

COVID-19's Pronounced but Temporary Effect on Power Sector Emissions

Adhurim Haxhimusa[§] Mario Liebensteiner*

18 February 2021

The coronavirus pandemic (COVID-19) has led to a massive collapse in economic activity and energy demand, with the result of significant emissions reductions at a global scale. However, the existing literature investigating abatement from COVID-19 mainly overlooked the overwhelming emissions reduction in Europe's power sector. We address this by assessing the intricate relationship between electricity demand shocks and heterogeneous generation technologies in the power sectors of 16 major European economies during January to March 2020. We apply an econometric model in an instrumental-variables framework. In a first step, we assess the impact of COVID-19 infections on electricity demand, and in a second step how this translates into emissions abatement. We find that, during full lockdown, COVID-19 reduced electricity demand by 19% and carbon emissions by an astonishing 34% per hour, whereas there is severe country heterogeneity depending on the electricity supply structure and demand shock intensity. From our estimates, we predict that power sector emissions fell by 18.4% in 2020. Our results reveal the importance of a carbon price, so that a demand reduction can offset large amounts of emissions by displacing coal at the margin. We derive several policy implications from our analysis to draw lessons from the pandemic.

Keywords: Coronavirus; COVID-19; Electricity demand; Emissions; Carbon pricing

JEL classifications: Q41, Q54, R11

Declarations of interest: none

[§]University of Applied Sciences of the Grisons, Centre for Economic Policy Research, Comercialstrasse 20, 7000 Chur, Switzerland, adhurim.haxhimusa@fhgr.ch

*Corresponding author: Friedrich-Alexander-Universität (FAU) Erlangen-Nürnberg, Chair of Energy Markets and Energy Systems Analysis, Lange Gasse 20, 90403, Germany, mario.liebensteiner@fau.de

1 Introduction

Despite massive efforts to fight climate change, over the last 30 years our planet has experienced an ever-increasing release of toxic energy-related CO₂ emissions, with a one-off exception of a 1.3% dip during the financial crisis in 2009 (IEA, 2020b). It was not until early 2020, when the unexpected novel coronavirus (COVID-19) pandemic hit the global economy, leading to “a macroeconomic shock that is unprecedented in peacetime” (IEA, 2020c, p. 5). Since the outbreak of COVID-19 in Wuhan, China, in December 2019, the virus has spread globally, with the first infections in Europe reported in Italy on 21 January 2020 (WEF, 2020). Most nations reacted to COVID-19’s spread with drastic containment measures, most notably social distancing, short-time work, and lockdowns of public life, leading to a collapse of economic activity, mobility, and energy consumption.

Our paper assesses by how much COVID-19 impacted power sector CO₂ emissions. This allows not only for making timely predictions about carbon abatement due to the pandemic, but also to derive policy implications from our results. We estimate a two-stage instrumental variables model, where we use the cumulative number of infections per country as an exogenous indicator of the treatment intensity, to identify causal effects. While the estimation of emissions as a function of electricity demand would suffer from endogeneity bias due to potential reverse causality, we can use exogenous COVID-19 infections to instrument for demand. The main idea is that cumulative COVID-19 infections are a good indication of decreasing economic activity and consequently electricity demand (c.f. Figure 2). In the first stage, we thus estimate the exogenous effect of COVID-19 on the electricity demand. In the second stage, we estimate the effect of a COVID-19-induced reduction in electricity demand on power sector emissions. Our sample covers hourly data from 16 major EU economies (plus Britain) for the period 2020/01/01–2020/03/23, during which COVID-19 spread across Europe and lead to significant reactions in electricity demand. Our data represent about 87% of the electricity generation in the EU. We find remarkable effects, which are highly relevant for policy. At its peak, COVID-19 reduced electricity demand by 19%, which in turn manifested in a significant drop in carbon emissions – 34% per hour. The country-individual estimates vary

by the electricity supply structure (i.e. which electricity sources are displaced) and the shock intensity (i.e. by how much does demand decrease). Our results show that CO₂ reductions (in absolute terms) are most intense in countries which heavily rely on coal-fired electricity and which suffered from severe COVID-19 infections (most noticeably Germany, but also Poland and Britain). This is particularly relevant, because during the time of the spread of the coronavirus, Europe experienced a relatively high price of CO₂ emission allowances, which made “dirty” coal-fired electricity production relatively more expensive than “cleaner” gas, so that a demand reduction could first displace CO₂-intensive electricity supply technologies.

The popular media reports that COVID-19 has brought about a significant drop in emissions around the globe. For example, a BBC report (Henriques, 2020) states that New York’s carbon emissions plummeted by 50% during March 2020 (compared to March 2019), when the virus spread across the city. It is also said that China’s emissions fell by 25% at the start of 2020, with a significant decrease in coal-fired electricity production (Henriques, 2020). Satellite images show significant reductions in air pollution over France, Germany, Italy, and Spain during March 2020 in a year-on-year comparison (ESA, 2020). However, many reports (e.g. EC, 2020; Henriques, 2020; IEA, 2020d; Wang and Wang, 2020) argue that the drop in emissions will only be temporary, giving earth’s climate a short break, and that emissions may return to their pre-crisis trend once the economy recovers from COVID-19, as it was the case after the economic crisis in 2009.

By now, some academic articles have been published on the nexus between COVID-19 and greenhouse-gas emissions. LeQuéré et al. (2020) investigate how the COVID-19 affected daily carbon emissions from various sectors in a large number of economies (69 countries, 50 US states, 30 Chinese provinces) from January through April 2020 and find that full containment reduced emissions by 26%. Liu et al. (2020) find that global CO₂ emissions plummeted by 8.8% during the first half of 2020 compared to the same period in 2019. Le et al. (2020) find significant reductions in NO₂ and SO₂ during 2020/01/23–2020/02/13 in China (with partly unexpected increases in PM_{2.5} and ozone in some regions due to unfavorable meteorological conditions). Wang and Su (2020) also show in a year-on-year comparison that COVID-19 sig-

nificantly reduced Chinese CO₂ and NO₂ emissions. Habib et al. (2020) link daily global CO₂ emissions and COVID-19 infections through the channel falling oil prices, as indicated by a drop in oil demand, using a Wavelet approach for January through March 2020. Han et al. (2021) use changes in Chinese national and sectoral GDP to make predictions about the effect of COVID-19 on emissions during the first quarter of 2020 (i.e. -11% at the national level). All these studies hold a reduction of energy demand (or oil demand), as induced by the COVID-19 confinement measure, responsible for the reduction in emissions. Santiago et al. (2021) estimate an electricity demand reduction of 13.5% during the COVID-19 lockdown for Spain in a year-on-year comparison. Meles et al. (2020) stress that COVID-19's emissions reduction will help reaching the 2030 EU emissions targets, whereas policy should not miss the opportunity to reach the targets set for the later future.

Despite their scientific scope and rigor, a potential drawback of many related studies (e.g. Le et al., 2020; LeQuéré et al., 2020; Liu et al., 2020) is their use of year-on-year or before-after comparisons as their mode of analysis, which cannot decompose the effect of COVID-19 from other parallel events, such as changing production from renewable energies, or temperature differences. Also, their analysis of several sectors of the economy comes at the expense that individual sectors cannot be investigated in detail. For example, IEA (2020a) reports that Europe's power sector emissions fell by an astonishing 17% from 2019 to 2020, outperforming any emissions-abatement effects reported for any other region or for any other economic sector. LeQuéré et al. (2020) reports an under-proportionate reduction in global electricity-based emissions for a certain reduction in electricity demand, which is passed over without comment. In contrast, our analysis explains that a sufficiently high carbon price, as observed during the time of the COVID-19 lockdown measures in Europe, may be responsible for the outstanding emissions reduction in the power sector. This is because a carbon price may lift the marginal costs of coal-fired electricity above those of gas, so that a decline in demand can first replace "dirty" coal and only thereafter "cleaner" gas. This also explains our finding of an over-proportionate reaction of emissions to a demand reduction.

