Empirical Methods for the Analysis of the Energy Transition

Slide Set 1

Prof. Mar Reguant

BSE Summer School 2024

Roadmap

0. Introduction and Organizational Issues

- Welcome
- Goal
- Organization
- Projects
- Content

I. Overview of major topics in the energy transition

II. The value of renewable power

- Levelized Cost of Electricity
- Case Study: Wind Power in Texas
- Case Study: Wind Power in Spain

Welcome

- Prof. Mar Reguant (PhD, MIT 2011).
- I work on the filed of energy economics and industrial organization.
- Focused on the study of electricity markets and the energy transition.

- Part-time full professor at Northwestern University and research fellow at BSE with an ERC Consolidator grant.
- Project: ENECML - "Understanding the energy transition with a machine learning toolkit"

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,...

Organization

- Each day will be structured around a theme:
  - Morning session (w/ Mar Reguant): Lecture about topic related to electricity markets and the energy transition.
  - Afternoon session (w/ Jacint Enrich): Practice with data and code based on my own research and a paper that we have covered in the morning.

- Slides, code, and data are made available on the website for the course: `https://mreguant.github.io/em-course`

- **Important**: We will be updating the materials throughout the week. The code should be downloaded at the time that we start practice to make sure it is at its latest version!

Project presentations

- Students taking this class for credit need to prepare a project presentation in groups of up to 4 people.
- The project will consist in proposing a modification to the basic electricity model that you will learn in the practical sessions.
- Ideally, you will examine a policy question using the model, even if it is quite simple.

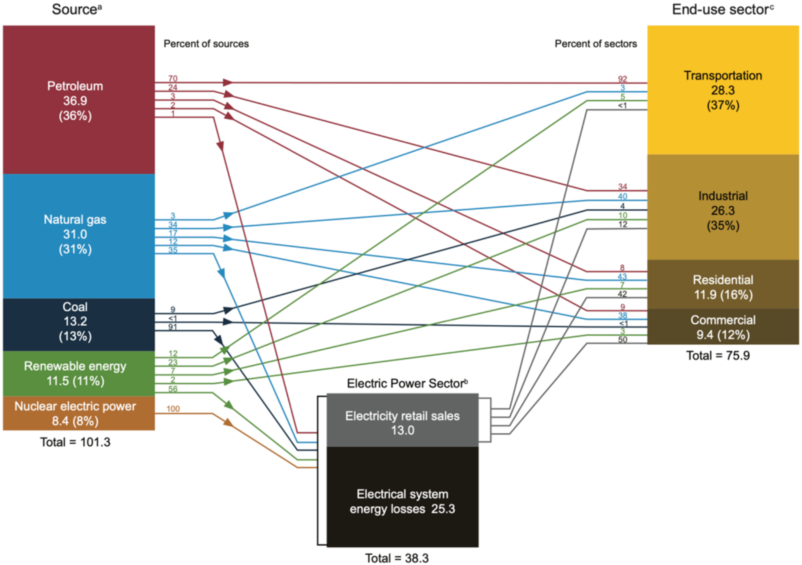
- **Example:** What happens when we put a carbon tax to the model?

Plan for the five days

1. Intro. Practicum: regression analysis.
2. Supply I. Practicum: building a first model.
3. Supply II. Practicum: adding climate policies.
4. Demand I. Practicum: modeling demand.
5. Demand II. Practicum: treatment effects/elasticities.

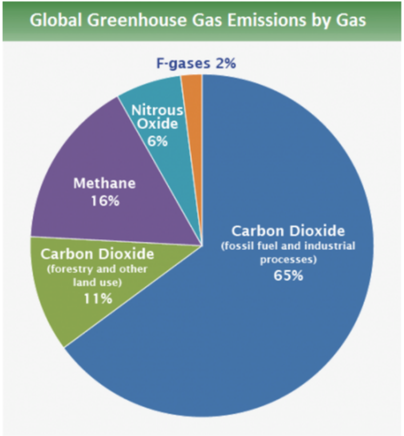
Roadmap

Electricity i



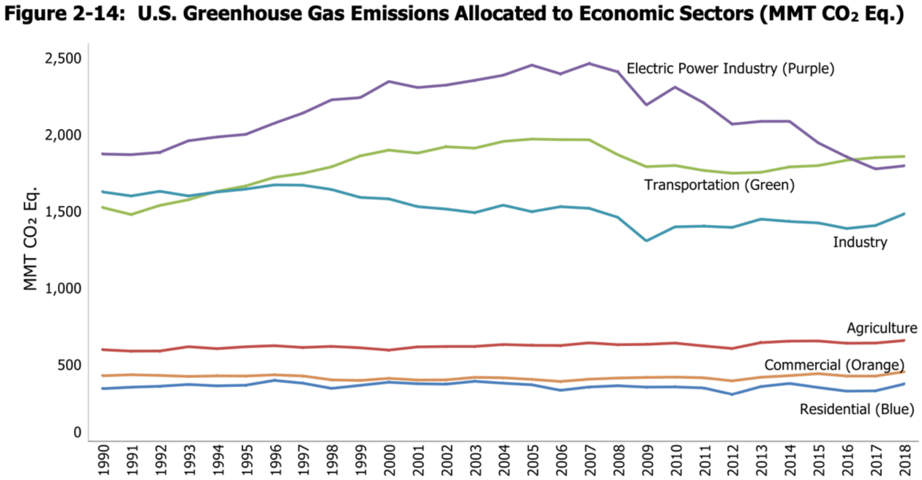
Why Energy?

