Science of the Total Environment 909 (2024) 168528

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Analysis of the carbon emissions trend in European Union. A decomposition and decoupling approach

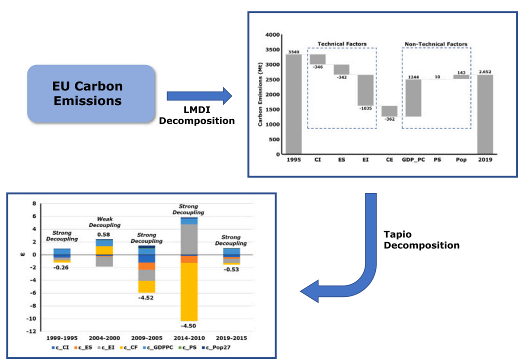
Vincenzo Bianco [a,*], Furio Cascetta [b], Sergio Nardini [b]

[a] Università degli Studi di Napoli Parthenope – Dipartimento di Ingegneria, Centro Direzionale Isola C4, 80133 Napoli, Italy
[b] Università degli Studi della Campania "Luigi Vanvitelli" – Dipartimento di Ingegneria, Via Roma 29, 81031 Aversa, CE, Italy

HIGHLIGHTS

- LMDI and Tapio's methodologies are used to study decomposition and decoupling of CO_2 emissions in EU.
- Technical, climatic, and socio-economic factors are highlighted by using a 7 factors identity.
- Technical factors contribute to the reduction of the carbon emissions and support the decoupling.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Pavlos Kassomenos

Keywords:
LMDI decomposition
Tapio decomposition
Decoupling
Carbon emissions
Energy consumption

ABSTRACT

This work is aimed to investigate the carbon emissions trend in the European Union. Logarithmic Mean Divisia Index and Tapio's methodology are used for decomposing the carbon emissions and investigating the decoupling factors respectively. Seven indexes are identified, namely carbon intensity of the energy sector, energy consumption structure, energy intensity, climatic factor, Gross Domestic Product per Capita, population distribution, and population evolution. These indexes are then grouped in three macro-categories, specifically technical factors, climatic effect, and socio-economic factors. The study covers the period 1995–2019 and considers EU 27 countries at an aggregate and individual level. Carbon emissions in EU 27 reduced of 689 Mt from 1995 to 2019. Technical factors are responsible for a decrease of 1723 Mt, the climatic effect determines a reduction of 362 Mt, whereas socio-economic factors cause an increase of 1397 Mt. The Strong Decoupling status is achieved in EU 27 in the period 1995–2019 with a decoupling index equal to −0.4. This means that carbon emissions reduced while Gross Domestic Product increased. To provide more precise insights, the paper also presents analyses at individual country level and the splitting in five temporal sub-periods.

* Corresponding author.
E-mail address: vincenzo.bianco@uniparthenope.it (V. Bianco).

https://doi.org/10.1016/j.scitotenv.2023.168528
Received 28 August 2023; Received in revised form 19 October 2023; Accepted 10 November 2023
Available online 12 November 2023
0048-9697/© 2023 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Carbon emissions are a critical parameter to be monitored since they are directly linked with the economic development and lifestyle. In general, the higher the economic development and lifestyle are, the higher is the level of carbon emissions, since the consumption of energy resources is more intensive and nowadays, despite the relevant increase of renewables, most of energy derives from fossil fuels. This is a critical issue as carbon dioxide is a greenhouse gas, namely one of the main driving forces of the global warming as noted in (Ozturk and Acaravci, 2010).

Considering the criticality of the global warming, the 2015 United Nations Conference of Parties (COP) held in Paris committed to reduce the carbon emissions to limit the increase of global average temperature to <2 °C compared to pre-industrial levels, with the ambition to keep the increase below 1.5 °C (King et al., 2017; Rogelj et al., 2016).

To limit carbon emissions, different policy tools can be developed such as carbon taxes or emission allowances markets. For instance, back in 2005, the European Union launched the Emission Trading Scheme, a marked-based mechanism where companies belonging to a set of carbon intensive sectors are obliged to buy carbon allowances (Zhang and Wei, 2010). Price is determined by the clearing of demand and offer; thus, companies are solicited to evaluate the convenience in developing investments for the abatement of carbon emissions (Tsai et al., 2012). Many of these investments are directly linked with the implementation of energy efficiency measures.

To reduce carbon emissions, it is fundamental to understand the driving forces influencing the emissions and how the different changes in the emissions levels from year to year can be explained.

A possible approach for determining the drivers responsible for the carbon emissions is the utilization of the Index Decomposition Analysis (IDA). A first model based on IDA for the decomposition of carbon emissions was proposed by Kaya as discussed by Štreimikienė and Balezentis (Štreimikienė and Balezentis, 2016). Kaya identity links carbon emissions to four parameters, namely carbon intensity, population, energy intensity, and economic activity. To assess the impact in terms of carbon emissions determined by each of the four factors, it is necessary to employ a decomposition methodology.

Ang (Ang, 2005; Ang, 2015) introduced the Logarithmic Mean Divisia Index (LMDI) methodology for decomposing the IDA identity in an additive form. LMDI is very powerful since it is based on a simple analytical framework and it has the enormous advantage to leave no residuals after the decomposition. Other methodologies, such as the Laspeyres method, have residual errors after the decomposition and complex formulas are needed for their redistribution (Ang, 2004). These two elements make the LMDI approach very popular among researchers.

