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Insights into CO2 emissions in Europe in the context of COVID-19: A panel data analysis

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ABSTRACT

This paper analyzes the dynamics of CO2 emissions over the last decade for a large group of 25 European countries, an issue that is at the center of the ecological transition project involving various commitments (COP21, COP26, G20 meetings, etc.). To this end, our model measures the repercussions of energy price shocks (oil, gas, coal) for carbon emissions, as well as changes in industrial production and sustainable development in the context of the coronavirus pandemic. Using annual data for 23 EU countries, together with Russia and the UK, our findings show that CO2 emissions reacted significantly to oil and coal price shocks and vary with industrial production cycles. We quantified this reaction while computing the related elasticities. Further, while a significant reduction in CO2 emissions was observed during the COVID-19 pandemic, the stepping up of investment in sustainable development and renewable energy consumption also had a negative impact on CO2 emissions. This suggests that the key driver to reducing the risk of climate change and lowering high carbon dioxide (CO2) emissions involves significant commitment to sustainable development.

1. Introduction

Several European economies have experienced various crises, events, and shocks over the last decade (Greek public debt in 2012, COVID-19 in 2019, a serious economic recession in 2020, high commodity price volatility, and excessive inflation caused by the ongoing war between Russia and Ukraine in 2022, etc.). These crises/shocks have demonstrated not only the fragility of some economies and their rules and regulations, but also the high dependence of European economies on fossil fuels (especially Russian gas) and the lack of diversification in their commodity resources. Germany's dependence on Russian gas, for example, is estimated at around 57% of its total gas consumption.¹ Simulations by Patrick Artus at Natixis suggest that a cut in Russian gas and oil would double oil prices and triple gas prices. In France, the Prime Minister announced in September 2022 that without assistance from the French government, French consumers would see an increase of around 130% in their gas/electricity bills in 2023. The Prime Minister thus introduced a 'tariff shield' estimated to cost the government around 16 billion euros, but which would cap gas and electricity price increases for French consumers at 15% in 2023. The strong dependency of EU countries on Russian gas is problematic as it has delayed the transformation of production systems into a more sustainable renewable resource model. Further, it prevents the European Union

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¹ From October 2022, France is expected to export gas to Germany and import German electricity to enable both countries to satisfy their respective populations needs in gas and electricity.

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from imposing more serious economic sanctions on Russia in order to stop the war with Ukraine, etc.

Consequently, it is now more urgent than ever to step up the ecological transition, reduce carbon emissions, reduce dependence on fossil fuels, and substitute the latter by more renewable energy resources in order to boost more efficient sustainable development. Given that the recent coronavirus pandemic lowered CO₂ emissions in various ways (reduced consumption, teleworking, distancing measures and restrictions, lockdown, production cuts, etc.), it is crucial to pursue this reduction in CO₂ emissions. Indeed, a recent study by Mousazadeh et al. (2021) identified several benefits during the first months of COVID on carbon emissions in the atmosphere. Indeed, the pandemic led to many positive changes in terms of pollution, as COVID-19-induced closures reduced nitrogen oxide emissions by 20–77%, with a 16–60% reduction in various cities in India. CO₂ emissions were also reduced overall by 5–10%. Similarly, there was a significant reduction in particulate matter levels globally, with New Delhi, for example, seeing the highest levels of change ever observed. These benefits in terms of lower carbon emissions may be linked to the reduction in fossil fuel use as well as spending on the global fuel supply, for example, which fell by 4% in 2020 compared to the same period in India in 2019.

However, these benefits appear to be transitory according to the latest report from the International Energy Agency (2021). Indeed, despite the activity restrictions adopted, 2021 saw a significant rebound in fossil fuel CO₂ emissions, suggesting that the forced savings due to the COVID pandemic in 2020 have already been erased.²

Furthermore, 2022 will probably see a new emissions record. Indeed, the world's inability to truly move away from fossil fuels can be seen in public and private drives for low-carbon renewable and nuclear energy, and energy savings. These efforts have been significant, since the IEA reports investment of around 400 billion dollars a year in the period 2021 to 2023. However, this represents only 40% of what is deemed necessary to achieve carbon neutrality by 2050. Nonetheless, it is worth recalling that at the same time, at least since the Paris Agreement in 2015, some sustainable energy investments, such as hybrid cars, have emerged and are continually developing and improving.

Accordingly, the dynamics of CO₂ emissions are somewhat complex and depend on a variety of factors, rules, and policies. Thus, it appears useful to analyze the trajectory of CO₂ emissions and to assess their main drivers, especially with respect to high inflation, rising commodity prices, and COVID-19. To this end, it is interesting to check whether upward or downward bounces in oil prices correlate closely with signs of lower CO₂ emissions. Has European industrial production, hit hard by the effects of COVID, had a significant impact on greenhouse gas production? Has the COVID death toll led to a reduction in the cycle of greenhouse gas emissions? Indeed, the strict measures taken to control the spread of COVID-19 led to a significant slowdown in economic activity, which in turn affected the environment by reducing greenhouse gases (GHG).

