.
- Data include market prices, intermittency costs, congestion, and other reliability services, emissions data (tons/CO2), subsidies received (millions), etc.
- We quantify the impact of wind on these variables:
  - **Benefits:** emissions reductions, reduced use of fuels, price reductions for consumers.
  - **Costs:** increased costs of intermittency (paid by consumers and by wind farms), price reductions for consumers.

Summary statistics

Table 1: Summary Statistics

	Mean	SD	P25	P50	P75
Actual Demand (GWh)	28.67	4.82	24.54	28.84	32.36
Wind Forecast (GWh)	5.26	2.94	2.95	4.66	7
Solar production (GWh)	.83	1.08	0	.05	1.66
Price DA (EUR/MWh)	45.97	15.78	37.68	47.62	55.69
Total System Costs (EUR/MWh)	3.85	3.12	1.87	3.1	4.92
Restrictions Costs (EUR/MWh)	2.48	2.34	.99	1.94	3.27
Insurance Costs (Euro/MWh)	.29	.76	0	.11	.38
Deviations Costs (EUR/MWh)	1.11	1.36	.42	.74	1.33
CO2 Emissions (tCO2)	7065.07	2728.48	4863	7161.17	9143.79

Notes: Price DA is the price at the day-ahead market. The variable "Total System Cost" is the sum of all other costs (restrictions, insurance, and deviations costs). $N = 83,840$.

Focus on operational challenges

- In the literature, often large emphasis on the costs of intermittency from renewable resources.
- Focus on the paper to quantify **intermittency costs** in the market.
- *Has wind contributed to large increases in operational costs?*

- We identify intermittency costs as the (accounting) **costs of providing congestion management, reliability services, balancing, etc**.
- These are additional costs that are required to reliably produce electricity and that are paid by consumers.

Regression results

Table 2: Marginal impacts of wind on system costs

VARIABLES	(1)	(2)	(3)	(4)
Forecasted wind (GWh)	0.194	0.194	0.196	0.191
	(0.0161)	(0.0161)	(0.0159)	(0.0162)
Forecasted demand (GWh)	-0.153	-0.155	-0.157	-0.157
	(0.0188)	(0.0188)	(0.0187)	(0.0188)
Solar production (GWh)	0.0265	0.0323	0.0530	-0.0124
	(0.0691)	(0.0684)	(0.0669)	(0.0645)
NG price (EUR/MWh)		0.0285	0.0243	0.0236
		(0.0424)	(0.0419)	(0.0419)
Mean temperature (F)			-0.0437	-0.0240
			(0.0339)	(0.0358)
Sq. mean temp. (F/1000)			0.256	0.157
			(0.254)	(0.261)
Mean dew point (F)				-0.00933
				(0.00684)
Observations	83,840	83,840	83,840	83,840
R-squared	0.560	0.560	0.561	0.561

Quantification of heterogeneous marginal impacts

- We use a simple **regression spline approach** to get at impacts:

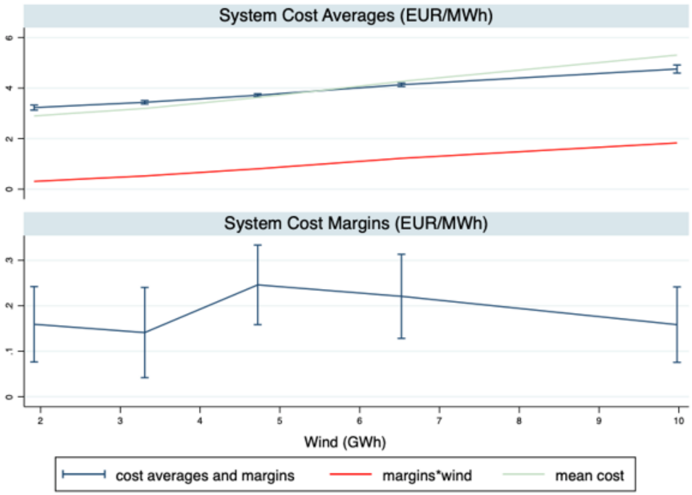
$$Y_t = \beta_0 + \sum_{q=1}^{5} \beta_q W_{qt} + \gamma X_t + \varepsilon_t$$

- Marginal impact of wind can differ at different quintiles (low vs. high wind conditions).