In the study of carbon emissions, it is relevant to understand the connection with economic growth, which is usually one of the main influential factors (Wang et al., 2018). The analysis of the decoupling, namely the degree of disconnection between carbon emissions and economic growth, is an important topic since it allows to investigate the decarbonization effort. The decoupling analysis attracted the interest of many researchers after the work of Tapio (Tapio, 2005) who developed and defined eight decoupling states. Tapio's methodology can be effectively combined with the LMDI decomposition analysis to understand the impact that each factor provoking carbon emissions has on the decoupling. The combination of these two approaches has raised the interest of many scholars worldwide.

The literature review, presented in Section 2, highlights the interest towards the investigation on the decomposition of carbon emissions since the comprehension of the driving forces suggests possible strategies to implement mitigation actions. On the other hand, it can be said that there is a special focus on some countries, e.g., China, whereas other countries are less represented. EU is scarcely analysed as a whole, despite its importance from both economic and energetic point view. Based on this, the present work attempts to answer the following research questions:

- Has the decarbonization process affected the economic development in the period 1995–2019?
- Which are the factors that drive the decarbonization in EU27 and its member countries?
- How much does each factor affect the decoupling/coupling of carbon emissions and economic development?

To answer these questions, the present work proposes an approach based on the additive LMDI decomposition and on the Tapio's methodology to assess the level of decoupling.

The novel contribution of the present work can be summarized as follows:

- An additional contribution to the limited studies on carbon emissions decomposition and the corresponding decoupling status in EU27 is proposed by considering each single country and the total EU27 for the period 1995–2019. LMDI additive decomposition and Tapio's decoupling model are jointly employed in the present analysis.
- An innovative seven factors decomposition analysis is introduced where the climatic effects are also considered. Since a relevant share of fossil fuels is consumed for buildings heating, climatic conditions affect the carbon emissions, and the proposed model allows to estimate this effect.

The proposed study is relevant since, based on an innovative decomposition equation, it provides a quantitative overview of the driving factors for carbon emissions in EU27 and the corresponding decoupling status. Additionally, the contribution of each factor to the decoupling is highlighted for each of the EU countries.

The rest of the paper is organized as follows: Section 2 contains the literature review, Section 3 illustrates the theoretical framework for developing the analysis, Section 4 describes the trend of the main variables, Section 5 reports the main results, and Section 6 presents the conclusions of our work.

2. Literature review

2.1. LMDI studies

The analysis of Carbon Emissions attracted the interest of many researchers who tried to understand which factors determine carbon emissions and how their effect can be estimated. To this aim LMDI decomposition approach proposed by Ang (Ang, 2005; Ang, 2015; Ang, 2004) gained relevant popularity for its simplicity and effectiveness. Different studies focusing on the LMDI decomposition of carbon emissions and energy consumption in EU can be found in the literature.

The LMDI decomposition analysis of GHG emissions in EU-15 is considered in (Bhattacharyya and Matsumura, 2010). A multiplicative decomposition framework is applied, while energy and non-energy related emissions contributions are highlighted. The period 1990–2007 is analysed and the study illustrates that, overall, EU-15 has developed a relevant effort to reduce its emission level, but when individual countries are evaluated, the performance varies considerably. In particular, Germany and UK represent two successful cases, whereas Italy and Spain are less successful (Bhattacharyya and Matsumura, 2010).

Similarly, EU-27 is analysed in (Fernández González et al., 2014a) in the period 2001–2008 by employing the standard multiplicative and additive LMDI based on five factor decomposition. Namely, population, GDP per capita, energy intensity, fuel mix, and carbon emission factor are included in the analysis. The study highlights that Mediterranean countries and former-socialist countries (e.g., most of the Eastern European Countries) should improve the effort in reducing their emissions (Fernández González et al., 2014a). The same authors propose another work (Fernández González et al., 2014b) where they focus on how to estimate energy intensity and how its definition impacts the decomposition analysis of the power sector carbon emissions. Overall, it is found that the energy mix factor has a strong impact, even though at country level the situation is more jeopardised and specific actions are needed. For such a reason, Moutinho et al. (Moutinho et al., 2015) propose a six factors additive decomposition analysis applied to four homogenous macro-regions, namely Eastern, Western, Northern and Southern Europe. The work highlights the impact of RES development on carbon emissions in the period 1999–2010. A reduction of the emissions is detected in the considered macro-regions driven by the change in the fuel mix (e.g., increased share of less carbon intensive fuels) and by the reduction of the fossil fuel amount for generating energy (i.e., increased share of RES).

Sectoral analyses are also important as they allow to investigate more in-depth the characteristic of specific sectors as is the case of power sector (Karmellos et al., 2016), which is one of the largest contributors to carbon emissions. The decomposition of CO_2 is studied within the period 2000–2012 for EU-28. Five driving factors are included in a LMDI additive analysis, namely the activity, electricity intensity, electricity trade-off (i.e., the opportunity to generate electricity for export purposes), efficiency effect, and fuel mix effect. The study highlights that the main factor determining an increase in emissions is the activity, oppositely the decrease in carbon emissions is mainly driven by a reduction of electricity intensity (Karmellos et al., 2016).

Due to its flexibility and analytical simplicity, the LMDI decomposition is often integrated within larger analytical framework as presented in (Trotta, 2019) where energy efficiency and energy dependence are also considered. The analysis is developed for the overall EU aggregation without the detail on the single countries within the period 1995–2015. A standard additive LMDI method is applied by considering activity, structure, and intensity effects. Industrial, transport, and residential end-uses are considered in the study. Carbon emissions savings are estimated by estimating a CO_2 emission coefficient in each sector. Thus, by multiplying this coefficient for the energy saving, an estimation of the carbon emissions is obtained. The paper concludes that the main driver for CO_2 reduction is the reduction of the intensity effect, namely an improvement in terms of energy efficiency (Trotta, 2019).