Our paper contributes to the literature in several dimensions. First, none of the aforemen-

tioned studies decomposed the effect of interest (i.e. emissions reduction due to COVID-19) from confounding effects, we make use of an econometric framework, which estimates the causal effect of COVID-19 on CO₂ emissions via the channel of electricity demand reduction, while controlling for simultaneous variations in other important driving forces of emissions, such as changes in renewable energies, temperature or other seasonal effects. Another reason for why our estimates are trustworthy is that we use COVID-19 infections as a credible, exogenous instrument for electricity demand, enabling us to get unbiased and precisely estimated coefficients. Second, our model can be applied more generally to assess how changes in electricity demand as induced by shocks other than COVID-19 (e.g. an economic recession or establishing energy efficiency policies) affect emissions. Third, our model provides sound and causal evidence of COVID-19's dampening effect on emissions particularly from the *power sector* of selected European economies. While it may be straightforward to assess emissions abatement from reduced energy demand in many sectors of the economy (e.g. in transportation or manufacturing), emissions in the power sector depend fundamentally on which particular technology at the margin has to cut production for a decrease in electricity demand. Our empirical results demonstrate that the COVID-19-induced demand reduction translates into significant (over-proportionate) emissions abatement only when coal-fired electricity supply decreases. While most European countries have both "cleaner" natural gas- and "dirtier" coal-fired power plants to produce electricity (c.f. Gugler et al., 2021), the high-enough carbon price (€20/tCO₂), as observed during March 2020 when COVID-19 spread across Europe, made it possible that power sector emissions reacted much stronger to the demand shock than in other economic sectors (c.f. IEA, 2020a; Le et al., 2020; LeQuéré et al., 2020; Liu et al., 2020). Thus, another contribution of our paper is that we can derive policy implications specifically for the power sector, as for example that energy efficiency measures may only unfold their full abatement potential when a sufficiently high carbon price is in place so that electricity demand reductions push "dirty" coal out of the market. Moreover, analyzing the power sector is of particular relevance, because it is responsible for the lion's share of global carbon emissions, 41% in 2017 (IEA, 2019, p. 23).

We can use the estimates of our econometric model to predict abatement of power-sector emissions for our 16 sample economies for the year 2020. A best-guess scenario prediction would be that power sector emissions will fall by around 18.4% during 2020 relative to a counterfactual scenario without the coronavirus pandemic. In this cautious scenario¹, we assume 3.5 months of full lockdown with the full effect of -34% emissions reduction and six months of partial lockdown, with about half the full effect (-17%) of emissions reduction.

We can derive several policy implications, which we will explain in more detail in this paper. First of all, our results demonstrate the abatement potential of reducing coal-fired electricity. In countries with both coal- and gas-fired electricity supply, and in the absence of a (high-enough) carbon price, demand reductions, for example from energy efficiency measures, may only induce little abatement when “cleaner” gas (with its higher marginal costs) is replaced first, and “dirty” coal only thereafter. Reversely, if a carbon price is in place to increase coal’s marginal costs above those of gas, demand reduction policies may immediately translate into vast emissions abatement. Another way of looking at this is that investments in energy efficiency measures may be specifically targeted as highly polluting plants. The coronavirus pandemic may thus be used as an opportunity, because government subsidies to strengthen the recovery of the economy may be directed towards clean technologies as to replace other highly polluting plants.

Another policy implication is that “across-the-board regulations”, e.g. of energy efficiency, which would apply equally for all EU member states, may not be optimal, as the effectiveness of demand reductions and/or carbon pricing depends on the national electricity supply structures – particularly on the amount of coal-fired electricity to be displaced. Thus, while for some economies having significant abundant gas capacity installed to replace coal power plants, carbon pricing may be an optimal policy with immediate abatement effect. For countries without coal plants, other policies, such as subsidies for investment and R&D in clean energy sources and energy storages may be better.

Despite its disastrous consequences on human health and economic welfare, COVID-19 resulted in a vast temporary reduction in emissions, which might soon again converge to their

¹See Section 5 for scenario details.

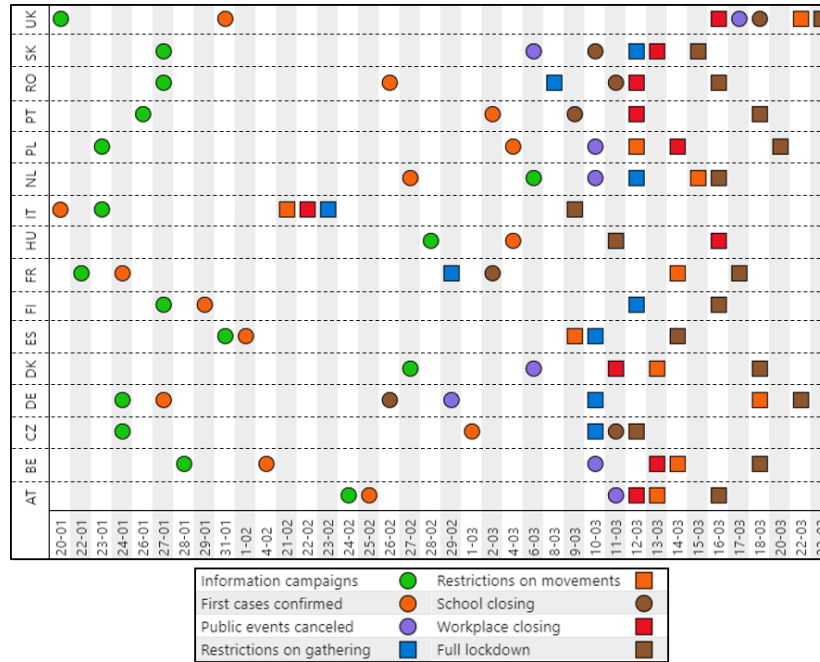
pre-pandemic trend once the economy recovers if policy does not manage to take the opportunity to induce a structural transition towards a more sustainable energy supply in particular, and “greener” economic growth in general. Our results and policy implications may be well extended to economies outside Europe, such as the USA, China, or India, with a considerable share of highly pollutive coal-fired power plants.

Moreover, our findings are informative beyond the effect of COVID-19, revealing how changes in electricity demand in general may translate into changes in CO₂ release. For example, without a fundamental change in the power supply structure, an *increase* in electricity demand, as induced for example by a significant rollout of electric vehicles or intensified sector coupling between power and heating, may lead to considerable additional emissions whenever coal is the marginal technology (i.e. coal power plants have to overtake the additional supply). Hence, policy needs to carefully evaluate whether a further electrification strategy (of mobility or heating) may be worthwhile in terms of additional emissions for the existing power supply structure. Such strategies may only pay off once the power sector achieves a transformation towards a low-carbon supply.

2 History of containment measures

The fast and wide spread of COVID19 forced governments around the globe to impose confinement measures to mitigate COVID-19 infections. Even before the World Health Organization declared COVID-19 a global pandemic on 11 March 2020 (Cucinotta and Vanelli, 2020), many countries have taken actions and imposed imposed various measures. Hale et al. (2020) gathered worldwide data on countries’ steps to control the pandemic situation. Figure 1 summarizes some main events on the confinement actions for our 16 sample economies during the sample period 2020/01/01–2020/03/23. We can see that our sample covers the early events of information campaigns warning of the spread of COVID-19, first cases of infections in the various countries, up to containment measures, such as cancellations of public events, restrictions on gathering and movements, school and workplace closings, and eventually full lockdown in each country.

