Empirical Methods for the Analysis of the Energy Transition: Day 1

CEMFI Summer School

2021

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Northwestern University & BSE

Today's outline

1) Introduction and organizational issues
    - Welcome
    - Organization
    - Content
2) Overview of major topics in the electricity energy transition
3) Case study: Wind power in Spain

Welcome

About this course:

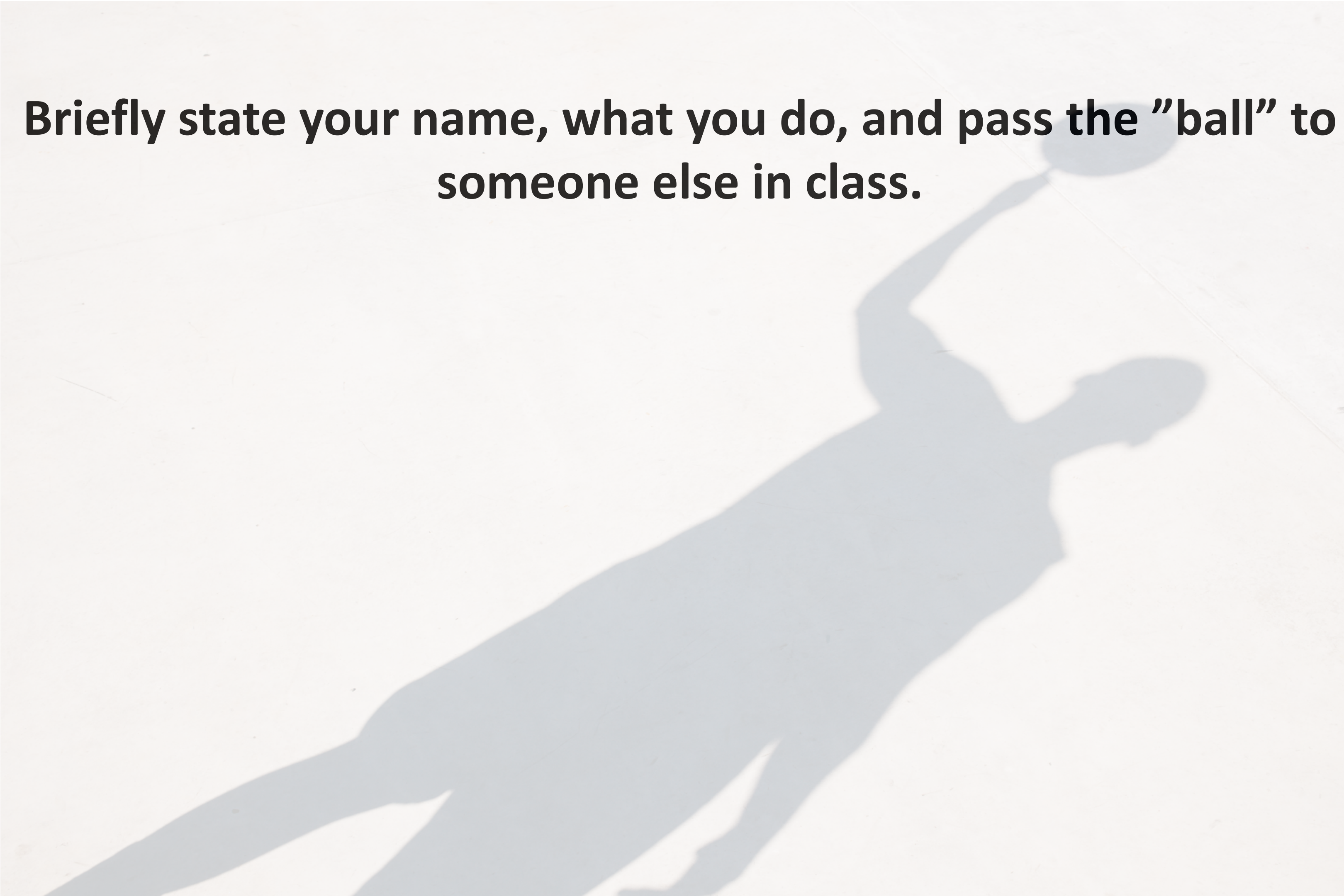
- Course to give an introduction to electricity markets modeling.
- Focus on practice with simple examples.

About us:

- Mar Reguant (Ph.D. MIT, 2011).
- Specialization: Industrial Organization, Energy and Environmental Economics.
- Student support: Pello Aspuru.

What about you?

Briefly state your name, what you do, and pass the ”ball” to someone else in class.



Organization

- Each day we will split the class in half (with small break):

    1. Lecture about topic.
    2. Practice with data and code based on my own research.

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

- **Important**: This is the first time I teach this course.

- I 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*!

Calendar

- **Intro**. Case study: Spanish wholesale market.
- **Supply I**. Case study: A simple model of CA market.
- **Supply II**. Case study: Leakage in CA market.
- **Demand I**. Case study: RTP with smart meter data.
- **Demand II**. Case study: heterogeneity in smart meter data.

- Note: Each case study is based on a paper.

Coding matters

- We will be using **Julia and Pluto notebooks** to work on the case studies.
- I am finding Julia to being extremely useful for mathematical programming.
- Mathematical programming is essential in the modeling of electricity markets.
  - For those of you with some experience, models often written in GAMS/AMPL.
  - These tools are used everyday to clear electricity markets!
- Julia has now an analogous library: **JuMP**.

Coding disclaimer

- Julia is a relatively new coding language.
- Online support is more limited than for some alternatives (Python, R, or Stata).
- I am myself a **novice**!
- It might require some patience at first, but I am finding that the computational power and mathematical programming libraries are worth it.
- One can use libraries from R and Python very easily, something that we will see.

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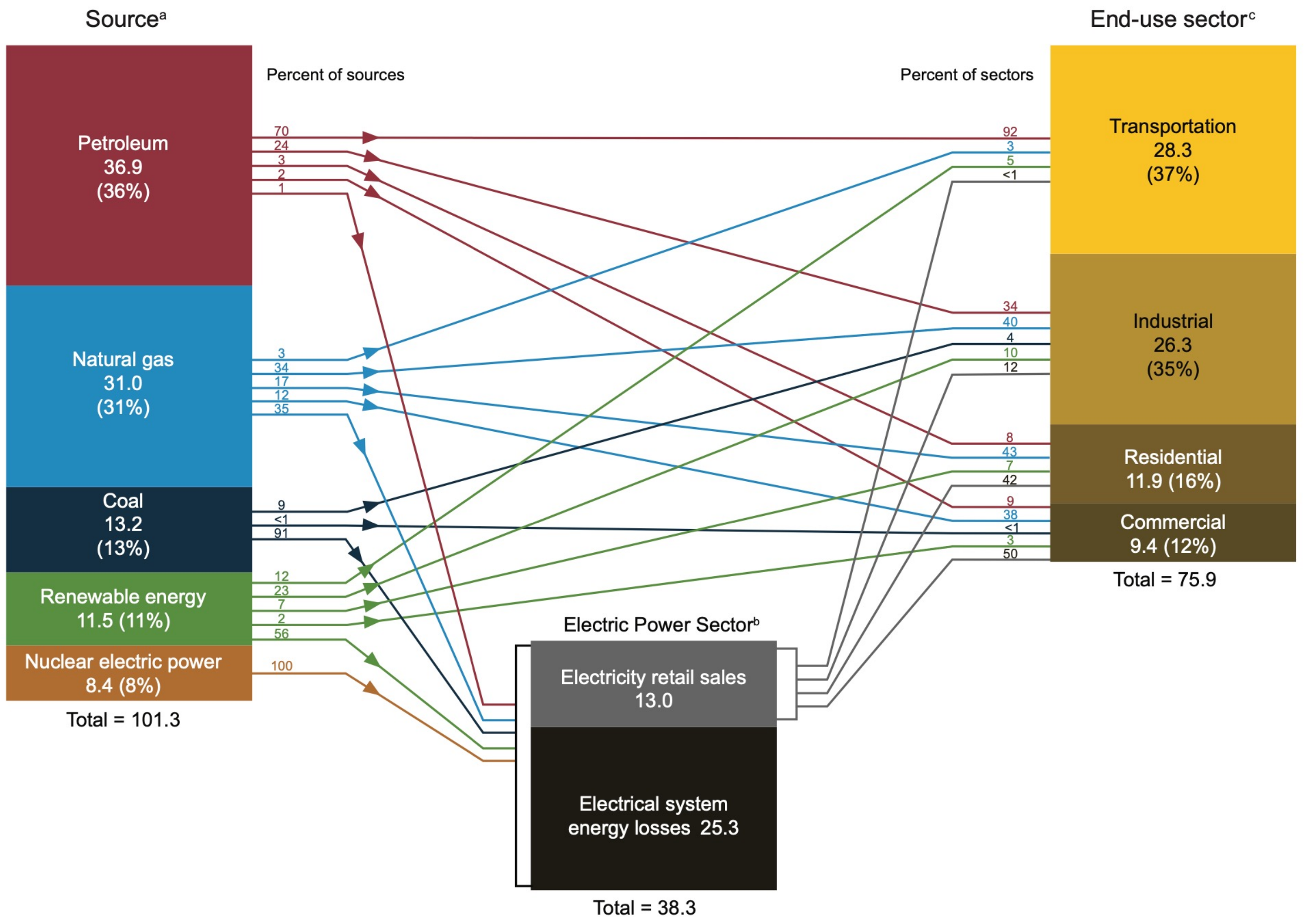
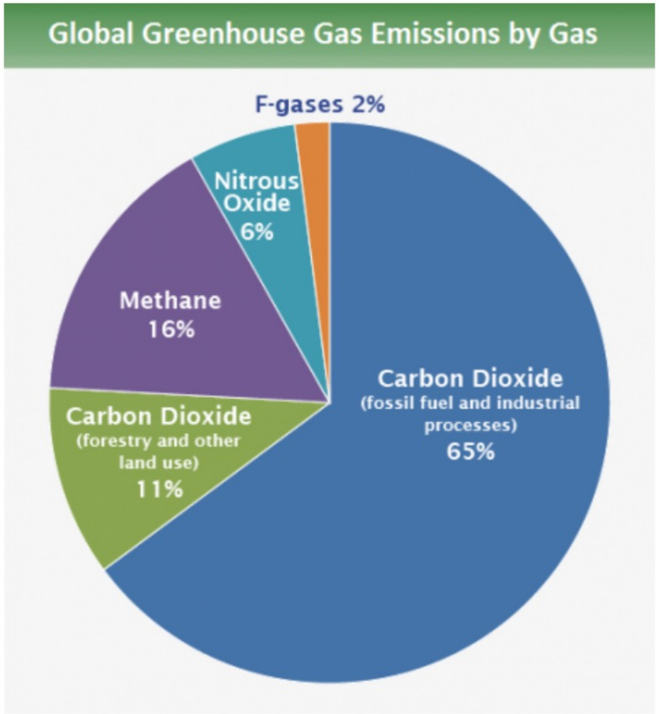
Energy is a Key Input in the Economy