Other studies (Pani and Mukhopadhyay, 2010; Moutinho et al., 2018) are developed at global level by including EU in the comparisons with other areas of the world. In particular, Pani and Mukhopadhyay (Pani and Mukhopadhyay, 2010) apply the standard Kaya equation to the decomposition of carbon emissions in 114 countries within the period 1992–2004. They conclude that the upper-middle income countries of Europe and Central Asia reduced their carbon emissions while keeping their economic growth. Whereas North America, East Asia Pacific and South Asia accompanied their economic growth with an increase of carbon emissions. A similar study is developed by Moutinho et al. (Moutinho et al., 2018) too. They propose a six factors decomposition covering the top 23 countries (10 of them from EU) in RES development for the period 1985–2011. The focus of the study is to evaluate the impact that RES development has on the level of carbon emissions. It is concluded that the situation is quite different among the different EU countries as also noticed in previous studies.

More studies on LMDI decomposition at EU level are developed in relation to different energy sources (Fernandez Gonzalez et al., 2014), energy efficiency (Román-Collado and Economidou, 2021) and very recently on energy intensity (Perillo et al., 2022).

The contribution of the present paper to the reviewed literature is threefold. First, the present paper analyses the decomposition of carbon emissions for EU27 countries over a longer period, i.e., 1995–2019, with respect to the reviewed works. Second, the present work proposes a novel decomposition equation which extends the usual Kaya formula, and it includes the effect of climatic variations on carbon emissions. Third, it provides the analytical details for all the 27 countries considered with the same level of details, thus consistent comparisons can be developed.

2.2. Decoupling studies

The investigation of the relationship between carbon emissions reduction and economic growth attracts the interest of many researchers since it is paramount to understand if the transition towards a carbon free society is achieved by limiting the economic growth. The decoupling represents the disconnection of carbon emissions from economic growth, namely carbon emissions can be reduced without affecting the economic development. To this aim, Tapio (Tapio, 2005) proposed a simple quantitative methodology to evaluate the level of the decoupling which has been widely used in the literature.

The study of the decoupling status in EU is relevant, since EU decided to be a frontrunner in the abatement of carbon emissions by developing and implementing innovative mechanisms, e.g., EU-ETS, for carbon emissions reduction and by setting-up ambitious goals (i.e., Gree Deal, Fit for 55, etc.). Thus, it is of pivotal interest to understand and evaluate the decoupling between carbon emissions and economic growth.

The impact of EU energy policies on the decoupling is analysed in (Papież et al., 2021), where the standard Kaya equation is used for decomposing carbon emissions and then the Tapio decomposition jointly with regression analysis is applied. Authors observe that in almost all EU countries the decoupling is linked to the EU energy policy, but in some areas reduction of carbon emissions has been achieved thanks to the relocation of carbon intensive activities. A similar approach is used by Madaleno and Moutinho (Madaleno and Moutinho, 2018), who present an analysis focused on EU15 in the period 1995–2014. They introduce a 6-factors decomposition analysis by highlighting the contribution to carbon emissions of petroleum products. They observe that in the first period of analysis the decoupling is weak, whereas in the second period it becomes stronger probably due to the effective implementation of the Kyoto protocol (Madaleno and Moutinho, 2018).

Carbon emissions from power generation sector are considered in (Karmellos et al., 2021) since it is one of the main contributors to carbon emissions. EU27 and UK are studied in the period 2000–2018 through a 7 factors LMDI decomposition and Tapio decoupling model. The main innovative element included in this work is the inclusion of an "electricity trade effect" in the decomposition, which considers the impact of the domestically generated and imported electricity. The analysis concludes that the EU power sector in the period 2013–2018 is in a strong decoupling status.

The number of studies which employee LMDI decomposition and Tapio's methodology applied to carbon emissions is very limited. More often EU or some relevant EU countries are considered as part of larger groups (Wang and Su, 2020; Yan et al., 2021; Chen et al., 2018; Akdoğan et al., 2023). Wang and Su (Wang and Su, 2020) study 192 countries by using the standard Kaya decomposition equation and Tapio decoupling in the period 2000–2014. They find that EU is in a strong decoupling status interrupted only by the economic crisis. Yan et al. (Yan et al., 2021) considered 78 countries, including the whole EU. A standard Kaya decomposition model is implemented by including the country effect, namely the share of each country on the total. Then Tapio decoupling model is applied to analyse the decoupling status. This study also confirms that EU was in recessive decoupling status during the financial crisis, whereas in the recovery phase a strong decoupling is detected (Yan et al., 2021). OECD countries are investigated in (Chen et al., 2018) through a six factors decomposition model where a factor measuring carbon emissions from productive processes is included. The decoupling is studied through the Tapio model within the period 2001–2015. Results are presented only in aggregate form without the detail per each country. Overall, it is concluded that technical factors are more influential than non-technical ones. Finally, top 19 world emitters are studied in (Akdoğan et al., 2023) by considering two approaches, namely the impact of materials and energy on carbon emissions. Furthermore, the

Decoupling Effort Index (DEI) is also introduced. DEI measures the degree of decoupling effort from generic year "t" and year "0". The study includes three EU countries, namely Germany, Italy and Poland. If the period 1990–2019 is considered, a strong decoupling is achieved in the three EU countries included in the study.

