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by

Marco Quatrosi

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Analysis of monthly CO_2 emission trends for major EU Countries: a time series approach

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Abstract

The following paper will analyse monthly trends for CO_2 emissions from energy consumption for 31 European countries, four primary fuels (i.e., Crude Oil, Natural Gas, Hard Coal, Lignite) and four secondary fuels (i.e., Gas/Diesel Oil, LPG, Naphta, Petroleum Coke, Coke-oven Coke) from 2008 to 2019. Carbon dioxide emission has been estimated following the Reference Approach in the 2006 Guidelines for National Greenhouse Gasses Inventories. Country-specific (e.g. Tier 2) coefficient were retrieved from the IPCC Emission Factor Database. Data on fuel consumption (e.g., Gross Inland Deliveries) were taken from the Eurostat database. This paper will fill some knowledge gap analysing monthly trends of carbon dioxide emissions for major EU Countries. As the progressive phase-out of carbon is taking place pretty much in all Europe, Crude Oil exerted the largest amount of carbon dioxide emissions in the period considered. Analysis of selected countries unveiled several clusters within the EU in terms of major source of emissions. As final step, the paper has endeavoured the task of fitting a model for monthly CO_2 forecasting. The whole series presents two structural breaks and can be explained by an autoregressive model of the first order. Indeed, further speculations on a more appropriate fit and more fuels in the estimation, is demanded to other works.

Keywords *emissions, energy consumption,* CO_2*, energy mix, energy transition, emission factors, time series*

JEL Q43, Q53, Q58

1. Introduction

The quality of air is considered one of the most significant pillars for human thriving. Many studies have shown how a clean air does not only affect health, but also well-being. However, the quality of air is constantly threatened worldwide by anthropogenic emissions. Greenhouse gasses (GHGs) have proved to be among the major causes of global warming with all the consequences for living and non-living components of the Planet (IPCC, 2018). Further than that, greenhouse gasses exert significant effects on human health and livelihoods in multiple aspects (Chaabouni et al., 2016; Rabl & Spadaro, 2000; Watts et al., 2018). Some studies have also highlighted the linkage of air pollution and living conditions (e.g., well-being) of people (Welsch, 2006; Yin et al., 2018). Air quality is also one of the top priorities for governments worldwide. For this reason, the level of emission in the atmosphere is constantly under control. Especially CO_2 represents the most present and the most controlled GHG in the atmosphere. From 1970 the emission of this gas has more than doubled reaching almost 40 Gt/yr in 2019 globally (PBL Netherland Environmental Agency, 2020). In this sense, national governments have pledged to reduce emissions within a certain range via several binding agreements (e.g., UNFCCC, COP25 Paris Agreement). In compliance with the objectives of those agreements, governments are required to monitor and collect data on national anthropogenic GHGs emissions. A particular treatment is reserved to the power sector due to its significant contribution to air pollution. Despite the increasing trend of renewables, fossil fuels still remain the largest sources for power generation (IEA, 2019). Especially in developing countries, fossil fuels (i.e., coal) represent the main contributor to power generation and a relevant challenge for energy transition (IEA, 2019). In this brief picture, the European Union has been among the most committed in reducing GHGs emissions (EU2020 Climate and Energy Package). In 2018 energy intensity of the power generation sector for the whole Union was lower than other large economies (270 gCO_2/kWh compared to 400 gCO_2/kWh for USA, 500 gCO_2/kWh for Japan 600 gCO_2/kWh for People's Republic of China and over 700 gCO_2/kWh for Australia) (IEA, 2020b). However, only around 13%[1] of the overall energy supply in the Union comes from renewable sources. Beside the idea of a worldwide carbon tax, Europe have come forward putting a cap on its level of emissions (e.g., European Emission Trading Scheme) with the power sector being among the biggest players.

The following work will be analysing estimated monthly CO_2 emission trends generated from the combustion of (solid and liquid) fuels for 31 European countries (27 EU Member States plus United Kingdom, Iceland, Lichtenstein, Norway). Monthly data on fossil fuel combustion for the energy sector are taken from Eurostat database on energy consumption. The methodology used to estimate emissions follows the one in (Eggleston et al., 2006a) for the energy sector. After a brief overview on global CO_2 emission trends, the work will proceed with disentangling the general reference for GHGs submission (and estimation). The discussion will move on the methodology used to estimate CO_2 from fuel combustion. As next step, the analysis will be dedicated to the trends per fuel with focus on representative EU Countries. Time series econometrics techniques will be employed to analyse the aggregate monthly trend of carbon dioxide emissions for the sample considered. At the time of writing this might represent the first collection of data on emission trends at monthly level[2] for European countries. As direct product of an estimation, CO_2 series strictly follows energy consumption of each single country (Andersson and Karpestam, 2013). Crude oil and Lignite appear to exert the most significant contribution to emission. Some emission trends, appear to be rather hit

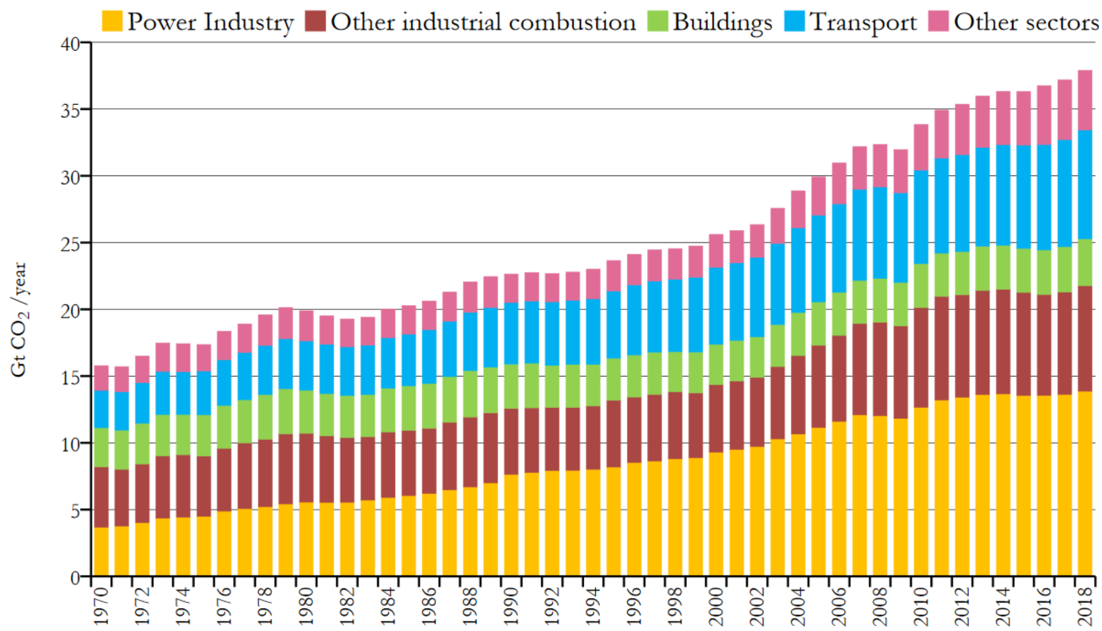
[1] Source Eurostat, data from 2017
[2] The dataset shall be available upon request at qtmrc@unife.it

by the recent economic downturn. Breakpoint analysis shows the series presents changes of trend in 2012 and 2018 respectively. Trends of selected country showed a sensible decrease in monthly emissions for some countries whereas for some others the trend was stable or increasing. Within the selected sample, it is possible to identify some clusters related to the major source of emission. As final step, a model fit has been tried, in order to approximate the true Data Generating Process (DGP) for the aggregated monthly carbon dioxide emissions.