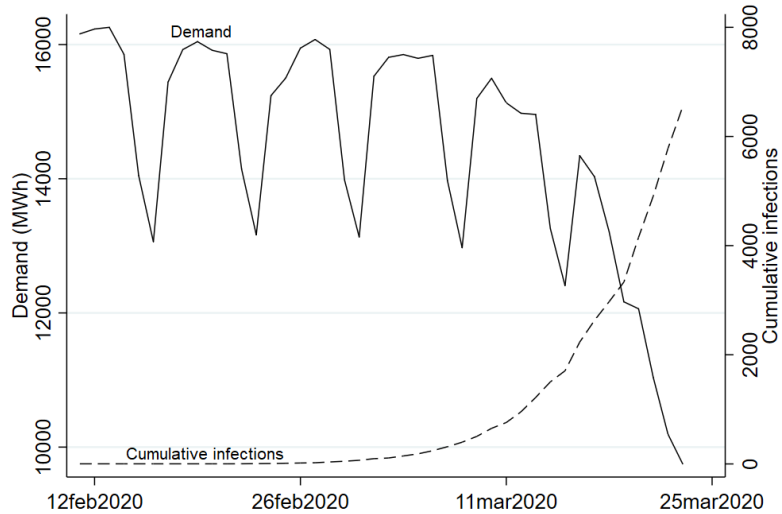
Figure 1: History of implemented containment measures



The figure depicts the dates of important confinement measures within our sample period 2020/01/01–2020/03/23. By the end of our sample, all economies were in a state of full lockdown. Dates without events are excluded for conciseness. Dates are obtained from Hale et al. (2020).

At the very beginning of the spread of COVID-19 in Europe, there was only little known about the contagiousness of the virus and how it was transmitted, while subsequently more and more research has been done to better understand its symptoms and health implications (Murthy et al., 2020). As a result, some countries, such as Poland, Slovakia, Czech Republic, and Portugal, were careful and started with information campaigns more than 30 days before the confirmation of the first infections, while other countries, such as the Netherlands started information campaigns only after their first reported infections. The early “soft” measures of information campaigns or cancellations of public events did not have any significant impact on economic activity. In contrast, the subsequent actions taken to control the spread of the virus severely affected everyday life and economic performance, such as restrictions on gathering, restrictions on national and international mobility, as well as school and workplace closings (Hale et al., 2020; Meles et al., 2020).

Figure 2: Demand and infections, daily averages



The figure shows daily electricity demand and cumulative COVID-19 infections, averaged across 16 European countries.

During February 21–23, Italy was the first European country to gradually close its schools, cancel public events, close workplaces, restrict public and private gatherings, and restrict the freedom of movement as a response to the rapid rate of new infections. Italy was also the first country to impose full lockdown on March 9, 2020. Figure 1 also shows that by mid of March 2020 almost all countries imposed full lockdown. The aim of the containment measures was to minimize physical contacts between individuals, with short-term fundamental reductions in economic activity and everyday life (Eichenbaum et al., 2020). Countries imposed increasingly stringent confinement measures step-by-step depending on the rate of confirmed infections up to full lockdown, with the consequence of reducing economic activity (e.g. Habib et al., 2020; Helm, 2020) and thus energy demand (e.g. Meles et al., 2020; Santiago et al., 2021) to a minimum – something that we will exploit in our econometric model.

Figure 2 shows the strongly negative relationship between the cumulative number of infections and electricity demand. The figure shows that average cumulative infections began to rise noticeably by the end of February 2020 and shot up in the middle of March, while at the same time demand for electricity fell sharply. In our empirical analysis, we take 23 March 2020

(the highest number of cumulative infections in our sample) as the date from which to predict the full effect of COVID-19. The total emissions reduction will then depend on the duration of the ongoing containment measures. We also assume that once the containment measures are relaxed, the economy will recover and adjust gradually to its pre-COVID-19 trajectory, thus leading to the recovery of emissions.

3 Methodology

Our main goal is to assess the effect of the spread of COVID-19 infections on power sector emissions. To do so, we develop an econometric two-step model, which traces out the effect of COVID-19 on electricity demand and further on power sector emissions. This way, we can disentangle the effect of interest from other confounding developments, which may have also had an effect on emissions, such as changes in the feed-in from renewable energy sources, temperature (or weather), or seasonal patterns. This makes our approach superior to other approaches, such as year-on-year or before-after comparisons, which are applied in COVID-19-emissions-impact assessments published in high-impact journals (Le et al., 2020; LeQuéré et al., 2020; Liu et al., 2020). Another feature is that our model identifies electricity demand reduction as the channel through which COVID-19 translated into emissions abatement. Thus, our model allows to predict changes in emissions for a change in electricity demand in general, which makes our results extrapolateable to demand shocks other than COVID-19 (e.g. energy efficiency policies).

The COVID-19 pandemic represents a severe exogenous shock to electricity demand because economic activity was driven to a minimum.² For this reason, we can use COVID-19 infections as an instrumental variable for electricity demand. In contrast, electricity supply, as part of the critical infrastructure of any economy, was not directly affected through COVID-19 infections. There is no evidence that COVID-19 led to any power outages or plant shutdowns.

We acknowledge that COVID-19 has also led to a decline in the price of emission al-

²Similarly, (LeQuéré et al., 2020, p. 1) argue that “the changes in emissions are entirely due to a forced reduction in energy demand.”

lowances (EUA) from the EU Emissions Trading System, which may have led to fuel substitution (e.g. the use of coal rather than natural gas). Yet, this is merely a second-order effect, induced by a drop in emissions caused by a drop in demand. Quite deliberately, we do not directly control for the EUA price in our regressions, because its inclusion may result in an endogeneity bias (i.e. the EUA price and emissions may suffer from reverse causality). Nevertheless, our instrumental variables approach eliminates omitted variable bias, so that our main coefficient of interest is still estimated without bias.

Crucially for identification, the cumulative number of reported infections represents our indicator of treatment intensity, which serves as an exogenous instrument for electricity demand. Figure 2 supports this notion by showing that daily average electricity demand fell when the cumulative COVID-19 infections took off.³

To trace out the effect of COVID-19 on electricity demand and then on CO₂ emissions, we estimate an instrumental variables model via two-stage least squares (2SLS). We run individual time-series regressions for each country to avoid bias from size-effects.⁴ In the first stage, we estimate the impact of cumulative infections (Inf) on electricity demand (D):

$$D_t = \alpha_{Inf} \cdot Inf_t + X_t' \alpha + \epsilon_t, \quad (1)$$

where t denotes the sample hour. X is a vector of relevant control variables, including wind and solar electricity, air temperature, hour-of-day, day-of-week, and monthly fixed effects, as well as a daily time trend. ϵ represents the error term. α_{Inf} and α are the respective parameters to be estimated.

The application of multivariate regression with control variables allows for disentangling the effect of COVID-19 from other influential factors, most notably developments of renewable energies (i.e. wind and solar electricity), but also temperature and seasonality, which cannot

³We acknowledge that individual countries may follow individual strategies of testing for COVID-19. For example, countries with high testing penetrations (i.e. a higher testing rate per capita) may also have a higher number of reported infected cases. Nevertheless, the variation in the time series should be unaffected as long as a given country's testing rate does not change significantly relative to other countries' rates.

⁴A fixed-effects panel regression with all variables adjusted for population yields almost identical results (not shown for brevity).

be adequately captured by the year-on-year comparisons found in Jones (2020) or LeQuéré et al. (2020).

