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The Impact of Natural Gas, Oil, and Renewables Consumption on Carbon Dioxide Emissions: European Evidence

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Abstract: Natural gas has returned to prominence in the agenda of European countries since the beginning of the invasion of Ukraine by Russia in 2022. However, natural gas is a fossil source with severe environmental implications. This paper aims to verify the impact of natural gas on carbon dioxide (CO_2) emissions for a European panel from 1993 to 2018 for sixteen countries. An Autoregressive Distributed Lag (ARDL) model in the form of an unrestricted error correction model was used to identify the short-run impacts, the long-run elasticities, and the speed of adjustment of the model. The results indicate that in the short-run, natural gas has a negligible impact on CO_2 emissions when faced with oil consumption (6.7 times less), whereas the consumption of renewables and hydroelectric energy proved to be able to decrease the CO_2 emissions both in the short- and long-run. The elasticity of oil consumption is lower than the unit, indicating that efficiency gains have been achieved during the process of the energy transition to clean energy sources. If economies use non-renewable energy, governments must continue to prefer natural gas to oil. Renewables and hydroelectric consumption must be used to revert the path of CO_2 emissions. Given the unstable scenario that has been caused by the War in Eastern Europe, politicians should focus on accelerating the transition from fossil to renewable energies.

Keywords: natural gas; carbon dioxide emissions; economic growth; consumption of renewables

1. Introduction

The development of the natural gas market in the European Union (EU) happened gradually. Firstly, with the Single European Act entrance, in force since 1986, the target of creating the internal market until 1992 was established. This market would develop an inter-institutional relationship of political cooperation and community competence among the European countries.

Liberalizing the natural gas market would protect consumers' interests in the final price, the quality of service, environmental sustainability, access to information, and supply security. Furthermore, natural gas is essential for citizens' lives in both electricity production and residential consumption. According to the article "EU energy mix and import dependency" from Eurostat [1], the European Union (EU) received more than 46% of its natural gas imports from Russia. Other important providers are Norway, Algeria, Qatar, the United States of America, the United Kingdom, Nigeria, and Libya making up collectively with Russia 90% of the EU's total natural gas imports.

In Figure 1, we show the energy imports dependency, namely natural gas in % of the total energy needs:

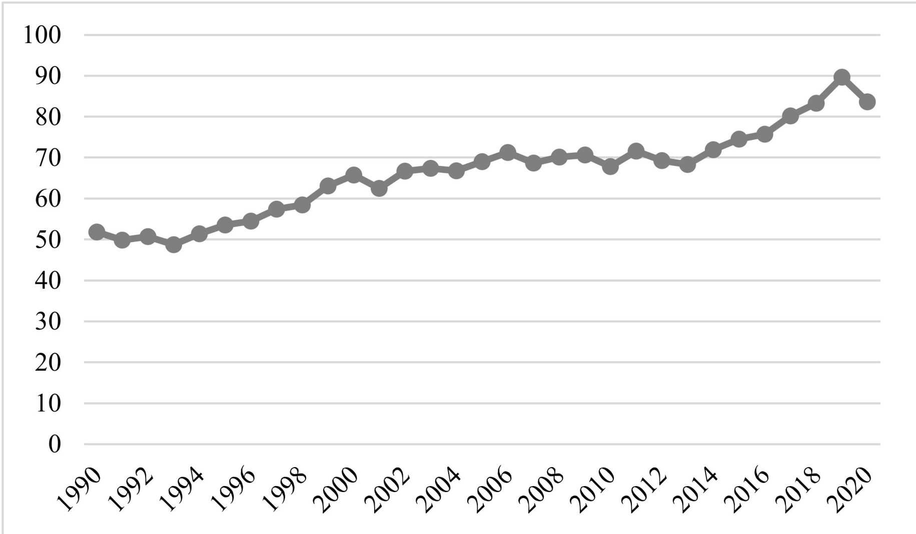

Figure 1. Natural gas in % of the total energy needs. Source: [1].

The numbers that are shown in Figure 1 suggest that some European countries are highly dependent on natural gas imports. However, due to the current scenario of War in Eastern Europe (invasion of Ukraine by Russia) and the strong European dependence on Russian natural gas, in parallel with all targets for reducing global warming, the replacement of natural gas with clean sources of energy is once again a matter of emergency. Finally, considering important aspects that were addressed by [2], such as energy efficiency, energy security in the EU, the living conditions of the population, and the conditions for economic development.

The European Union economy is increasingly using energy that was obtained from renewable energy sources [3]. Nonetheless, regarding the relevance of natural gas for the EU, this research aims to identify the impact of natural gas consumption on carbon dioxide (CO_2) emissions, analyzing an EU countries' panel.

The criteria for selecting countries for this research were: (a) being a member of the EU, a sophisticated natural gas market; (b) having data for a long-time horizon for the series; and (c) availability of data for all the variables. These rules resulted in annual data, a time horizon from 1993 to 2018, and sixteen EU countries.