2. Monitoring and tackling CO_2: analysis of global trends and methodologies

According to the latest estimates, the power sector accounts for 74% of the global GHG emissions (IEA, 2020a) (for Europe, the percentage reaches 82%[3]). Globally, CO_2 emissions have followed an increasing trend over the last 3 years (respectively, +1.8% from 2017 to 2018 and +1.2% from 2016 to 2017)(Crippa et al., 2019). Population growth and intensifying economic activities were among the drivers for an increase in 2018 (IEA, 2020a). 2019 saw a slight decrease of CO_2 emissions mostly due to milder weather conditions and a decrease in power sector for advanced economies. Global emission from coal decreased by around 200 million tonnes (-1.3%)[4] with respect to 2018. Despite the relevant performance (-1.9% from 2017 to 2018), Europe accounts for 9.1% of global CO2 emissions (Crippa et al., 2019).

Figure 1- Total global annual emissions of fossil CO2 in Gt CO2/yr by sector[5]



Source (Crippa et al., 2019)

Figure 1 shows the global trend of fossil CO_2 emissions from 1970 to 2018. It can be noticed the share of the power sector have increased along with the overall fossil emissions reaching almost 15 $GtCO_2$/year in 2018. Indeed, the power sector still accounts for the highest share of emission of fossil fuel combustion. From this very short overview of the trend, CO_2 emission still accounts for the largest share of GHG emissions and a potential threat for the environment and human health and in

[3] Source Eurostat, data from 2018
[4] Source IEA, data from 2019
[5] Fossil CO2 emissions include sources from fossil fuel use, industrial processes and product use (combustion, flaring,cement, steel, chemicals and urea).

turn economic growth. In this sense, the bulk of the information on emissions is tailored to fulfil government requests of monitoring the level of CO_2 in the atmosphere. Those nations that have joined the United Nations Framework Convention on Climate Change (UNFCCC) are required to submit updated national greenhouse gasses (GHGs) national inventories pursuant to Articles 4 and 13 of the Convention. Technical and legal framework is provided by the *Guidelines for the preparation of national communications by Parties included in Annex I to the Convention*[6]. Annex I Parties should follow criteria of transparency, consistency, comparability, completeness in holding their national inventories. In fact, the default methodology mentioned in the Guidelines refers to the 2006 Guidelines for National Greenhouse Gasses Inventories (Eggleston et al., 2006a). Sources of data on emissions can come from national statistic offices, experts, relevant stakeholders, international organizations, universities, peer-reviewed articles. Where direct sources (partially) lack, data can be generated using employing past data via different methodologies (i.e., averaging, interpolation). Research centres such as NOAA hold datasets on pollutants in the atmosphere from weekly air samples from the Cooperative Global Air Sampling Network (US Department of Commerce). Data on emissions in the atmosphere are normally modelled starting from the sampling of air and sea in areas with specific characteristics (i.e., NOAA samples air and seawater from Mauna Loa site). Other approaches for direct data are surveys of economic activities (e.g., industrial, agricultural, energy) or selected proxies (e.g., waste, forest)(Eggleston et al., 2006a). In either the two cases, some biases might arise related to the estimation procedure and the survey methodology (Eggleston et al., 2006a). Indeed, most of the data on emissions, only cover annual time span in line with the objectives set out at international level (Report of the Conference of the Parties on Its Nineteenth Session, Held in Warsaw from 11 to 23 November 2013, 2013).

2.1 IPCC Guidelines Reference Approach to CO_2 estimation from fuel combustion

In line with the IPCC Guidelines in (Eggleston et al., 2006a) national inventories are required to report estimates of relevant GHGs distributed per sector and sub-sector where appropriate. A simple approach links the immediate outcome of human activity (e.g., *activity data*) with coefficient that quantify the emission (or removals) per unit of activity (e.g., *emission factors*):

$$Emissions = AD * EF$$

The equation displays the basic equation for emission estimation from human activity data. This methodology can valid for virtually every GHG and economic sector. Estimation quality can be increased provide country-specific (e.g., *Tier 2*) or sector-specific (e.g., *Tier 3*) data on emission factors and activity data. The methodology used to estimate CO_2 emissions in this work follows the one in (Eggleston et al., 2006b) specifically conceived for the energy sector. In Chapter 6 the authors deploy what is called as "*Reference Approach*" to estimate CO_2 at country level. This methodology can be expressed by the equation as follows:

$$CO_2\,Emissions = \Big[\Big(\big(Apparent\ Consumption_{fuel} * Conv\ Factor_{fuel} * CC_{fuel}\big) * 10^{-3} - Excluded\ Carbon_{fuel}\Big) * COF_{fuel} * 44/12\Big]$$

[6] (Report of the Conference of the Parties on Its Nineteenth Session, Held in Warsaw from 11 to 23 November 2013, 2013)

As first step, $Apparent\ Consumption$ can be calculated via the algebraic sum of production (+) import (-) export (-) international bunkers (-) stock changes of each fuel. To perform the algorithm combustibles energy units will be converted to (net) calorific values when multiplied by their Conversion Factor ($Conv\ Fact$). Notice that carbon content may vary by fuel type according to the fuel composition. In fact, during the process part of the carbon can be either be accounted as emission in another sector (i.e. as industrial process emissions) or stored in some manufactured product as result of the combustion of the fuel. Indeed, some fuels are used as feedstock (e.g., LPG, Naphta, Ethane) or as reductant (e.g. Coke oven coke, Natural Gas) of some industrial processes. Bitumen, lubricants, paraffin can also be employed in non-energy uses. For this reason, $Excluded\ Carbon$[7] will be subtracted from the overall quantity. As final step, the methodology also takes into account part of the carbon that might escape the process of combustion and so oxidized, multiplying by the carbon oxidation factor COF[8]. The quantity obtained represents the total carbon emitted from the process of combustion. To transform it in CO_2 the quantity will be multiplied by the molecular weight ratio of carbon dioxide to carbon (i.e. 44/122). To refine the estimation, it is possible to introduce more specific data at country or at industry level for conversion factor and carbon content. This will produce what is defined Tier 2 (country specific) and Tier 3 (industry specific) estimates of CO_2 emission from fuel combustion. Similar approaches have already been used in (Olivier and Peters, 2005) for estimation of carbon dioxide emissions for non-energy consumption.

For the estimation of the emissions used in this work, data on consumption are taken from Eurostat database. Eurostat holds monthly data on energy consumption (e.g., *Gross Inland Deliveries*[9]) for selected fuels[10]. Data on country specific coefficients (e.g, conversion factor, carbon content) are retrieved from the UNFCCC Common Reporting Format (CFR) for the 27 EU Countries plus Iceland, Norway, United Kingdom. As part of the Convention, States are required to submit their national inventories for several pollutants, along with the whole methodology and coefficients used. Table 1 reports a summary of the primary and secondary fuel time series with the relative span.