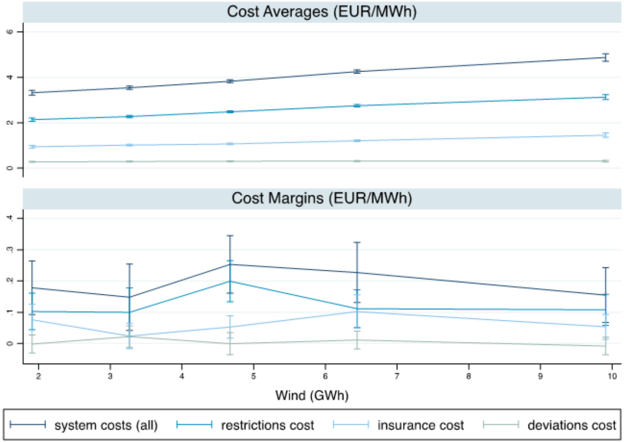
- Use *forecasted wind* to deal with endogeneity.
    - Wind power can respond to market conditions, e.g., if there is too much wind and the market cannot take it, or if firms find it profitable to "throw it away".

Impacts on operational cost

Figure 4: Average Marginal Effects of Wind on System Costs



Impacts on various operational cost



The importance of market design

- The costs of integrating wind power into the electricity market can depend on **how well-designed the market is**.
- Market design also interacts with **subsidies**.
  - E.g., negative prices in Texas or Germany, zero prices in Spain.
- Several markets have adapted their functioning to accommodate renewable power:
  - *California:* EIM market to allow for trade between regions.
  - *Germany:* half-hour markets (instead of hourly).
  - *Europe:* move towards continuous trading to have more flexibility.

- In Spain, focus on a change in **wind premium**.

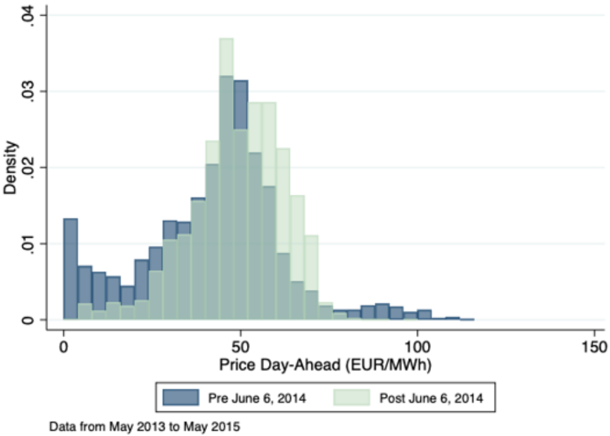
Regulation change in 2014

- In 2014, Spain changed how wind power plants are rewarded.
  - Moving away from output-based to capacity-based subsidy.
  - Leaving many plants without support because market price was more attractive.
- Typical **renewable support schemes**:
  - Feed-in tariff: constant reward for output (e.g., 60 Euro/MWh) or for capacity (i.e., proportional to installed capacity, sometimes with minimum production requirements).
  - Premium: added premium to the market price (e.g., extra 30 Euro/MWh), final reward is price + premium (sometimes combined with cap, e.g., only premium if price below a threshold). Problem: they sometimes lead to negative prices (e.g., Texas/Germany) or zero prices (Spain).
  - Renewable tradable permits (RPS in the United States): equivalent to a premium for green output, but traded in the market to determine the price.