After the Autoregressive Distributed Lag (ARDL) model estimation, the results support the Kuznets curve's presence, revealing a negative impact on the gross domestic product (GDP) per capita (PC) in curbing the carbon dioxide (CO_2) emissions and evidence of the impact of renewables consumptions on reducing CO_2 emissions. The results, as expectable, also reveal that the consumption of natural gas and other fossil energy sources has different environmental impacts. However, the natural gas contribution to increasing CO_2 emissions is very small compared to other fossil energy sources. These results provide a better comprehension of the liberalization of natural gas in the European common market and sets a scientific basis for further comprehension of the phenomenon of CO_2 emissions in the EU.

The research is organized as follows: The first section shows the introduction. The second section (literature) reviews the existing literature about CO_2 emissions and the liberalization of natural gas in the EU. Section three (methodology) describes the data, the methods, and the model that was used. The empirical results and discussion are presented in Section four. Finally, the conclusions and policy recommendations are shown.

2. Literature

There have been significant changes in the integrated energetic gas and electricity market in the last decades. According to the Fact Sheets of the Internal Energy Market [4], the 1990's directives are the starting point for the liberalization of the internal market for natural gas and electricity since, at this time, the major part of the national markets for electricity and gas were objects of monopoly [4]. The United Kingdom and Wales were the first countries to establish liberalization measures (e.g., [5,6]).

Newbery [5], in his analysis of the liberalization of the British electricity market, points out that the main factors that led to this were the little government incentive for the good use of available resources, in addition to the choice, often by political influence, by managers that were not qualified to take on projects in the area. In addition, liberalization was looking for a system to deliver energy efficiently, safely, and sufficiently at competitive prices [5].

This liberalization in Great Britain was positive, as [7] points out. For example, in the first five years after opening to the private market, the costs decreased by 6%, labor productivity more than doubled, the actual cost of fuel that was used to create energy dropped substantially, and new and important investments were made at a much lower cost (per unit of energy) than the cost before liberalization [7].

Thus, there were significant changes in the energy markets [8–10]; competitive markets replaced monopolies of public services, and the traditional public management tended to disappear, with its place being taken over by the private administration [5,10].

State members of the EU decided to open their markets gradually to the competition. In 1996, measures were adopted that predicted the countries would establish the rules as the electricity market liberalization until 1998. While for the gas market liberalization, the measures were adopted only two years later and predicted the establishment of legislation until the year 2000 [4].

According to information from the European Commission [11] in 2009, legislation about the energy market, known as the third package of energy, was approved. The package aimed to improve the internal energy market's functioning and resolve structural problems in the energy sector [11]. Again, according to the European Commission [12], difficulties were found in entering new companies. The increased competition in the energy market failed due to the huge number of regulated prices that are still practiced by the countries.

According to the European Parliament [13], new measures were adopted in June 2019, named the directive 2019/944/EU, and three regulations (Electricity Regulation (2019/943/EU); Risk Preparedness Regulation (2019/941/EU); Regulation EU 2019/942/EU establishing an Agency for the Cooperation of Energy Regulators (ACER)). These measures introduce rules in the energy market to adapt to the necessity of renewable energies, besides attracting new investments. In addition, incentives for consumers and the introduction of the Member States' obligation to prepare emergency plans to deal with possible electricity crises are also highlighted.

De Campos [14] also points to the importance of the Community Directive 98/30/EC, which approved the opening of the internal gas markets and reported topics such as transportation, infrastructure, storage, organization, and operation of the sector. Ref. [8] stated that these changes over time are attributed to good regulation, which solved unforeseen problems in the proceedings.

The dependence on natural gas from foreign suppliers is very high in the European Union, leaving countries in a unique situation regarding supply security [15]. The EU is dependent on imports of natural gas from an oligopoly of important producers [16].

Hulshof et al. [17] warned that the number of gas suppliers to the European market is limited. The author points out that the market faces periodic shocks in both supply and demand, which is one reason for the price distortion [17]. Given the dependence of Member States on gas imports, following the Russian-Ukrainian dispute (for natural gas) in 2009, the European Parliament established specific regulations (for further details on the regulations please access measure No 994/2010 [4]) that created ways to ensure gas imports [13].

Natural gas has a great advantage over electricity because it can be stored [18,19]. In addition, [20] reports that natural gas, contrary to electricity, does not have what can be described as "captive uses", forcing natural gas to be market competitive with its substitutes, at least in industrial, domestic, and tertiary sectors.

Golombek et al. [21] pointed out the various effects of partial liberalization of energy markets and stresses that liberalization causes higher CO_2 emissions using fossil fuels. Based on extended tests of the proposed model, there would be an increase of approximately 8% in CO_2 emissions from Western Europe in a scenario of complete liberalization. Also, according to the model, even with the increase in emissions, the proportion of the overall increase in welfare that would be generated by liberalization is valid [21].

The International Energy Agency [22] highlights that the substitution of coal with natural gas leads to a reduction in the emission of CO_2 and methane in the energy sector by 50% and by 33% in the heating sector. In addition, natural gas is the cleanest source compared to other non-renewable energy sources [18]. Another advantage is the backup function for electricity production when renewable sources do not operate [23].

All over the world, several contemporary authors have studied the relationship between natural gas consumption and economic growth. See Table 1.