Table 1- Summary of primary and secondary fuels

Fuel	Category	Type	Time
Hard Coal	Primary fuel	Solid	01/2008-11/2019
Lignite (Brown coal)	Primary fuel	Solid	01/2008-12/2019
Crude Oil	Primary Fuel	Liquid	01/2008-07/2019
Natural Gas	Primary Fuel	Liquid/Gaseous	01/2008-12/2019
Gas/Diesel Oil	Secondary Fuel	Liquid	01/2008-12/2019
LPG	Secondary Fuel	Liquid	01/2008-12/2019
Naphta	Secondary Fuel	Liquid	01/2008-12/2019
Petroleum Coke	Secondary Fuel	Liquid	01/2008-12/2019
Coke Oven Coke	Secondary Fuel	Solid	01/2008-12/2019

[7] See Appendix A for the methodology to estimate excluded carbon

[8] If not otherwise reported, default value for COF is set as 1

[9] In Reg (EC) 764/2008 of the European Parliament Gross Inland Deliveries (calculated):
Solid fuels: production + imports−exports + stock changes
Liquid fuels: primary product receipts + gross refinery output + recycled products−refinery fuel + imports−exports−international marine bunkers + interproduct transfers−products transferred−stock changes
Natural gas: indigenous production + imports−exports−stock change

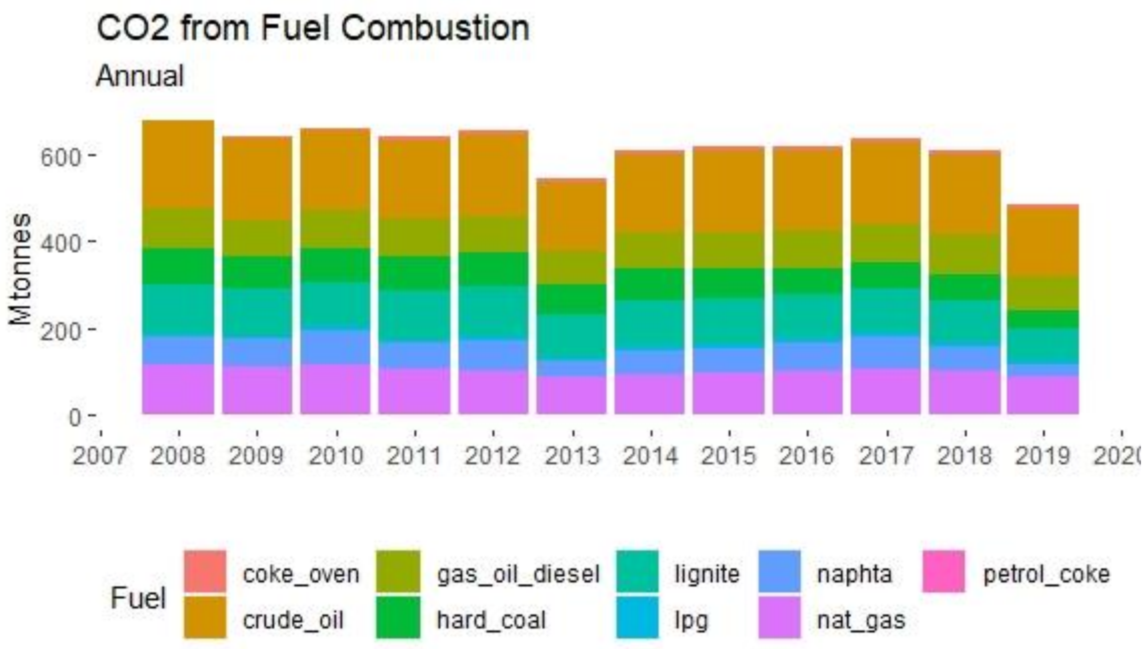
[10] The full list available in Annex A-B-C of Reg (EC)764/2008 of the European Parliament

Primary fuels are those directly used for energy consumption, whereas secondary fuels are the products of a certain treatment of primary fuels. The dataset object of analysis contains four primary fuels (two solid and two liquid) and four secondary fuel mostly derived from oil.

3. Analysis of monthly trends of CO_2 from fuel combustion

According to the latest estimates, the share of fossil fuels in the energy mix is below 50% for only 4 out of the 28 countries of the European Union (Eurostat, 2019).Overall, the European Union positions itself as a net importer in energy trade (especially for Oil and oil products) (DG Energy, 2020). Russian Federation and Norway are respectively first and second exporting countries to the Union for Oil and Natural Gas. Indeed, looking at the sample, Crude Oil appears to generate the highest level of emissions with a maximum value of 17,531 million of tonnes registered in December 2008 (Figure 2). In this sense, crude oil represents the largest source of emission and the most consumed fuel in the sample considered. However, the difference of scale might also be explained by the different percentage of carbon dioxide each fuel emits from burning (Suárez-Ruiz et al., 2019). Another cause might also be related to the increase of carbon price, mostly accounted during Phase III of the European Emission Trading Scheme. As one of the heavily polluting, the power sector is under the scheme with marked attention for coal-fired power plants (Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 Establishing a Scheme for Greenhouse Gas Emission Allowance Trading within the Community and Amending Council Directive 96/61/EC (Text with EEA Relevance), 2003).

Figure 2 - Total annual CO_2 emissions from fuel combustion



In fact, some EU countries (i.e., France) have decided to rely on crude oil imports as a much cheaper and flexible alternative than inland coal production (Mackay and Probert, 1993). The second largest share is for Lignite with some countries (i.e., Germany, Poland, Czech Republic) emitting among the highest levels. The progressive decrease of coal-sourced emission has been partly absorbed by natural gas as the result of the progressive fuel switching in power generation (i.e., UK and Italy)(Capece, 2014; Cooper, 2020; Pearson and Watson, 2012). The whole series presents a decrease in 2013 and a decreasing trend from 2018 onwards. In terms of composition, the fuels maintain the same share over the years with Crude Oil taking on average around 30%, Hard Coal, Natural Gas and Lignite accounting for around 15% each. The rest of emission sources can be accounted to secondary fuels with the highest share pertaining to Gas/Oil Diesel 15%. According to the latest data, Oil and oil products account for around 38% of energy consumption (647 Mt in 2018) for Europe whereas Natural Gas 23% and Coal only 13% (394 and 222 Mtoe[11] respectively) (Cooper, 2020).