The first-stage regression should identify a decrease in demand for an increase in Inf . We thus expect the estimate of α_{Inf} to be negative and statistically significant. In stage two, we regress CO₂ emissions from the power sector (E_t) on the predicted values of demand (\hat{D}):

$$E_t = \beta_D \cdot \hat{D}_t + X_t' \beta + \mu_t, \quad (2)$$

which should yield an unbiased estimate of β_D (which measures the magnitude of the effect).

Our 2SLS model allows for estimating a “causal chain”. That is, we estimate the consequent effect on emissions (Δ_E) as the number of infected cases influenced first demand and then emissions, using the first-stage estimate of α_{Inf} and the second-stage estimate of β_D (Kling, 2001):

$$\Delta_E = Inf \cdot \hat{\alpha}_{Inf} \cdot \hat{\beta}_D. \quad (3)$$

For each country, we evaluate Δ_E for the maximum number of cumulative infections by the end of our sample period on 23 March 2020, \overline{Inf} :

$$\Delta_E(\overline{Inf}) = \overline{Inf} \cdot \hat{\alpha}_{Inf} \cdot \hat{\beta}_D. \quad (4)$$

This should give us an estimate of the *maximum* treatment effect on emissions. The idea behind this is that by 23 March 2020, all of our sample countries were in a state of full lockdown, such that economic activity and thus electricity demand were at their minimum.

Finally, to get a feel of the *percentage* impact, we assess this emissions-reducing effect relative to the average of predicted pre-treatment emissions (\hat{E}_{pre}):

$$\% \Delta_E = \Delta_E(\overline{Inf}) / \hat{E}_{pre} \cdot 100, \quad (5)$$

where $\hat{E}_{pre} = \sum_{t=1}^T \hat{E}_t(Inf_t = 0) / T$ and $t = \{1, \dots, T\}$ represents the pre-treatment hours dur-

ing which infections are zero. We use *predicted* pre-treatment emissions as a benchmark for evaluating the emissions-reducing effect, because, in contrast to *actual* emissions, these are adjusted for seasonality and other influential factors.

4 Data

We utilize data on power sector emissions, COVID-19 infections, and other control variables from various data sources for 16 European countries⁵. Our sample spans the period from 1 January 2020 to 23 March 2020, covering the spread of COVID-19 across Europe. Our sample represents about 87% of the electricity generation in the EU (i.e. EU27 plus the UK; the number is based on 2018 electricity data from Eurostat).

Our dependent variable is CO₂ emissions from the power sector. We calculate this variable using data on hourly electricity generation from burning fossil fuels, such as lignite, hard coal, or natural gas, as obtained from the Transparency Platform of the European Network of Transmission System Operators for Electricity (ENTSO-E, 2020). We then apply emission factors, weighted by each country’s average plant vintage, which are provided in Table A1 of Gugler et al. (2020). For our main variable of interest, we rely on data about cumulative daily COVID-19 infections per country, as provided by the platform “Our World in Data” (Roser et al., 2020). The idea is that COVID-19 infections measure the treatment intensity. That is, with the spread of the virus across Europe, countries subsequently carried out their confinement policies (e.g. social distancing, public lockdowns), which resulted in a collapse of economic activity, part-time working and job terminations, and consequently a significant decrease in energy use.

Data on each country’s hourly electricity demand (load) comes from ENTSO-E (2020). As control variables, we obtained data on hourly infeed of wind and solar power, which were also obtained from ENTSO-E (2020). Moreover, we include a measure of hourly air temperature. That variable represents the average temperature over all available weather stations in each country, as provided by the National Centers for Environmental Information (NCEI, 2020).

⁵Austria (AT), Belgium (BE), Czech Republic (CZ), Germany (DE), Denmark (DK), Spain (ES), Finland (FI), France (FR), Hungary (HU), Italy (IT), Netherlands (NL), Poland (PL), Portugal (PT), Romania (RO), Slovakia (SK), and Great Britain (UK).

Table 1: Sample statistics

		AT	BE	CZ	DE	DK	ES	FI	FR	HU	IT	NL	PL	PT	RO	SK	UK
Emissions (tCO ₂)	Mean	726	971	4,471	14,147	694	3,026	687	2,225	926	5,465	3,000	12,243	693	2,079	356	5,028
	Max	1,373	1,753	6,190	33,658	4,315	6,620	1,388	4,390	1,307	10,686	4,948	17,814	2,401	3,029	561	12,138
	Min	232	277	2,218	5,100	288	1,312	376	903	360	2,510	805	7,114	105	1,245	96	90
Cum. COVID-19 inf. (#) ^a	Mean	187	180	61	1,200	135	1,530	42	466	8	4,636	243	30	66	27	11	303
	Max	3,631	3,401	1,165	24,774	1,395	28,572	626	7,730	167	59,138	4,204	634	1,600	433	185	5,683
	Min	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Demand (MWh)	Mean	7,575	10,054	8,378	59,409	4,215	29,030	10,168	62,799	5,347	32,722	11,910	20,111	6,107	7,246	3,572	38,059
	Max	9,710	13,065	10,620	76,591	9,618	40,137	12,388	82,832	6,680	47,153	16,620	25,251	8,848	9,233	4,702	52,132
	Min	5,170	6,911	5,496	38,099	2,920	18,697	7,534	43,771	3,552	17,019	4,942	12,943	3,753	5,129	2,570	11,540
Wind (MWh)	Mean	1,108	1,696	119	23,735	2,759	6,553	1,115	6,388	97	2,709	968	2,627	1,564	973	1	9,058
	Max	2,969	3,175	280	46,064	5,748	17,056	1,994	12,976	304	7,448	1,546	5,331	4,418	2,756	8	14,477
	Min	4	13	4	789	59	315	64	667	0	130	1	23	5	0	0	1,290
Solar (MWh)	Mean	94	219	152	2,623	51	1,438	0	864	112	1,720	13	0	112	112	39	684
	Max	828	3,031	1,593	29,654	756	7,512	0	6,103	924	9,679	329	0	576	856	343	8,155
	Min	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Temp. (°C)	Mean	2.2	6.1	2.6	5.2	5.4	10.5	-3.0	7.9	3.8	7.6	6.7	3.6	12.0	2.7	1.8	6.0
	Max	17.2	15.4	15.4	15.4	10.9	21.9	4.4	16.1	20.2	17.2	13.6	16.3	22.3	17.8	17.6	11.8
	Min	-5.5	-2.4	-5.2	-3.5	-3.1	-2.0	-15.1	-0.8	-6.3	-2.4	-0.1	-4.9	3.8	-9.1	-8.3	0.0

Note: Sample period is 2020/01/01–2020/03/23 for the hourly observation. ^a Daily variation.

Table 1 provides sample statistics for each country. We can see that all variables have sufficient variation for empirical analysis and do not suffer from extreme outliers or obvious measurement errors.⁶

5 Results

Table 2 provides the first- and second-stage regression estimates of α_{Inf} and β_D . The first-stage estimates of α_{Inf} are, as expected, negative (i.e. more infections reduce the demand for electricity) and statistically significant at the 1% level (i.e. the likelihood that the estimates are driven by chance is less than 1%). Hence, this is evidence that cumulative COVID-19 infections identify electricity demand and indeed serve as a valid exogenous instrument for electricity demand. Moreover, the high first-stage F statistics suggest that cumulative infections is not a weak instrument for demand.

Furthermore, the second-stage estimates are positive and statistically significant at the 1% level, which is again in line with expectations. On average, we find that an increase (decrease) in demand by one MWh is associated with an increase (decrease) in emissions by 0.495 tCO₂. However, the average masks severe heterogeneity of our results across European economies, which is largely driven by each country's respective electricity production mix. That is, the estimate of β is high for countries that have to use CO₂-intensive generation technologies (such as lignite or hard coal) to meet an increase in electricity demand.