Why Energy?

- Energy is a key factor for almost all economic activities:
  - Production of goods
  - Transportation of goods and services
- World energy consumption growing, 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

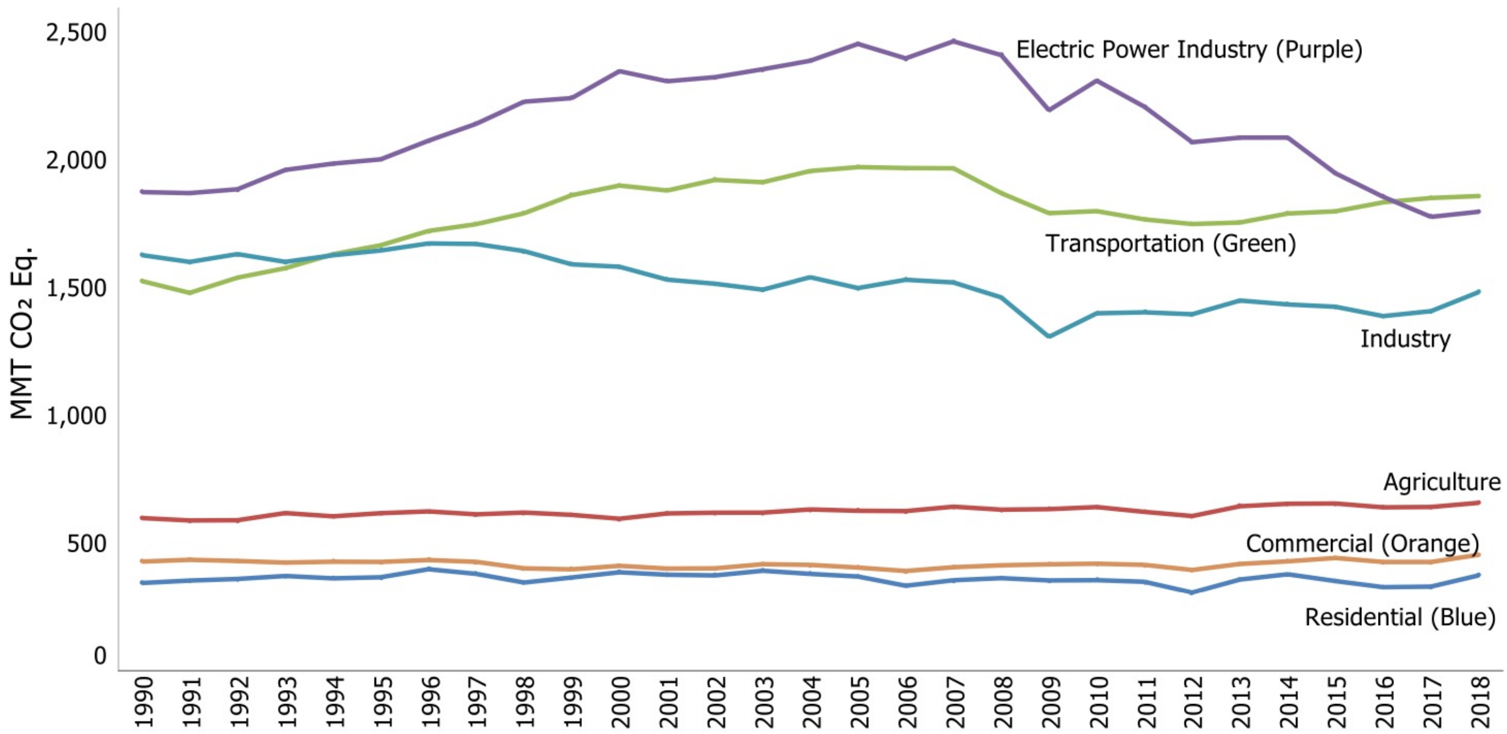
Why Economics?

- 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 these are extremely relevant in the energy sector!

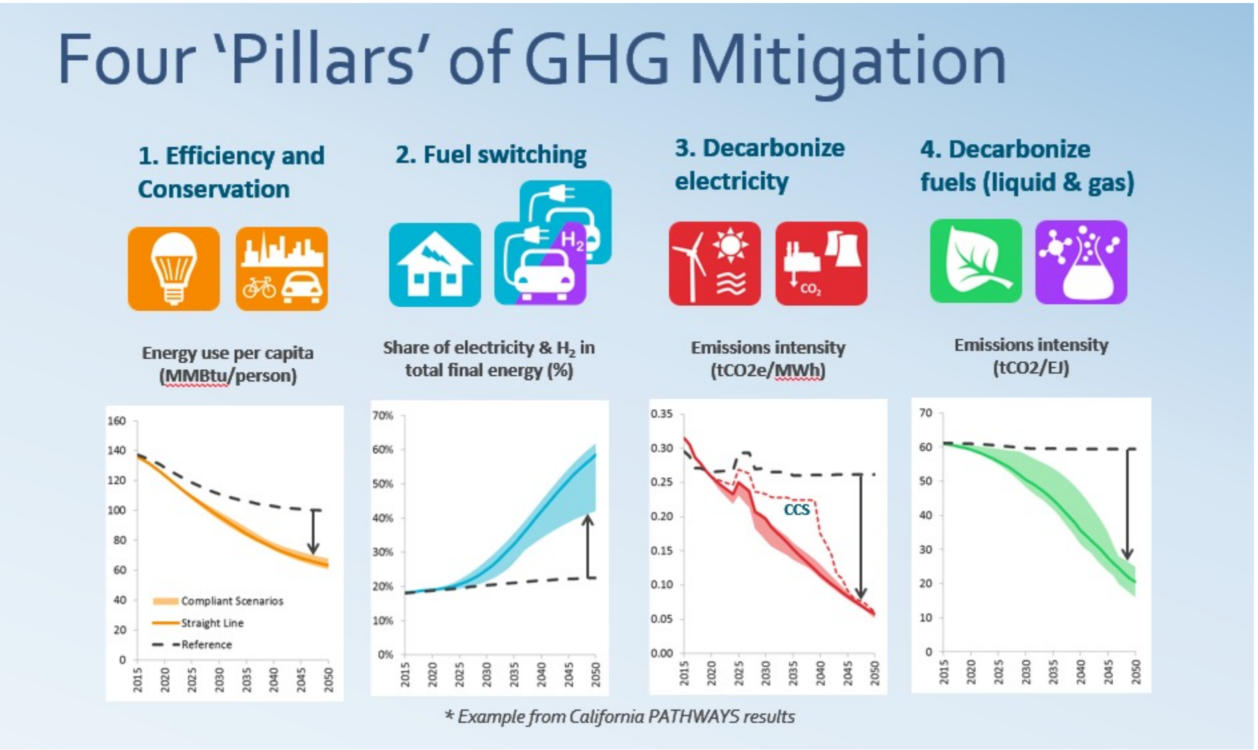
Energy is a big source of GHGs…

Figure 2-14: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO_2 Eq.)