The contribution of the present paper to the existing literature is twofold. First, it increases the very limited amount of work dedicated to the application of Tapio's methodology to decoupling studies by adding a paper with the analytical detail of each of the EU-27 countries in a long period of time (i.e., 1995–2019). Furthermore, it includes the climatic effect which has never been considered in the reviewed literature.

3. Material and methods

3.1. Decomposition model

The decomposition analysis of carbon dioxide emissions presented in this paper is based on the LMDI approach (Ang, 2005; Ang, 2015; Ang, 2004), which offers a simple and powerful analytical framework for the quantitative estimation of the driving forces determining the emissions.

The proposed mathematical model introduces a seven-factor index decomposition to identify, quantify and explain the drivers determining the carbon emissions in EU27. The aim is to consider the main technical, non-technical, and climatic factors which influence the emissions level.

The seven indexes considered in the decomposition equation are the carbon intensity (CI), the energy consumption structure (ES), the climatic factor (CF), the energy intensity (EI), Gross Domestic Product per capita (GDPPC), population share (PS), and total EU27 population (Pop). Eq. (1) represents the general form of the model:

$$CO_2 = CI \bullet ES \bullet CF \bullet EI \bullet GDPPC \bullet PS \bullet Pop \tag{1}$$

The seven indexes can be described in the following way:

- CI represents the carbon intensity of the energy sector, and it is calculated as the ratio between the carbon emissions, CO_2, and the fossil fuel energy consumption, Fos. The index is expressed in kt/GWh. It measures how much carbon dioxide is emitted for the utilization of one unit of energy by using the fossil fuel mix of a specific region.
- ES is the energy consumption structure of the energy sector, namely the ratio between the fossil fuel energy consumption, Fos, and the total energy consumption, Ene. It gives a measure of the share of fossil fuels in each region.
- CF shows the climatic factor, namely the ratio between the total energy consumption, Ene, and the weather adjusted energy consumption, Ene_{wa}. It offers a quantitative measure on how much climatic variations affect the carbon emissions. Ene_{wa} consists in the normalization of Ene based on the historical trend of the Heating Degree Days (HDDs) as illustrated in the next section.
- EI is the energy intensity estimated as the ratio between weather-adjusted energy consumption, Ene_{wa}, and the GDP expressed in real monetary units. The index is expressed in GWh/M€$_{2015}$. It can be seen as a measure of the efficiency of the economy of a country.
- GDPPC is the GDP per capita estimated as the ratio between the GDP and the population of a country. It is expressed in k€/head and it can be interpreted as a proxy of the individual spending capacity.
- PS is the population share of a country related to the total of the region under investigation. It is estimated as the ratio between the population of a single country, Pop, and the total population in EU27, Pop_{27}. It considers the relative evolution of a specific country within a larger region, EU 27 in the present case.
- Pop_{27} is the total population of EU27. The variation of the total population has an impact on the carbon dioxide emissions.

CI, ES, and EI can be defined as technical factors since they are linked to the technical structure of the energy sector and to the technical efficiency of the productive structure. CF is a climate factor since it illustrates the impact of weather volatility on the emissions. GDPPC, PS, and Pop_{27} are socio economic factors as they describe the social and economic context.

Based on the index definitions, it is possible to express Eq. (1) in a more explicit form as follows:

$$CO_2 = \frac{CO_2}{Fos} \bullet \frac{Fos}{Ene} \bullet \frac{Ene}{Ene_{wa}} \bullet \frac{Ene_{wa}}{GDP} \bullet \frac{GDP}{Pop} \bullet \frac{Pop}{Pop_{27}} \bullet Pop_{27} \tag{2}$$

It can be noted that Eq. (2) is an identity therefore the proposed index decomposition is appropriate.

To normalize the energy consumption data with respect to weather conditions, the weather adjusting procedure proposed in (Bianco et al., 2014) is considered. The procedure consists in the calculation of a coefficient based on the actual and historical average of HDD.

$$WAC_i = \frac{HDD_i}{HDD_{avg}} \tag{3}$$

Energy consumption in year "i" is thus multiplied by WAC_i to find the Weather adjusted energy consumption, i.e. ENE_{wa}.

To estimate the change in CO_2 within a time interval, the additive LMDI approach can be used so that ΔCO_2 can be estimated as the sum of the variation in CI, ES, CF, EI, GDPPC, PS, and Pop_{27}, as follows:

$$\Delta CO_2 = \Delta CI + \Delta ES + \Delta CF + \Delta EI + \Delta GDPPC + \Delta PS + \Delta Pop_{27} \tag{4}$$

The estimation of the terms reported in Eq. (4) can be determined according to the following expressions:

$$\Delta CI = w \bullet ln\frac{CI_{\theta 1}}{CI_{\theta 0}} \tag{5}$$

$$\Delta ES = w \bullet ln\frac{ES_{\theta 1}}{ES_{\theta 0}} \tag{6}$$

$$\Delta CF = w \bullet ln\frac{CF_{\theta 1}}{CF_{\theta 0}} \tag{7}$$

$$\Delta EI = w \bullet ln\frac{EI_{\theta 1}}{EI_{\theta 0}} \tag{8}$$

$$\Delta GDPPC = w \bullet ln\frac{CIGDPPC_{\theta 1}}{GDPPC_{\theta 0}} \tag{9}$$

$$\Delta PS = w \bullet ln\frac{PS_{\theta 1}}{PS_{\theta 0}} \tag{10}$$

$$\Delta Pop_{27} = w \bullet ln\frac{Pop_{27\_\theta 1}}{Pop_{27\_\theta 0}} \tag{11}$$

w is the weighting factor determined as:

$$w = \frac{CO_{2\_\theta 1} - CO_{2\_\theta 0}}{ln\left(CO_{2\_\theta 1}\right) - ln\left(CO_{2\_\theta 0}\right)} \tag{12}$$

The analysis is developed with yearly data and θ_1 and θ_0 represent the final and initial year of the period under investigation. The mathematical procedure is straightforward and guarantees a perfect decomposition without the presence of any residual. This property is one of the most important features of LMDI approach and contributes to its popularity within the scientific community.