Impact on market prices: no zero prices

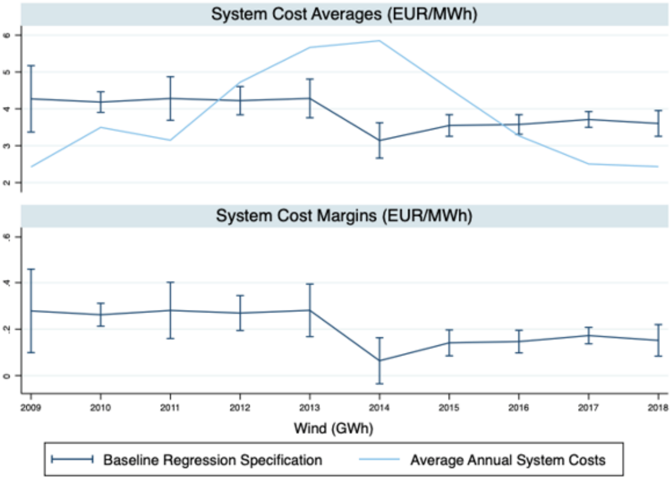
Figure 2: Price and wind outcomes before and after the 2014 policy change

(a) Day-ahead marginal prices before and after policy change



Leads to reduction in system cost

Figure 3: Annual Average and Marginal System Cost Effects



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Getting at welfare effects of wind

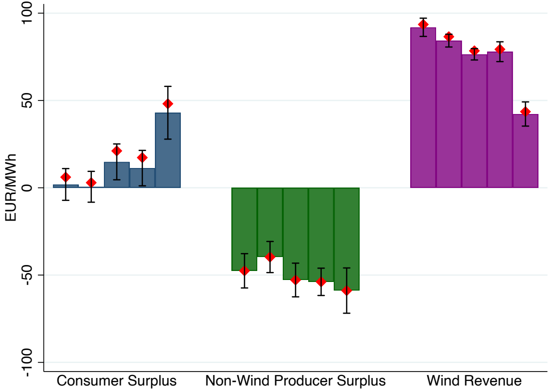
- **Consumer surplus**
  - Benefit: reduced price.
  - Cost: subsidy, costs of intermittency paid by consumers.
- **Producer surplus**
  - Benefit: subsidy, reduced fossil fuel costs.
  - Cost: reduced price, costs of intermittency paid by wind farms.
- **Emissions reduction**
  - Above and beyond what is already internalized by EU-ETS.
  - For alternative values of SCC.
- **Cost of investment**
  - For alternative LCOE values.

How to obtain these values?

- **Consumer surplus**
  - Benefit: regression for price impacts.
  - Cost: subsidy from data, regression for system cost impacts.
- **Producer surplus**
  - Benefit: subsidy from data, fuel costs proxied by market price.
  - Cost: regression for price impacts and cost of intermittency.
- **Emissions reduction**
  - Compute value of emissions reductions and regress on wind power to obtain marginal impacts.
  - For alternative values of SCC.
- **Cost of investment**
  - Ex-post calculation to get at "breaking even" point.

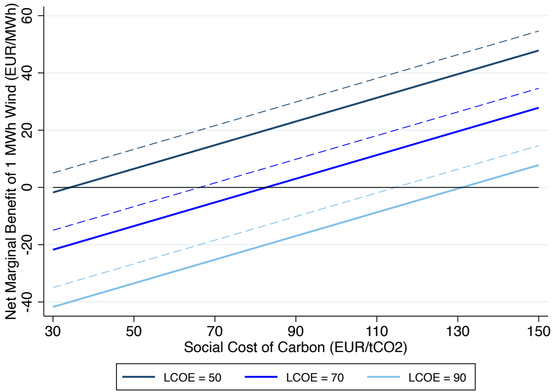
Welfare effects of wind by group

- Marginal increases in wind benefit consumers more than they hurt them, even if they have to pay subsidies.
- Biggest losers are traditional producers of electricity.
- Wind farms receive large revenues, key for welfare is how that compares with costs.
- Intermittency has modest overall effects.



Cost-benefit for different SCC and LCOE

- Overall cost benefit sensitive to assumptions on the cost and benefits of wind power.
- LCOE = (mostly) capital costs of wind.
- SCC = social cost of carbon, global environmental benefits.
- Intermittency has some impacts, but does not affect qualitative findings.