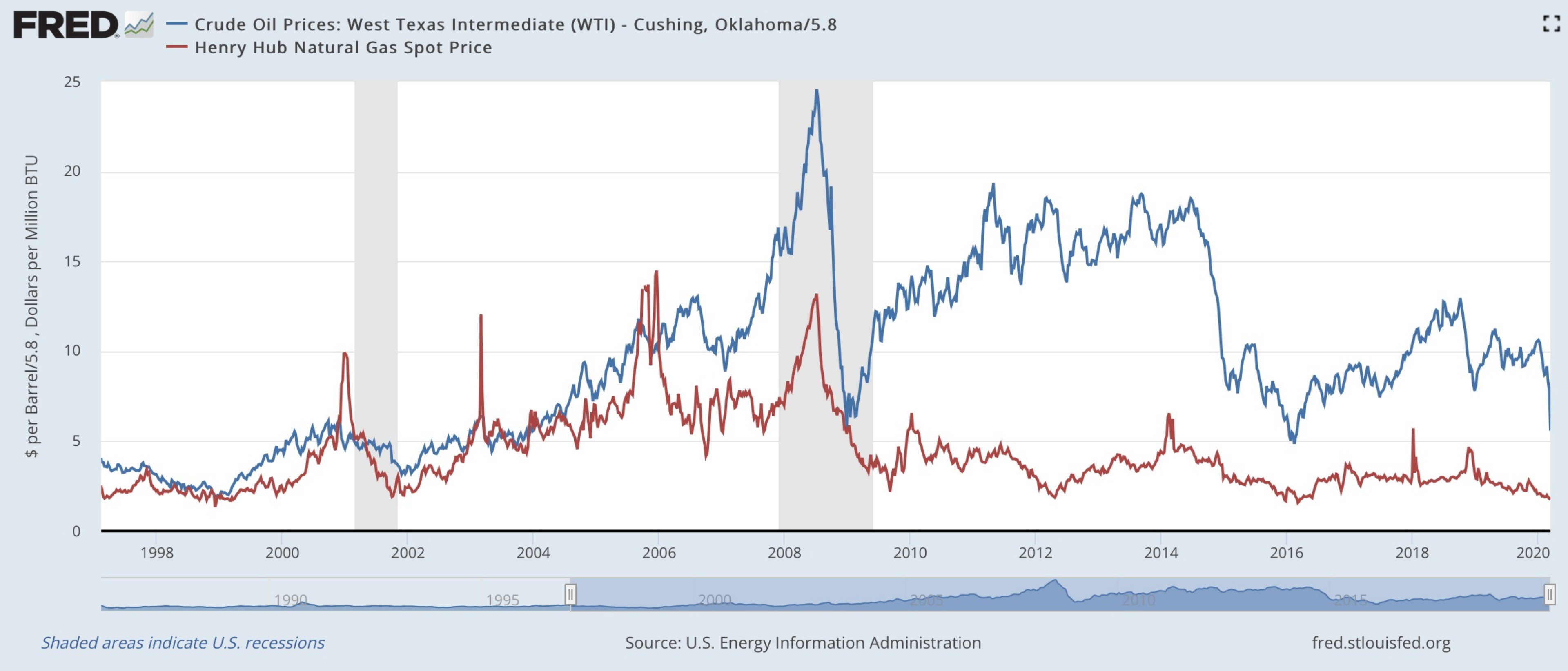


<https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks>

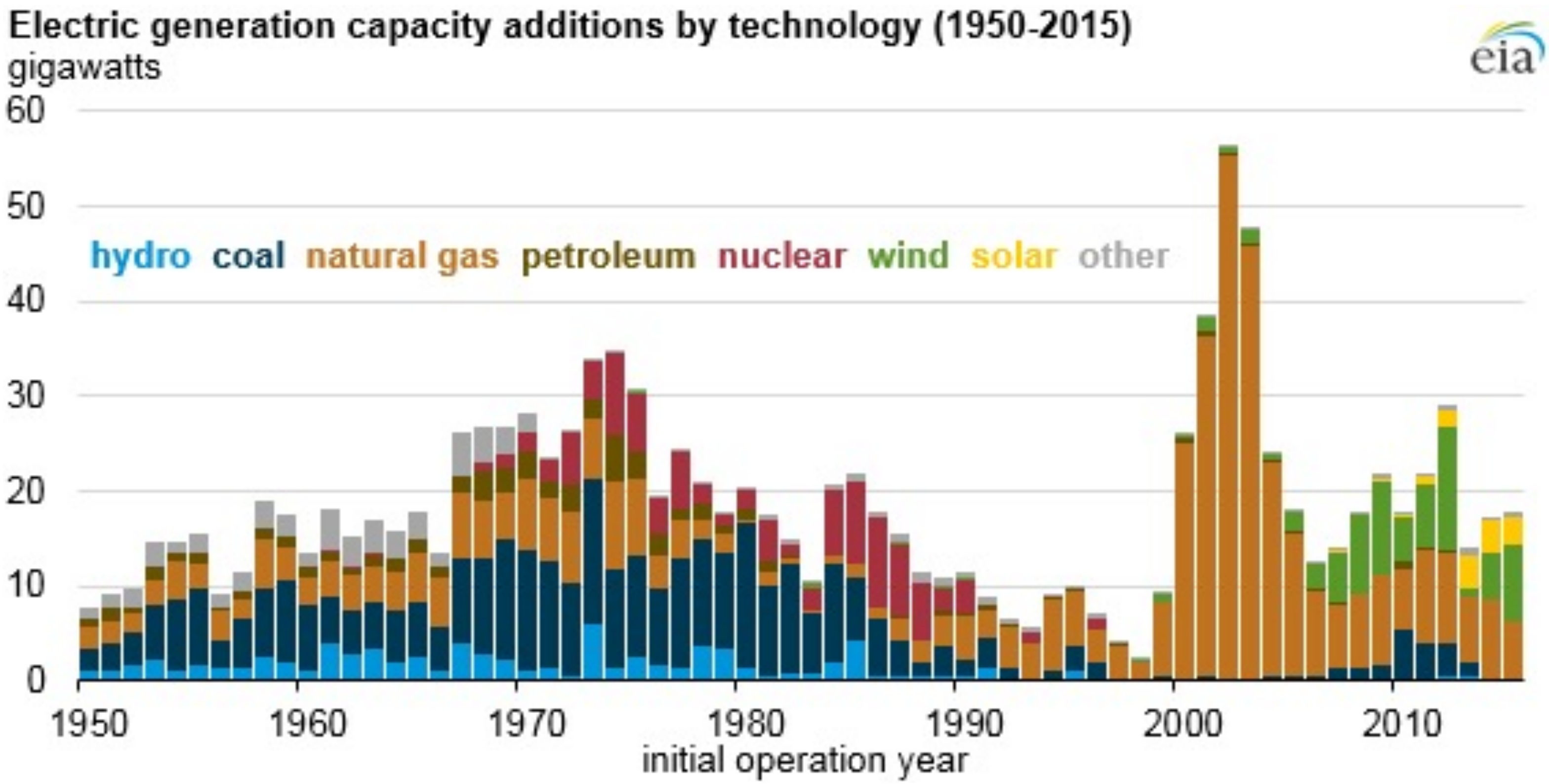
…also needs to be part of the solution



Important changes recently: shale gas

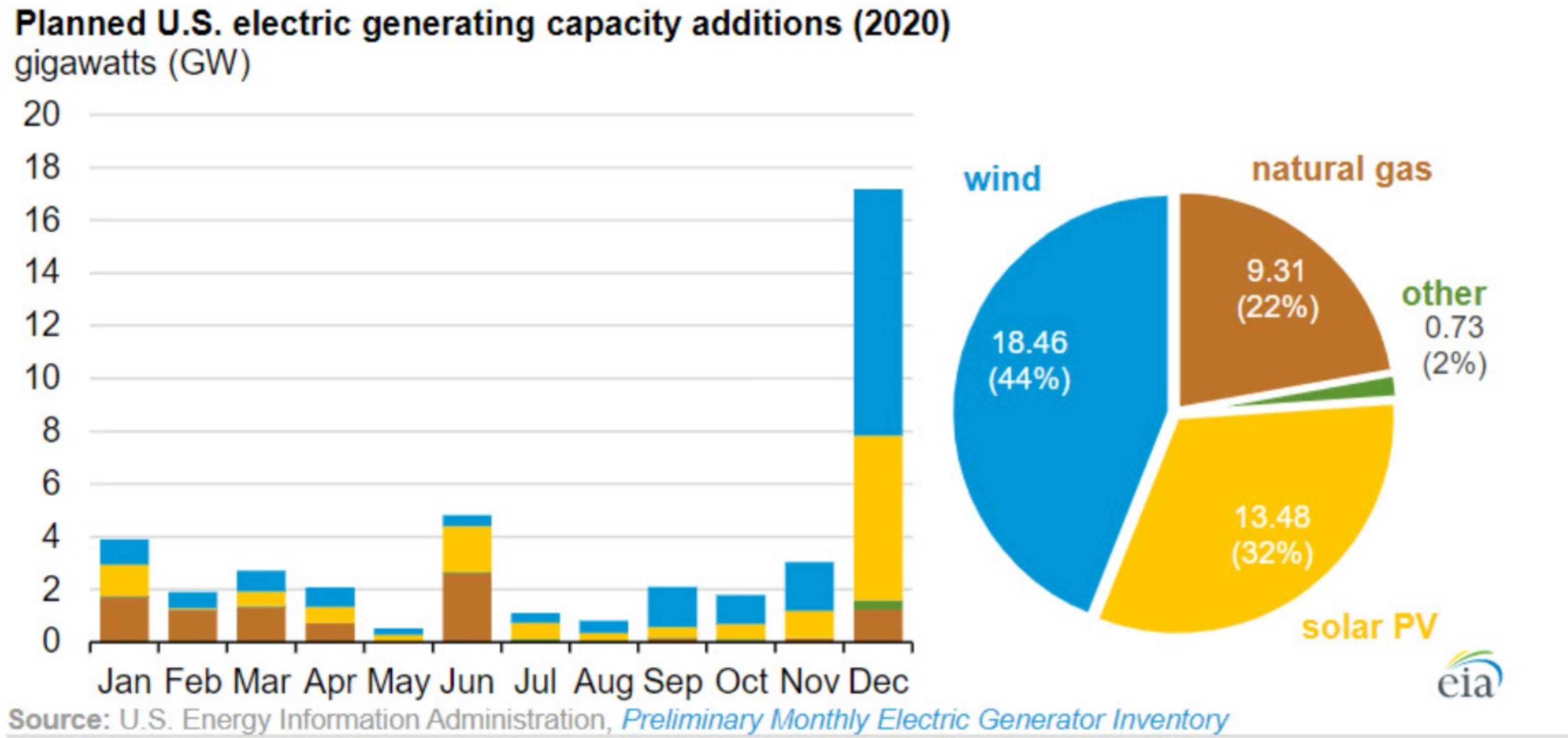


Important changes recently: also renewables



Important changes recently: also 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.