In order to address all these questions, we investigated three types of driver to assess the dynamics of CO₂ emissions. Accordingly, this paper investigates the main drivers governing reductions in CO₂ emissions. In particular, we first double checked whether industrial production and commodities have had an impact over time and across countries on the goal to reduce CO₂ emissions. Second, we investigated whether investment and involvement in sustainable development would accelerate the reduction in CO₂ emissions or not. Interestingly, given that the whole economy has been impacted by the coronavirus pandemic that not only involved several lockdowns, but also impinged on different sectors of activity, projects, and agreements, we also examined the pandemic's impact on the CO₂ emissions reduction program.

To this end, we proceeded as follows: first, we used three main commodities (oil, gas and coal) and a proxy for renewable energy resources related to sustainable development to test their impact on CO₂ emissions. Second, we retained certain macroeconomic factors (industrial production) in order to assess the reaction of CO₂ emissions on the economic cycle. Finally, we used an extra-economic factor (COVID-19 news) to measure the impact of the ongoing pandemic on CO₂ emissions. We used these three classes of factors and built a flexible univariate and multivariate model framework to identify the main drivers of CO₂ emissions and to analyze their trajectory across the main European countries.

Our results offer several contributions. First, we found that CO₂ emissions reacted significantly to shocks in oil and coal prices, and also varied with the industrial production cycle. Second, while a significant drop in CO₂ emissions was observed during the COVID-19 crisis, the stepping up of investment in sustainable development and renewable energy consumption had a negative impact on CO₂ emissions. This finding suggests that a key driver to reducing the risk of climate change and lowering high carbon dioxide (CO₂) emissions requires significant commitment to sustainable development. Overall, the interest of this contribution is twofold. On the one hand, our study provides an analysis of CO₂ emissions in the specific context of COVID-19 and analyzes the effect of the pandemic on their reduction. At the same time, our model identifies the main drivers of CO₂ emissions and explains ways and policies to increase their reduction. Accordingly, in spite of the fact that research on CO₂ emissions reduction is not new and has been addressed in several related papers, our study differs from previous studies at different levels. First, we focus on a large sample of European countries which have received less interest in the literature. Second, as well as identifying fossil energies as a major source of CO₂ emissions, and sustainable development as a key investment area to reduce CO₂, we also estimate the related elasticities, enabling us to quantify this dependence. The use of panel data provides us with a large amount of information for more efficient estimators. Finally, to our knowledge, unlike earlier related literature, this study is the first to tackle the issue of CO₂ emissions in the context of COVID-19.

The rest of the paper is organized as follows. Section 2 provides a brief literature survey. Section 3 briefly reviews the panel VAR

² Indeed, over 6% and a total of 36.3 billion tons have indeed been sent into the atmosphere. This figure was further boosted by the price effect in 2021, as gas began its explosive price increase, which shifted electricity production to coal, emitting even more CO₂, especially in the US and Europe. Consequently, according to the International Energy Agency (2021), CO₂ emissions from fossil fuels and industry (cement, steel) reached a new peak in 2021. The rebound in 2021 was spectacular, since, according to the International Energy Agency, at over 2 billion tons, it is the highest ever recorded in history.

methodology. The main empirical results are discussed in Section 4, and Section 5 concludes.

2. Literature

First, it is important to mention that the use of fossil energy resources implies an ongoing challenge for economists, analysts, and policymakers alike. Indeed, it is widely accepted that inefficient and inappropriate use of energy resources is responsible for the decline in environmental quality and, consequently, the risk of climate change (COP21, COP26, [Report of the Intergovernmental Panel on Climate Change \(2022\)](#), etc.). The issue has become even more urgent in view of many alarming recent events (fires in Australia, hurricanes in the US and Canada, etc.). However, at the same time, it is clear that the solutions are extremely complex. In fact, while fossil fuels do harm the environment and cause a lot of pollution and crises, at the same time, EU nations' dependence on fossil fuels remains high and is a serious obstacle to further changes in the production model, even it is clear that subsidies for renewable energy and higher fossil fuel prices can reduce the EU's CO2 levels. From this perspective, Haseeb *et al.* (2021) argue that European countries need to increase their share of renewable energy by investing massively in renewable energy projects.

However, the debate on fossil fuels remains animated. Indeed, [Narayan \(2020\)](#) and [Chatziantoniou et al. \(2021\)](#) agree that oil price volatility, especially during the COVID-19 pandemic, impacted industrial production and thus the environment, but the relationship is complex. Indeed, while oil prices fell sharply during the first wave of the pandemic, and lockdown and distancing restrictions reduced economic activity and thus carbon emissions, the subsequent rapid economic recovery had an adverse effect. [Gil-Alana and Monge \(2020\)](#) also studied the effects of oil price and concluded that the effects of an oil shock are transitory. [Hammoudeh et al. \(2021\)](#) explored the causal relationships between oil price and renewable energy sources both before and during the COVID-19 pandemic and argued that oil returns had a major impact on renewable energy stock index returns over the entire period before the pandemic, while there was no significant causal relationship between oil price and renewable energy stocks during the pandemic period. [Chien et al. \(2021\)](#) investigated the time-frequency relationship between the recent COVID-19 crisis, oil price, geopolitical risks, and economic policy uncertainty in the US, Europe, and China. Their results highlight the reduction in industrial productivity and CO2 emissions, which deepened as the severity of the pandemic increased. [Zheng et al. \(2021\)](#) tested the impact of oil shocks on EU carbon allowance (EUA) returns using a quantile regression method, concluding that oil supply and demand shocks have a positive effect on EUA returns.