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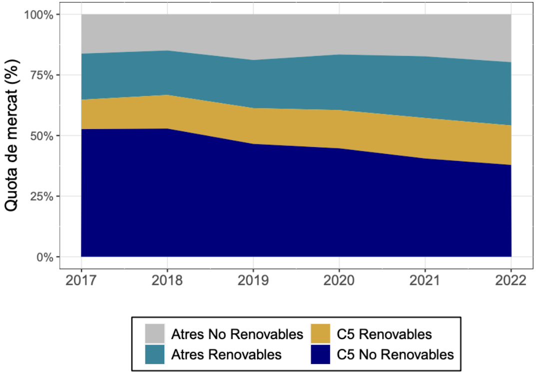
Summary

- Wind investments had a positive impact on welfare for reasonable SCC.
- On average, the policy benefited both consumers and (wind) producers.
- Details on market design and compensation can substantially impact winners and losers.
- Sometimes perceived as a costly mistake, but a huge early success in climate policy has led to over 20% of generation in Spain being from the wind.
- Regulatory changes can provide useful innovations that reduce costs.

Remaining challenges

- One result that we see in the previous paper and follow-up policy work (Enrich et al., 2024) is that renewables have also greatly increased competition in the market.
- In the previous paper, we also observed that prices for reliability products were not "out of hand."
- However, with the increasing adoption of renewables, especially solar power, Spain is now facing growing challenges in these markets.
- This is in line with other solar-heavy markets (Bushnell and Novan, 2021).

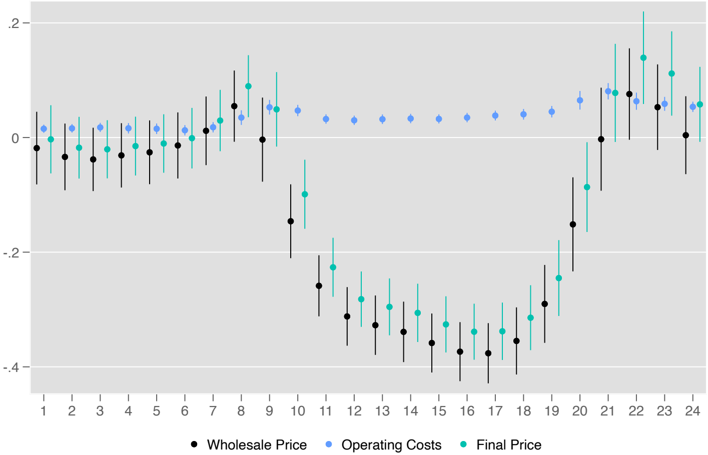


Work in progress with David Brown (U of Alberta)

- **Question:** How are reliability markets working and how do they need to be redesigned? How does the impact differ with wind and solar?
- **Methods:** Detailed analysis of bidding data at the unit level, with a combination of descriptive statistics (for now) and structural modeling (TBD).
- **Data details:**
  - Spanish data on reliability markets has an unprecedented level of detail.
  - We can examine the bidding strategies of every single firm, how they update it over time, how it interacts with the day-ahead and other energy markets, etc.

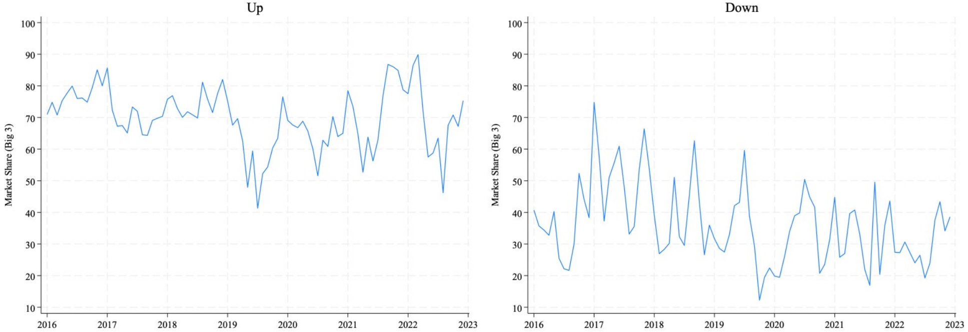
We extend the data period to include the presence of solar

- Solar impacts of intermittency can be larger on costs, although the overall picture still remains.
- Yet, some very high prices in some hours.