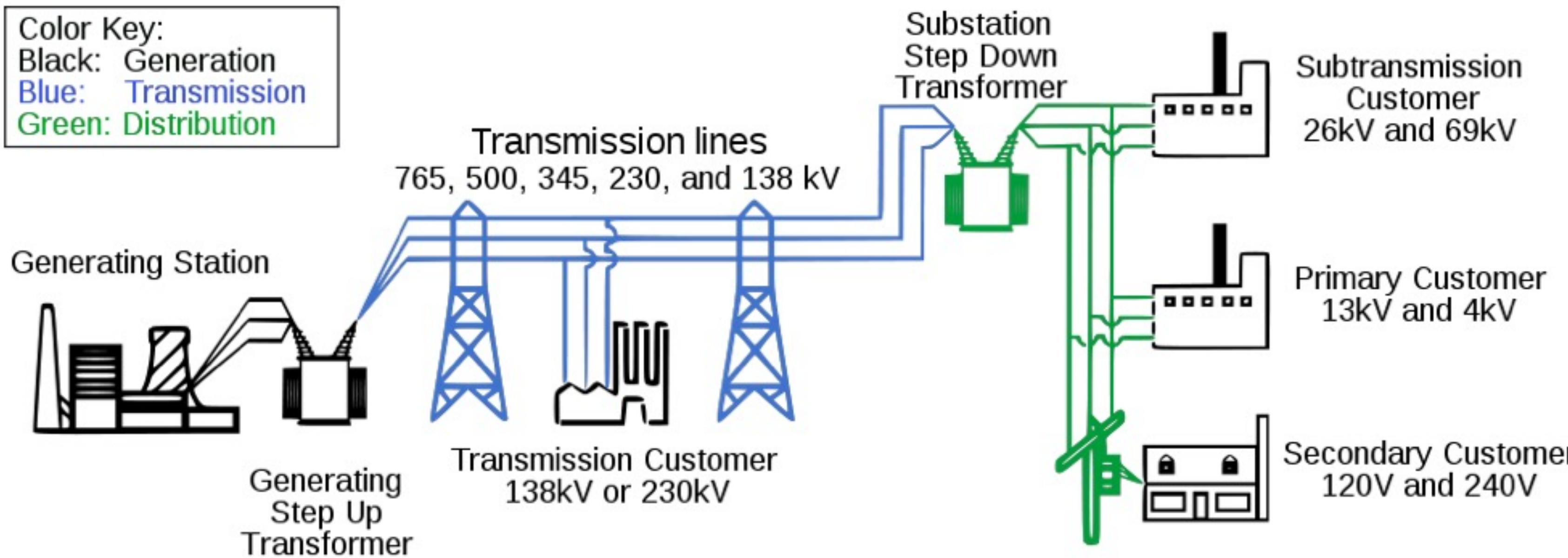


Implications for energy use and GHG

- 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.