Second, other recent studies have focused on the impact of the ongoing coronavirus pandemic on the reduction in carbon emissions. [Chevallier \(2020\)](#) examined the correlation between the macro-financial environment and CO2 emissions following the COVID-19 outbreak. He showed that freezing the economy alleviates some of the greenhouse gas burden on the environment caused by human activity. The study combined deaths and cases of COVID-19 in the United States with the US Energy Information Administration's index of total industrial production and total CO2 emissions from fossil fuels. Accordingly, confirmed cases and COVID-19 deaths negatively appear to influence macro-financial variables and CO2 emissions. [Sarfraz et al. \(2022\)](#) demonstrated a significant effect of closures, the number of new confirmed cases, and the number of newly confirmed deaths due to COVID-19 on CO2 emissions. Using data for Spain and the UK, they carried out a Granger causality test to show a bidirectional relationship between CO2 emissions and COVID-19 news (confirmed cases and deaths) for the UK. The results from Spain also confirmed the unidirectional relationship between CO2 emissions and COVID-19. Accordingly, the authors concluded that the pandemic clearly reduced CO2 emissions. In the same context, [Kumar et al. \(2022\)](#) also examined the substantial impact of COVID-19 on gas emissions. They showed that production shutdowns during the pandemic, even for a short period of time, resulted in a substantial decrease in gas emissions worldwide.

Thus, while several studies have documented the presence of key factors driving CO2 emissions, our paper aims to reconsider the analysis of CO2 emission dynamics in the context of COVID-19 and commodity price volatility. The issue is important, especially with regard to the debate on ecological transition. Accordingly, our paper contributes to the literature by taking three types of driver into account to examine the dynamics of CO2 emissions. First, we looked at the main commodities and fossil fuel resources (oil, gas, and coal) as well as a proxy for renewable energy resources related to sustainable development. Second, we used some macroeconomic factors (industrial production). Finally, we used an extra-economic factor (COVID-19 news). These three classes of factors were used to build a flexible model to identify the main drivers of CO2 emissions.

3. Methodology

This section briefly presents the Panel Vector Auto-Regression (PVAR) methodology. A PVAR has the advantage of including several variables in the system as endogenous. Further, in addition to the time series dimension, the model allows us to apprehend heterogeneity among individuals through the use of a panel structure. Formally, a PVAR can be specified as:

$$X_{i,t} = \Gamma_0 + \Gamma(L)X_{i,t} + \nu_i + b_{c,t} + \varepsilon_{i,t} \quad i = 1, \dots, N \quad t = 1, \dots, T_i \quad (1)$$

where $X_{i,t}$ denotes a vector of endogenous variables, Γ_0 refers to a vector of constants, $\Gamma(L)$ denotes a matrix polynomial in the lag operator, ν_i are country-specific fixed effects, $b_{c,t}$ are country-specific time effects, and $\varepsilon_{i,t}$ is a vector of error terms.

In line with [Holtz-Eakin et al. \(1988\)](#), [Arellano and Bover \(1995\)](#) and [Blundell and Bond \(1998\)](#), we performed our model using a two-step procedure which stipulates, first, forwarding mean-difference and thus removing only the mean of all future observations available for each country-year ([Arellano and Bover, 1995](#)); and second, estimating the system by GMM using the regressor lags as instruments ([Blundell and Bond, 1998](#)). As for the impulse-response functions, these are estimated using the Choleski decomposition of the variance-covariance matrix of residuals ([Hamilton, 1994](#)). The use of this modelling enables us to check the sensitivity of CO2 emissions to fossil energies as well as sustainable development among others.

4. Empirical analysis

4.1. The data

Our main research question aimed to assess the evolution of the dynamics of CO₂ emissions in Europe. To this end, our data was annual, and our sample covered 2010–2020, a period when several commitments regarding ecological transition and the reduction of CO₂ emissions were introduced. We collected data (when available) for all 25 countries of the European Union (Germany, Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Finland, France, Greece, Hungary, Iceland, Italy, Lithuania, Luxembourg, Norway, Poland, Portugal, Romania, Slovakia, and Sweden) and two other major European countries (Russia and the UK).³