Table 1. Literature on gas consumption and growth.

Author(s)	Features
[2]	Natural gas and electricity were the main sources of energy that were consumed by the EU industrial sector between 1995 and 2019
[24]	Natural gas consumption provided economic growth in China, but no relationship between these variables occurred in India in the short-run. However, there is a two-way causal relationship between natural gas consumption and economic growth in the long run.
[25]	A non-linear programming approach predicts the wider inter-regional and inter-industry impacts of natural gas flow disruptions. The impacts on GDP are positive for the European Union and negative for Russia.
[26]	The natural gas shortage reduced Mexico's annual GDP growth rate by 0.28 percentage points in the second quarter of 2013. In addition, a 10% increase in natural gas supply shortages reduces industrial production by 0.32%.
[18]	Gas consumption and gross domestic product (GDP) growth are cointegrated. Therefore, there is feedback causality between gas consumption and long-run GDP growth.
[27]	The results provide evidence of the growth hypothesis in Iraq, Kuwait, Libya, Nigeria, and Saudi Arabia. Conservation hypothesis Algeria, Iran, United Arabian Emirates, and Venezuela. Further evidence suggests hypotheses of neutrality in Angola and Qatar.
[28]	The results indicate a positive relationship between economic development and natural gas consumption. In contrast, the relationship between natural gas consumption and economic development in the European Union is negative.
[29]	There is a cointegration relationship between natural gas consumption and economic development in China and Japan. In China, the results indicated the existence of a unidirectional causality of natural gas consumption to economic development. In Japan, there is a two-way causality between natural gas consumption and economic development.
[30]	Granger's causality test revealed two-way causality between natural gas energy consumption and GDP growth.

Table 1. *Cont.*

Author(s)	Features
[31]	Iran is considered a major world producer of natural gas. However, natural gas prices negatively and significantly impact natural gas consumption in Iran. Therefore, there is a positive impact on gas consumption growth.
[32]	Natural gas consumption, capital, labor, and exports positively affect Pakistan's economic growth. Therefore, the hypothesis of natural gas consumption growth is also supported, and it is suggested that natural gas conservation policies may delay economic growth.

The enormous importance of natural gas for the development of nations goes beyond the articles and its importance in world geopolitics. For example, the main gas-producing countries, such as Iran, have their economy strongly influenced by their price, as the increase in price harms domestic gas consumption, which in turn harms economic growth [31]. Alcaraz & Villalvazo [26] present another example of this direct relationship between the availability of natural gas and the country's growth in Mexico, which, in 2013, faced a severe lack of gas supply due to a significant increase in consumption, which was not accompanied by investments in infrastructure. This lack of supply was responsible for a 0.28% reduction in the Mexican GDP in the second quarter of 2013 alone.

Due to its direct relationship with economic growth and the increased regulation of CO_2 emissions, natural gas consumption has been represented in many countries as an important source of electricity generation [18]. Table 2 shows the relationship between electric energy consumption and economic growth.

Table 2. Literature on electricity consumption and economic growth hypotheses.

Author(s)	Features
[33]	The increasing production of economic activities consumes much energy. Consequently, this leads to an increase in CO_2 emissions.
[34]	The energy field plays a critical role in countries' growth
[35]	Energy use is essential to promote economic activity but generates environmental problems.
[36]	Proposes that new variables be related to nexus energy-growth.
[37]	Within the extended Nexus of Fuinhas & Marques (2019), the authors relate carbon dioxide emissions and economic growth to domestic credit to verify its effect on self-income economies.
[38]	Link the globalization process and its dimensions with energy consumption levels with the analysis of urbanization and economic growth.
[39]	Analyze the impact of renewable energy consumption on economic welfare using panel data techniques.
[40]	It is a recent study on the link between energy consumption and economic growth.
[41]	Perform a meta-analysis of 51 published studies, given worldwide since 1949, on the relationship between energy consumption and GDP growth.
[42]	Panel analysis. Relationship between economic growth and pressure on nature from environmental sustainability.
[43]	Forecast 2005–2035, China will replace the United States as the world's leading embodied energy consumer by 2027, when per capita energy consumption will be a quarter of the United States.
[44]	Study of the use of renewable energy in European countries, through panel data techniques.

Table 2. *Cont.*

Author(s)	Features
[45]	Studied the assumptions associated with the causal relationship between electricity consumption and economic growth.
[46]	The literature between growth and energy is not conclusive on the main hypotheses.
[47]	The causality test is applied to examine the causal relationship between primary energy consumption (EC) and actual gross domestic product (GDP) for Turkey during 1970–2006.
[48]	It is a pioneering test to prove the US's causal relationship between Energy and GDP.

Several studies from several countries report the importance of the relationship between electricity consumption and economic growth. The neutrality, feedback, growth, and conservation hypotheses are usually tested and verified for sets of countries or time-series analyses. Belucio & Fuinhas [49] stated that, in a certain way, electricity consumption can be considered a proxy variable for the general sophistication of a society/economy.