Figure 3 - CO_2 emission from fossil fuel combustion monthly trend

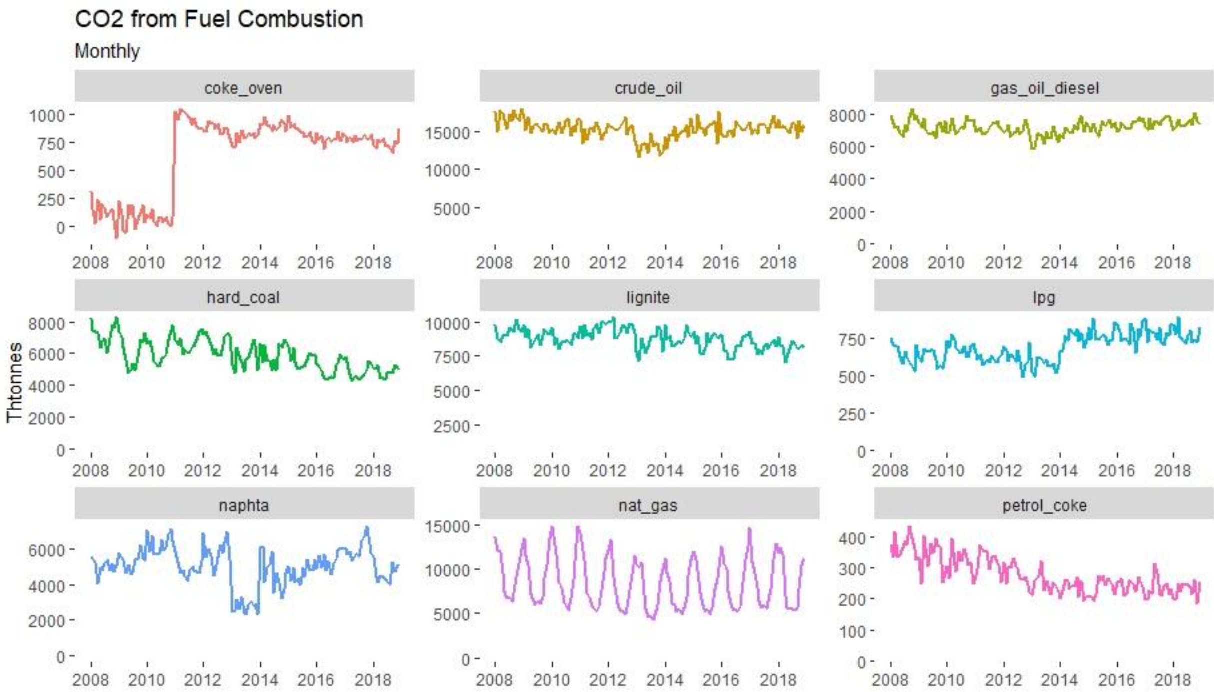


Figure 3 shows monthly trends of CO_2 emissions for each and every fuel object of analysis. Trends appear to be affected by seasonality in the first place. Natural Gas (nat_gas) shows the most evident seasonal trend with peaks correspondent to winter season. An interesting trend is shown by Coke Oven coke (coke_oven) where it is possible to see even negative emissions before 2012 and positive level of emissions afterwards. Naphta and Gas/Oil Diesel, on the other hand, experiences a drop in emissions from 2013 to 2014. Indeed, those secondary fuels are mostly used in industrial processes. Therefore, the drop in emission in those years might be related to a slowdown of the economy at European level (International Monetary Fund, 2012, 2013). To show the more evident trend in emissions, Figure 4 displays annual trend for the same years and fuels.

[11] Mtoe= million of tonnes of oil equivalent

Figure 4 - CO_2 emission from fossil fuel combustion annual trend

In fact, all primary fuels considered appear to show a minimum 2013 before increasing afterwards. Trends in emissions appear to lower as time goes by, for almost all the fuel considered except for Liquified Petroleum Gasses (lpg), Gas/Oil Diesel and Naphta. For those three, after reaching the minimum in 2013, level of CO_2 emissions turned back to previous levels, if not higher, in more recent years. Hard Coal, Lignite and Petroleum Coke shows a downward trend over the whole period considered. In fact, according to the latest EU Climate and Energy Plan, Member States pledged to phase-out carbon within 2030 (Agora Energiewende and Sandbag, 2020). However, despite pressures from the EU for a lower-carbon energy sector, countries such as Romania, Poland, Slovenia, Bulgaria have not considered a strategy to phase-out carbon (Europe Beyond Coal, 2020). Almost all the drop in power generation from coal/lignite has been absorbed by natural gas and renewable sources (Agora Energiewende and Sandbag, 2020). Indeed, those results seem to be in line with other findings in the field (Fosten, 2019)

3.1 Focus on monthly CO_2 trends for representative EU Countries

The analysis will now proceed with a focus on trends of CO_2 emissions for a group of representative EU countries. In the process of selection, the choice has been performed to provide a more diverse picture in terms of socioeconomic characteristics, historical background and energy consumption patterns (Agora Energiewende, 2019; Cofala, 1994; Diakoulaki and Mandaraka, 2007; Dienes, 1976; 'Energy in Eastern Europe — Part 1 The Institutional Framework', 1991; Mackay and Probert, 1993). Fossil fuels still represent the greatest share of primary energy consumption for EU countries (and globally)(Dincer and Abu-Rayash, 2020). In fact, despite the presence of inland reserves, Europe as a whole is accounted as net importer of fossil fuels (80% of oil and oil products and 60% of gas) (Högselius and Kaijser, 2019; Kopnina, 2016).

Figure 5 - Total monthly CO_2 emission from fossil fuel combustion for selected countries

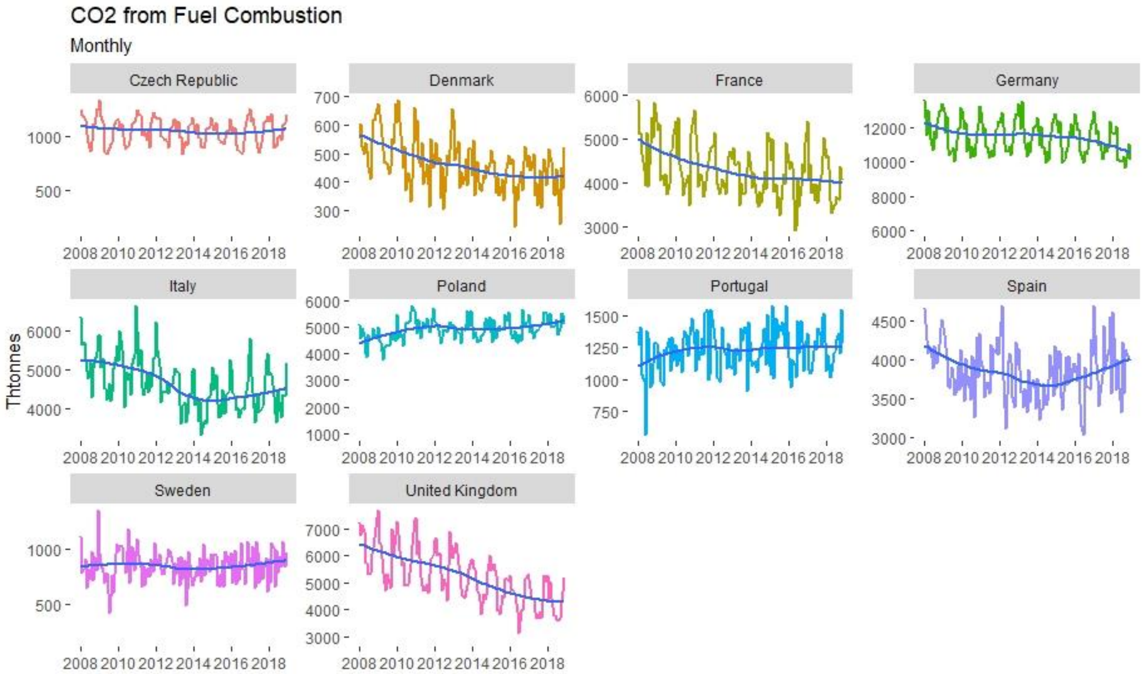
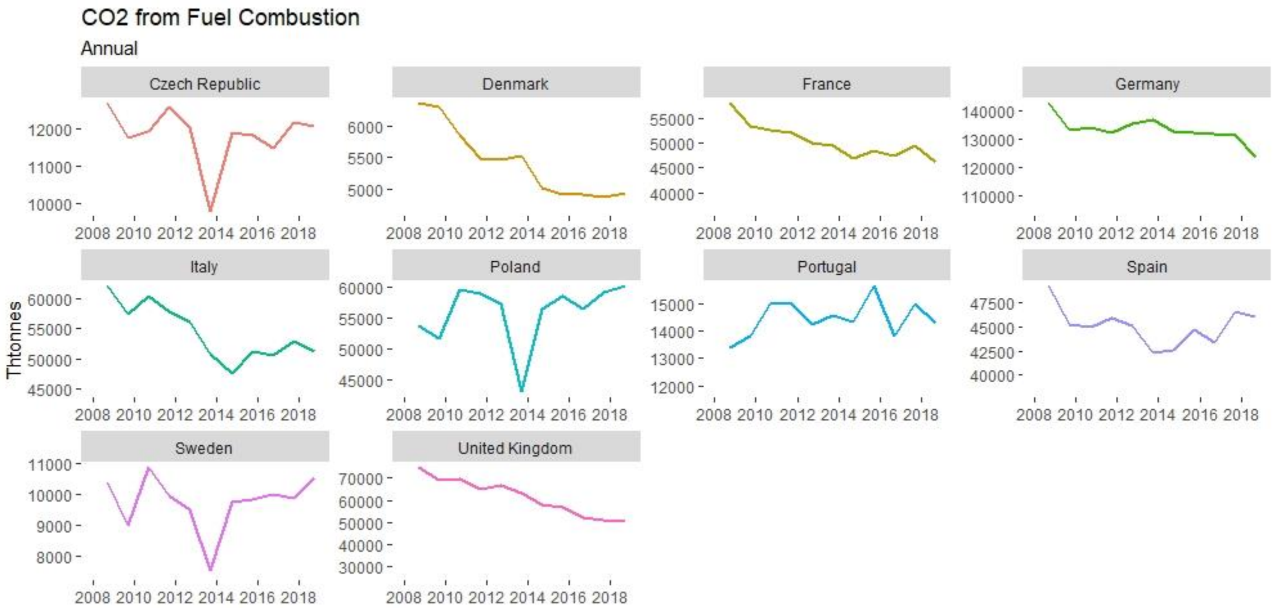