Table 3 reports our main results. Across economies, we find a significant reduction in electricity demand, evaluated for the national number of cumulative infections as of the end of our sample period on 23 March 2020. On average, COVID-19 reduced the hourly demand for electricity in our sample of 16 European countries by 19%, which is an economically sizable effect. Intuitively speaking, as long as the COVID-19 effects last (e.g. as long as economic activity is reduced to a minimum due to the lockdown measures), electricity demand will be reduced by almost 20% in Europe. Yet, we can see significant variations in the measured effects ($\% \Delta_D$). Countries, such as Italy or France, which implemented the most drastic lockdown measures,

⁶We also checked all variables by hand for any inconsistencies.

Table 2: First- and second-stage regression estimates

Country	1 st stage: $\hat{\alpha}_{Inf}$	2 nd stage: $\hat{\beta}_D$	Obs.	Kleib.-Paap F
AT	-0.3900 (0.0271)	0.0847 (0.0152)	1,969	208
BE	-0.5510 (0.0394)	0.4294 (0.0232)	1,969	196
CZ	-1.2153 (0.0797)	0.3354 (0.0480)	1,969	232
DE	-0.2191 (0.0282)	1.0566 (0.1084)	1,969	60
DK	-0.2231 (0.0260)	0.8329 (0.0996)	1,969	74
ES	-0.1811 (0.0156)	0.3078 (0.0188)	1,969	135
FI	-1.3452 (0.1561)	0.1947 (0.0169)	1,969	74
FR	-2.5490 (0.0639)	0.0705 (0.0034)	1,850	1,592
HU	-4.0437 (0.3282)	0.3524 (0.0310)	1,969	152
IT	-0.2049 (0.0120)	0.2092 (0.0052)	1,969	290
NL	-0.3829 (0.0441)	0.5724 (0.0509)	1,969	75
PL	-4.8862 (0.4175)	0.7195 (0.0296)	1,969	137
PT	-0.5050 (0.0568)	0.2393 (0.0549)	1,969	79
RO	-1.7356 (0.1534)	1.0853 (0.0868)	1,968	128
SK	-2.7495 (0.1659)	0.2421 (0.0176)	1,956	275
UK	-0.7720 (0.0934)	0.4612 (0.0480)	1,967	68
Weighted avg.	-1.2424	0.4948		

Heteroskedasticity-robust standard errors in parentheses. All estimates are statistically significant at the 1% level. The regressions include wind and solar electricity, air temperature, a daily time trend, hour-of-day, day-of-week, and monthly fixed effects, as control variables. Missing values reduce the number of observations for some countries. Average weighted by countries' population.

Table 3: Results

country	Predicted pre-treatment values		Treatment		Effects on demand and emissions			
	Demand (MWh)	Emissions (tCO ₂)	Max. infected	(in % of population)	Δ_D (MWh)	% Δ_D	Δ_E (tCO ₂)	% Δ_E
AT	7,648	732	3,631	(0.0413%)	-1,416	-18.5%	-120	-16.4%
BE	10,154	1,013	3,401	(0.0298%)	-1,874	-18.5%	-805	-79.4%
CZ	8,452	4,497	1,165	(0.0110%)	-1,416	-16.8%	-475	-10.6%
DE	59,672	14,424	24,774	(0.0299%)	-5,428	-9.1%	-5,735	-39.8%
DK	4,245	719	1,395	(0.0263%)	-311	-7.3%	-259	-36.1%
ES	29,309	3,112	28,572	(0.0612%)	-5,174	-17.7%	-1,593	-51.2%
FI	10,224	698	626	(0.0114%)	-842	-8.2%	-164	-23.5%
FR	63,974	2,308	7,730	(0.0115%)	-19,704	-30.8%	-1,389	-60.2%
HU	5,380	937	167	(0.0017%)	-675	-12.6%	-238	-25.4%
IT	33,672	5,664	59,138	(0.0979%)	-12,117	-36.0%	-2,535	-44.8%
NL	12,003	3,053	4,204	(0.0244%)	-1,610	-13.4%	-921	-30.2%
PL	20,258	12,348	634	(0.0017%)	-3,098	-15.3%	-2,229	-18.1%
PT	6,143	701	1,600	(0.0155%)	-808	-13.2%	-193	-27.6%
RO	7,292	2,129	433	(0.0022%)	-752	-10.3%	-816	-38.3%
SK	3,603	364	185	(0.0034%)	-509	-14.1%	-123	-33.9%
UK	38,292	5,136	5,683	(0.0085%)	-4,387	-11.5%	-2,023	-39.4%
	$\Sigma = 320,322$	$\Sigma = 57,835$			$\Sigma = -60,121$	$\emptyset = -18.8\%$	$\Sigma = -19,618$	$\emptyset = -33.9\%$

see the highest reductions in electricity demand.

These demand-dampening effects translate into significant carbon abatement. On average, we find that COVID-19 reduced hourly CO₂ emissions from the power sector by 34%. Again, as long as the economic shock of COVID-19 lasts, emissions will be significantly reduced. We estimate that COVID-19 is responsible for a reduction of almost 20 million tonnes of carbon dioxide (actually 19,618 tCO₂) emissions per hour in our 16 sample countries, as long as economic activity is as during full lockdown.

We can use our model estimates to predict the annual effect of COVID-19 on the power-sector emissions of our 16 sample economies for 2020. A well-educated guess would be to assume two months of full lockdown during the first wave of COVID-19 (March and April 2020) and another 1.5 months during the second wave (mid of November and December 2020), with the full effect of -34% emissions reduction, and six months of partial lockdown in between, with about half the full effect of emissions reduction (i.e. -17%). This scenario would result in 18.4%⁷ less CO₂ emissions from the EU power sector in 2020.

5.1 Results explained by countries' supply structures

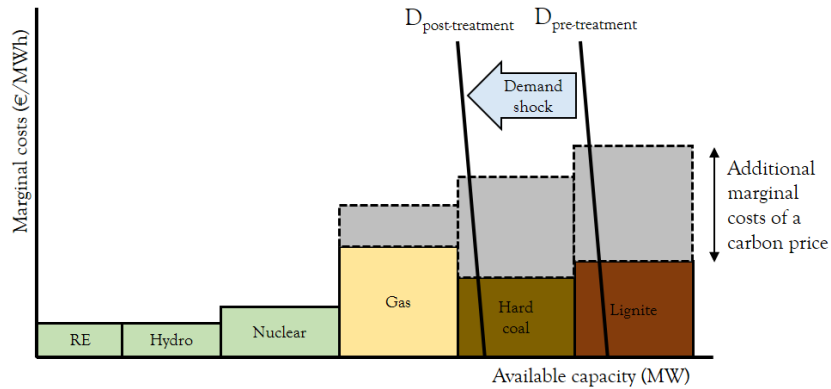
The emissions-reducing effects vary considerably across countries, depending not only on the shock intensity (i.e. the magnitude of the demand-reducing effect) but also on the specific electricity supply structure (i.e. which technologies are mainly replaced). Figure 3 provides a stylized example of which technologies are offset by a demand shock, both for a high carbon price (of around 24 €/tCO₂), as observed during the beginning of 2020 when COVID-19 hit Europe (see Figure 3a), and for a low carbon price, as during most of the existence of the EU Emission Trading System since 2005 (see Figure 3b). Figure 4 shows that the price of emission allowances (EUA) was indeed low (well below 15 €/tCO₂) for years up to mid 2018.