In particular, we used tons of CO₂ emitted into the atmosphere, taking the carbon balances produced annually by EU countries (plus Russia and the UK) into account. All sectors of economic activity were taken into account, using statutory declarations. Data was obtained from the [International Energy Agency \(IEA\) Statistics](#). We also took gas, oil, and coal prices from the St Louis FRED (US Federal Reserve) into consideration. Use of this data is justified by the fact that the issue of CO₂ reductions is always linked to fossil fuel use. The main fossil fuels considered in our sample were oil and gas. We also collected industrial production data by country from the World Bank database. Our industrial production indicator, *Industrial activities*, corresponds to ISIC divisions 10 to 45 and includes manufacturing (ISIC divisions 15 to 37). Industrial activities include value added in mining, manufacturing, construction, electricity, water, and gas. This value added is calculated without deductions for the depreciation of goods produced, loss of value, or degradation of natural resources. This variable is particularly interesting to investigate how the industrial production cycle impacts on national commitments in terms of reductions in CO₂ emissions. Interestingly, we also collected the share of consumption in green energies communicated by INSEE. The share of renewable energy in the EU is calculated on the basis of an energy mix. The percentage represents the share of energy consumption considered renewable by the EU (solar energy, biomass, wind energy ...) in the country's total energy mix. This data helps to capture the impact of sustainable development and renewable energy use on reducing CO₂ emissions.⁴ Finally, we also examined data relative to COVID-19 news (COVID-19 cases and mortality) from John Hopkins University and Eurostat ([Whittemore, 2020](#)).⁵ However, given that COVID-19 news was only available for less than two years for the sample under consideration (2019 and 2020),⁶ and not for all countries, we used a dummy variable that took the value of 1 for 2019 and 2020, and 0 for the rest. The dummy variable related to COVID-19 news was very useful as it allowed us to assess the impact of the ongoing coronavirus pandemic on ecological transition and the commitment of European countries to reducing their CO₂ emissions.

Overall, we included three types of data in our sample: specific energy industries and commodity-related data (i.e., oil, gas, coal), as well as renewable energy data (i.e., share of consumption in green energies), macroeconomic data (i.e., industrial production), and extra-financial data (i.e., COVID-19 news). Accordingly, our sample gave us sufficient input to identify the main drivers of reductions in CO₂ emissions.

4.2. Preliminary results

First, we transformed all series under consideration into a logarithm using Box-Cox transformation in order to reduce their variance. We did not transform the gas price series given that its variance is relatively low. Second, we applied a panel unit root test to check for the presence of a unit root in the data. To increase robustness, we applied three panel unit root tests from first-generation panel unit root tests. Recall that a first panel unit root test assumes that cross-section units are cross-sectionally independent, while second panel unit root tests allow for potential cross-sectional dependence. In particular, we applied Hadri (2000)'s test, [Levin et al. \(2002\)](#)'s test, and [Im et al. \(2003\)](#)'s test to examine the unit root hypothesis under different assumptions. Indeed, while [Levin et al. \(2002\)](#)'s and Hadri (2000)'s tests assume the presence of a common unit root process or homogeneity across section units, [Im et al. \(2003\)](#)'s test relies more on heterogeneous cross-section formation. Accordingly, the above three panel unit root tests confirm the assumption of stationarity for our series.⁷

Next, we plotted the data related to CO₂ emissions in [Fig. 1](#) and tracked its evolution over the period under consideration and for the different countries in our sample. Two observations were noted. On the one hand, unsurprisingly, most developed and industrialized economies (France, Germany, the UK, Italy, and Russia) show the highest level of CO₂ emissions, while CO₂ emissions for the other countries appear relatively heterogeneous. On the other hand, we observed a reduction in CO₂ emissions over the last decade, especially when less industrialized countries in the panel were considered.

We also plotted both series of CO₂ emissions and commodity prices in [Fig. 2](#). Accordingly, we can note significant but time-varying comovements between commodity prices and CO₂ emissions, suggesting that changes in oil and gas prices might be relevant to explain the volatility of CO₂ emissions.

³ Data on CO₂ emissions is not publicly available at high frequency level, so we used annual data.

⁴ It would also be useful to include green energy indices.

⁵ For more details, see <https://www.ecdc.europa.eu/en>.

⁶ Data on CO₂ emissions are available until 2020.

⁷ We do not report the results of the panel unit root tests to save space, but they are available upon request.

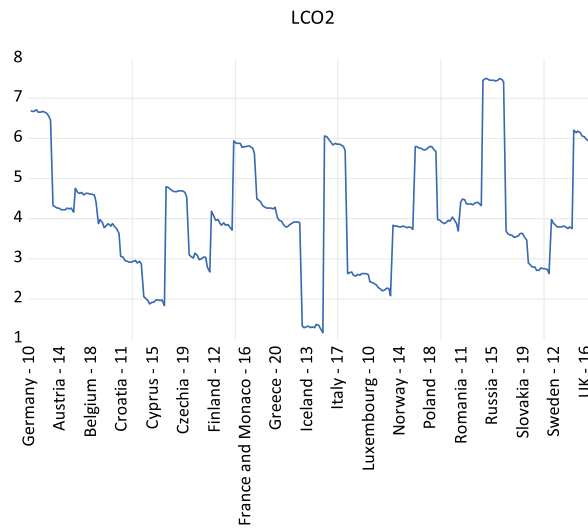


Fig. 1. Dynamics of CO2 emissions by logarithm.

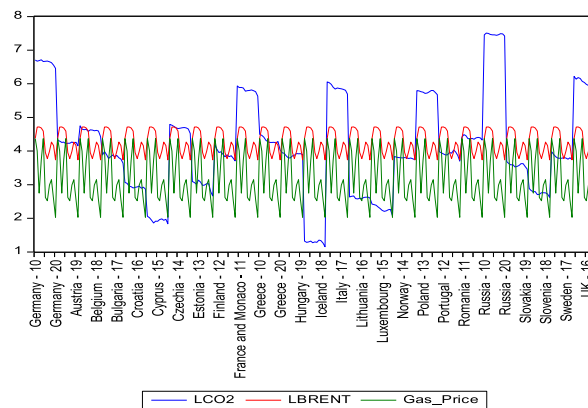


Fig. 2. Dynamics of CO2 emissions against commodity prices.