Figure 6 shows monthly trends for CO_2 emissions for 10 European countries. The total level of emissions appears to show a clear downward trend for Denmark, France, United Kingdom. Italy, after a consistent decrease, hit the minimum in 2013 before slightly increasing afterwards. However, the Country managed not to reach pre-2013 levels of CO_2 emissions. Germany manifests the highest performances in terms of emissions with an average level of around 10 million tonnes for the period considered and 50% of the stock[12] reached in 2013. Spain shows another clear trend, with a downward pattern until 2013 and an increase afterwards almost returning back to the previous CO_2 levels. Much clearer patterns can also be detected in the annual trend (Figure 7).

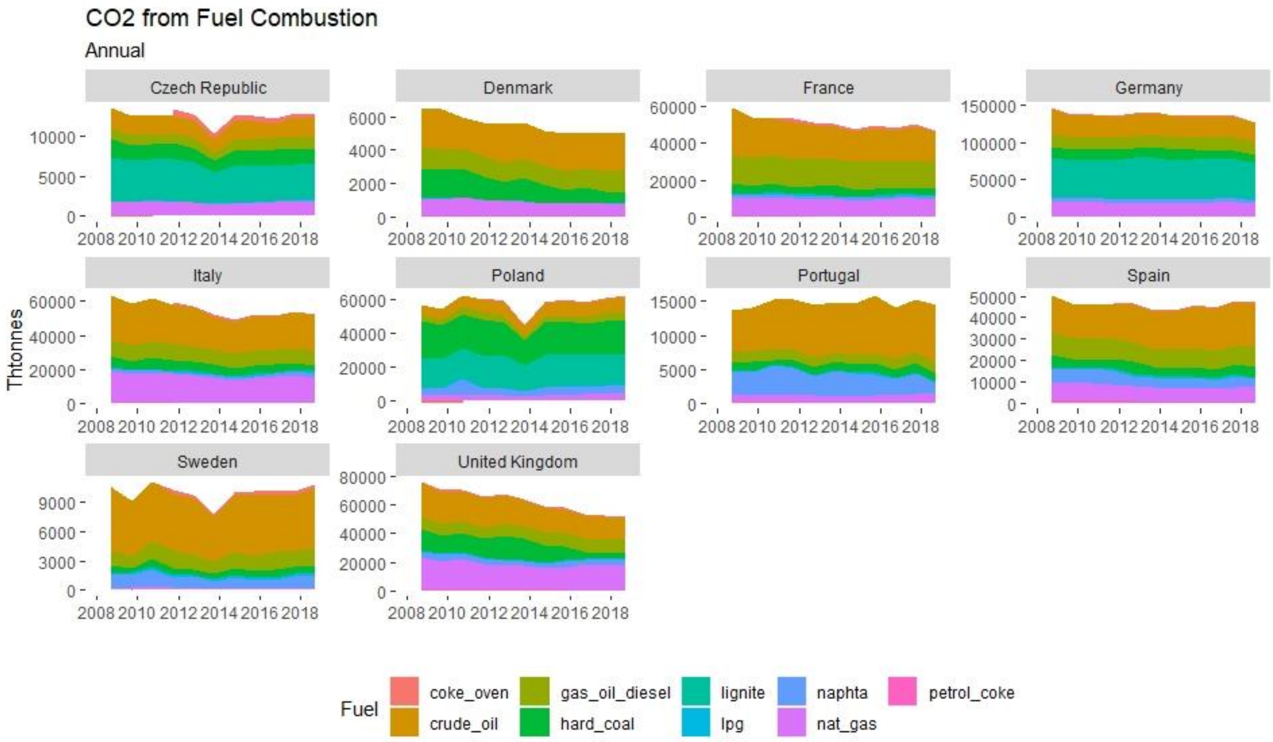
[12] The timespan considered is 2008-2019

Figure 8 - Total annual CO_2 emission from fossil fuel combustion for selected countries



Along with the patterns already identified, it is possible to appreciate how Poland, Sweden and Czech Republic show a minimum point in 2013. Another interesting representation in Figure 8 shows carbon dioxide emissions for the selected countries per type of fuel. In fact, within the EU it is possible to identify several clusters based on the degree of diversification of their energy mix. The study conducted by (Csereklyei et al., 2017) identified 7 clusters according to the degree of concentration of one source of energy. There are countries that heavily rely on liquid (e.g., oil and oil products) fuels such as Cyprus, Malta, Luxemburg. On the other hand, some countries (e.g., Estonia, Poland) shows a higher share of solid (e.g., coal) in their energy mix. Among the countries that are performing a sensible transition towards renewable sources there are Italy, France, Portugal, Finland, Sweden, Greece. In those countries the share of renewables can also reach half of the total energy mix. Also, sources of emissions might also vary according to the availability of that specific resource. Countries such as Denmark with oil, United Kingdom with natural gas, Poland with coal show a higher share of emission from that source.