In power markets, the supply curve ranks the available electricity generation capacity by marginal cost, which yields a typical upward-sloping step function (called the “merit order”). Power plants' marginal costs are essentially determined by the fuel input costs and, if a carbon

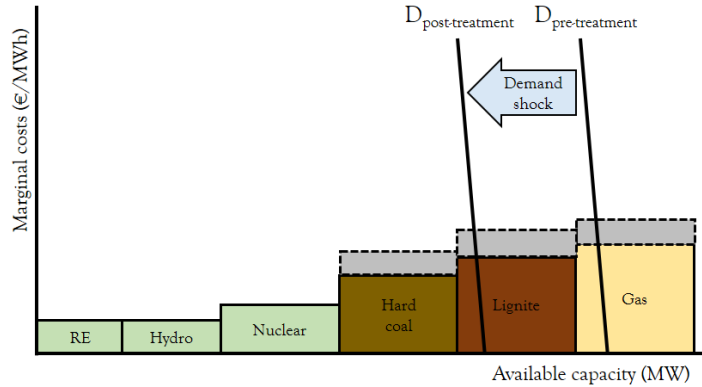
⁷ $(3.5 \cdot 0.34 + 6 \cdot 0.17) / 12 = 0.184$

Figure 3: Stylized effect of a demand shock from COVID-19

(a) High carbon price (as during our sample period)

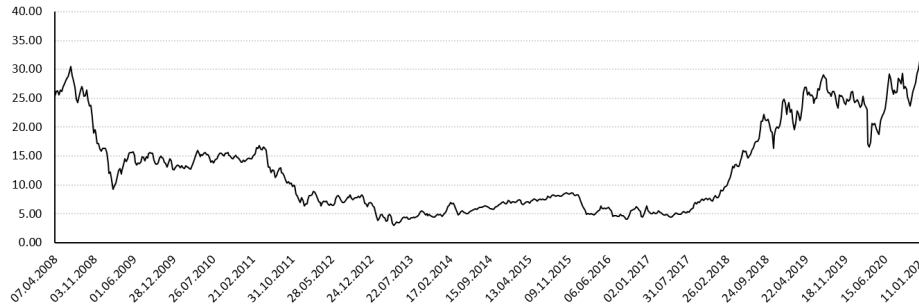


(b) Low carbon price



The figure shows the effect of COVID-19 by the means of a stylized electricity supply curve (a) for a high carbon price and (b) for a low carbon price). The emissions-reducing effect hinges not only on the intensity of the demand shock but also on the order of the supply technologies. During the spread of COVID-19 in Europe, the price of emissions certificates in the EU Emission Trading System was high enough that the marginal costs of lignite and hard coal power plants exceeded those of natural gas power plants. Thus, a demand reduction first replaced “dirty” coal (lignite and hard coal) and only thereafter “cleaner” gas (as in (a)). For a low carbon price, gas will be replaced first (as in (b)).

Figure 4: Price of EU emission allowances (EUA), €/tCO₂-eq.



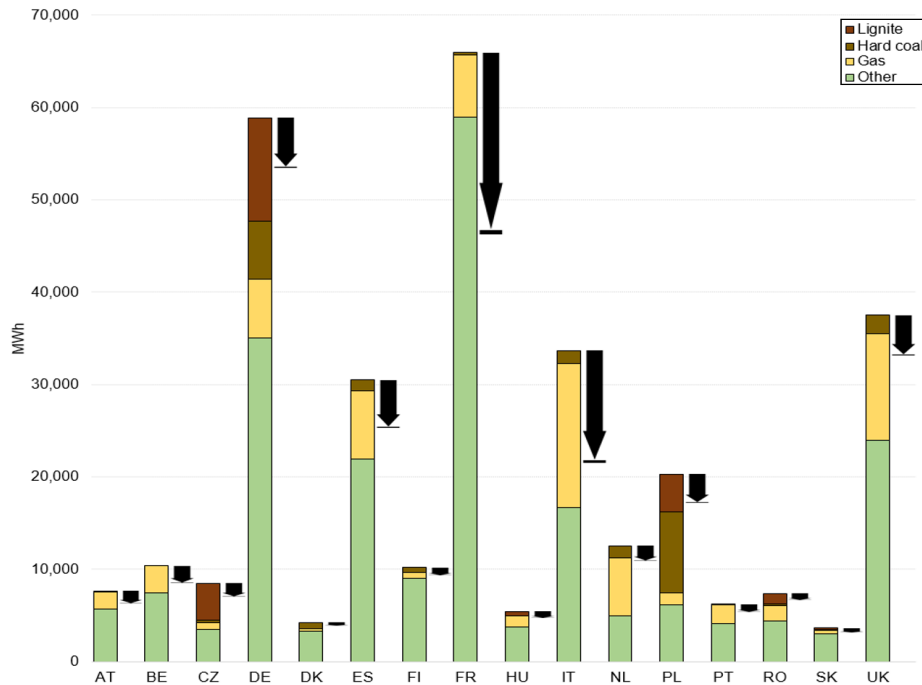
Daily price of emission allowances (EUA) within the scope of the EU Emissions Trading System in Euro per ton of CO₂ equivalent. Source: Ember (2021).

price is in place as in the EU, by the costs of CO₂ emissions. For a low carbon price (Figure 3b), gas would be more expensive than lignite and hard coal, and therefore rank last in the merit order. This is why gas plants exhibit typical peak-load features (e.g. ability of flexibly adjusting output to variations in demand or feed-in of wind and solar power). However, the emissions of all power plants in our 16 European sample economies are subject to an emissions allowance price, which is determined in the EU Emission Trading System, a cap-and-trade program. During the beginning of 2020, before COVID-19 spread across Europe, the price of emission allowances was around 24 €/tCO₂ (mean = 24.31, min = 23.38, max = 25.38 during January and February 2020), which was high enough to lift the marginal costs of coal-fired (lignite and hard coal) plants above those of gas-fired power plants (Gugler et al., 2021). Thus, during the period of evaluating the effect of COVID-19, gas was ranked before lignite and hard coal. This is important because natural gas plants create less than half (around 40%) the carbon emissions per unit of electricity of coal plants (Wilson and Staffell, 2018)⁸ and most other technologies produce few or even no emissions.

Thus, Figure 4 indicates that for a high-enough carbon price that makes coal relatively more expensive than gas, a demand reduction lead to significant abatement, because it can marginally offset “dirty” coal-fired electricity supply. In contrast, for a low carbon price,

⁸According to our own calculations for the German power plant fleet, emissions of natural gas plants are 0.37 tCO₂/MWh, those of hard coal are 0.81 tCO₂/MWh, and those of lignite are 0.98 tCO₂/MWh. These numbers are composed of the carbon content (i.e. CO₂ per energy unit) and the heat rate (i.e. efficiency factor, which varies considerably by power plant type and vintage) and represent averages weighted by capacity.

Figure 5: Pre-treatment energy mix and shock intensity by country



The graph shows the average pre-treatment energy mix in MWh (bars) as well as the demand shock intensity (arrows), as induced by COVID-19, in MWh. Given the relatively high price of CO₂ certificates during January and February 2020 (around 24 €/tCO₂), coal is replaced first (higher marginal costs), followed by gas (lower marginal costs), and then other technologies (nuclear, run-of-river hydro, renewable energies, as well as imports; lowest marginal costs). However, the graph cannot capture certain dynamics, such as the fact that “must-run” nuclear power plants cannot adjust output to match demand fluctuations, so flexible gas plants still have to operate for balancing purposes (e.g. in France) even though the demand shock would indicate their entire displacement.

“cleaner” gas will be marginally replaced, limiting the abatement effect of a demand reduction.