Electricity industry consists of four segments

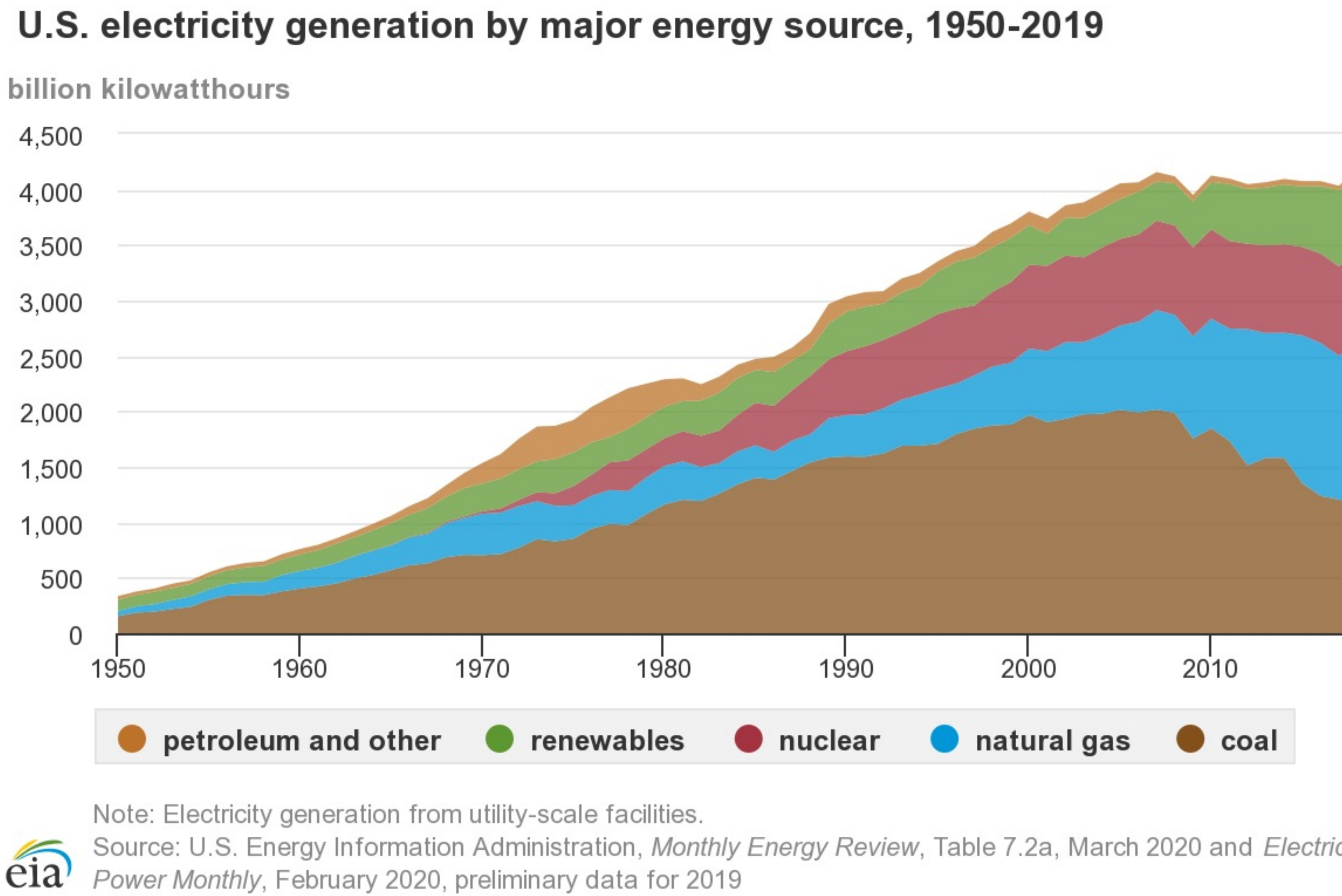


Generation	Transmission	Distribution	Retailing

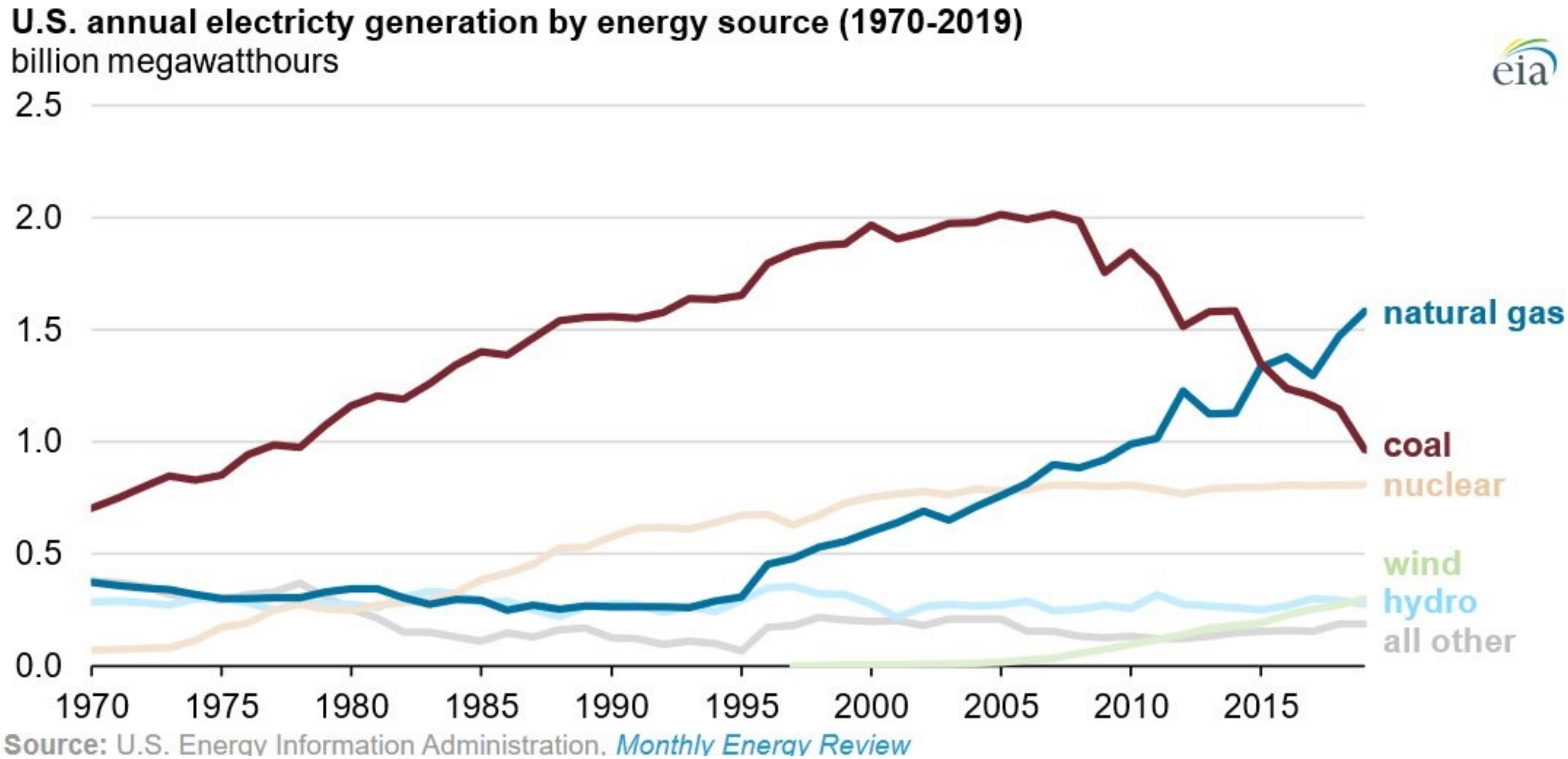
Four sectors of electricity

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

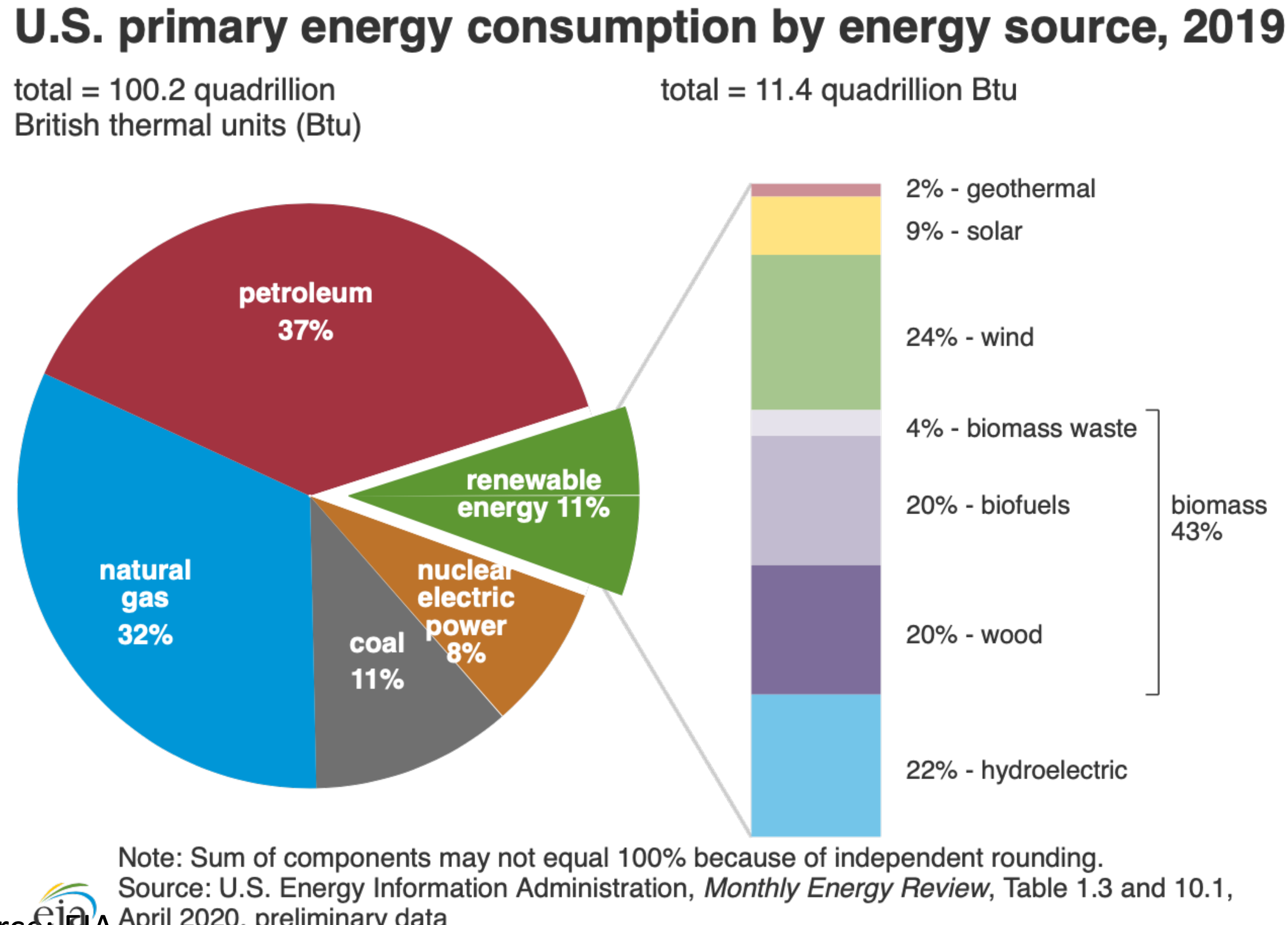
Generation by energy source, US



Generation by energy source, US

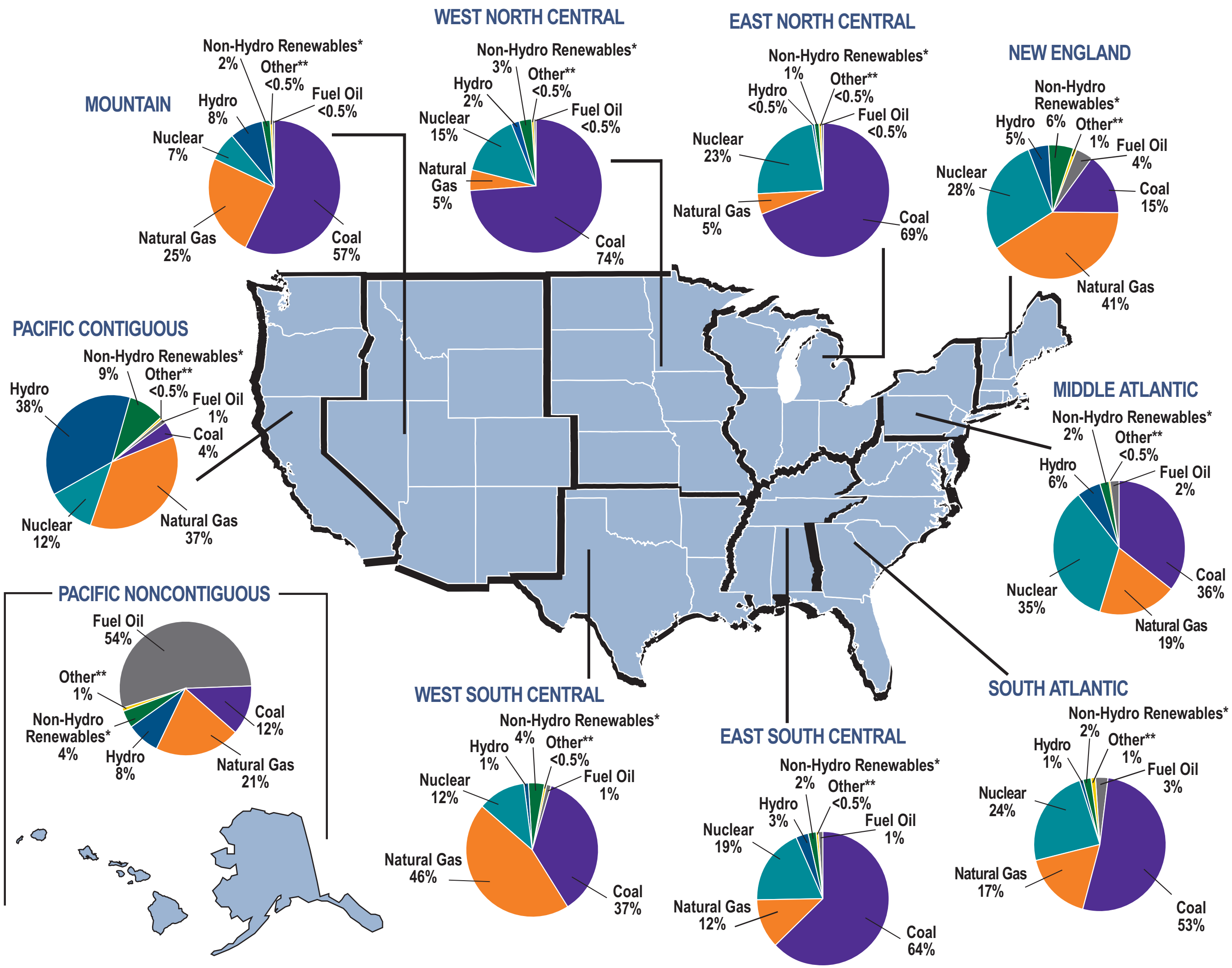


US Mix in 2019

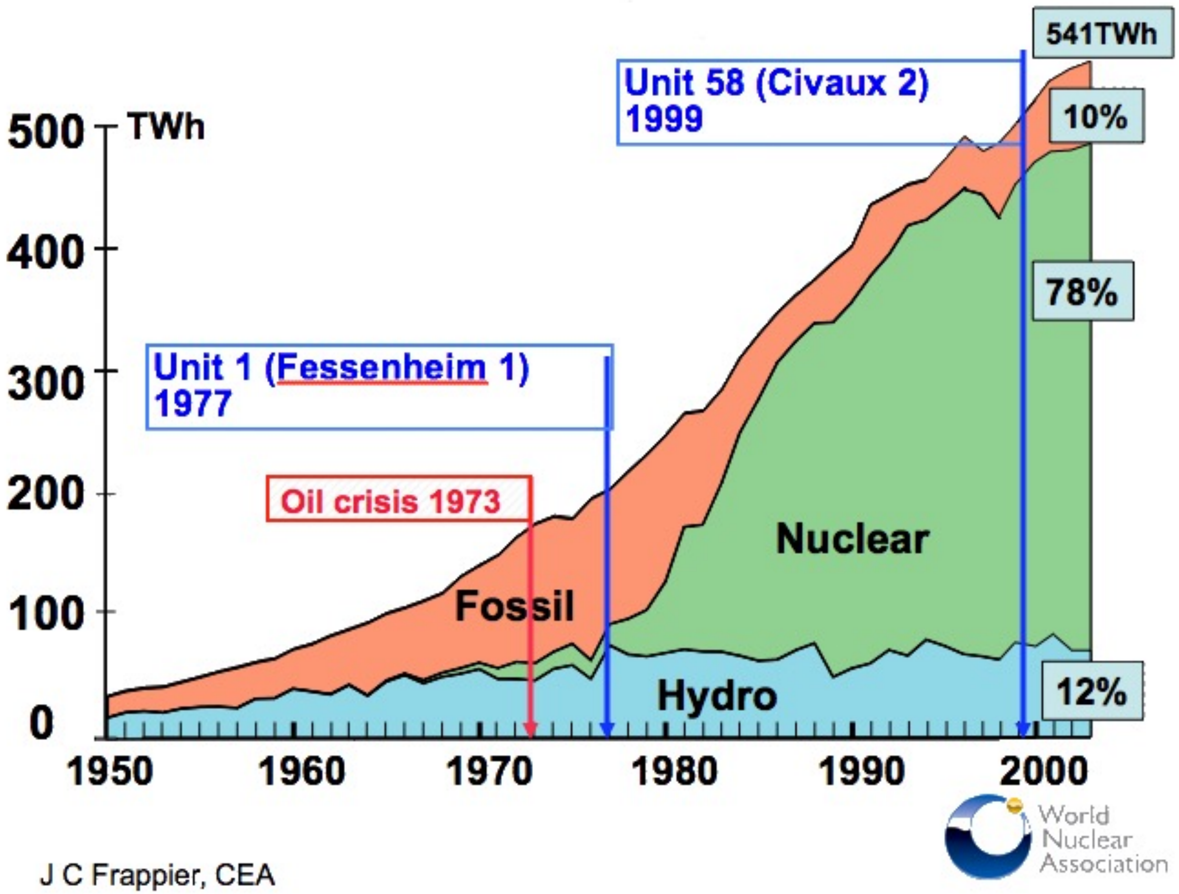


Source: EIA

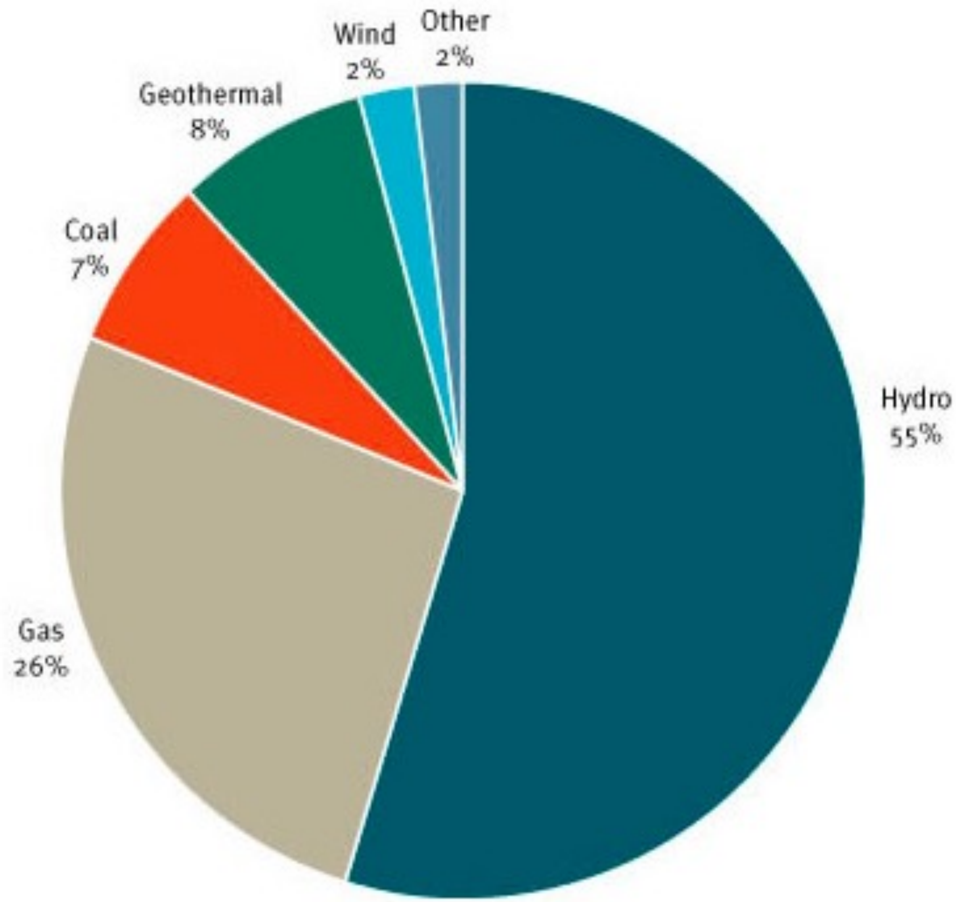
Variation across regions



By energy source, France



By energy source, New Zealand



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
- Several technologies can co-exist!

Key features of electricity

- It cannot be easily stored (yet).
- Demand and supply need to balance each other in real-time
  - Otherwise blackouts can occur
- Transportation of electricity follows very particular laws of physics
  - The whole system is connected

- All these features affect how we think about electricity using economics.

Electricity cannot be stored! (economically)

- 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.

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.

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

Expansion of renewables

- There have been some discussions on the value of renewables in the presence of these technical constraints.
- Renewables fluctuate substantially and/or cannot produce at night (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":