- 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



Source: IPCC (2014) EXIT based on global emissions from 2010. Details about the sources included in these estimates can be found in the *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. EXIT

Why Electricity?

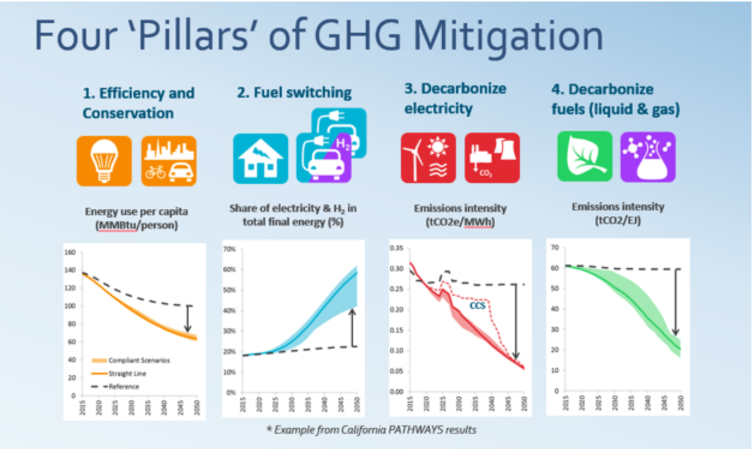


Why Economics?

- 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.

All of the above are extremely relevant in the energy sector!

A crucial element of the solution

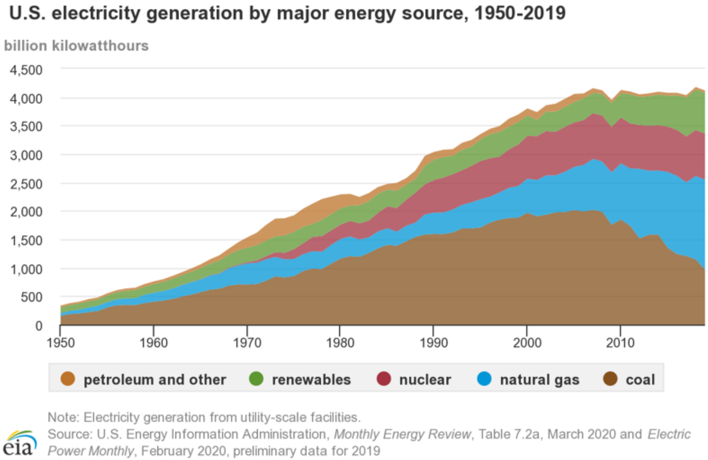


Implications for energy use and GHG

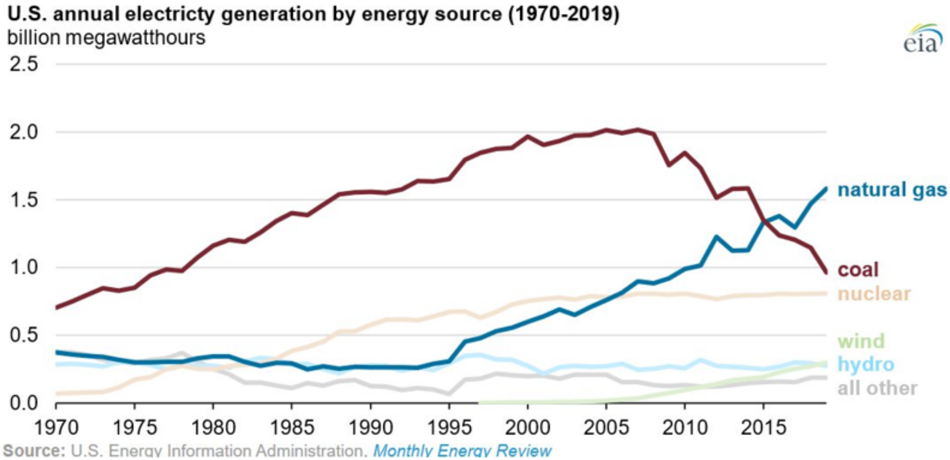
- Electricity generation contribution to GHGs has been steadily declining (both in % and even in levels).
- More attention shifting towards transportation and heating.

- 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**.