It is difficult to trace out the exact emissions reduction by technology for each sample economy. However, Figure 5 provides a crude indication of which technologies are mainly replaced for each country’s demand shock. We can see that in many countries, significant proportions of their coal-fired generation (if they have coal plants) are displaced because of the demand reduction created by COVID-19. It is nevertheless important to interpret Figure 5 with caution, because it yields a static picture, which cannot adequately capture dynamic effects.⁹

For example, France’s electricity generation stems to a large part from nuclear power (as

⁹In contrast, our econometric estimates very well capture must-run effects and therefore the coefficient estimates provide a precise measure of the emissions reduction from a demand shock.

part of the category "Other" in green), which is a "must-run" technology, designed to serve base load. These must-run technologies cannot easily accommodate their electricity output to fluctuations in demand or to the infeed of intermittent renewable energies. As a consequence, flexible gas plants were still needed to balance the system against a blackout. Thus, even though Figure 5 indicates that the demand shock would have displaced the entire fossil-fueled generation, which would imply an emission reduction by 100%, gas plants were still in operation and thus we *estimate* a CO₂ reduction by 60% according to our econometric model.

In any case, Figure 5 helps understanding the effects estimated by econometric model. It shows that countries, such as Germany or Poland, in which the demand shock from COVID-19 mainly replaced coal-fired electricity, experienced the strongest reductions in CO₂ emissions in absolute terms. For other countries, we estimate a huge *relative* decrease in emissions (e.g. -79.4% for Belgium), whereas emissions fell only slightly in absolute terms (-805 tCO₂ per hour), because the demand shock induced by COVID-19 could only offset gas-fired electricity (but not coal).

5.2 Validity of our results

Let us put our results into perspective. Our estimate of a 19% reduction in electricity demand during full lockdown aligns well with descriptive evidence reported by the International Energy Agency (IEA, 2020b), which states that electricity demand fell by around 20% during periods of full lockdown in several countries. Also, LeQuéré et al. (2020) estimate an average demand reduction due to COVID-19 by around 15% during full lockdown across a large number of global economies (69 countries, 50 US states, 30 Chinese provinces), supporting our results. Moreover, Santiago et al. (2021) estimate COVID-19's impact on electricity demand at the height of the lockdown measures to be -13.5%, which is close to our estimate of -17.7%.

Jones (2020) reports that electricity-related emissions in Europe were 39% lower during 28 March to 26 April 2020 in a year-on-year comparison, while we estimate a reduction by 33.9%, which is a close match. However, at first glance, our finding of an emissions reduction of around 34% seems to stand in marked contrast to LeQuéré et al. (2020), who estimate a re-

duction in power-sector emissions by 7.4% by 7 April 2020 in a year-on-year comparison for a large sample of nearly all countries in the world. Besides differences in the sample period (2020/01/01–2020/04/30 vs. 2020/01/01–2020/03/23) and the method of analysis (year-on-year comparison vs. multivariate regression), the effect measured by LeQuéré et al. (2020) can be mainly attributed to the fact that their study incorporates a large share of economies outside the EU, which have no (high-enough) carbon price in place, so that electricity production from their gas-fired power plants will be replaced first by a reduction in electricity demand, and only thereafter will coal-fired electricity be reduced. This is the only explanation for the under-proportionate reaction of relative emissions to relative demand, i.e. a reduction of emissions by only 7.4% for a demand reduction by 15%, as found by LeQuéré et al. (2020).

In an electricity generation system fed solely by coal, a one MWh reduction in demand induces approximately a reduction in emissions by one tCO₂ (i.e. one MWh of coal-fired electricity emits about one tCO₂). But in a system in which gas is the marginal technology to be offset first, a reduction in demand by one MWh will only reduce (gas-based) emissions by around 0.4 tCO₂. Thus, overall emissions reduction depends heavily on which technology is replaced first by a demand reduction. Under a high carbon price, coal's marginal costs are higher than those of gas (which was the case in Europe at the time of the outbreak of COVID-19), so that a demand reduction first affects coal and thus induces an *over-proportionate* carbon reduction. In contrast, without carbon pricing or for a low carbon price, gas gets replaced before coal and thus a drop in demand is associated with an under-proportionate abatement of emissions (as found in LeQuéré et al., 2020).

Our prediction of -18.4% CO₂ emissions from the power sectors of 16 select European sample economies comes surprisingly close to IEA (2020a)'s finding of -17% emissions reduction during 2020 in Europe's power sector in a year-on-year comparison. IEA's finding is even more so compelling as it underlines our discussion that with a high-enough carbon price in place, as it was the case in Europe during February 2020, a demand reduction brings about an over-proportionate emissions reduction (by first offsetting coal-based electricity supply), while the report finds only low emissions abatement (i.e. -5%) at the global level, where most economies

have no or only very low carbon prices in place.

6 Conclusion and Policy Implications

The coronavirus pandemic and the subsequent measures to curtail its spread across Europe created severe and unexpected distortions to economic activity. The demand for electricity collapsed considerably due to this exogenous shock, resulting in a substantial reduction of power sector carbon emissions.

We apply an econometric model in an instrumental-variables framework to trace out how COVID-19 reduced electricity demand and further how the drop in demand translated into emissions abatement. For this purpose, we make use of a data sample of 16 advanced European economies for the hourly period 2020/01/01–2020/03/23, during which COVID-19 infections proliferated across Europe. For identification, we use cumulative COVID-19 infections as an exogenous indicator of treatment intensity, implying that economic activity (and thus electricity demand) decreased with the surge in infections.

We estimate that COVID-19 brought about a drop in electricity demand by around 20% per hour at the peak of the pandemic and that countries that implemented strict lockdown measures, such as Italy and France, experienced demand reductions of 30% and higher. Moreover, we estimate considerable emissions abatement across economies, depending on the magnitude of the demand shock (i.e. treatment intensity) and on which electricity generating technologies were replaced (i.e. the supply structure). On average, we find that COVID-19 reduced CO₂ emissions by around 34% per hour. This is equivalent to a reduction of almost 20 MtCO₂ per hour of full lockdown. The overall emissions-reducing effect thus depends on how long the lockdown measures against COVID-19 last. Our best-guess scenario of two months of full lockdown and seven months of partial confinement (one month prior to and six months post full lockdown) predicts that carbon emissions from the power sector in 2020 will fall by 18.4% in Europe relative to a counterfactual scenario without a coronavirus pandemic.

COVID-19's drastic emissions reduction may have bought us some precious time to fight climate change, whereas it did not come from any political success but from an unprecedented

natural catastrophe, and it has not induced a structural change towards a lower-carbon energy supply. Carbon abatement induced by COVID-19 may be even so pronounced that some countries, such as Germany, may unexpectedly reach their climate targets set for 2020, which would not have happened without the pandemic (Radowitz, 2020). This implies that the climate benefits are brought simply by a reduction in economic wealth (see also Howarth et al., 2020) and that the effects may not translate into a long-run structural transition towards a low-carbon energy supply. Without convincing climate-change policies to decarbonize power supply, emissions will likely increase back to their pre-treatment trajectory once the economy recovers from the pandemic. A sustainable climate policy would thus require decoupling GDP growth from emissions as well as a long-run transition towards a low-carbon energy system.

In this light, our results reveal that energy efficiency measures may only unfold their full abatement potential if they are backed by a carbon price that is high enough to increase the marginal costs of coal-fired electricity relative to those of gas. In such a case, a demand reduction will first offset “dirty” coal and only thereafter “cleaner” gas. Our results thus underline the importance of carbon pricing as an effective climate policy. A sufficiently high price on emissions would immediately spur the efficacy of energy efficiency policies, and in the longer run support the structural transition of electricity supply by incentivizing investment in less emissions-intensive technologies.

This gives also rise to caution regarding strategies to couple other sectors of the economy with electricity, as for example mobility (electric vehicles) or heating, because our estimates demonstrate that an increase in electricity demand (especially during peak load) may marginally increase coal-fired electricity supply, thereby leading to significant additional emissions release. Thus, any electrification strategy has to be carefully evaluated against the air additional pollution it causes for a given supply structure.