The concern to promote economic development allied with gas emissions control passes through great environmental responsibility goals. In 2019, at COP 25 in Madrid, the need to take even more extreme measures than those that were agreed upon in Paris 2015 during COP 21 was noted, where world leaders accepted the measures that were proposed by the UN (United Nations Organisations) to reduce greenhouse gas emissions [50–52].

However, there was no consensus on the measures to be taken. The discussion was postponed since several developing countries, such as Brazil and China, are unwilling to take drastic measures to reduce CO_2 emissions. Another significant change in the global scenario was the USA's departure, the second-largest CO_2 emitter in the world, from the Paris Agreement in 2017, seriously compromising the viability of the goals set so far.

Natural gas is an important fuel source for Europe and is expected to remain so for the next decades [53]. However, the way this gas is extracted has changed in recent years, with a significant increase in the extraction of so-called shale gas. According to the Energy Information Administration [54], shale gas is natural gas that is trapped in small pores inside shale formations (more frequent), sandstone, and other sedimentary rocks.

The world's reserves of shale gas are vast and also, according to the Energy Information Administration [55], it is estimated that only in technically recoverable reserves outside the USA, there are 6914.1 trillion cubic feet (195.79 trillion cubic meters) of shale gas, with China having the most significant reserves. However, the United States is now the world's largest producer, which pioneered the development of extraction technologies and increased the percentage of extracted shale gas concerning the total natural gas produced from 1.6% in 2000 to 23.1% in 2010 [26].

Also, in 2019 the Energy Information Administration [54] estimates that dry shale gas production amounted to 25.28 trillion cubic feet (715.85 billion cubic meters), accounting for 75% of the total dry natural gas production in the USA (the main gases on the market are wet natural gas and dry natural gas. Wet gas is composed of several other gases besides methane, making its use as fuel unfeasible. It does not reach the consumer without going through the processing that turns it into dry natural gas, composed almost solely of methane. This, in turn, is the gas that runs through pipelines and is delivered to the final consumer). This significant increase in production caused a drop in the price of natural gas in the USA market, from $7.7 per thousand cubic feet (28.31 cubic meters) in 2007 to $3.8 in 2012 [26].

In the environmental aspect, there is much discussion about the increase in shale gas extraction to the increase in greenhouse gas emissions [56]. According to [57], fugitive (fugitive emissions are the diffuse emissions that occur during the process of extraction, refining and transport of gas, mainly through leaks) greenhouse gas emissions from shale gas extraction in 2010 corresponded to 3.6% of all emissions that related to natural gas.

According to an analysis of methane emissions from shale gas extraction, between 3.6% and 7.9% of the extracted methane escapes into the atmosphere during the lifetime of an extraction well [58]. Also, according to this research, the environmental impact of methane greenhouse gases is greater than that of conventional gas or petroleum for any time horizon observed, especially from 20 years [58].

3. Methodology

3.1. Data

The time horizon comprises of data from 1993 to 2018 for sixteen countries (Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Luxembourg, Ireland, Italy, Netherlands, Poland, Spain, and Sweden). Initially, 25 countries were considered for the study, but the reduction was inevitable due to the lack of statistical data.

Table 3 shows, in detail, the variables that seek to explain the phenomenon of emissions, the origin of the data, and the transformations to which the variables were submitted.

Table 3. Variables.

Variables	Abbreviation	Base	Unit	Transformations
CO_2 emissions	CO_2pc	BP	Million tonnes	It is divided by the population to transform the variable into its per capita (PC) value.
Natural gas consumption	ngcpc	BP	Millions of tons of oil equivalent	It is divided by the population to transform the variable into its per capita (PC) value.
Renewables and Hydroelectric consumption	rchcpc	Author, own calculations based on BP	Millions of tons of oil equivalent	It is the sum of renewable and hydroelectric consumption. It is divided by the population to transform the variable into its per capita (PC) value.
Oil consumption	ocpc	BP	Millions of tons of oil equivalent	It is divided by the population to transform the variable into its per capita (PC) value.
Gross Domestic Product	gdp	World Bank	Constant LCU	It is divided by the population to transform the variable into its per capita (PC) value.

Notes: The population data were obtained from the "World Development Indicators" of the World Bank (WB) and are measured by the total number of persons; the renewables and hydroelectric consumption data was retrieved from the BP "Statistical Review of World Energy" and are both measured in millions of tons of oil equivalent.

In Table 4, the descriptive statistics are presented. The acronyms "l" and "dl" in front of the variables mean that they were transformed into natural logarithms and first differences, respectively. Again, the number of observations makes it possible to confirm that the panel is balanced.

Table 4. Descriptive statistics.