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

- In words: *what is this?*

Variation

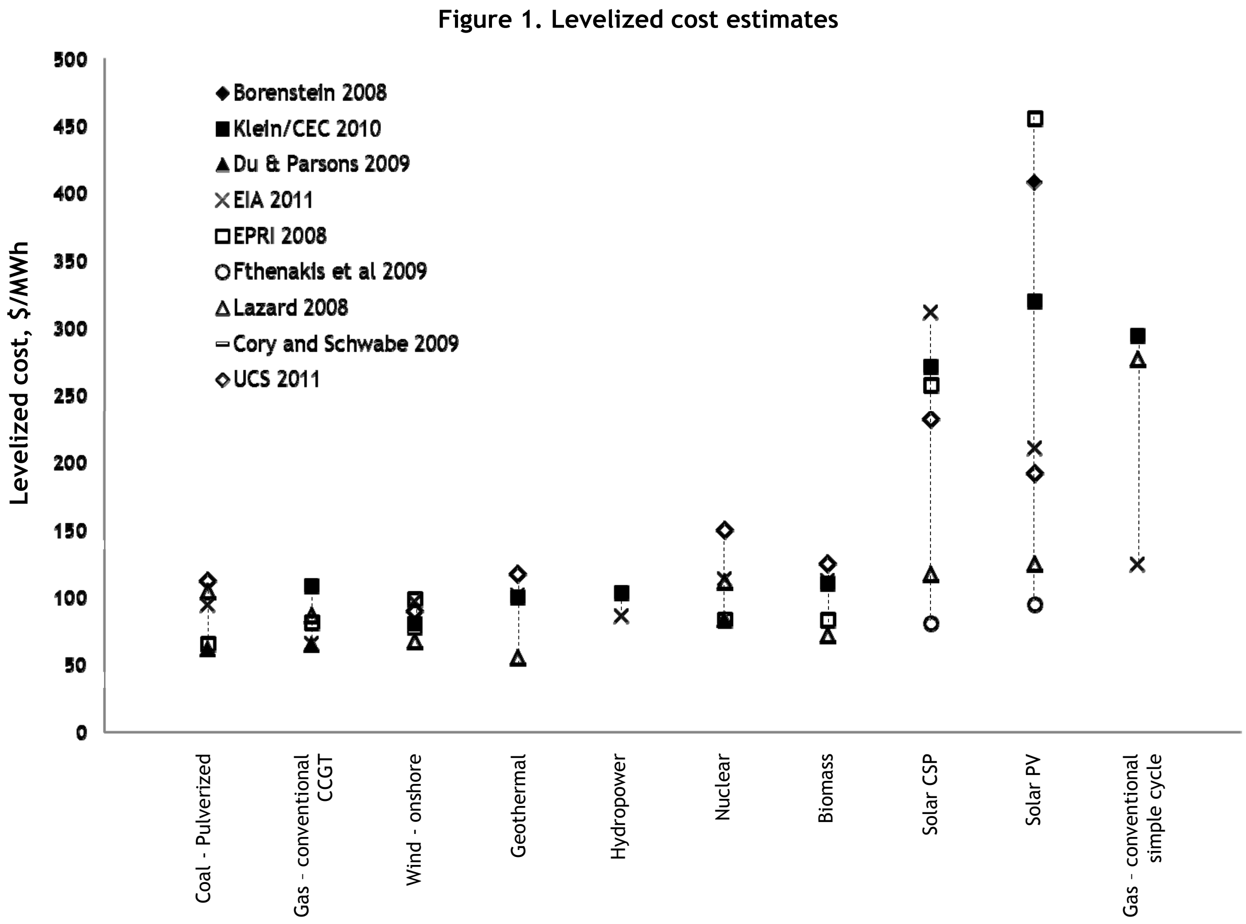
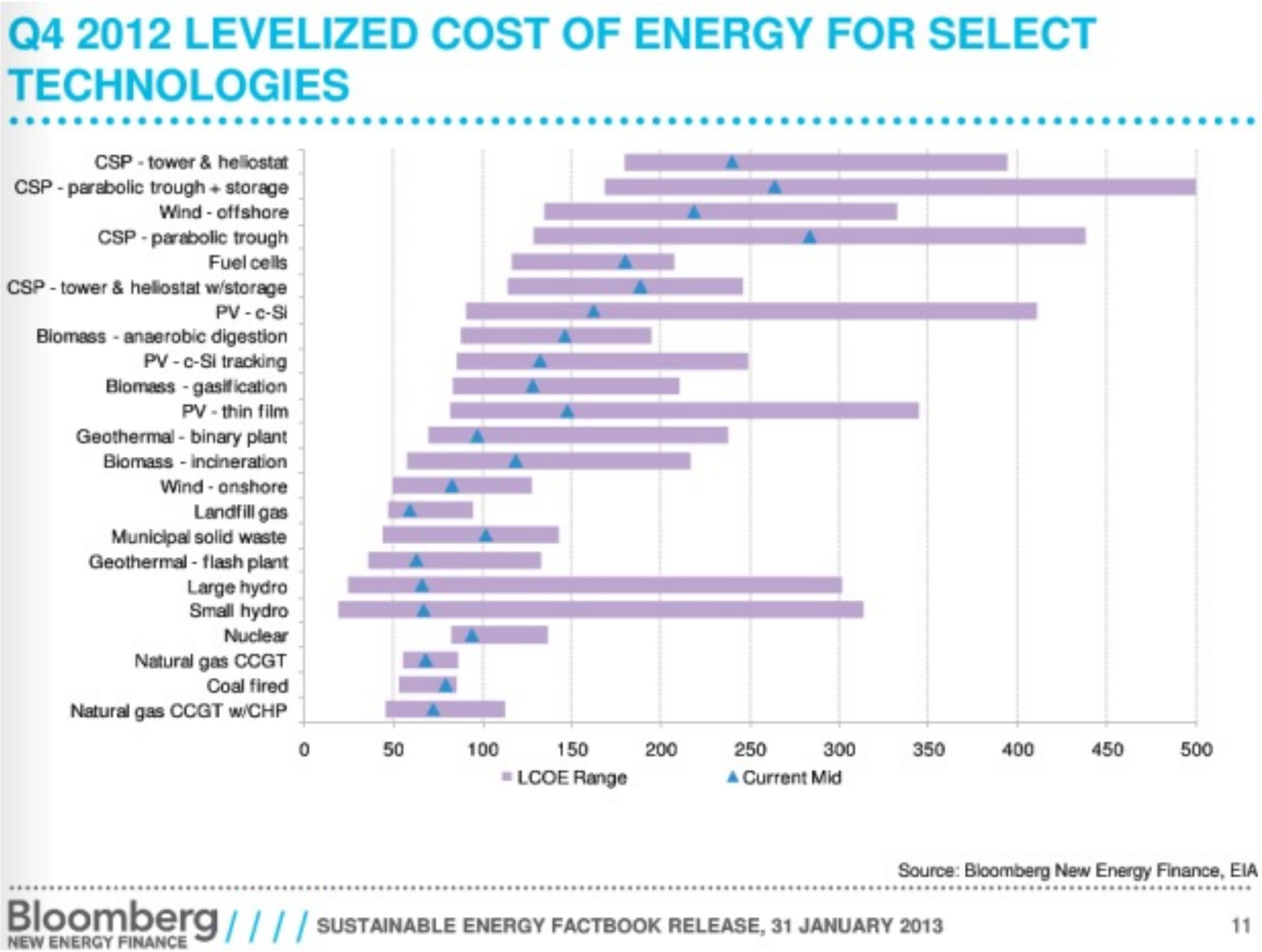
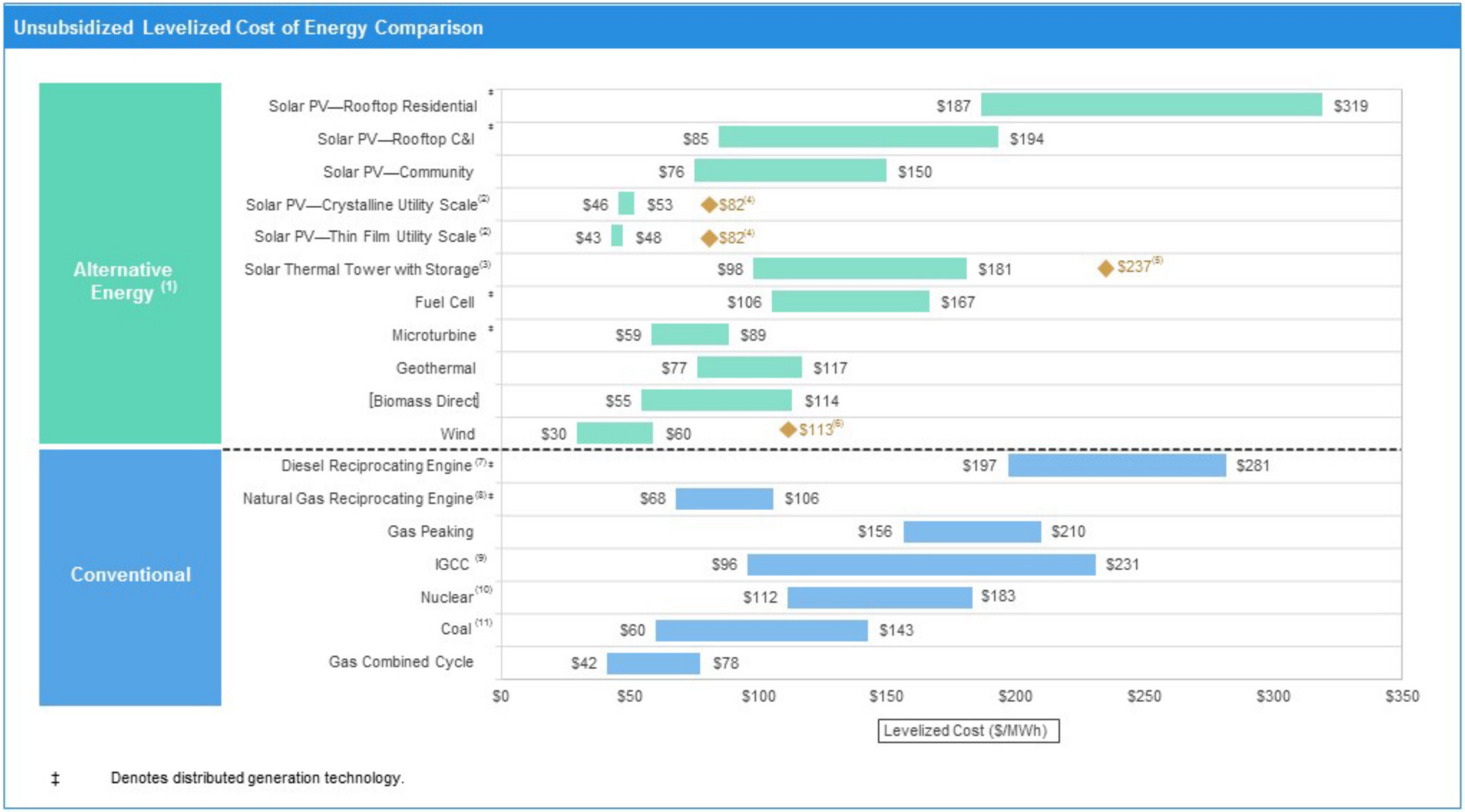


Figure 1. Levelized cost estimates
Levelized cost, $/MWh
500
450
400
350
300
250
200
150
100
50
0
Borenstein 2008
Klein/CEC 2010
Du & Parsons 2009
EIA 2011
EPRI 2008
Fthenakis et al 2009
Lazard 2008
Cory and Schwabe 2009
UCS 2011
Coal - Pulverized
Gas - conventional CCGT
Wind - onshore
Geothermal
Hydropower
Nuclear
Biomass
Solar CSP
Solar PV
Gas - conventional simple cycle