Third, to better understand these linkages, we examined the underlying drivers of CO2 emissions for the economies under consideration. To this end, we analyzed the unconditional static correlation between CO2 emissions and a list of economic variables as well as extra-economic variables (i.e., COVID-19). We report the main results in Table 1, giving rise to several remarks. First, there is a positive correlation between industrial production and CO2 emissions, suggesting that an increase in industrial activity will generate more pollution and thus an increase in CO2 emissions. A similar result was observed when examining the correlation between oil price (Brent or WTI), gas price, and coal price, but the correlation with these commodity prices is relatively low. Interestingly, the correlation between CO2 emissions and the proxy for sustainable development is negative, suggesting that the higher the share of renewable energy consumption to total energy consumption, the more efficient the country is at reducing its CO2 emissions and thus its share of pollution. Finally, COVID-19 enters CO2 emission rates negatively, suggesting that the ongoing pandemic has had a negative impact on CO2 emissions, which is line with previous studies (Chevallier, 2020). Overall, these results conform with Fig. 2, which shows some high levels of CO2 that are not explained by variations in commodity prices.

To double check these correlation effects, we then run some panel data regressions.

Table 1
Unconditional correlations.

	LCO2	LCOAL	LIP	LWTI	LBRENT	GAS_PRICE	SD_P	COVID-19
LCO2	1							
LCOAL	0.0306	1						
LIP	0.5574	-0.0019	1					
LWTI	0.0275	0.6591	-0.0085	1				
LBRENT	0.0260	0.6713	-0.0080	0.9918	1			
GAS_PRICE	0.0283	0.5456	-0.0074	0.7832	0.7129	1		
SD_P	-0.4573	-0.0701	0.1055	-0.0847	-0.0803	-0.0839	1	
COVID-19	-0.0290	-0.4113	0.0080	-0.4738	-0.4237	-0.5495	0.0782	1

Note: **Local** denotes the logarithm of Coal Price. **LIP** is the logarithm of industrial production. **LWTI** and **LBrent** denote the logarithm of West Intermediate and BRENT oil prices respectively. **LCO2** is the logarithm of CO2 emissions in Tones. **SD_P** is a sustainable development proxy that corresponds to the share of energy consumption considered renewable by the EU in the country’s total energy consumption. **COVID-19** is a dummy variable that takes value 1 for 2019 and 2020 and value 0 for the rest to capture the pandemic impact.

4.3. Empirical results

4.3.1. Linear univariate panel regression

First, we analyzed the impact of the industrial production cycle, commodity prices, and sustainable development on the dynamics of CO2 emissions in a linear univariate framework over the period 2010–2018 for a panel of 25 countries. To this end, we built the following panel data model with random effects⁸:

$$LCO2_{i,t} = \alpha_0 + \alpha_1 LBRENT_{i,t} + \alpha_2 LCOAL_{i,t} + \alpha_3 GAS.Pr\ ice_{i,t} + \alpha_4 LIP_{i,t} + \alpha_5 SD_P_{i,t} + \varepsilon_{i,t}$$

where : $\varepsilon_{i,t} = \mu_i + \eta_{i,t}$, μ_i is assumed to be random for each country,
 $\forall t = 2010, \dots, 2020$ and $i = 1, \dots, 25$.
 $\alpha_0, \dots, \alpha_5$ are the slope coefficients. (2)

Consideration of a model with random effects given our finite simple is recommended to provide more precise estimators than a specification with fixed effects. Interestingly, the above specification enabled us to analyze the model coefficients in terms of elasticity. Further, consideration of a model with random effects is particularly useful to allow greater flexibility for the specification under consideration. Despite this argument, we carried out a Hausman (1978) test to double check whether a model with random effects is more suitable or not. Our result, reported in Table 2, shows that the p-value for the Hausman test is statistically higher than the standard threshold of 5%, suggesting that the null assumption of random effects cannot be rejected. We then estimated model (1) and reported the main results in Table 3.

From Table 3, various interesting results can be noted. First, oil and gas price show close-to-zero effect on CO2 emissions entering positively and negatively respectively, but their effects are statistically insignificant. Unlike these two commodity prices, coal price has a significant and positive effect, but is also quite low with regard to CO2 emissions. Second, the elasticity of CO2 emissions toward industrial production is positive at around 0.17, suggesting that an increase in industrial production may lead to an increase in CO2 emissions. However, within an elasticity coefficient of less than one, the industrial production variation is higher than that of CO2 emissions. Finally, the impact of sustainable development on CO2 is negative and significant, confirming the negative correlation mentioned earlier. This result is important and implies that when a country invests more in sustainable development, resulting in an increase in the share of renewable energy in total energy consumption, it leads to a reduction in CO2 emissions. More interestingly, elasticity is negatively higher than one in absolute value, which means that the variation in CO2 emissions induced by an increase in the share of renewable energy consumption is higher than the latter. This also suggests a substitution of usual production by more sustainable intensive production in renewable energy sources.

