The Implicit Cost of Carbon Abatement During the COVID-19 Pandemic

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Motivation

Impact of pandemic on electricity consumption and carbon emissions:

- Is there a silver lining?

EU Green Deal:

- By 2050, reach net zero CO2 emissions by 2050
- By 2030, reduce emissions by at least 55% vs 1990 levels

Debate on how to achieve those goals:

- Is it possible without sacrificing **economic growth**?
- What are the implicit costs of different strategies?

Research Question

Focusing on the case of Spain:

What are the implicit costs of carbon abatement according to alternative strategies?

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1. **Slowing down economic activity**:
   - Pandemic as a natural experiment
   - Caveat: Pandemic was a shock, not planned "degrowth"
   - Pandemic is proxy of slow down, holding economic structure fixed

Research Question

Focusing on the case of Spain:

What are the implicit costs of carbon abatement according to alternative strategies?

1. **Slowing down economic activity**:
   - Pandemic as a natural experiment
   - Caveat: Pandemic was a shock, not planned “degrowth”
   - Pandemic is proxy of slow down, holding economic structure fixed
2. **Decoupling strategy**:
   - How much investment in renewables would we need to achieve the same carbon abatement as that observed during the pandemic?

Steps of the analysis

1. We measure the effects of the pandemic on **emissions reductions**.
   - Counterfactual predictions in the power sector.
   - Emissions from other sectors (from external references).
2. We measure the pandemic effects on the Spanish economy.
   - Counterfactual forecasts of **GDP**.

   $\longrightarrow$ After steps 1 and 2, calculate implicit cost of carbon from slowing down economic activity

3. Simulate **investments** in renewables necessary to achieve CO2 reductions similar to those observed in the power sector during the pandemic.
4. Compare the implicit cost of carbon abatement from the pandemic versus from decoupling.

Predicting Counterfactual Electricity Consumption

- **Objective:**
  - Predict counterfactual electricity consumption in absence of the pandemic
    - Obtain precise hourly predictions, which will be used later in electricity market simulations
    - Use only covariates that are not affected by the pandemic
- **Data:**
  - Hourly consumption in Spain from 2015-2020
  - Weather variables: temperature, precipitation, wind speed, and wind direction
  - Holidays
  - Date/time fixed effects (seasonality)
  - Time trends

Predicting Counterfactual Electricity Consumption

- **Predictive machine learning model of consumption:**

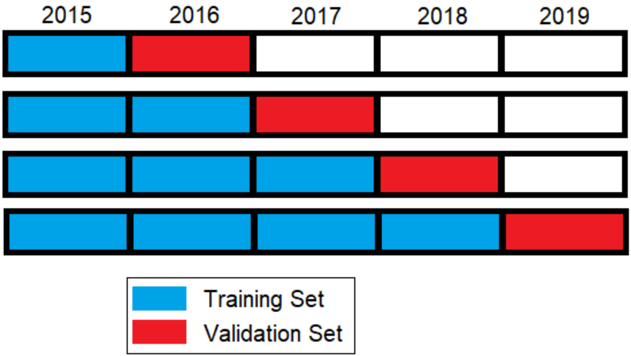
$$Y_t(0) = g(\mathbf{X}_t) + \varepsilon_t$$

- Covariates $\mathbf{X}_t$: weather and date/time fixed effects
- Model trained and cross-validated with past data (2015-2019)
  - Model selected based on **out-of-sample** performance
  - Using forward chaining cross-validation (Hyndman and Athanasopoulos, 2018):
- $g()$: Gradient Boosted Trees (GBT; Chen and Guestrin, 2016)
- Impact of the pandemic on electricity demand:

$$\hat{b}_t = Y_t(1) - \hat{Y}_t(0) = Y_t(1) - \hat{g}(\mathbf{X}_t)$$

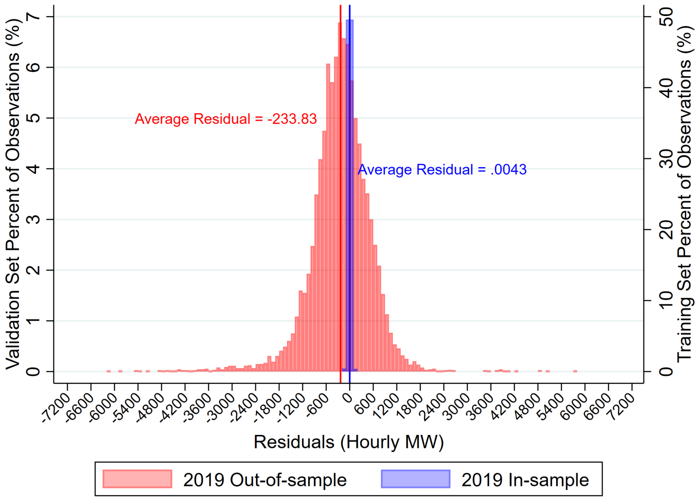
Main assumption: relationship $g()$ between energy consumption and covariates would not have changed from 2019-2020.

Forward Chaining Cross-Validation



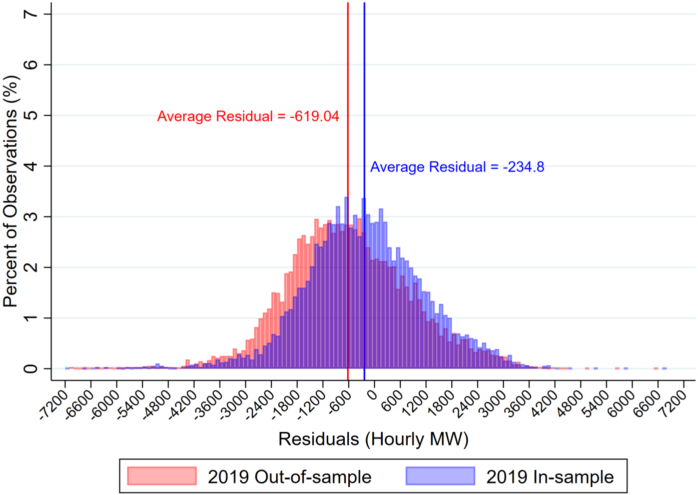
- Choose model based on prediction errors (RMSE) in 2019
- GBT results in RMSE of 809 MW; compared to avg. hourly consumption in 2019 = 28,528 MW; or std. dev. = 4,525.

Cross-Validation Results – ML



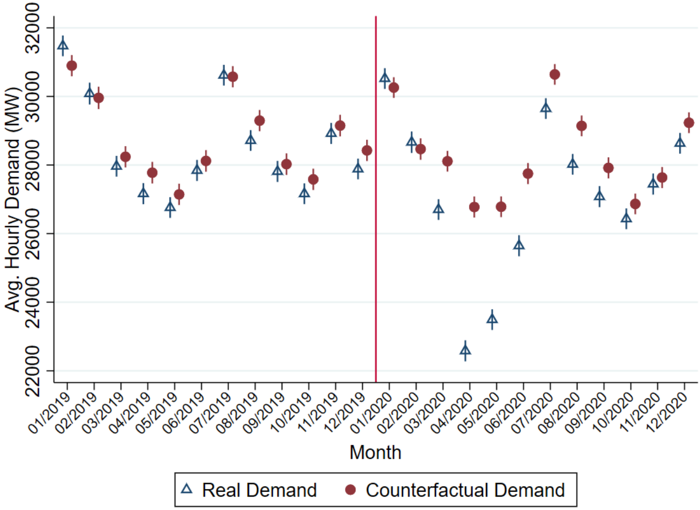
Average out-of-sample residual is less than 1% of average hourly consumption

Cross-Validation Results – fixed effects model



Day of year FE; hour of day interacted with weather; lagged (up to 3) weather

Counterfactual Consumption in the Power Sector



Counterfactual Emissions in the Power Sector

- Use the hourly consumption estimates to **simulate the hourly electricity market outcomes** with and w/o the pandemic
- Simulations based on De Frutos and Fabra (2012)
- Identify which plants would have been dispatched $\longrightarrow$ obtain carbon intensity of the market

Counterfactual Emissions in the Power Sector

- Use the hourly consumption estimates to **simulate the hourly electricity market outcomes** with and w/o the pandemic
- Simulations based on De Frutos and Fabra (2012)
- Identify which plants would have been dispatched ⟶ obtain carbon intensity of the market
- We take all else as given:
  - Hourly availability of renewables
  - Monthly hydro availability
  - Existing capacity of gas/coal/nuclear plants
  - Daily prices of gas/coal/CO2
  - Caveats: nuclear availability and gas/coal/CO2 prices may have changed

Simulated Change in Emissions from Power Sector

Emissions in Spanish Power Sector

	MtCO2 Emissions		
	Realized	Counterfactual	Difference
Natural Gas	13.01	16.40	3.39
Cogen + Others	9.26	9.67	0.41
Coal	0.48	0.52	0.03
Total	22.75	26.59	3.83

Notes: Using data up to September 2020. Assuming competitive market structure.
Results from strategic equilibrium presented in the paper.