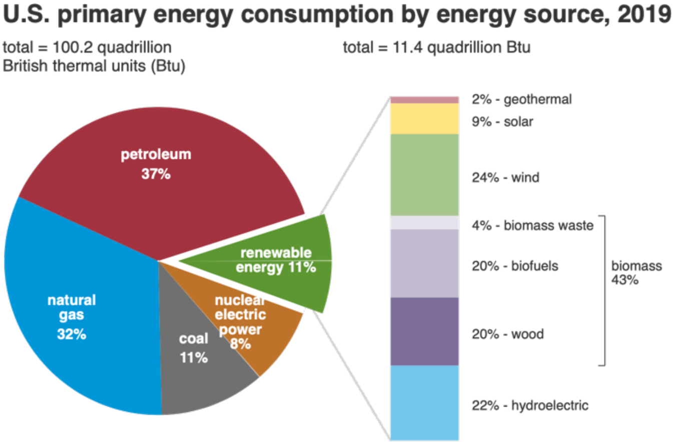
Generation by energy source, US



Generation by energy source, US

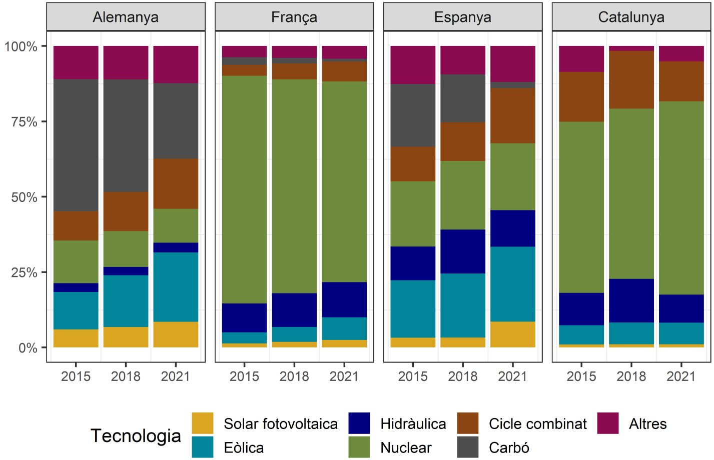


US Mix in 2019



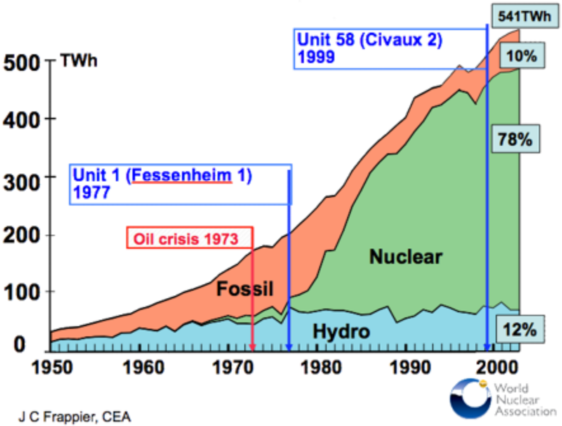
Note: Sum of components may not equal 100% because of independent rounding.
Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3 and 10.1, April 2020, preliminary data

Large variations across regions and countries!



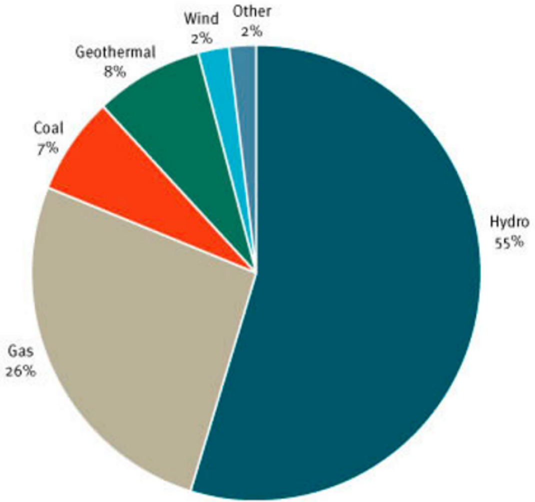
Generation by energy source, France

- 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.



Generation by energy source, New Zealand

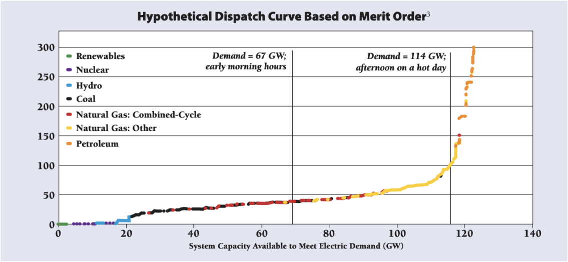
- Water availability is also a big driver of adoption.
- Example: Brazil, New Zealand, or Nordic countries have a large reliance on hydro.
- Decarbonized energy source but not available everywhere.