Next, we assessed for the impact of the above drivers on CO2 emissions in the context of COVID-19, taking the effect of the recent pandemic into account through a dummy variable. To this end, we extended the sample under consideration to include data for 2019 and 2020. We also performed a dummy variable that took 1 for the COVID-19 period, and zero otherwise. Accordingly, we respecified model (2) as follows to produce model (3), defined as:

$$LCO2_{i,t} = \alpha_0 + \alpha_1 LBRENT_{i,t} + \alpha_2 LCOAL_{i,t} + \alpha_3 GAS.Pr\ ice_{i,t} + \alpha_4 LIP_{i,t} + \alpha_5 SD_P_{i,t} + \alpha_6 COVID - 19_{i,t} + \varepsilon_{i,t}$$

where : **COVID - 19** is a dummy variable that captures COVID - 19 news,
 $\alpha_0, \dots, \alpha_6$ are the slope coefficients. (3)

We estimated model (2) under the same assumption as model (1) for which we used the Wallace-Hussain random effects method, and we reported the main results in Table 4.

Our results contribute two interesting findings. First, the coronavirus pandemic had a negative and significant impact on CO2

⁸ **LCO2** is the logarithm of CO2 emissions in Tones. **Local** denotes the logarithm of Coal Price. **LIP** is the logarithm of industrial production. **LBrent** denotes the logarithm of oil price and, given the perfect correlation between BRENT and West Intermediate Texas Prices, we proxied oil price using BRENT. **SD_P** is a sustainable development proxy that corresponds to the share of energy consumption considered renewable by the EU in the country’s total energy consumption.

Table 2
Hausman test.

Test	P-value
Hausman test	0.960

Table 3
Estimation results of model (2).

Variable	Estimator
Constant	0.273 (0.72)
LCOAL	0.077 (0.00)***
LIP	0.174 (0.00)***
SD_P	-2.368 (0.00)***
LBRENT	-0.016 (0.25)
Gas_Price	0.008 (0.14)
\bar{R}^2	0.63
F-Statistic	93.42 (0.00)

Note: \bar{R}^2 denotes the adjusted determination coefficient. The values between brackets denote the p-value of student tests. (***), (**) and (*) denote statistical significance at 1%, 5% and 10% respectively. F-Statistic denotes the statistics of the global Fisher test.

Table 4
Estimation results of model (3).

Variable	Estimator
Constant	-0.363 (0.63)
LCOAL	0.070 (0.00)***
LIP	0.198 (0.00)***
SD_P	-2.006 (0.00)***
LBRENT	-0.007 (0.68)
Gas_Price	0.004 (0.56)
COVID-19	-0.038 (0.00)**
\bar{R}^2	0.56
F-Statistic	56.64 (0.00)

Note: \bar{R}^2 denotes the adjusted determination coefficient. The values between brackets denote the p-value of student tests. (***), (**) and (*) denote statistical significance at 1%, 5% and 10% respectively. F-Statistic denotes the statistics of the global Fisher test.

emissions. Indeed, various distancing measures, teleworking, and lockdown rules and restrictions led to both consumption and production falling sharply, resulting in a serious economic recession in 2020. The slowdown reduced CO2 emissions, which is captured by our model with negative elasticity of CO2 emissions toward COVID-19. Second, we noted an indirect effect of the pandemic as it lowered sustainable development elasticity, while marginally increasing elasticity in industrial production.

Thus, while our model identified the drivers of CO2 emissions (industrial production, coal pricing, etc.) as well as anti-drivers (sustainable development, COVID-19), our above framework only captured linkage effects and cannot reproduce further causality relationships between CO2 emissions and these variables. In the next step, we thus propose building a multivariate model that extends the framework, based on a panel VAR model. This econometric framework is particularly useful to assess for further cause-effect relationships.

4.3.2. Linear multivariate modeling

4.3.2.1. Assessing for panel causality relationships. Before performing a Panel VAR model, we tested for further causality relationships between the CO2 emissions variable and its above drivers. This was carried out through the application of causality tests (Granger, 1969). In order to test for causality relationships across our panel data sample, we applied the causality tests of Dumitrescu and Hurlin (2012), enabling us to check for causality effects while taking further panel data heterogeneity into account. In principle, Dumitrescu and Hurlin (2012)'s test works in the same way as a Granger causality test: for example, CO2 emissions (respect. their driver) cause

their drivers (respect. CO2 emissions) if the past values of CO2 emissions (respect. their driver) help to improve forecasts of their drivers (respect. CO2 emissions). That is, the null hypothesis of Dumitrescu and Hurlin (2012)'s test supposes a homogeneous non-causality, while its alternative hypothesis indicates a homogeneous causality. The test statistics correspond to the cross-sectional average of individual Wald statistics for the Granger causality test and are distributed following a $\chi^2(J)$ distribution (J denotes the degree of freedom given by the lag number of the underlying regression). The number of lags is specified using information criteria and autocorrelation functions. We applied this test to our sample and set out the main results in Table 5.

From Table 5, we can first note that the null hypothesis of non-homogeneous causality is rejected for a couple of series at the statistical levels of 1% or 5% (see Table 5), indicating further lead-lag effects between our variables. Second, when focusing on CO2 emissions, which is our variable of interest, we observed that coal price, oil price, and COVID-19 have a causality effect on the dynamics of CO2 emissions. To better investigate the reaction of CO2 emissions on shocks affecting these variables, we next performed a PVAR model using a system of three variables (LCO2, Brent, and Coal price).