Figure 9 - CO_2 emission from fossil fuel combustion for selected countries annual trend

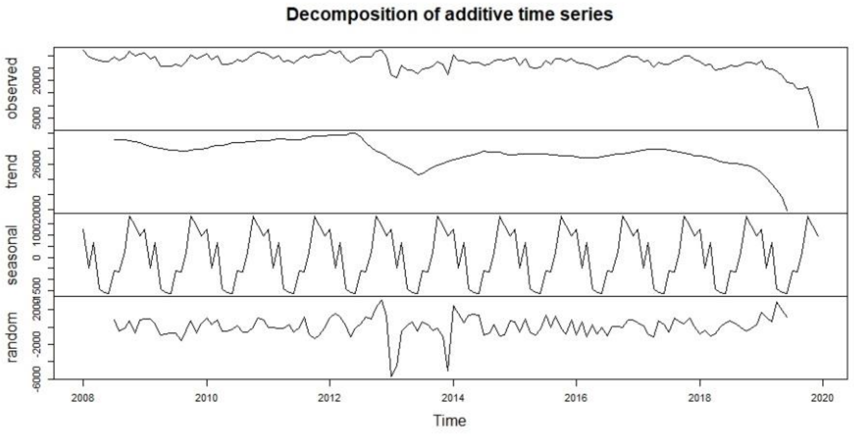


For some countries (Sweden, Portugal, France, Spain) the largest share of emissions comes from crude oil. On the other hand, in Germany, Czech Republic, Poland emissions appear to be more coal-sourced. Historically, eastern European countries have always relied more on coal for power generation, given also the availability of this resource in their territory (Cofala, 1994). Due to the current European framework on energy and climate and environmental issues, Czech Republic have experienced a decrease in coal and lignite production (Sivek et al., 2020). In Germany Lignite and Hard coal produced 24GW and 21 GW respectively (Keles and Yilmaz, 2020). Poland represents the first largest coal producer and the second largest lignite producer in Europe (Brauers and Oei, 2020). For this reason, Polish government has always adopted a proactive approach to protect coal industries and supply chain (Brauers and Oei, 2020). Further, coal accounts for more than half (56% in 2019) of primary energy supply (Budzianowski, 2012). In 2013 around 52% of polish generating units were power plants based on coal and 25% lignite-fired plants (Gawlik et al., 2015). Of further note, according to the last account oil demand for Czech Republic and Poland have increased in 2019 (+3.2% and +4.6% respectively) whereas for Italy decreased to -2.6% (Cooper, 2020). For Italy and United Kingdom, also natural gas exerts a consistent contribution to the emission toll of carbon dioxide. After the liberalization of the natural gas market (Directive 2009/73/EU), Italy has become the fourth largest consumer of this fuel (Capece, 2014). UK's coal phase-out started nearly at the end of the '70s with the progressive privatization of all the energy sector, cheaper prices for oil and gas and an increasing concern for the environment (Pearson and Watson, 2012). Indeed, both the two countries saw an increase (in Italy +12 TWh in 2019) in gas generation also due to the progressive phase-out from carbon (especially for UK)(Agora Energiewende and Sandbag, 2020).

3.2 Time series analysis of aggregated monthly trend

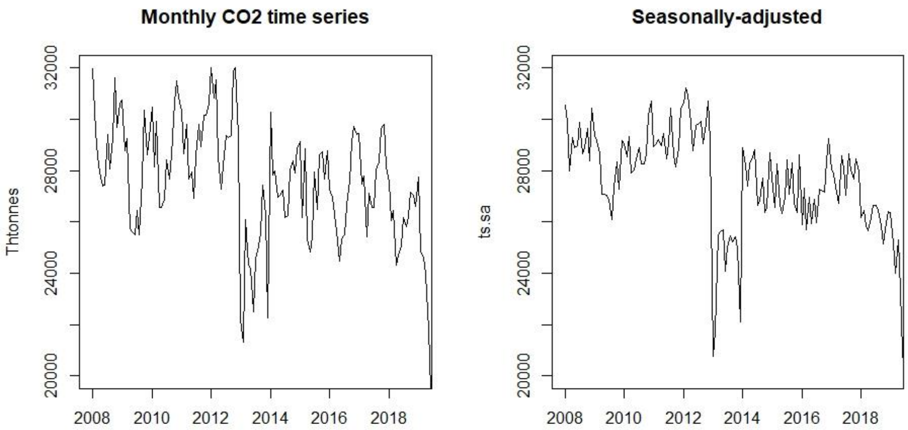
The analysis will follow with a graphical representation of the aggregated monthly CO_2 series along with seasonal trends. Further, structural break analysis will be delivered to single out eventual break points in the series. As final step, considering this preliminary analysis the best fit to forecast the series will be presented. Figure10 shows the representation of the decomposed time series for CO_2 monthly series

Figure 10 – Decomposition of monthly CO_2 emissions



As it is possible to appreciate from the trend, CO_2 levels hit the maximum at the beginning of 2013 and the minimum at the end of the same year. However, the aggregated level of emissions did not reach the same levels as pre-2013. The seasonal trend, manifests peaks during colder seasons. In Figure 11 both seasonalized and de-seasonalized[13] time series are depicted to allow a better comparison. From this representation it is also possible to spot another drop around the end of 2009.

Figure 11 – Monthly CO_2 emissions with seasonal-adjusted trend

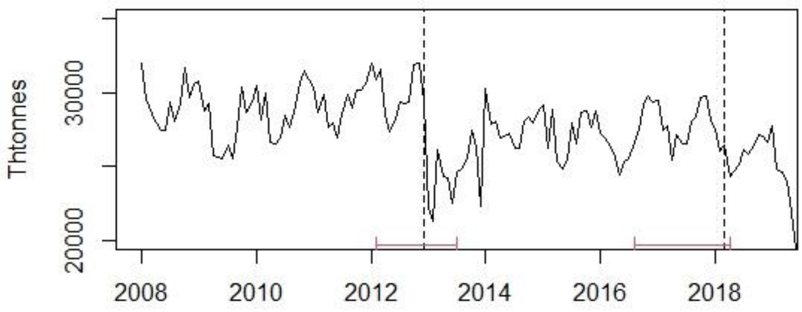


Perhaps, this one it might be also related to the economic and financial downturn in those years. As for structural breakpoint, the following plot (Figure 12) shows the two identified using the approach in (Bai & Perron, 2003). The plot depicts CO_2 monthly series with breakpoints and confidence

[13] In Appendix B also available the seasonal plot of the series

intervals. As depicted in the chart, the series presents to breakpoints: one in December 2012 and one in March 2018. The one in 2013 has also been identified in the previous analyses of the whole dataset.

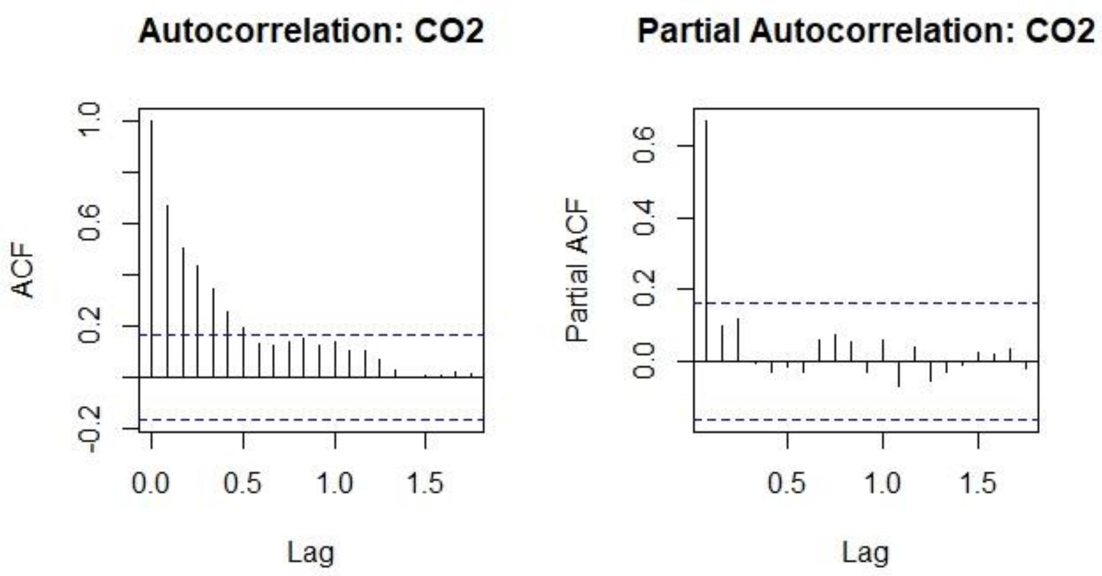
Figure 12 – Monthly CO_2 emissions with structural breakpoints