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/`

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 $\Rightarrow$ run always.
  - Some of them have much smaller fixed costs, but higher marginal costs (natural gas) $\Rightarrow$ 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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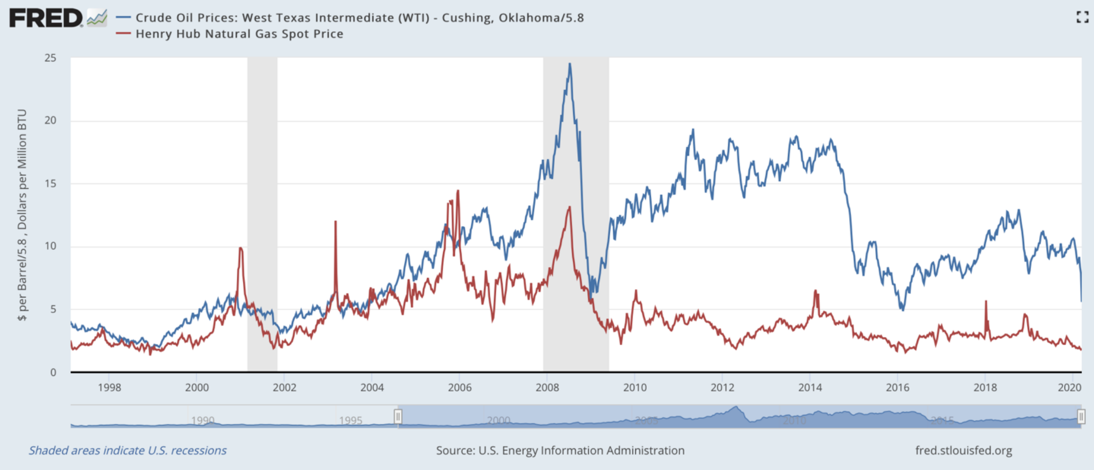
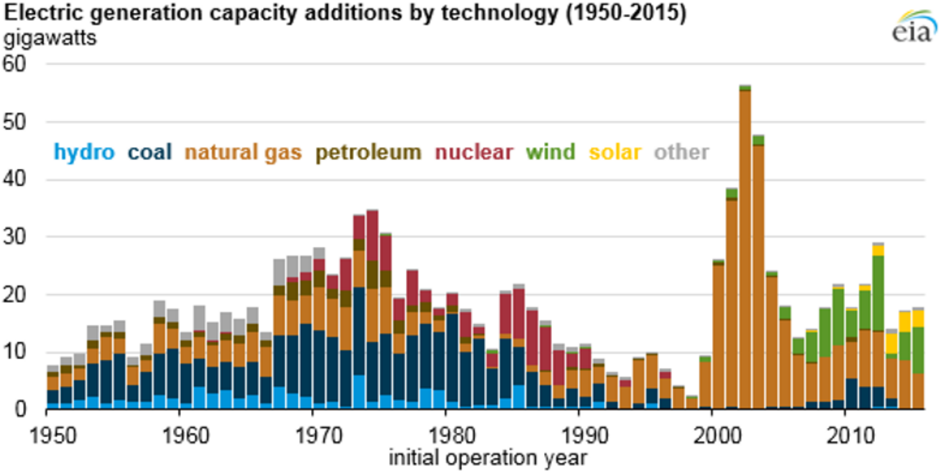
Important changes recently: shale gas



Important changes recently: Renewables



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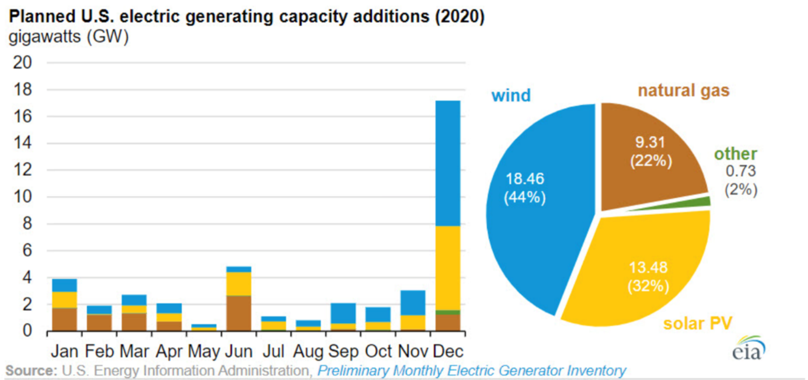
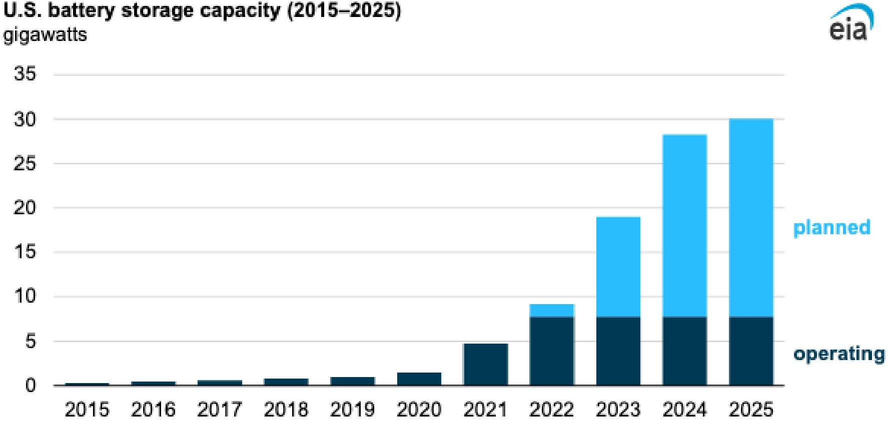
Important changes recently: Renewables

EIA expects 42 gigawatts (GW) of new capacity additions to start commercial operation in 2020. Solar and wind represent almost 32 GW, or 76%, of these additions.