Tons of LCOEs out there…



…and getting cheaper by the minute



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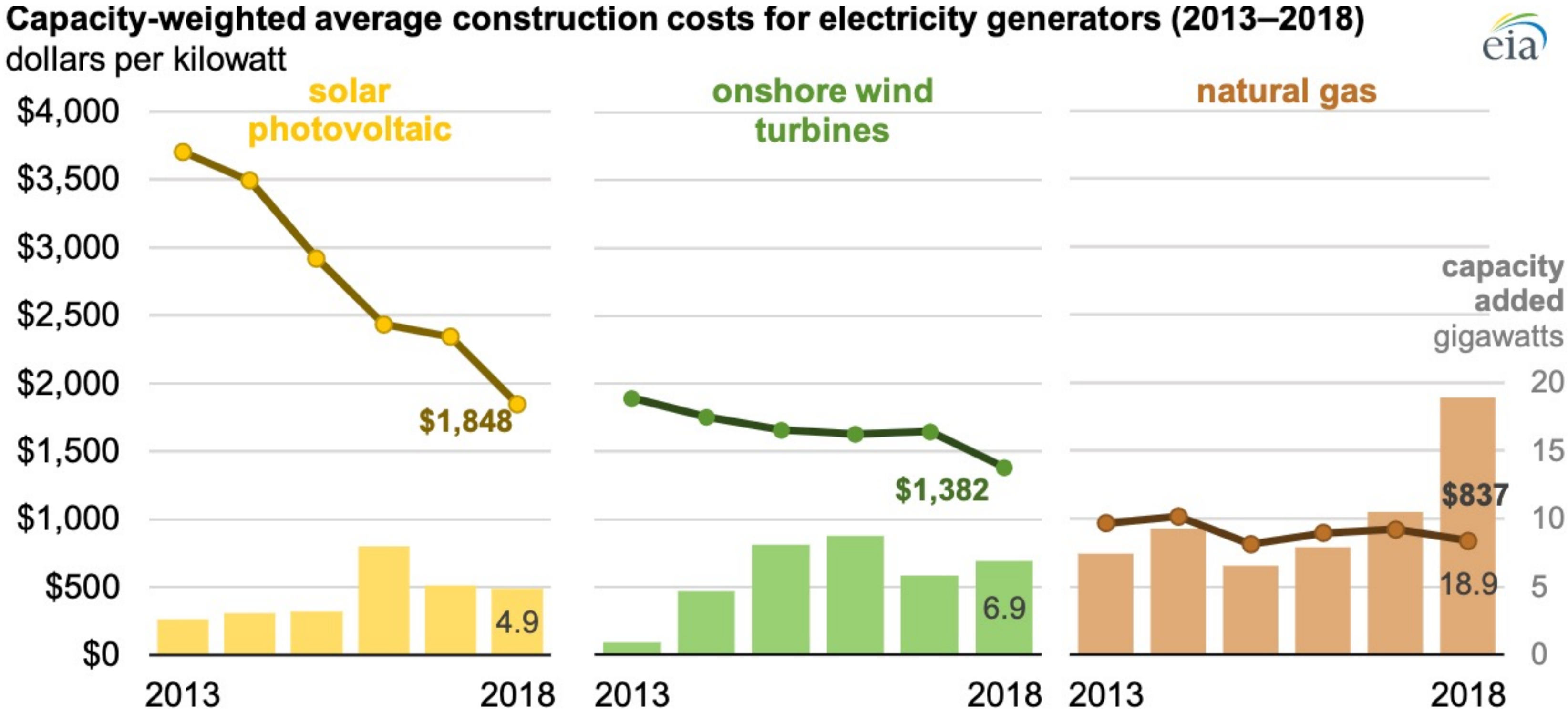

Why so much variation in LCOEs?

- Two things go into calculating the LCOE
  - Engineering assumptions
  - Economic assumptions
- Engineering assumptions
  - Costs
  - Output
- Economic assumptions
  - Discount rate
  - Time horizon
  - Future input costs
  - Private v. social costs (subsidies, taxes, regulation)
  - Opportunity/less-salient costs

Some limitations of LCOEs

1. Intermittency (costs of reliability)
2. Output and price (cannibalization)
3. Location (limits on ability to site optimally)
4. Externality benefits not (sometimes) included

How beneficial is it to expand renewables?

Growing literature examines impacts of wind to date to assess ex-post costs and benefits.

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

- Some papers complement regressions with quantification framework (e.g., Abrell et al., Liski and

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The Welfare Impacts of Wind Power

Measuring the Impact of Wind Power:
Output- vs. Capacity-based Subsidies*

Claire Petersen† Mar Reguant‡ Lola Segura§

September 2, 2021

Abstract

We provide a comprehensive welfare assessment of the impact that wind power has had on the Spanish electricity market during the years 2009-2018. Using detailed hourly data on demand, production, prices, operational costs, and emissions, we provide estimates of the marginal and average impacts of wind on these welfare components. We also document how major market design changes can impact the dispatch of intermittent resources. We exploit a policy change that shifted output-based wind subsidies to capacity-based subsidies to show how such policies can significantly impact the operational effects of wind. We find that capacity-based subsidies removed the presence of zero and near-zero marginal prices and reduced congestion and adjustment costs in the market. However, it also led to a lower utilization of wind generation, reducing the environmental benefits of the installed wind capacity. In net, we find that consumers were worse off with the change, traditional producers benefited, and the overall economic surplus increased due to the reduction in the costs of intermittency.

Goals of the exercise

- Get familiar with time-series data of electricity markets.
- Get familiar with how to measure impacts of wind power via regression analysis.

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.
- 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.

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.

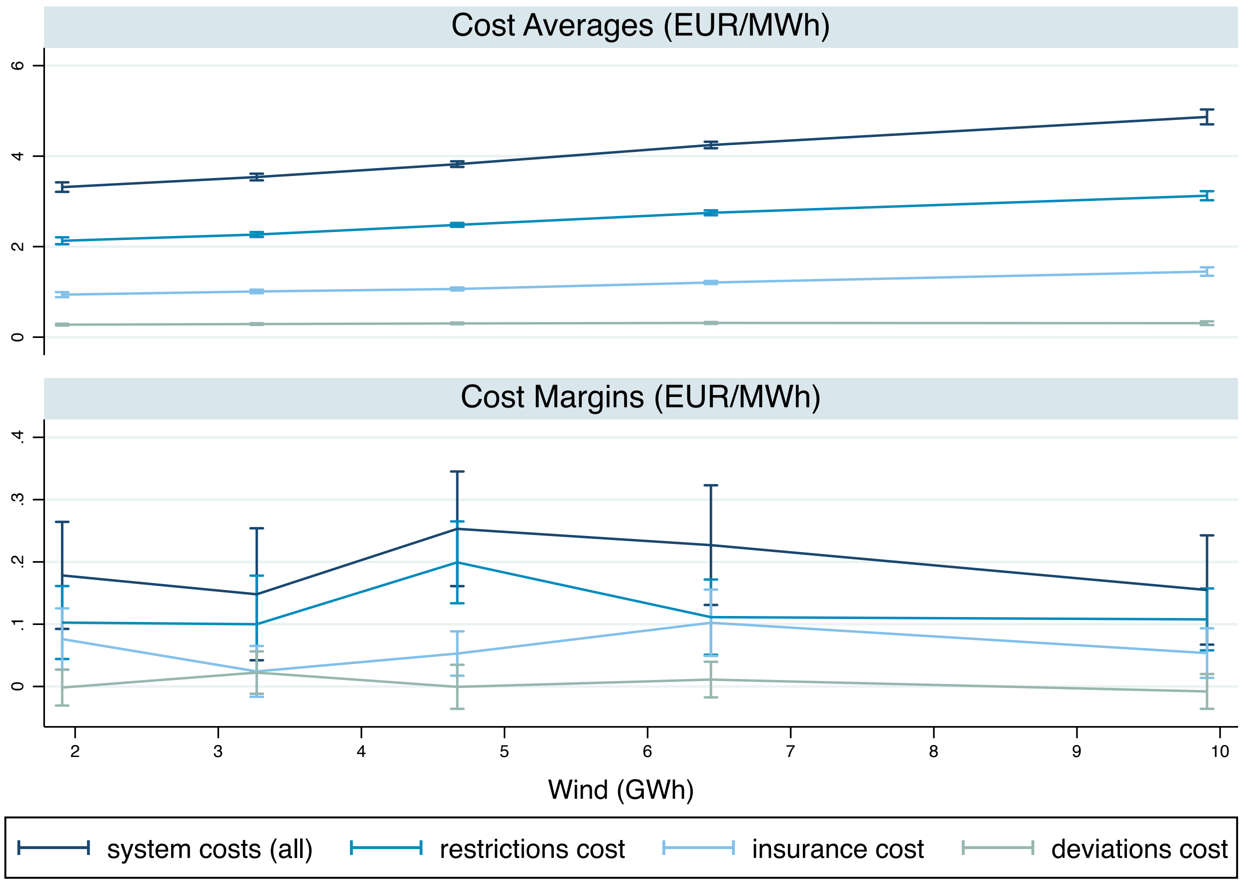
Quantification of marginal impacts

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

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

- Marginal impact of wind can differ at different quintiles (low vs. high wind conditions).
- Use *forecasted* wind to deal with endogeneity.

Impacts on operational costs



In the paper…

- 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 reductions
  - Above and beyond what is already internalized by EU-ETS.
  - For alternative values of SCC.
- Cost of investment.
  - For alternative LCOE values.

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?

References

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