Moreover, our results also demonstrate that climate policies in the form of “across-the-board regulations”, which would apply equally for all EU member states, may only be sub-optimal. For example, a carbon price may induce an immediate switch between coal and gas in the power supply, thereby pushing out coal-fired electricity for given demand and support-

ing the effectiveness of demand-reduction policies – but only in a power system with coal and gas plants in the preexisting supply structure. For countries having gas but no coal plants (e.g. Austria, Belgium, Italy), phasing out of gas means that policy has to find other ways to ensure security of supply, for example by supporting dispatchable (weather-independent) renewable energies (e.g. biogas or biomass) and utility-scale energy storages (e.g. hydro-pumped storages, hydrogen storages, or batteries). Policy should not ignore the opportunity to emerge from the pandemic with a sustainable transition, for example by targeting subsidies towards R&D and investment in low-carbon technologies and fostering energy efficiency.

References

- Cucinotta, D., Vanelli, M., 2020. Who declares COVID-19 a pandemic. *Acta Bio Medica Atenei Parmensis* 91, 157–160.
- EC, 2020. Short-term reduction in daily global carbon dioxide emissions during Covid-19 lockdown. European Commission, Science for Environment Policy, November 9, https://ec.europa.eu/environment/integration/research/newsalert/pdf/552na3_en-short-term-reduction-in-daily-global-carbon-dioxide.pdf.
- Eichenbaum, M., Rebelo, S., Trabandt, M., 2020. The macroeconomics of epidemics. National Bureau of Economic Research.
- Ember, 2021. EU ETS carbon price viewer. accessed February 17, 2021. <https://ember-climate.org/data/carbon-price-viewer/>.
- ENTSO-E, 2020. Transparency platform. <https://transparency.entsoe.eu/>.
- ESA, 2020. Coronavirus lockdown leading to drop in pollution across Europe. European Space Agency, 27 March 2020, www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-5P/COVID-19_nitrogen_dioxide_over_China.
- Gugler, K., Haxhimusa, A., Liebensteiner, M., 2021. Effectiveness of climate policies: Carbon pricing vs. subsidizing renewables. *Journal of Environmental Economics and Management* 106, 102405.
- Gugler, K., Haxhimusa, A., Liebensteiner, M., Schindler, N., 2020. Investment opportunities, uncertainty, and renewables in European electricity markets. *Energy Economics* 85, 104575.
- Habib, Y., Xia, E., Fareed, Z., Hashmi, S.H., 2020. Time-frequency co-movement between COVID-19, crude oil prices, and atmospheric CO2 emissions: Fresh global insights from partial and multiple coherence approach. *Environment, Development and Sustainability*.
- Hale, T., Webster, S., Petherick, A., Phillips, T., Kira, B., 2020. Oxford COVID-19 government response tracker. Blavatnik School of Government. Data use policy: Creative Commons Attribution CC BY standard.

- Han, P., Cai, Q., Oda, T., Zeng, N., Shan, Y., Lin, X., Liu, D., 2021. Assessing the recent impact of COVID-19 on carbon emissions from china using domestic economic data. *Science of The Total Environment* 750, 141688.
- Helm, D., 2020. The environmental impacts of the coronavirus. *Environmental and Resource Economics* 76, 21–38.
- Henriques, M., 2020. Will Covid-19 have a lasting impact on the environment? BBC, 27 March 2020, www.bbc.com/future/article/20200326-covid-19-the-impact-of-coronavirus-on-the-environment.
- Howarth, C., Bryant, P., Corner, A., Fankhauser, S., Gouldson, A., Whitmarsh, L., Willis, R., 2020. Building a social mandate for climate action: Lessons from COVID-19. *Environmental and Resource Economics*.
- IEA, 2019. CO₂ emissions from fuel combustion. International Energy Agency, www.indiaenvironmentportal.org.in/files/file/CO2_Emissions_from_Fuel_Combustion_2019_Highlights.pdf.
- IEA, 2020a. Electricity market report – December 2020. International Energy Agency, December <https://www.iea.org/reports/electricity-market-report-december-2020/2020-global-overview-capacity-supply-and-emissions>.
- IEA, 2020b. Global CO₂ emissions in 2019. International Energy Agency, www.iea.org/articles/global-co2-emissions-in-2019.
- IEA, 2020c. Global energy review 2020. International Energy Agency, www.iea.org/reports/global-energy-review-2020.
- IEA, 2020d. The impact of the COVID-19 crisis on clean energy progress. International Energy Agency, June 11 <https://www.iea.org/articles/the-impact-of-the-covid-19-crisis-on-clean-energy-progress>.
- Jones, D., 2020. Coronavirus has cut CO₂ from Europe's electricity system by 39%. CarbonBrief, 29 April. <https://www.carbonbrief.org/analysis-coronavirus-has-cut-co2-from-europes-electricity-system-by-39-per-cent>.
- Kling, J.R., 2001. Interpreting instrumental variables estimates of the returns to schooling. *Journal of Business & Economic Statistics* 19, 358–364.
- Le, T., Wang, Y., Liu, L., Yang, J., Yung, Y.L., Li, G., Seinfeld, J.H., 2020. Unexpected air pollution with marked emission reductions during the COVID-19 outbreak in China. *Science* 369, 702–706.
- LeQuéré, C., Jackson, R., Jones, M., et al., 2020. Temporary reduction in daily global CO₂ emissions during the COVID-19 forced confinement. *Nature Climate Change* 3, 365–372.
- Liu, Z., Ciais, P., Deng, Z., et al., 2020. Near-real-time monitoring of global CO₂ emissions reveals the effects of the COVID-19 pandemic. *Nature Communications* 11.
- Meles, T.H., Ryan, L., Wheatley, J., 2020. COVID-19 and EU climate targets: Can we now go further? *Environmental and Resource Economics* 76, 779–787.
- Murthy, S., Gomersall, C.D., Fowler, R.A., 2020. Care for critically ill patients with COVID-19. *JAMA* 323.

- NCEI, 2020. National Oceanic and Atmospheric Administration's National Centers for Environmental Information (NCEI). www.ncei.noaa.gov/access/search/index.
- Radowitz, B., 2020. Coronavirus may help Germany reach its 2020 climate target. Recharged, www.rechargenews.com/transition/coronavirus-may-help-germany-reach-its-2020-climate-target/2-1-775330.
- Roser, M., Ritchie, H., Ortiz-Ospina, E., Hasell, J., 2020. Coronavirus disease (COVID-19). Our World in Data, <https://ourworldindata.org/coronavirus>.
- Santiago, I., Moreno-Munoz, A., Quintero-Jiménez, P., Garcia-Torres, F., Gonzalez-Redondo, M., 2021. Electricity demand during pandemic times: The case of the COVID-19 in Spain. *Energy Policy* 148, 111964.
- Wang, Q., Su, M., 2020. A preliminary assessment of the impact of COVID-19 on environment – a case study of China. *Science of The Total Environment* 728, 138915.
- Wang, Q., Wang, S., 2020. Preventing carbon emission retaliatory rebound post-COVID-19 requires expanding free trade and improving energy efficiency. *Science of The Total Environment* 746, 141158.
- WEF, 2020. Coronavirus came to Italy almost 6 months before the first official case, new study shows. World Economic Forum, November 16. <https://www.weforum.org/agenda/2020/11/coronavirus-italy-covid-19-pandemic-europe-date-antibodies-study>.
- Wilson, I.A.G., Staffell, I., 2018. Rapid fuel switching from coal to natural gas through effective carbon pricing. *Nature Energy* 3, 365–372.