We see evidence of concern

- Back-up power is especially concentrated in the top firms, oftentimes with very few power plants offering their services in a given regulation area.
- This can make the system fragile, as observed during the blackout.



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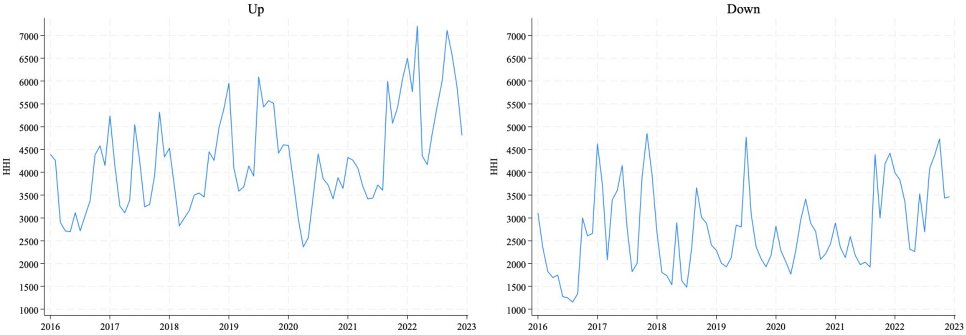
We see evidence of concern

- Standard HHI indices can be as high as 7000 in recent years, and this is without accounting for market segmentation of the regulation areas.



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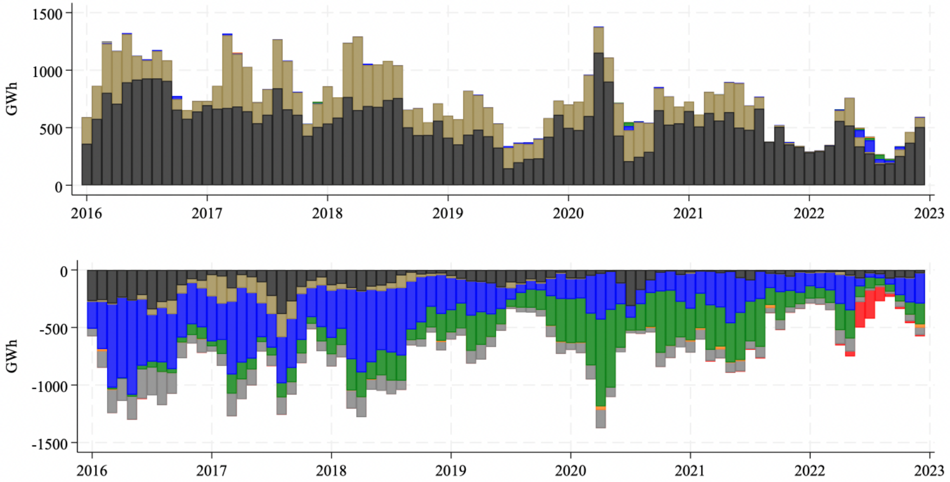
Competition among the Last of Them

- Competition in the restriction market (and related products) will only increase as newer sources (e.g., batteries, hybrid renewable installations) are incorporated in the market.



The need for adaptive regulation

- The Spanish market is working to improve the participation of other units in these reliability markets.
- Some previous experience allowing wind farms to provide 'down' services suggests that competition can increase substantially, and some minor evidence in 2022.
- Properly pricing these services and the dispatch of resources can avoid crowding out better alternatives and should encourage the entry of batteries in the system.
- Still extremely early work: infinite data, and plenty of regulatory changes.

Next class

- **Supply I**
  - How do electricity markets work?
  - How do different technologies participate in the market?
  - How do we translate this knowledge into equations?