Important changes recently: Batteries

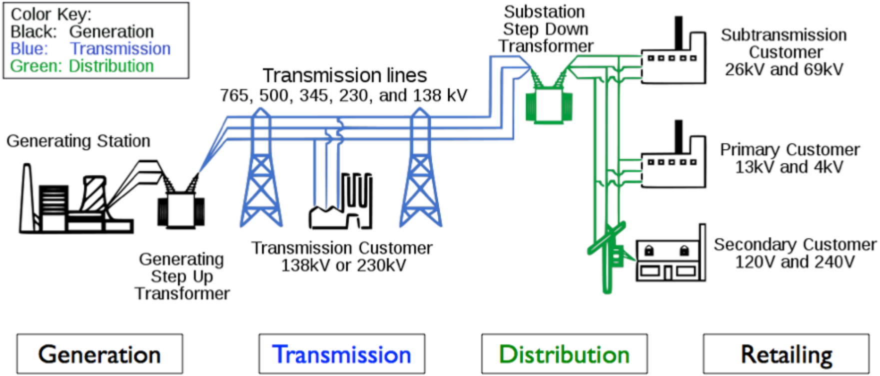


Data source: U.S. Energy Information Administration, Preliminary Monthly Electric Generator Inventory, October 2022

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

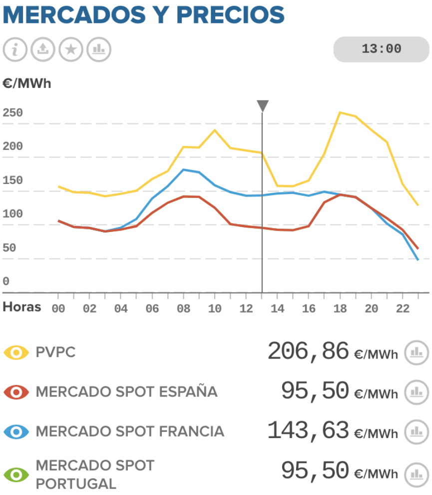
Key features of electricity

- 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*.



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 are both on one side of a transmission constraint
  - Defining prices that vary by location is both theoretically and practically challenging

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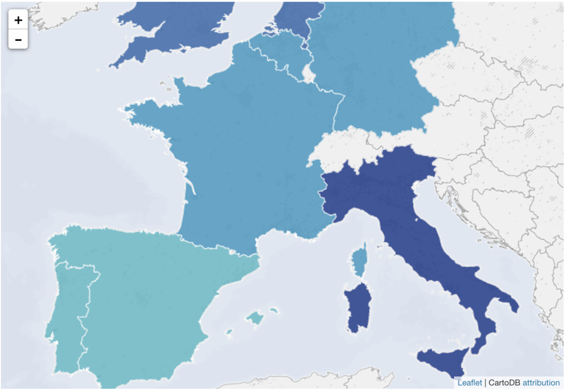

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Grid must stay within frequency band

- 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.

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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.

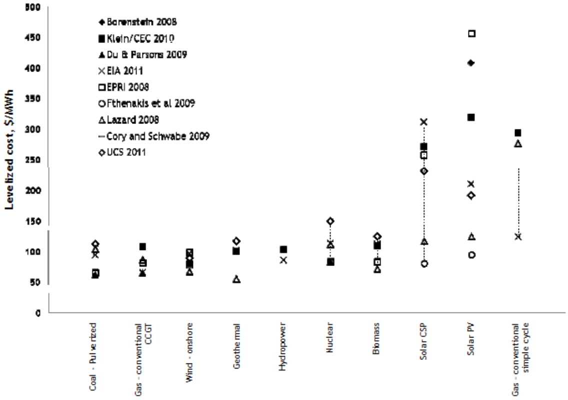
The economics of renewables

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

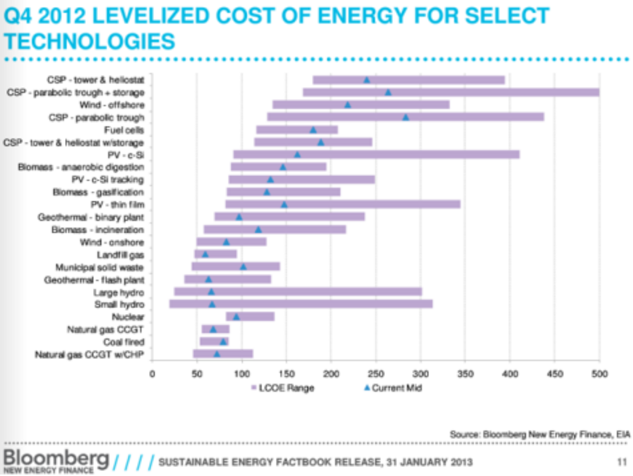
$$LCOE = \frac{\sum_{t=0}^{T} \frac{C_t(q_t)}{(1+r)^t}}{\sum_{t=0}^{T} \frac{q_t}{(1+r)^t}}$$