Almost 90% of abatement due to reduced gas usage.

Emissions from Other Sectors

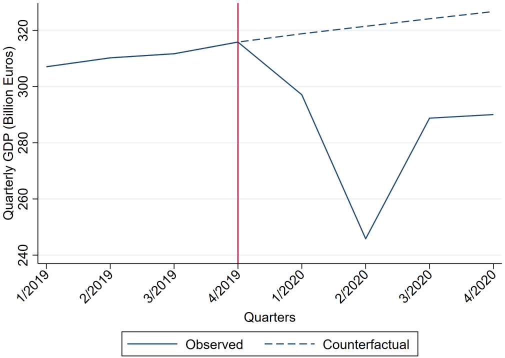
Other Sectors' CO_2 Emissions

	MtCO2 Emissions			
	2019	2020	Diff.	Pct. Diff.
Ground Transport	84.83	75.40	-9.43	-11.12
Industry	62.25	55.63	-6.62	-10.64
Domestic Aviation	5.64	3.00	-2.63	-46.68
Residential	36.70	36.14	-0.56	-1.53

Source: (Carbon Monitor; Liu et al., 2020)

Counterfactual Economic Activity

- Counterfactual GDP based on forecasts from Bank of Spain
- Forecasts made at the end of 2019 (no info. about pandemic)



- Total GDP loss in 2020: 169.37 Billion Euros
- Implicit cost of carbon = 6.510 €/Ton CO_2

Decoupling Strategy

- Simulate the market, varying types of investments
- Keep simulations that yield the same emissions reductions in the power sector as the pandemic

	Emission Reductions (M Tons CO2)	Investment Costs (M €)		Implicit Cost of Carbon (€/Ton CO2)
		Total	Investment+O&M (Q1-Q3)	
Solar Investments	4.01	5,917.5	230	57.4
Wind Investments	3.80	10,486.7	482	126.9
Hybrid Investments	3.93	8,202.1	356	90.5

Notes: Assuming competitive market structure. Results from strategic equilibrium presented in the paper.

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The implicit cost of carbon under each strategy is:

1. Slowing down economic activity: 6.510 €/Ton CO2
2. Decoupling: 57.4 €/Ton CO2

Conclusions

Carbon abatement may be obtained by slowing down economic activity and/or investing in renewables

1. Our results suggest that simply halting growth may be too costly
   - The pandemic has weakened economic activity more than what is reflected in aggregate electricity consumption data
   - Carbon abatement was short-lived, while economic losses are expected to be long-lasting
2. Investments in renewables can achieve abatement at relatively lower cost
   - Renewables could even provide more benefits in terms of economic stimulus
3. Of course, these strategies should be complemented with:
   - Improving energy efficiency, revolutionizing transport and mobility, etc.

Thank You!

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Comments? Feedback? Questions?

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References

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- De Frutos, María-Ángeles and Natalia Fabra (2012). "How to allocate forward contracts: The case of electricity markets". *European Economic Review* 56(3), pp. 451–469.
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- Liu, Zhu, Philippe Ciais, Zhu Deng, Steven J Davis, Bo Zheng, Yilong Wang, Duo Cui, Biqing Zhu, Xinyu Dou, Piyu Ke, et al. (2020). "Carbon Monitor, a near-real-time daily dataset of global CO 2 emission from fossil fuel and cement production". *Scientific data* 7(1), pp. 1–12.

Appendix: Why Machine Learning?

- ML flexibly accounts for nonlienarities and high-order interactions
- Agnostic about which variables are most important
- Agnostic about functional forms
- Best **out-of-sample** performance
  - Will compare to fixed effects models

Appendix: Cross-Validation Results

Using RMSE as accuracy metric. Values are in MW.