3.2. Decoupling model

As suggested by Tapio (Tapio, 2005), the decoupling between economic growth and carbon dioxide emissions can be measured by considering the elasticity of the emissions with respect to the GDP and according to the obtained value, different decoupling status, described in Tables 1 and 2, can be highlighted. The elasticity, ε, can be

Table 1
Tapio decoupling states (Tapio, 2005; Li and Jiang, 2020).

Decoupling state	Specific conditions	ΔCO_2	ΔGDP	E
Decoupling	Weak decoupling	>0	>0	$0 < \varepsilon < 0.8$
	Strong decoupling	<0	>0	$\varepsilon < 0$
	Recessive decoupling	<0	<0	$\varepsilon > 1.2$
Negative decoupling	Expansive negative decoupling	>0	>0	$\varepsilon > 1.2$
	Weak negative decoupling	<0	<0	$0 < \varepsilon < 0.8$
	Strong negative decoupling	>0	<0	$\varepsilon < 0$
Coupling	Expansive coupling	>0	>0	$0.8 < \varepsilon < 1.2$
	Recessive coupling	<0	<0	$0.8 < \varepsilon < 1.2$

Table 2
Description of specific decoupling conditions (Pan et al., 2022).

Specific conditions	Description
Weak decoupling (WD)	Carbon emissions and GDP are growing but the pace of growth of CO_2 is lower than that of GDP.
Strong decoupling (SD)	GDP is growing and carbon emissions are decreasing. A full decoupling is achieved.
Recessive decoupling (RD)	Carbon emissions and GDP are decreasing but the pace of decrease of CO_2 is higher than that of GDP.
Expansive negative decoupling (END)	Carbon emissions increase with a higher pace with respect to GDP.
Weak negative decoupling (WND)	Carbon emissions and GDP are decreasing but the pace of decrease of GDP is higher than that of CO_2.
Strong negative decoupling (SND)	Carbon emissions increase while GDP decreases
Expansive coupling (EC)	Carbon emissions and GDP are growing with a similar pace.
Recessive coupling (RC)	Carbon emissions and GDP are declining with a similar pace.

determined according to Eq. (13):

$$\varepsilon = \frac{\frac{\Delta CO_2}{CO_{2\_t0}}}{\frac{\Delta GDP}{GDP_{t0}}} \tag{13}$$

Eq. (4) can be substituted in Eq. (13) to highlight the different factors contributing to the carbon dioxide emissions:

$$\varepsilon = \frac{\frac{\Delta CI + \Delta ES + \Delta CF + \Delta EI + \Delta GDPPC + \Delta PS + \Delta Pop_{27}}{CO_{2\_t0}}}{\frac{\Delta GDP}{GDP_{t0}}} \tag{14}$$

Eq. (14) can be split in seven contributions so that the contribution of each index to the elasticity can be estimated:

$$\varepsilon_{CI} = \frac{\frac{\Delta CI}{CO_{2\_t0}}}{\frac{\Delta GDP}{GDP_{t0}}} \tag{15}$$

$$\varepsilon_{ES} = \frac{\frac{\Delta ES}{CO_{2\_t0}}}{\frac{\Delta GDP}{GDP_{t0}}} \tag{16}$$

$$\varepsilon_{CF} = \frac{\frac{\Delta CF}{CO_{2\_t0}}}{\frac{\Delta GDP}{GDP_{t0}}} \tag{17}$$

$$\varepsilon_{EI} = \frac{\frac{\Delta EI}{CO_{2\_t0}}}{\frac{\Delta GDP}{GDP_{t0}}} \tag{18}$$

$$\varepsilon_{GDPPC} = \frac{\frac{\Delta GDPPC}{CO_{2\_t0}}}{\frac{\Delta GDP}{GDP_{t0}}} \tag{19}$$

$$\varepsilon_{PS} = \frac{\frac{\Delta PS}{CO_{2\_t0}}}{\frac{\Delta GDP}{GDP_{t0}}} \tag{20}$$

$$\varepsilon_{Pop27} = \frac{\frac{\Delta Pop_{27}}{CO_{2\_t0}}}{\frac{\Delta GDP}{GDP_{t0}}} \tag{21}$$

The sum of Eqs. (15)–(21) is equal to Eq. (14):

$$\varepsilon = \varepsilon_{CI} + \varepsilon_{ES} + \varepsilon_{CF} + \varepsilon_{EI} + \varepsilon_{GDPPC} + \varepsilon_{PS} + \varepsilon_{Pop27} \tag{22}$$

Eq. (22) represents the total decoupling elasticity of carbon emissions with respect to GDP, whereas Eqs. (15)–(21) respectively represent the elasticity of the carbon intensity, energy consumption structure, climate factor, energy intensity, GDP per capita, population share, and total population components with respect to GDP. These equations allow to determine the decoupling status of each of the driving force determining the emission level.