Variable	Obs.	Mean	Std. Dev.	Min.	Max.
lCO_2pc	416	2.20569	0.3777207	1.456253	3.331839
lgdppc	416	11.13046	1.37738	9.54555	15.19928
lngcpc	416	−0.4648637	0.9243719	−5.483719	0.9595549
locpc	416	−13.32239	0.5286551	−14.78923	−11.88321
lrchcpc	416	−15.53361	1.396328	−19.22397	−12.95452
$dlCO_2pc$	400	−0.0090524	0.0509482	−0.2076705	0.1845551
dlgdppc	400	0.0190884	0.0280064	−0.0942888	0.2149944
dlngcpc	400	0.0162301	0.1318025	−0.6753016	1.404376
dlocpc	400	−0.0005098	0.0454565	−0.1489391	0.1560745
dlrchcpc	400	0.067968	0.1579153	−0.5162868	1.026718

It is possible to measure the degree of linear association between the variables by the correlation matrix (Table 5), in which we can have three possible results: (i) negative correlation, that is, when one increases, the other always decreases; (ii) positive correlation, shows that the variables vary in the same direction; and (iii) neutral, when the variables do not depend linearly on each other.

Table 5. Correlation Matrix.

	lCO_2pc	lgdppc	lngcpc	locpc	lrchcpc
lCO_2pc	1.0000				
lgdppc	−0.2070	1.0000			
lngcpc	0.4397	0.0102	1.0000		
locpc	0.6721	−0.2885	0.2944	1.0000	
lrchcpc	−0.2449	−0.1119	−0.2457	0.1987	1.0000
	$dlCO_2pc$	**dlgdppc**	**dlngcpc**	**dlocpc**	**dlrchcpc**
$dlCO_2pc$	1.0000				
dlgdppc	0.3305	1.0000			
dlngcpc	0.3669	0.1532	1.0000		
dlocpc	0.5675	0.4843	0.1770	1.0000	
dlrchcpc	−0.2375	0.0502	−0.1182	−0.0551	1.0000

The matrix of correlations shows an apparent absence of collinearity since all the coefficients are below 70%. Although, in order to confirm the existence or not of multicollinearity, we also conduct the VIF (variance inflation factor) test. Multicollinearity can cause distortions in the results, so it is always important to check the statistics. The results of the VIF statistics are shown in Table 6.

Table 6. VIF Results.

Dependent Variable: $dlCO_2pc$			Dependent Variable: lCO_2pc		
Variables	**VIF**	**1/VIF**	**Variables**	**VIF**	**1/VIF**
dlocpc	1.33	0.750125	locpc	1.30	0.766698
dlgdppc	1.33	0.753464	lngcpc	1.23	0.810356
dlngcpc	1.05	0.949279	lrchcpc	1.16	0.858642
dlrchcpc	1.03	0.975430	lgdppc	1.10	0.906230
Mean VIF	1.18		Mean VIF	1.20	

Table 6 confirms that multicollinearity is not a problem for estimating the model, given that the VIF values were all slightly above 1, not reaching the usually accepted benchmark of 10 (if they surpassed this value, multicollinearity could be a problem).

We also conducted Pesaran's [59] cross-sectional dependence (CD) test (Table 7). Again, the test's null hypothesis, cross-sectional independence, was rejected, meaning that our panel countries share an interdependency and are susceptible to the same shocks.

Table 7. Cross-sectional independence.

Variable	CD-Test	*p* Value	corr	abs(corr)
lCO_2pc	38.58	0.000	0.691	0.702
lgdppc	48.37	0.000	0.866	0.866
lngcpc	28.24	0.000	0.505	0.563
locpc	17.88	0.000	0.320	0.538
lrchcpc	43.59	0.000	0.780	0.780
$dlCO_2pc$	17.78	0.000	0.325	0.347
dlgdppc	35.14	0.000	0.642	0.642
dlngcpc	24.49	0.000	0.447	0.451
dlocpc	14.93	0.000	0.273	0.292
dlrchcpc	5.06	0.000	0.092	0.239

Note: The CD test has N(0,1) distribution under the H_0: cross-sectional independence.

Finally, the unit root tests showed that our data are constituted by I(0) and I(1) variables and that no variable showed signs of being I(2). The details of the unit root tests are shown in Table A1 in the Appendix A. The unit root testing was conducted by using the Pesaran [60] CIPS test, which is robust to the phenomenon of cross-section dependence.

3.2. Methodology

This study's methodological approach was based on the autoregressive distributed lag (ARDL) model in the form of an unrestricted error correction model (UECM). This approach enables us to inquire about the explanatory variables' short- and long-run effects on the dependent variable. Additionally, the ARDL model has the advantage of being appropriate in the presence of cointegration and endogeneity, produces efficient estimates with relatively small or moderate samples, and allows the incorporation of I(0) and I(1) variables in the same estimation. This last point is especially important given that the unit root tests (Table A1) indicated the presence of variables in both integration orders (I(0) and I(1)). In Equation (1), we present the ARDL model specification in the form of an unrestricted error correction model (UECM):

$$\begin{aligned} dlco2pc_{it} = {} & \alpha_{1i} + \beta_{1\,1} dlgdppc_{it} + \beta_{1\,2} dlngcpc_{it} + \beta_{1\,3} dlocpc_{it} + \\ & \beta_{1\,4} dlrchcpc_{it} + \gamma_{1\,1} lco2pc_{it-1} + \gamma_{1\,2} lgdppc_{it-1} + \gamma_{1\,3} lngcpc_{it-1} + \\ & \gamma_{1\,4} locpc_{it-1} + \gamma_{1\,5} lrchcpc_{it-1} + \varepsilon_{it} \end{aligned} \quad (1)$$

where the α_i represents the intercept, β_{it} and γ_{it}, with $t = 1, \ldots, 5$ denotes the estimated parameters, while ε_{it} represents the error term. Again, the prefixes "l" and "dl" denote natural logarithms and first differences, respectively. After this brief explanation of the methodological approach, in the following section, we will present the results from our model and their subsequent discussion.