	Panel A: Validation Year RMSE			
	2016	2017	2018	2019
Model 1	1155.88	934.42	856.18	809.13
Model 2	1160.67	984.78	871.45	815.45
Model 3	1517.53	1219.22	1165.42	1063.05
Model 4	1532.10	1266.84	1152.23	1083.03

	Panel B: Hyperparameters			
	ntrees	max_depth	shrinkage	minobspernode
Model 1	2000	10	0.05	20
Model 2	2000	30	0.05	20
Model 3	2000	10	0.5	20
Model 4	2000	30	0.5	20

Compared to avg. hourly consumption in 2019 = 28,528 MW; or std. dev. = 4,525.

Appendix: Inference With Machine Learning

Let b_t be the effect of the pandemic.
$Y_t(1)$ is realized demand, and $Y_t(0)$ is counterfactual demand

$$\begin{aligned} \hat{b}_t &= Y_t(1) - \hat{Y}_t(0) \\ \hat{b}_t &= Y_t(0) + b_t - \hat{Y}_t(0) \\ \longrightarrow b_t &= \hat{b}_t + \hat{Y}_t(0) - Y_t(0) \\ \longrightarrow b_t &= \hat{b}_t - \hat{r}_t \end{aligned}$$

Where $\hat{r}_t$ are residuals from the prediction of $Y_t(0)$

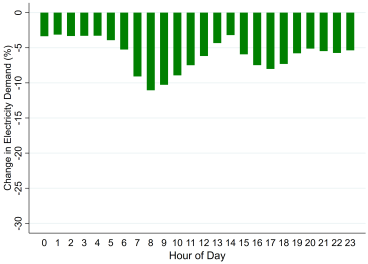
Then we also have (assuming $\hat{b}_t$ and $\hat{r}_t$ independent):

$$Var(b_t) = Var(\hat{b}_t) + Var(\hat{r}_t)$$

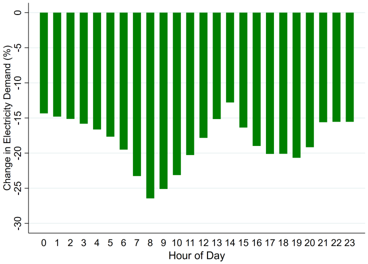
Note that $\hat{r}_t$ cannot be observed, so we proxy it with the variance of the (out-of-sample) residuals from 2019

Effect of the Pandemic on Electricity Consumption

Reduced electricity consumption by hour of the day



1st Partial Lockdown
(March 11 - March 28)



Full Lockdown
(March 29 - April 10)

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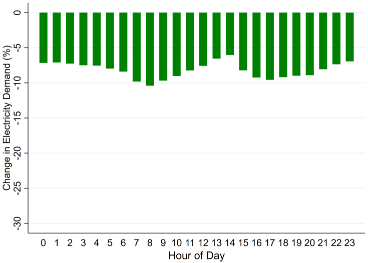
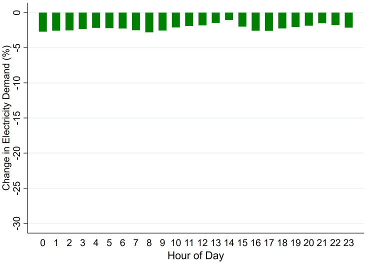
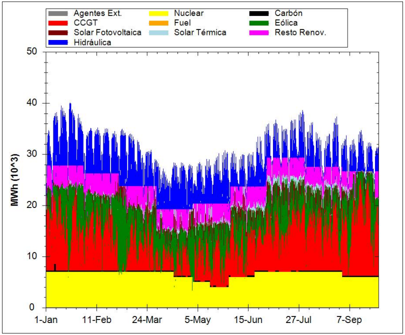


Partial Lockdowns
(April 11 - August 14)

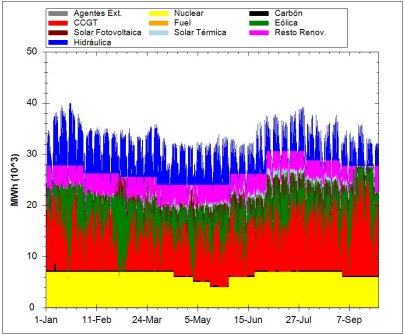


Rest of Year
(August 15 - December 31)

Generation Mix in the Power Sector



(a) Realized consumption



(b) Counterfactual consumption

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