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

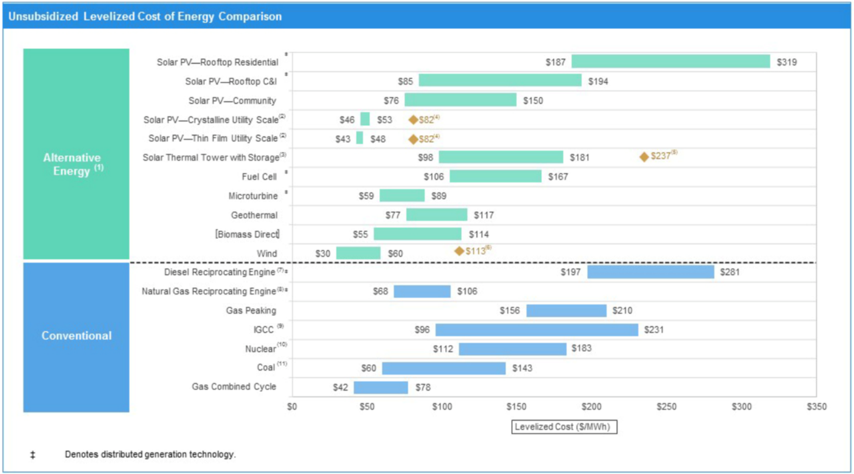
Figure 1. Levelized cost estimates



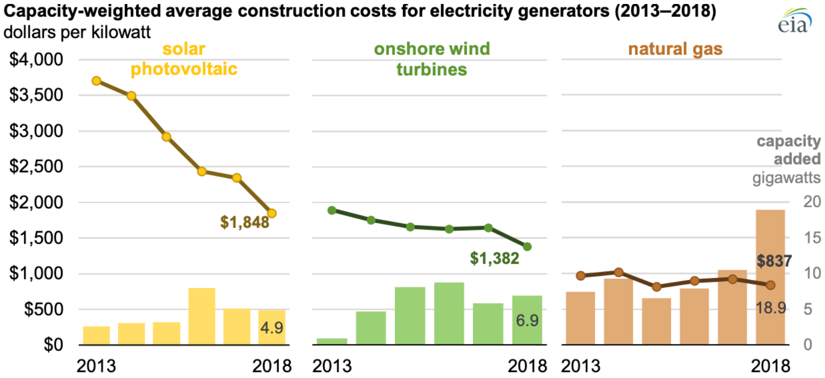
Variation in LCOEs (newer estimates)



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., & Vehvilinen (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 Texas

Valuing the Wind: Renewable Energy Policies and Air Pollution Avoided†

By Kevin Novan*

Exploiting variation in the hourly production from wind turbines, this paper quantifies the heterogeneity in the marginal impact of renewable electricity on pollution. The results reveal that output from competing renewable capacity additions—e.g., wind turbines versus solar panels—provide different marginal external benefits. This finding suggests that, if governments continue to subsidize renewables, an emphasis should be placed on designing policies that internalize the heterogeneous benefits. More generally, my results highlight that, by incorrectly assuming renewable electricity is a homogenous good, we will understate the relative efficiency of the first-best pollution prices. (*JEL* L94, L98, Q42, Q48, Q51, Q53, Q58)

Paper overview

- **Question**
  - What have been the impacts of wind generation between 2007-2011?
- **Methodology**
  - Regression analysis of generation and emissions on wind power.
- **Finding**
  - Significant reductions of emissions documented.

Summary stats

Table 1—Hourly Net ERCOT Generation by Fuel Source

	Natural gas	Coal	Nuclear	Wind	Hydro.	Other
Observations	43,795	43,795	43,795	43,795	43,795	43,795
Mean (MWh)	14,841	13,589	4,656	2,188	96	390
Standard deviation (MWh)	7,488	2,030	768	1,599	86	267
Minimum (MWh)	1,963	2,342	909	0	1	16
Maximum (MWh)	42,052	18,606	5,189	7,279	446	1,210
Share (percent)	41.5	38.0	13.0	6.1	0.3	1.1

Notes: Hourly net generation is from ERCOT. "Other" generation includes production from biomass, landfill gas, other fossil fuels, and solar. Share of total generation is calculated by dividing the aggregate generation by fuel source over the total ERCOT generation between January 1, 2007–December 31, 2011.