4. Results and Discussion

Before proceeding with the model estimation, some specifications need to be checked. First, the Hausman test [61] translates into a clarification of which specification is the most correct for the proposed data panel analysis: the rando effects (RE) or the fixed effects (FE)? The test has the following null hypothesis: the random effects are the most suitable specification. If we reject the null, the fixed-effects specification is the most suitable. The outcomes of the Hausman test, with (chi2(9) = 42.00 with Prob > chi2 of 0.000) and without (chi2(9) = 46.41 with Prob > chi2 of 0.000), the Stata sigmamore option (which reflects more robust results), were unanimous, indicating the fixed effect specification has the most suitable one. Next, we computed a series of specification tests to decide on the best-suited estimator to conduct the analysis. Table 8 presents the results of the specification tests.

Table 8. Specification's tests.

Test	Statistics
Modified Wald's test	347.72 ***
Pesaran's test	8.350 ***
Friedman's test	85.412 ***
Wooldridge's test	32.875 ***
Breusch-Pagan LM test	228.321 ***

Notes: H_0 of Modified Wald's test: sigma(i)^2 = sigma^2 for all I; H_0 of Pesaran's test: residual are not correlated; H_0 of Friedman's test: residual are not correlated; H_0 of Wooldridge's test: no first-order autocorrelation; H_0 Breusch-Pagan LM test of independence is that residuals across entities are not correlated; *** denotes statistical significance at 1% level.

In Table 8, we show the results from the modified Wald's test [62], Wooldridge's test [63], Pesaran's [59], and Friedman's tests [64] for cross-sectional independence, and the Breusch-Pagan Lagrange multiplier (LM) [65]. All the tests reject the null at the 1% level, meaning there is evidence of heteroscedasticity, first-order autocorrelation, and contemporaneous correlation in the model. Given these results, the use of the Driscoll & Kraay [66] estimator (fixed effects (FE)-DK) seems to be the most suitable option, given that it "*is capable of producing standard errors robust to the disturbances being cross-sectionally dependent, heteroskedastic, and autocorrelated up to some lag*" [67].

Before presenting the results, we should refer to that in the first model estimation, the variables "dlgdppc" and "lngcpc" were not statistically significant. Consequently, they were excluded from the model estimation. Therefore, the most parsimonious model has now the following specification (Equation (2)):

$$dlco2pc_{it} = \alpha_{2i} + \beta_{2\,1} dlngcpc_{it} + \beta_{2\,2} dlocpc_{it} + \beta_{2\,3} dlrchcpc_{it} + \gamma_{2\,1} lco2pc_{it-1} + \gamma_{2\,2} lgdppc_{it-1} + \gamma_{2\,3} locpc_{it-1} + \gamma_{2\,4} lrchcpc_{it-1} + \varepsilon_{it} \quad (2)$$

Additionally, six dummy variables were included in the model to correct the outliers that were detected in the residual's analysis (e.g., [68]). There were three dummies for Denmark (den1996, den2003, and den2006, for the years 1996, 2003, and 2006, respectively); two for Finland (fin2005 and fin2006, for the years 2005 and 2006, respectively); and one for Luxembourg (lux1995, for the year 1995) that were used. For Denmark, the explanations for these outliers were a peak in coal consumption and an increase in oil and gas in 1996, and peaks in coal consumption in 2003 and 2006. Finland experienced a sharp drop in coal consumption in 2005. However, it is unclear what caused the 2006 abnormal increase in CO_2 emissions (it may just be the effect of returning to the pre-existing situation). Luxembourg faced a sharp drop in coal consumption in 1995. In Table 9, we display the results from the model estimation (the specification tests from Table 8 were remade to ensure that the results concerning their null hypotheses stayed the same for this most parsimonious model). Moreover, we also present the results with the FE estimator to see the differences in using the FE-DK estimator.

Table 9. Estimation results.

Dependent Variable: $DLCO_2PC$	Coef.	FE	Coef.	FE−DK
Constant	2.4081	***	2.4081	***
den1996	0.1654	***	0.1654	***
den2003	0.1504	***	0.1504	***
den2006	0.1667	***	0.1667	***

Table 9. *Cont.*

Dependent Variable: $DLCO_2PC$	Coef.	FE	Coef.	FE−DK
fin2005	−0.1491	***	−0.1491	***
fin2006	0.1725	***	0.1725	***
lux1995	−0.1338	***	−0.1338	***
dlngcpc	0.0845	***	0.0845	**
dlocpc	0.5666	***	0.5666	***
dlrchcpc	−0.0497	***	−0.0497	***
$lCO_2pc(-1)$	−0.1473	***	−0.1473	***
lgdppc(−1)	−0.0382	**	−0.0382	*
locpc(−1)	0.1326	***	0.1326	***
lrchcpc(−1)	−0.0065		−0.0065	*
	Diagnostic Statistics			
N	400		400	
R^2	0.6321		0.6321	
F stat	F(13, 371) = 49.04		F(13, 24) = 2065.38	
Prob	***		***	

Notes: ***, **, * denote statistical significance at 1%, 5%, or 10% level, respectively; the Stata command *xtscc* was used to estimate the models; The model was tested with the trend, but it was not statistically significant.