One possible explanation has already been given, since 2013 witnessed a wide slowdown of the EU economy. Also, in 2013 the European Emission Trading Scheme enters its Phase III. As for the second one, it might be related to the progressive lack of data approaching the year 2019. As a matter of fact, in March 2018 US President Donald Trump announced the imposition of tariffs to foreign aluminium and steel imports (Baker and Swanson, 2018; Zurcher, 2018). At that time, the EU represented the third supplier of the two raw materials (US$ 6.2 billion for steel, US$ 1.1 billion aluminium)[14] behind Canada. Also, in 2018 with Decision 2015/1814/EU the European Commission established the introduction of the Market Stability Reserve in force by January 2019 within the EU ETS. This introduction represented a substantial reform of the scheme dealing with the structural over-supply of emission permits as effect of the very first phases. To proceed further on, with the best model that fits the series, Figure 13 shows Autocorrelation (ACF) and Partial-Autocorrelation (PACF) plot for the whole series.

[14] Data from US Department of Commerce

Figure 13- Autocorrelation and Partial Autocorrelation plot



The two plots above show ACF and PACF for the series whereas the two below for its first difference. In fact, according to the Augmented Dickey-Fuller (ADF) test, it is possible to reject the null hypothesis, therefore the series results stationary in its levels[15]. Table 2 shows the results for the best model fit for the time series following the procedure in (Hyndman and Khandakar, 2008)[16].

Table 2 – Model fit for monthly CO_2 emissions

ARIMA (1,0,0) with non-zero mean

	AR1	**mean**	
Coefficient	0.4279	28839.6	
SE	0.1139	406.2799	
sigma^2 estimated as 3754975: log likelihood=-592.31			
AIC= 1190.62	AICc= 1191.01		BIC= 1197.19

According to the estimation, the series could be explained by an Autoregressive Integrated Moving Average (ARIMA) model with q =1. Furthermore, the analysis of the residuals (Figure 14, Appendix C) shows no sign of patterns. In this sense, the best fit for the series is a mean-reverting autoregressive process of the first order (AR (1)). A more refined estimation goes beyond the scope of the present

15 Results of the tests are available in Appendix D

16 The selection procedure takes into account Augmented Dickey-Fuller (ADF) Test for unit root and Canova - Hansen test to check stability of seasonal patterns. The best fit, is also the one that minimizes the Akaike Information Criterion (AIC) statistics. For further insight on the method consult (Hyndman and Khandakar, 2008)

work. Indeed, considering the limits of this estimation, further speculations on the model fit might be object of another piece of research. However, the Canova-Hansen[13] test showed a quite weak seasonal pattern for the series (see also PACF in Figure 13).

4. Conclusions and policy implications

As highlighted by the most recent events, the need of cleaner air it is not strictly an environmental threats, but also a concern for human health (Coker et al., 2020). In this sense, CO_2 represents the widest and one of the most dangerous pollutants in the atmosphere. A better control of its emissions, is crucial to comply with the (hopefully) more and more stringent objectives posed at international level to curb air pollution. The aim of the present work is to provide a further level of specification on the analysis of CO_2 patterns via analysing monthly levels. Furthermore, as one of the heavily-polluting and one of the most pivotal, the energy sector has always been the focus of much stricter regulations for emissions. The data displayed above, represents one of the few instances of analysis of emissions at monthly level in Europe[17]. Data on emissions show a quite homogeneous trend for most of the fuels considered. The majority of the trends shows a minimum level in 2013 as the primary result of a generalized slowdown in industrial production. Another interesting pattern is related to coal-sourced emissions (e.g., Hard Coal, Lignite). From the analysis of the data it is possible to appreciate the progressive decrease over time of the levels of carbon dioxide emitted as the results of their combustion. This piece of evidence can be considered in line with a process started decades ago of the progressive substitution of carbon for energy consumption. Despite the high emitting potential and the relative consistent heat content, solid fuels were overcome by Crude Oil in emissions. In fact, with the data at disposal it is not possible to assess whether this change in emissions (and consumption) patterns has led to more environmentally-concerned sources (e.g., renewables) or to a more conscientious behaviour (e.g., energy efficient) of the enterprises in the sector. However, it is out of doubt renewable energy are now a considerable part of the energy mix in Europe (IEA, 2019). Furthermore, in 2008 production of renewable energy overcame production of coal in the European Union (DG Energy, 2020). The analysis proceeded with the focus on 10 representative EU countries. Despite the quite homogeneous path over time, differences can be found in major sources of emissions. Some countries continue relying on coal-sourced energy (e.g., Poland, Germany). In some others, liquid (e.g., crude oil) fuels appear to exert the largest amount of emissions (e.g., Denmark, Spain, Sweden). For some others sources of emissions are more mixed, with a high prevalence of liquid/gaseous fuels (e.g., Italy, United Kingdom). Reasons of this clustering can be tracked down to the historical energy consumption patterns of the single countries and to the resources, eventually, present in each territory. Overall, despite some exceptions, the data show the majority of countries is now in the process of phasing out coal from their energy mix. Aside from other possible factors, this process might be considered one result of the policy efforts at EU level in terms of carbon pricing (e.g., EU ETS). As final step, this work has ventured to analyse the aggregated monthly series of carbon dioxide adopting a time series econometrics approach. Time series econometrics allows for a better understanding of the characteristics of the series (e.g., stationarity, seasonality, structural breaks, cointegration), hence will provide more pieces of information for the analysis of the phenomenon under object. In the realm of GHGs emissions, time series analysis may enable more tailored policy responses to changes in trends and a more profound understanding of the linkages with other socioeconomic variables (e.g., GPD, population, innovation). The series presents two structural

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[17] In the US, US Energy Information Administration (US EIA) publishes the *Monthly Energy Review* with estimates of monthly CO_2 emissions from energy consumption for the USA.

breaks at the end of 2012 and in March 2018, respectively. According to the tests, presented some (weak) seasonal trend in relation to winter periods. ACF and PACF plots for the series in levels, highlighted how the series appears stationary for the period considered. However, an approximation of the Data Generating Process (DGP) suggested an ARIMA model with one lag in the deterministic component.