4.3.2.2. Panel vector autoregressive specification. Pursuant to Canova and Ciccarelli (2013), we may recall that a PVAR framework has a double advantage (see section 3 for more details). It can be used to build a multivariate specification in line with Sims (1980), which simultaneously involves a dual dimension (N and T).

Accordingly, it is possible to perform a PVAR specification for CO2 emission dynamics as:

$$Y_{i,t} = \lambda_i + \Theta(L) Y_{i,t} + \varepsilon_{i,t} \quad (4)$$

where $Y_{i,t}$ is a vector of endogenous and explanatory variables i ($i = 1, \dots, 25$) and t ($t = 2010, \dots, 2020$). $\Theta(L)$ is the matrix polynomial in the lag operator L , while λ_i is the vector of country-fixed effects. $\varepsilon_{i,t}$ denotes the vector of errors.

Taking the results of panel causality tests into account, we consider a system of three equations (CO2 emissions, coal price, and Brent), while using industrial production, sustainable development, COVID-19, and gas price as the exogenous variables.

From an econometric perspective, we estimate our panel VAR model using the generalized method of moments (GMM) and the Helmert procedure, in line with Love and Zicchino (2006), to take further correlations between fixed effects and our regressors into account. Indeed, as Gnimassoun and Mignon (2016) point out, this procedure is essential to remove the fixed effects through the transformation of all variables into deviations from forward means. The procedure is also used to respect the orthogonality between transformed variables and lagged regressors, always used as instruments for the GMM method.

Our main findings from the estimation of a three-equation panel VAR model with one lag offer several contributions.⁹ First, both industrial production and sustainable development have an insignificant impact on the three endogeneous variables, while gas price has a significant and positive effect only on Brent and coal price. Second, COVID-19 has a negative and highly significant effect on the three dependant variables, which suggests that the coronavirus pandemic lowered oil and coal price (by 30% and 25% respectively), and contributed to reducing CO2 emissions in the short term by 6%. Third, we confirm the causality effects between Brent and CO2 emissions. Indeed, an increase in oil price on (t-1) provoked a significant decrease in CO2 emissions of 2.8%, while coal price had a negative but insignificant effect on CO2 emissions.

We also computed the IRFs (Impulse-Response Functions), but we reported in Fig. 3 only significant results, using our PVAR specification and following Cholesky's decomposition of the variance-covariance matrix of residuals. In particular, we assessed for the reaction of CO2 emissions following a shock affecting BRENT. Our findings show that an increase in oil price leads to a reduction in CO2 emissions as it generates a high cost and may therefore reduce production. However, the reaction function appears to be cyclical and persistent since some years are required to amortize the effect of this shock. Smoothness in the reaction function can also be associated with the use of annual and low frequency data.

Finally, we checked the forecasting performance of our model and our results (forecasting evaluation tests in Table 6 and in-sample forecasts in Fig. 4), confirming the robust forecasting performance of our model.

Overall, our univariate and multivariate panel data analysis enabled us to reproduce the dynamics of CO2 emissions and to analyze their evolution over the last decade, while taking further heterogeneity across countries in the sample into account. In particular, we found that the coronavirus pandemic had a negative effect on CO2 emission volumes, further confirming that the ongoing pandemic helped to reduce carbon emissions (Chevallier, 2020). Second, we found that changes in oil price acted as a key driver for carbon emissions, since higher oil prices have a negative impact on fossil fuel demand, consequently reducing CO2 emissions. Finally, while investment in renewable energy and sustainable development does not have a significant impact on carbon emissions in the short term, there is a high level of elasticity in the long run, suggesting that renewable energy investment can lead to far higher reductions in carbon emissions.

This finding suggests that the production model commitment is renewable energy resource-intensive, and the improvement in sustainable development projects are key factors to better control and combat the risks related to climate change and to lower carbon dioxide emissions (CO2), even if the results of the static model differ from the causality analysis. This could help to accelerate ecological transition, which obviously requires input from a range of players (consumers, stakeholders, firms, regulators, policy-makers, etc.).

⁹ We do not report the results of the PVAR model to save space, but they are available upon request.

Table 5
Results of the panel causality test.