With the analysis of the results (Table 9), we see that the estimated coefficients have the expected signal according to economic theory. The ECM coefficient has the expected (negative) sign, which is within the expected range [−1; 0], being statistically significant at the 1% significance level.

Although the information is displayed in Table 9, we should note that the long-run elasticities are not shown in this table. This is because they had to be calculated by dividing the coefficients of the variables by the lCO_2pc (ECM) coefficient, both lagged once, and then we had to multiply this ratio by (−1). Table 10 shows the short-run impacts, the model speed of adjustment, and the computed long-run elasticities.

Table 10. Elasticities and speed of adjustment.

Dependent Variable: $DLCO_2$	Coef.	FE	Coef.	FE−DK
Short−run impacts				
dlngcpc	0.0845	***	0.0845	**
dlocpc	0.5666	***	0.5666	***
dlrchcpc	−0.0497	***	−0.0497	***
Long−run elasticities				
lgdppc(−1)	−0.2590	**	−0.2590	**
locpc(−1)	0.9002	***	0.9002	***
lrchcpc(−1)	−0.0442	*	−0.0442	*
Speed of adjustment				
ECM	−0.1473	***	−0.1473	***

Notes: *, **, and *** denote statistical significance at the 10%, 5% and 1% levels, respectively; the ECM denotes the coefficient of the variable LCO_2 lagged once.

As we can see by the results from Table 10, the impact of natural gas consumption on CO_2 emissions is positive and statically significant, but only in the short -un. This fact is not in line with, for example, the results from [69], who analyzed a similar relationship for the case of 14 Asia-Pacific countries, and whose results pointed to the existence of a short- and long-run relationship between natural gas consumption and CO_2 emissions. Nevertheless, this result probably derives from the fact that although for many years, natural gas has been seen as a precious energy source, the natural gas development in Europe has been suffering a deceleration due to environmental concerns, with policy-makers starting to primarily focus on the investment on renewable sources of energy [28]. This contrasts with the situation of Asia-Pacific countries, where it is predicted that natural gas consumption will continue to grow steadily in the future [70]. In addition, there is also the case of the extreme dependence of the European countries on, for example, Russian natural gas, a fact which also contributed to cooling the consolidation of natural gas in the energy mix of many European countries due to economic and political reasons [28]. Moreover, the fact that natural gas presents a positive coefficient is not surprising, given that although natural gas emits less CO_2 when it is compared with oil or coal, it still emits some amount of CO_2 [71].

Nevertheless, in the short-run, we see a great difference in terms of oil consumption vs. natural gas impacts. More precisely, when compared with oil consumption, natural gas has an impact that is 6.7 times lower on CO_2 emissions. Moreover, we should also stress that contrary to natural gas, oil consumption has also presented a positive and statistically significant effect on CO_2 emissions in the long run. This result was far from unexpected, given that oil consumption is considered one of the major contributors to CO_2 emissions increase [72].

Another result that is far from unexpected is the one from renewable and hydroelectric energy consumption. As we can see in Table 10, the energy consumption from this type of source negatively impacts CO_2 emissions both in the short- and long-run. However, in the long-run, the coefficient is only statistically significant at the 10% level. Despite this last fact, we can say that the estimation results corroborate the already widely accepted view that investment in renewables is one of the major strategies to reduce emissions in the short- and long-term [73].

Regarding the GDP, the results point to, in this group of countries, economic growth had been grounded in a way that contributes to the decrease in CO_2 emissions. More precisely, looking at Table 10, we see that the coefficient of GDP is revealed to have a negative sign and to be statistically significant at the 1% level in the long-run. This result is similar to the one from Dogan & Aslan [74], who analyzed a similar relationship for the case of a panel of EU countries and candidate countries. The authors also found a negative coefficient for the case of the effect of GDP on emissions, with this result following the Environmental Kuznets Curve (EKC) hypothesis. Indeed, the authors state that since their sample is primarily composed of high-income and upper-middle-income countries, the countries from their panel should be beyond the threshold level, enabling "increases in real income lead to environmental improvements" [74].

Finally, the ECM coefficient (i.e., the model's speed of adjustment) is negative and statistically significant at the 1% level, as it should, and has a value of 14.73%, which is fast enough for the model to achieve the equilibrium in the medium-run.

5. Conclusions

A per capita analysis of natural gas' impact on carbon dioxide emissions was performed for sixteen European countries from 1993 to 2018. An autoregressive distributed lag (ARDL) model in the form of an unrestricted error correction model, controlling for the variable's renewables and hydroelectric consumption, oil consumption, and gross domestic product was used to conduct the analysis. The ARDL approach is a robust econometric technique that identifies the short-run impacts, the long-run elasticities, and the speed of adjustment in the variables' relationships.