As noted in (Cheng et al., 2022), if one decoupling state emerged in the period of analysis, it would suggest that the decoupling between carbon emissions and GDP is quite stable. The contrary would result in a relatively unstable decoupling relation.

LMDI decomposition and Tapio decoupling model are effective and widely used tools in the study of energy consumption and GHG emissions. However, their utilization is hindered from some limitations, namely: (i) the selection of the decomposition variables is subjective, thus it is important to choose parameters that really affect the indicator object of the study (i.e., by analysing correlation indexes); (ii) data availability is crucial to develop the analysis; (iii) the accuracy of the weather adjusting parameter considered in this work is affected by the length of the historical series of the HDDs.

4. Data analysis

The proposed investigation covers the period 1995–2019 and all the data are retrieved from the European Statistical Office (Eurostat) (Eurostat, n.d.). Individual country data are obtained and analysed.

Fig. 1 reports the historical trend of the source data used for computing the indexes highlighted in Eq. (2).

Fig. 1(a) displays the trend in EU27 carbon emissions. A decreasing trend characterized by fluctuations can be noticed. The maximum level of CO_2 emissions is 3.5 Gt and it was recorded in 2004. In general, it can be said that emissions are pushed by economic development and climatic conditions since most of energy used in both economic activities and heating systems is based on fossil fuels. Anyway, from 2007 onward a steadily decrease in carbon emissions is observed. It can be partially explained by the economic downturn of the 2008–2012 but also by the decarbonization and energy policies launched at EU level (Radovanović et al., 2022; Paraschiv and Paraschiv, 2020). Furthermore, it can be added that DE, FR, IT and ES account for approximately the 60 % of CO_2 emissions in EU27. These four countries account for the majority of the EU27 also for the other considered parameters, namely energy consumption, population, and GDP. Thus, their trend influences EU27 tendency.

Fig. 1(b) shows the energy consumption trend in the analysed period. A fluctuating behaviour similar to that of carbon emissions can be observed. The plot also highlights the increasing share of renewables on the energy consumption, which substantially contributed to the change of the energy sector. The increase in RES generation has a direct impact on the amount of carbon emissions. It is found that carbon emissions and RES generation have a linear correlation coefficient equal to −0.91 in the period 1995–2019. This means that an almost negative (i.e., at the increase of RES generation there is a decrease of carbon emissions) linear relationship exists between these two variables. Furthermore, the weather-adjusted energy trend is highlighted to exclude the impact of climatic conditions. A better understanding of energy consumption in the period 2009–2013 can be gained since there was the contemporary presence of two effects, namely the economic crisis and variable climatic conditions. For example, in 2010 energy consumption was higher than that of 2009, but this could be mainly ascribed to cold climatic