Empirical strategy

$$(2) \qquad E_t = \beta \cdot W_t + \sum_{n=1}^{3} (\theta_{1,n} \cdot D_{1,t}^n + \theta_{2,n} \cdot D_{2,t}^n) + \alpha_{h,m,y,w} + \delta_d + \varepsilon_t,$$

where

$$E_t = \text{Aggregate hourly } CO_2 \text{ (tons), } NO_X \text{ (lbs), or } SO_2 \text{ (lbs),}$$

$$W_t = \text{Aggregate hourly ERCOT wind generation (MWh),}$$

$$D_{1,t}^n = \text{Hourly ERCOT demand (MWh) raised to } n = [1, 2, 3],$$

$$D_{2,t}^n = \text{Hourly SPP demand (MWh) raised to } n = [1, 2, 3],$$

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Generation

TABLE 4—GROSS GENERATION OFFSET PER MWH OF WIND GENERATION

	ERCOT gross fossil fuel generation (MWh)			
	Coal	Combined cycle	Gas turbine	Total fossil
Wind generation	−0.315**	−0.321**	−0.304**	−0.941**
	(0.010)	(0.008)	(0.009)	(0.009)
ERCOT demand ^{n}	Yes	Yes	Yes	Yes
SPP demand ^{n}	Yes	Yes	Yes	Yes
Hourly FE	Yes	Yes	Yes	Yes
Observations	43,794	43,794	43,794	43,794
R^2	0.43	0.67	0.74	0.89
	ERCOT + SPP gross fossil fuel generation (MWh)			
	Coal	Combined cycle	Gas turbine	Total fossil
Wind generation	−0.330**	−0.349**	−0.337**	−1.017**
	(0.012)	(0.009)	(0.012)	(0.013)
ERCOT demand ^{n}	Yes	Yes	Yes	Yes
SPP demand ^{n}	Yes	Yes	Yes	Yes
Hourly FE	Yes	Yes	Yes	Yes
Observations	43,794	43,794	43,794	43,794
R^2	0.42	0.67	0.73	0.87

Notes: Each model is estimated using daily fixed effects. Newey-West standard errors using a 24-hour lag are reported in parentheses. Explained within variation is given by R^2.

**Significant at the 1 percent level.

*Significant at the 5 percent level.

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Emissions

TABLE 6—AVERAGE EMISSIONS AVOIDED (PER MWH) BY MARGINAL RENEWABLE CAPACITY

	AEA(K)			Average external benefit	
Wind capacity (MW)	CO_2 (tons)	NO_X (lbs)	SO_2 (lbs)	Only CO_2	All pollutants
0	0.65**	0.95**	1.40**	$20.76**	$23.26**
	(0.05)	(0.14)	(0.37)	(1.46)	(1.80)
1,000	0.65**	0.98**	1.49**	$20.76**	$23.40**
	(0.03)	(0.10)	(0.26)	(1.04)	(1.27)
2,000	0.65**	1.01**	1.57**	$20.83**	$23.60**
	(0.02)	(0.07)	(0.18)	(0.72)	(0.87)
3,000	0.66**	1.04**	1.65**	$20.96**	$23.87**
	(0.02)	(0.05)	(0.13)	(0.50)	(0.60)
4,000	0.66**	1.07**	1.73**	$21.16**	$24.21**
	(0.01)	(0.03)	(0.10)	(0.38)	(0.46)
5,000	0.67**	1.09**	1.81**	$21.43**	$24.61**
	(0.01)	(0.03)	(0.09)	(0.33)	(0.40)
6,000	0.68**	1.10**	1.89**	$21.77**	$25.08**
	(0.01)	(0.02)	(0.08)	(0.29)	(0.35)
7,000	0.69**	1.12**	1.97**	$22.17**	$25.60**
	(0.01)	(0.01)	(0.07)	(0.26)	(0.32)
8,000	0.71**	1.13**	2.04**	$22.64**	$26.20**
	(0.01)	(0.02)	(0.08)	(0.32)	(0.41)
9,000	0.72**	1.14**	2.12**	$23.18**	$26.86**
	(0.02)	(0.05)	(0.14)	(0.52)	(0.69)
10,000	0.74**	1.14**	2.19**	$23.78**	$27.58**
	(0.03)	(0.08)	(0.22)	(0.84)	(1.11)

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Case Study: Wind Power in Spain

Wind Power and Intermittency: The Impact of Subsidy Design*

Claire Petersen† Mar Reguant‡ Lola Segura§

December 10, 2021

Abstract

Renewable power is crucial to decarbonizing electricity markets but is often intermittent, which can be of concern. We assess the welfare impact of wind power on the Spanish electricity market during the years 2009-2018. We estimate modest adverse effects of wind intermittency on operational costs, even at relatively high levels of wind generation. We examine a policy change that shifted output-based wind subsidies to capacity-based subsidies. We find that capacity-based subsidies improved market operations, leading to a net welfare gain. This finding suggests that improved incentive design can diminish the negative impacts of wind intermittency.

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:

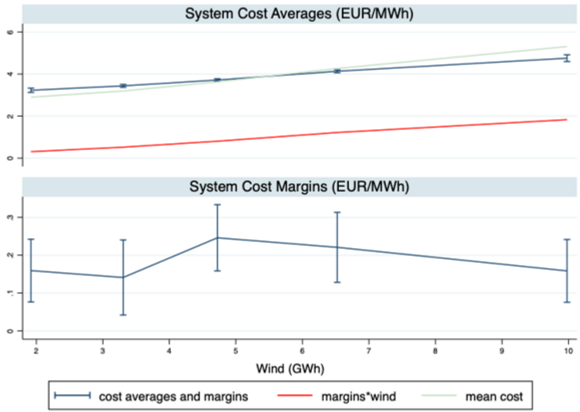
$$Y_t = \beta_0 + \sum_{q=1}^{5} \beta_q W_{qt} + \gamma X_t + \varepsilon_t$$