Denmark (in 1996, 2003, and 2006), Finland (in 2005 and 2006), and Luxembourg (in 1995) suffered shocks in CO_2 emissions that can be related to changes in their energy mix. Furthermore, these outliers can be related to atypical coal consumption, stressing that alterations in the energy mix favoring coal use result in additional environmental damage. To cope with these outliers, "country-year" impulse dummies were included in the models' estimation. This artifact allows for modeling of the relationships without being disturbed by the anomalous events on CO_2 emissions.

The results from the ARDL model were essentially the following: (1) natural gas consumption has a positive impact on carbon dioxide emissions in the short-run; (2) oil consumption has a positive impact on carbon dioxide emissions both in the short- and long-run; (3) renewables and hydroelectric energy consumption have a negative impact on carbon dioxide emissions both in the short- and long-run; and (4) the GDP has a negative impact on carbon dioxide emissions in the long-run.

Due to these results, we can state that, first, it seems that this group of countries is being able to reduce the environmental impacts (measured by CO_2 emissions) of their economic activity. The fact that GDP presents a negative coefficient in the long-run highlights the environmental improvements that are made in these economies and follows the EKC hypothesis (we should not forget that the countries from our sample are mostly high-income or upper-middle-income economies). In this sense, these countries should continue on this path. More appropriately, these countries' governments should continue to promote the energy transition process in their respective economies. The importance of such a transition becomes clear when we look at the impacts of oil consumption vs. renewables/hydroelectric consumption on CO_2 emissions. Suppose these countries want to decrease their level of emissions. In that case, they need to continue to support the promotion of low carbon energy sources, with the increase of the share of renewables in their energy mix and, at the same time, reduce the dependence of their economic activity on fossil fuels, as well as the incentives to the use of this type of energy (e.g., fossil fuel subsidies). Regarding natural gas consumption, we can state that the lack of a statistically significant long-term effect does not fully allow us to develop more profound political implications regarding this energy source. Strictly speaking, although theoretically natural gas is seen as an effective alternative to reduce greenhouse gases (it emits a significantly lower level of emissions during combustion when compared with oil and coal), the lack of a long-run relationship between this energy source and CO_2 emissions does not allow us to completely corroborate this hypothesis for the sample of countries under study. However, even with the absence of a statistically significant effect in the long-run, if we compare the overall effects of natural gas and oil on CO_2 emissions, it seems that the use of natural gas is indeed less harmful to the environment than oil (in the short-run, natural gas has an impact that is 6.7 times lower on CO_2 emissions). Thus, we can say that, by the results that were achieved, it appears that having to use non-renewable energy, governments should continue to prefer natural gas over oil.

Given this last issue/limitation (the lack of a statistically significant effect from natural gas in the long run), future investigations on this thematic should be centered on a panel of European countries where natural gas already has a considerable weight in their energy mix and where the natural gas industry is already at an adequate level of development. This approach is required to obtain more robust results regarding the impact of natural gas on CO_2 emissions.

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Appendix A

Table A1. Unit roots test Pesaran [61] Panel Unit Root test (CIPS).

Without Trend				With Trend			
Variable	**Lags**	**Zt−bar**	***p*-Value**	**Variable**	**Lags**	**Zt−bar**	***p*-Value**
lCO_2pc	0	−3.259	0.001	lCO_2pc	0	−3.062	0.001
lCO_2pc	1	−2.110	0.017	lCO_2pc	1	−1.861	0.031
lgdppc	0	1.643	0.950	lgdppc	0	1.573	0.942
lgdppc	1	−1.599	0.055	lgdppc	1	−1.683	0.046
lngcpc	0	−3.092	0.001	lngcpc	0	−4.825	0.000
lngcpc	1	−1.553	0.060	lngcpc	1	−4.028	0.000
locpc	0	0.443	0.671	locpc	0	−3.233	0.001
locpc	1	1.354	0.912	locpc	1	−2.053	0.020
lrchcpc	0	−3.525	0.000	lrchcpc	0	−3.193	0.001
lrchcpc	1	−1.93	0.027	lrchcpc	1	−1.185	0.118
$dlCO_2pc$	0	−13.29	0.000	$dlCO_2pc$	0	−11.987	0.000
$dlCO_2pc$	1	−9.44	0.000	$dlCO_2pc$	1	−7.86	0.000
dlgdppc	0	−5.770	0.000	dlgdppc	0	−3.805	0.000
dlgdppc	1	−3.938	0.000	dlgdppc	1	−2.137	0.016
dlngcpc	0	−11.614	0.000	dlngcpc	0	−9.811	0.000
dlngcpc	1	−8.741	0.000	dlngcpc	1	−6.51	0.000
dlocpc	0	−12.596	0.000	dlocpc	0	−11.217	0.000
dlocpc	1	−7.988	0.000	dlocpc	1	−5.849	0.000
dlrchcpc	0	−13.933	0.000	dlrchcpc	0	−12.567	0.000
dlrchcpc	1	−8.284	0.000	dlrchcpc	1	−6.534	0.000

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