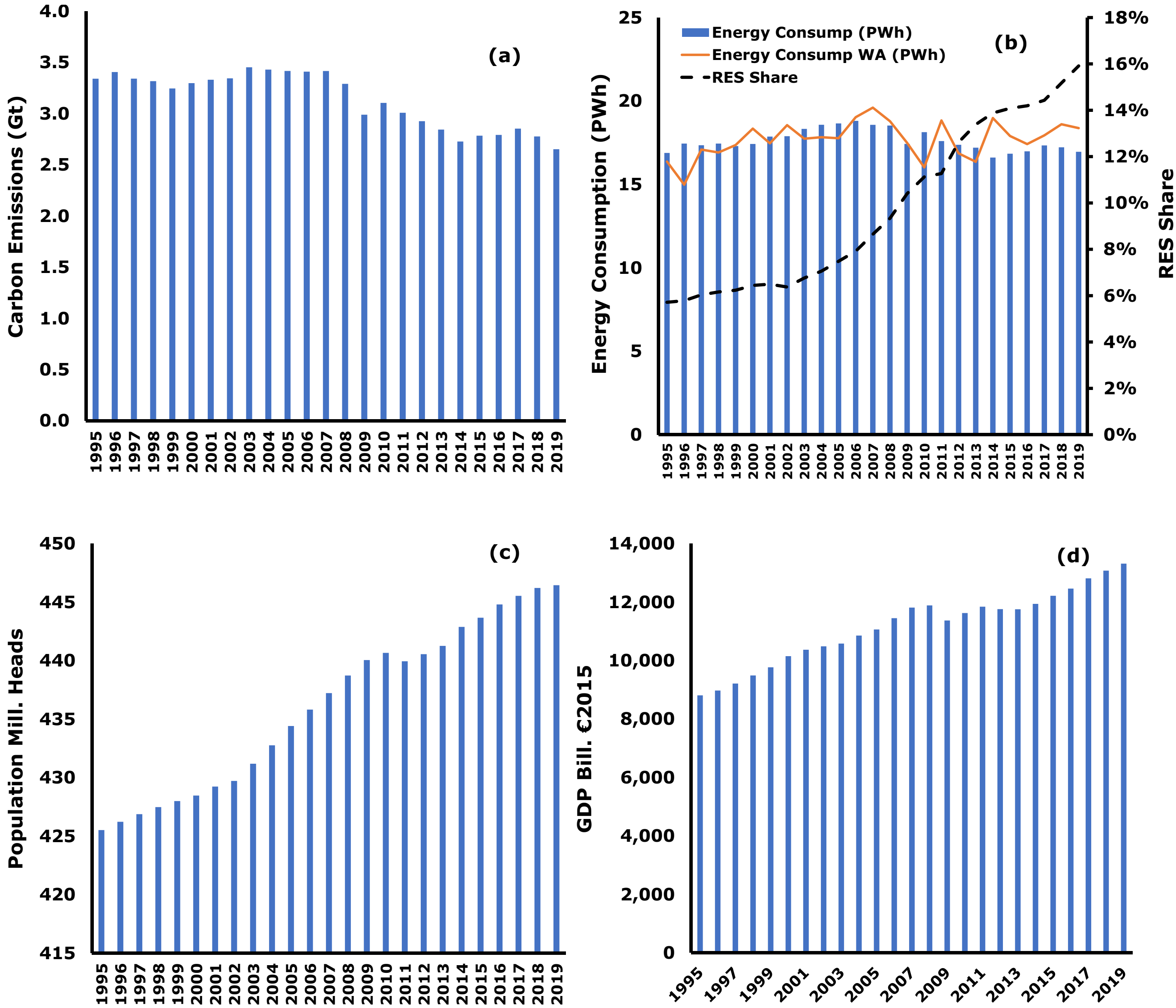


Fig. 1. Trend of the main data sources used for the analysis: (a) CO_2 emissions; (b) energy consumption; (c) population; (d) GDP.

conditions.

HDDs are chosen as parameter for weather normalization since they show a substantial degree of linear correlation with the energy consumption as shown in Table 3. Table 3 also highlights the level of linear correlation with the Cooling Degree Days (CDDs), that are a measure of how much warm the climate is (e.g., the higher the CDDS, the warmer the climatic conditions). Thus, at high CDDs level, an increased energy consumption for air-conditioning could be expected. This does not happen if the period 1995–2019 is considered because the trend in increasing use of air-conditioning is relatively low in EU (*The Future of Cooling Opportunities for Energy-efficient Air Conditioning*, 2018), thus the correlation between overall energy consumption and CDDs is still weak.

Table 3
Linear Correlation Coefficient (LCC) between energy consumption and HDDs/CDDs. The countries listed in the table represent >60 % of the EU energy consumption in 2019.

Country	HDDs-energy consumption LCC	CDDs-energy consumption LCC
Belgium	0.30	−0.24
Bulgaria	0.67	−0.33
Denmark	0.55	−0.28
Germany	0.54	−0.33
Spain	0.39	0.34
Italy	0.46	0.05
Hungary	0.34	−0.12
Netherland	0.32	−0.10
Portugal	0.42	−0.03
Romania	0.76	−0.47
Slovakia	0.61	−0.46
Sweden	0.31	0.11

Fig. 1(c) illustrates the population trend which shows a constant increase. Finally, Fig. 1(d) reports the GDP trend in €2015. Real monetary values are used since it is necessary to compare data and indexes in different years thus homogeneous quantities must be considered. GDP trend highlights the impact of the economic crisis in 2009. The EU27 GDP value of the 2008 is recovered only in 2014.

5. Results and discussion

5.1. LMDI analysis

The present paper considers the LMDI methodology for the decomposition of carbon emissions in EU27 in the period 1995–2019, namely a time span of 25 years. The decomposition is based on seven indexes representing the carbon intensity of the energy sector (CI), the energy consumption structure of the energy sector (ES), the climatic factor (CF), the energy intensity (EI), the GDP per capita (GDPPC), population share (PS) and the total population in EU27 (Pop_{27}). The indicators can be grouped in three macro categories, namely CI, ES, and EI represent the technical factor, CG is the climatic factor, and GDPPC, PS and Pop_{27} are the socio-economic factors.

Total carbon emissions showed a reduction of 689 Mt between 2019 and 1995, namely a reduction of 21 %. On the other hand, this raw result is difficult to interpret since the effects that caused this reduction are not highlighted. The proposed decomposition allows to explain this reduction according to the seven defined indexes.

Fig. 2 reports the contribution of all the factors and some general trends can be illustrated. In particular, it can be observed that the technical factor contributes to the reduction of carbon emissions. More specifically, all the indexes composing the technical factor promote the decrease of carbon emissions. This means that, overall, the energy system evolved towards more sustainable solutions, since a reduction of CI means that more sustainable fuels are used, a decrease of ES means that the contribution of renewables increased over the years, and a reduction of EI shows that a more efficient utilization of energy is achieved. Thus, from the technical point of view, effective measures are implemented with a positive impact for the reduction of carbon emissions at EU27 level. The deployment of effective technical measures is the result of the implemented EU energy policies to support the development of renewables, promoting the abatement of carbon emissions, and incentivizing energy efficiency measures (i.e., 20-20-20 targets). This is also noted in (Bel and Joseph, 2018), where it is highlighted the role of technological change in achieving the decarbonization objectives. Namely, policies oriented to the support of technical innovation provide effective results (Bel and Joseph, 2018).

The climatic effect also determines a reduction of carbon emissions. This result can be interpreted as one of the consequences of the average increase of the temperature during the winter season, which determines a reduction of fossil fuel consumption for heating. Whereas, as shown in Table 3, the relation between energy consumption and CDDs is weak, thus energy consumption from summer air-conditioning does not seem to have an overall relevant impact. However, if a seasonal or monthly analysis focused on power consumption is developed, it can be possible that correlation with CDDs is much stronger. This is explained by the fact that most of the air-conditioning units are powered by electricity.