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

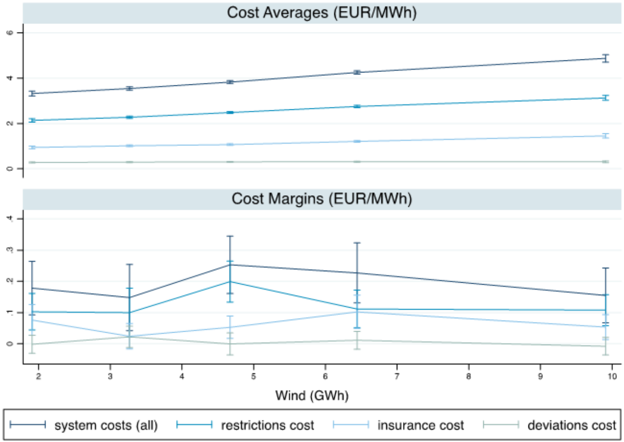
- Use *forecasted wind* to deal with endogeneity.
  - Wind power can respond to market conditions, e.g., if there is too much wind and the market cannot take it, or if firms find it profitable to "throw it away".

Impacts on operational cost

Figure 4: Average Marginal Effects of Wind on System Costs



Impacts on various operational cost



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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

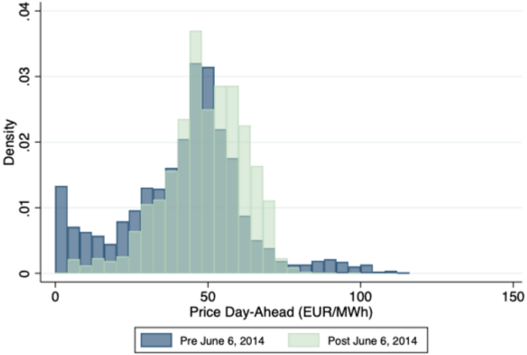
- In 2014, Spain changed how wind power plants are rewarded.
  - Moving away from output-based to capacity-based subsidy.
  - Leaving many plants without support because market price was more attractive.

- 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

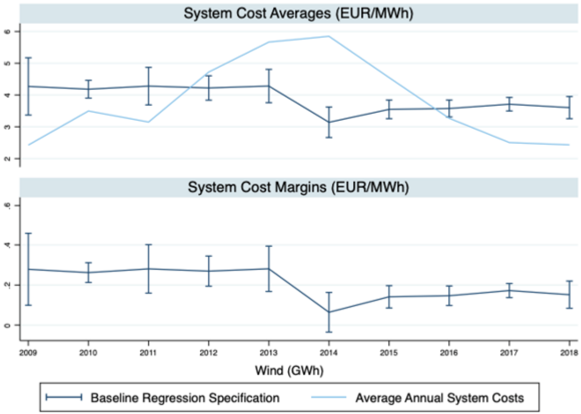
(a) Day-ahead marginal prices before and after policy change



Data from May 2013 to May 2015

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

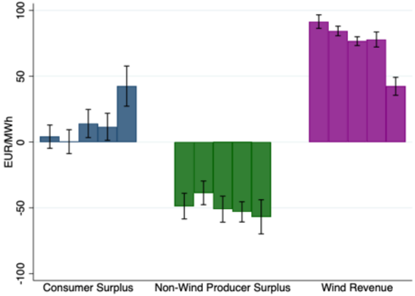
- **Consumer surplus**
  - Benefit: reduced price.
  - Cost: subsidy, costs of intermittency paid by consumers.
- **Producer surplus**
  - Benefit: subsidy, reduced fossil fuel costs.
  - Cost: reduced price, costs of intermittency paid by wind farms.
- **Emissions reduction**
  - Above and beyond what 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 the 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 break-even point.

Welfare effects of wind by group

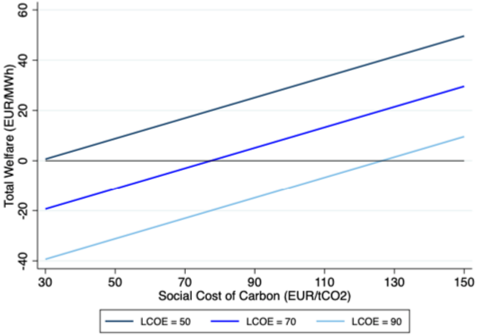
Figure 6: Average Welfare Effects of Wind



Notes: This figure shows the impacts of wind on various welfare components. Within each component, the effect is depicted at the five different wind quintiles, starting with the smallest quintile on the left, and moving to the largest quintile on the right.

Cost-benefit for different SCC and LCOE

Figure 7: Welfare Sensitivity Analysis



Notes: This figure illustrates the sensitivity of the overall welfare impacts of wind as a function of two key variables: levelized cost of wind, and social cost of carbon. The figure shows the "break-even" social costs of carbon (on the x-axis) of the policy intervention for different LCOE values (y-axis).

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?