Null Hypothesis:	Obs	Prob.
LIP does not Granger Cause LCO2	250	0.7929
LCO2 does not Granger Cause LIP		0.3478
LCOAL does not Granger Cause LCO2	250	0.0013
LCO2 does not Granger Cause LCOAL		0.8233
LBRENT does not Granger Cause LCO2	250	0.0351
LCO2 does not Granger Cause LBRENT		0.7344
GAS_PRICE does not Granger Cause LCO2	250	0.2742
LCO2 does not Granger Cause GAS PRICE		0.8498
SDP does not Granger Cause LCO2	250	0.7232
LCO2 does not Granger Cause SDP		0.4122
COVID19 does not Granger Cause LCO2	250	2.E-17
LCO2 does not Granger Cause COVID19		0.9221
LCOAL does not Granger Cause LIP	250	0.0015
LIP does not Granger Cause LCOAL		0.9669
LBRENT does not Granger Cause LIP	250	0.0014
LIP does not Granger Cause LBRENT		0.9562
GAS_PRICE does not Granger Cause LIP	250	0.8299
LIP does not Granger Cause GAS_PRICE		0.9147
SDP does not Granger Cause LIP	250	0.2505
LIP does not Granger Cause SDP		0.5340
COVID19 does not Granger Cause LIP	250	2.E-10
LIP does not Granger Cause COVID19		0.9096
LBRENT does not Granger Cause LCOAL	250	3.E-18
LCOAL does not Granger Cause LBRENT		1.E-27
GAS_PRICE does not Granger Cause LCOAL	250	0.9550
LCOAL does not Granger Cause GAS_PRICE		0.0443
SDP does not Granger Cause LCOAL	250	0.5774
LCOAL does not Granger Cause SDP		0.0151
COVID19 does not Granger Cause LCOAL	250	3.E-14
LCOAL does not Granger Cause COVID19		3.E-08
GAS_PRICE does not Granger Cause LBRENT	250	0.0232
LBRENT does not Granger Cause GAS_PRICE		3.E-05
SDP does not Granger Cause LBRENT	250	0.3967
LBRENT does not Granger Cause SDP		0.0482
COVID19 does not Granger Cause LBRENT	250	2.E-16
LBRENT does not Granger Cause COVID19		0.2263
SDP does not Granger Cause GAS_PRICE	250	0.5335
GAS_PRICE does not Granger Cause SDP		0.8099
COVID19 does not Granger Cause GAS_PRICE	250	3.E-12
GAS_PRICE does not Granger Cause COVID19		0.0566
COVID19 does not Granger Cause SDP	250	4.E-07
SDP does not Granger Cause COVID19		0.5418

Note: The test was performed with one lag, taking all variables in the sample. *Prob.* denotes the p-value of the test and P-values marked in bold indicate the rejection of the null hypothesis of no causality.

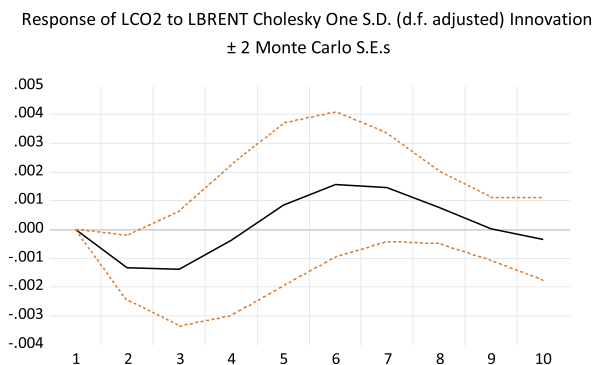
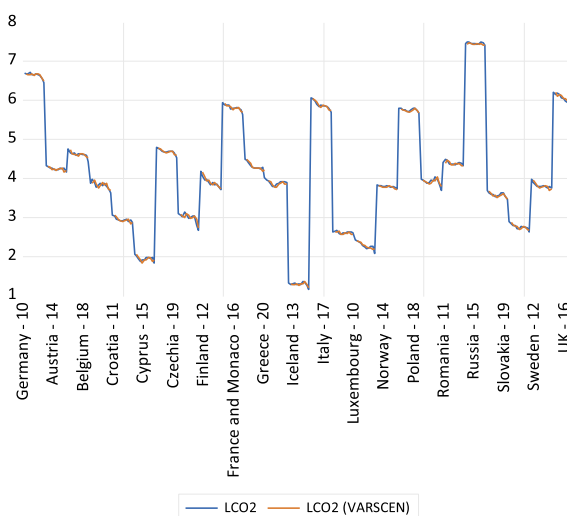


Fig. 3. Impulse response functions (IRFs).

Table 6
Forecast evaluation results.

Variable	Observations	RMSE	MAE	MAPE	Theil
LBRENT	275	0.0482	0.0439	1.0413	0.0056
LCO2	275	0.0472	0.0359	1.0496	0.0053
LOCAL	275	0.0563	0.0445	0.9887	0.0063

Note: RMSE is the Root Mean Square Error. MAE denotes the Mean Absolute Error. MAPE denotes the Mean Absolute percentage Error. Theil measures the Theil Inequality Coefficient.



Note: LCO2 is the observed CO2 time series and LCO2 (VARSCEN) is its forecast.

Fig. 4. Results of In-sample forecasts.¹⁰

Note: LCO2 is the observed CO2 time series and LCO2 (VARSCEN) is its forecast.

5. Conclusion

Our paper investigates and specifies the main drivers for CO2 emissions and shows causality effects. In particular, while COVID-19, considered as an unprecedented exogenous shock, had a negative effect on CO2 emission volumes, oil and coal prices are also key drivers of carbon emissions. In addition, if investment in renewable energy resources does not have a significant impact on carbon emissions in the short term, sufficient sustainable investment seems contributing significantly to reducing carbon emissions in the atmosphere. An extension of this work could be to add the use of green finance indexes for sustainable development and to extend the sample by covering more countries.

Declaration

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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¹⁰ Fig. 4 plots the LCO2 (blue line), which is the observed series of CO2 emissions against its in-sample forecast using the PVAR specification.

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