In its essence, this work tries to present this dataset and its potentialities for further analysis. From this first attempt, some interesting points have been arisen that might be object of further research efforts. Starting with empirically assessing whether the decrease in coal-sourced emissions might be appointed to the increasing carbon price at EU level, namely the European Emission Trading Scheme. Another long-debated question is related to the possible decoupling of emissions and economic growth[18](e.g., *Environmental Kuznest Curve*)(Fosten, 2019; Piaggio and Padilla, 2012). Furthermore, a possible addition of carbon dioxide estimates of ulterior fossil fuels might provide a more comprehensive picture of monthly trends of the complete European energy mix. Of further interest might be a deeper analysis at country-level of national CO_2 emission trends from fossil fuel combustion. As for the estimation of the DGP, a further investigation could involve non-linear models within the time series domain.

[18] According to (IEA, 2020b)

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Appendix A

The methodology to calculate $Excluded\ Carbon$ follows (Eggleston et al., 2006b). In this sense, excluded carbon represents that amount of carbon that does not lead to fuel combustion emissions. Some fuels are used in industrial processes as feedstocks, reductants or for non-energy purposes. Therefore, for the estimation of carbon from energy consumption, that part not strictly employed in the energy sector shall be excluded from the computation. Table 3 summarizes all the fuels employed and their functions in industry.

Table 3- Products used as feedstocks, reductants and for non-energy purposes

Feedstock	Naphta
	LGP (buthane/propane)
	Refinery gas
	Gas/diesel oil and Kerosene
	Natural Gas
	Ethane
Reductant	Coke oven coke (metallurgical coke) and petroleum coke
	Coal and coal tar pitch
	Natural Gas
Non-energy products	Bitumen
	Lubricants
	Paraffin waxes
	White spirits

Source (Eggleston et al., 2006b)

Some fuels, especially those employed as feedstocks are also used for heat raising. Most of the fuel products are used in the iron and steel industries. The equation below shows the computation of excluded carbon for the relevant fuels

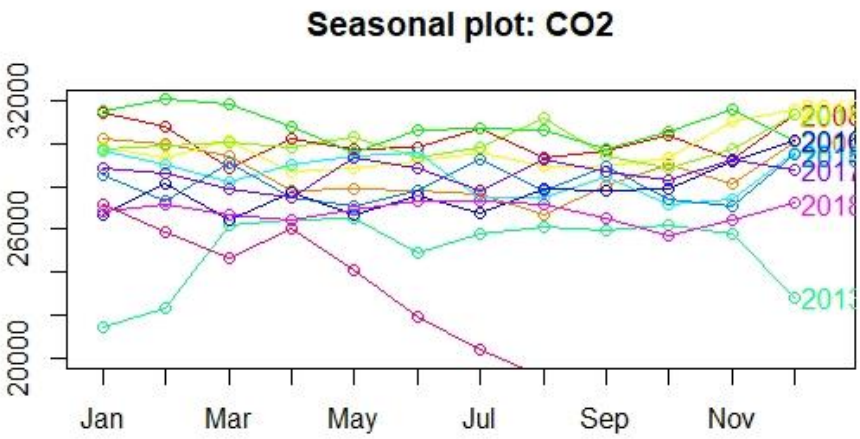
$$Excluded\ Carbon_{fuel} = Activity\ Data_{fuel} * CC_{fuel} * 10^{-3}$$

Activity data are those flows of fuels that are delivered to other sectors. Therefore, their carbon emissions are reported in other sections of national inventories.

Appendix B

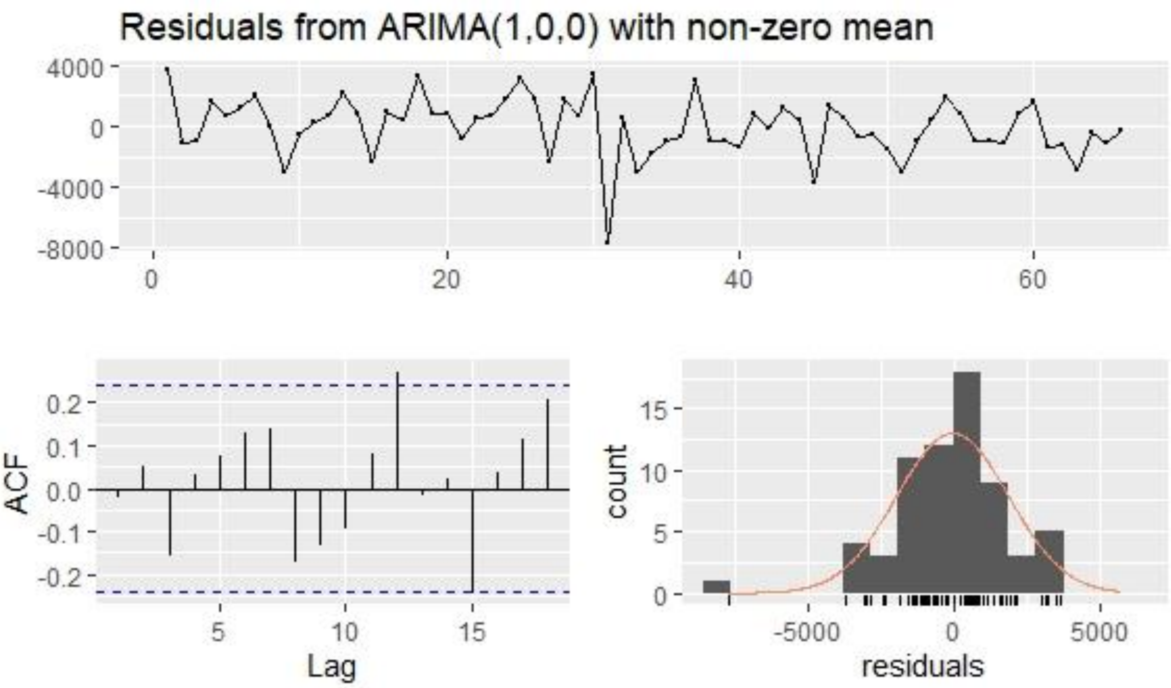
Figure 14 shows the seasonal plot for the whole CO_2 monthly series. As it is possible to deduce, the trend is similar pretty much all over the sample.

Figure 14- Seasonal plot monthly CO_2 aggregated trend



In fact, data points seem to converge within a specific interval with the exception of two years. As already pointed out above, 2013 appears to be the divergent period in the sample. Causes of this occurrence, have always been speculated in the previous sections. Indeed, the aggregated series presents one structural break at the end of 2012 (Figure 12). Also, as it can also be viewed in Figure 11, after 2013 the series shows lower level of emissions on average. Another outlier is represented by the 2019. Indeed, especially at the end the period country series presented a lot of missing values approaching the end of the year.

Appendix C



Appendix D

Table 4- Augmented Dickey-Fuller test

Statistics	Value	p-value
Augmented Dickey-Fuller test	-6.2003	0.01
Alternative hypothesis: stationarity		

Table 5- Canova-Hansen test

Canova-Hansen test		
	Coeff.	**p-value**
Jan	0.3142	0.1337
Feb	0.3443	0.1075
Mar	0.6	0.0142 *
Apr	0.5871	0.0158 *
May	0.4809	0.0376 *
Jun	0.3935	0.0746 .
Jul	0.5191	0.0278 *
Aug	0.3693	0.0895 .
Sep	0.4326	0.055 .
Oct	0.5586	0.021 *
Nov	0.2295	0.2486
Dec	0.228	0.2516
Joint	1.6684	0.4462

Sign. Codes	0 ‘***’ 0.001 ‘**’ 0.01 ‘*’	0.05 ‘.’ 0.1 ‘ ’ 1
Test type: seasonal dummies		
		NW covariance matrix lag order: 13