Oppositely, the non-technical factors are responsible for an increase of carbon emissions in EU27, all of them contribute to the increase of the emissions. In particular, GDPPC is the most relevant factor determining the increase of CO_2 emissions. It can be directly connected with the economic development and improved living conditions. Instead, PS has limited impact on the growth of CO_2 emissions. This is a measure of how the relative change in population among the EU27 countries affected CO_2 emissions. Finally, Pop_{27} accounts for the evolution of the population in EU27 and at an increase of the population corresponds an increase of CO_2 emissions since more people consumes more resources.

The overall results do not allow to fully understand the dynamic of the evolution of carbon emissions thus it is relevant to split the analysis in sub-periods. Five sub-periods of five years each are considered as reported in Table 4. By analysing the total change of each sub-period, it can be observed that only in the period 2000–2004 there was an increase of carbon emissions, whereas in all the other periods a decrease is noticed. CI contributes to the reduction of CO_2 in all the sub-periods with two peaks in the period 1995–1999 and 2005–2009, which can be ascribed to the sharp reduction in the consumption of coal/lignite in the energy sector and the increase of the natural gas share. The first sub-period overlaps with the “first-wave” of CCGTs installation in EU because of the liberalization of the power generation market in EU (Bianco et al., 2015). Namely, after the market liberalization power generators tried to enter to new EU markets and the simplest way to do it was by building CCGTs which have low CAPEX in comparison with other thermal power plants and are much easier to operate (e.g., lower maintenance and personnel cost) (Bianco et al., 2015). This led to an increase of CCGTs capacity all around EU with a consequent increase in natural gas consumption for power generation and a decrease of carbon

Table 4
LMDI Decomposition of carbon emissions in EU27.

EU27 (Mt)	1995–1999	2000–2004	2005–2009	2010–2014	2015–2019
CI	−154	−36	−116	−14	−95
ES	−16	−28	−105	−93	−59
EI	−145	−364	−165	399	−165
CF	−131	304	−177	−759	−71
GDPPC	327	213	91	77	233
PS	5	8	4	−2	9
Pop_{27}	19	33	41	15	17
Total	−95,5	131,8	−427,4	−377,3	−132,0

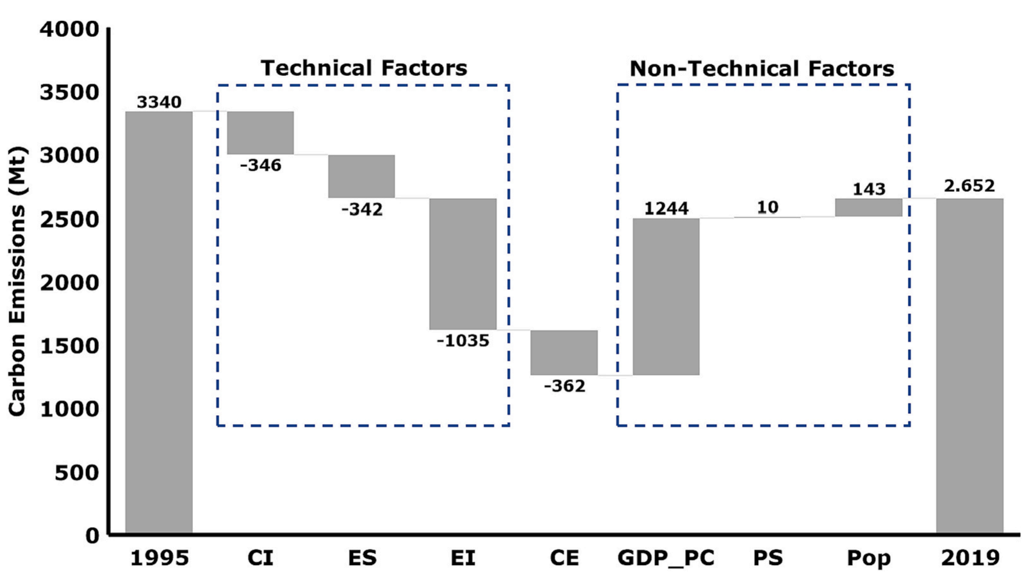


Fig. 2. Decomposition of Carbon Emissions in the period 1995–2019. The impact of all the factors considered in the decomposition analysis is illustrated, as well as the aggregation of technical and non-technical factors is shown.

intensity. The new CCGTs displaced/substituted old oil, coal or lignite units (Bianco et al., 2015). The reduction of CI in 2005–2009 can be explained by the entering into force and effects of different environmental directive and schemes, especially the EU-ETS, which aimed at limiting carbon emissions. This is also confirmed in (Laing et al., 2014), where an analysis of the impact of EU-ETS on the level of carbon emissions in EU is proposed. The phenomenon is the same, namely reduction of carbon/lignite consumption and substitutions with natural gas. In the other periods the phenomenon is the same but with less intensity.

ES contributes to the reduction of CO_2 emissions in all the sub-periods with the maximum impact in the periods 2005–2009 and 2014–2010, which correspond to the launch of the 20-20-20 EU directive which aimed at covering at least 20 % of energy consumption with renewables. Thus, in those years the member states launched incentive policies to reach their targets in terms of renewables generation. Often the incentives had the form of a Feed-In Tariff (FIT) with different rules according to the different EU countries. The impact of the FIT is different according to the considered EU country since, as discussed in (Alolo et al., 2020), the simple existence of a FIT does not necessarily enhance investments, which are linked to the specific rules and conditions of the FIT (Alolo et al., 2020). Same conclusions are also obtained in (Jenner et al., 2013), where it is found that investments in wind technology in EU are not driven by FITs, rather than by the combination of FITs with power market price and power generation requirements (Jenner et al., 2013). Finally, it is also important to highlight that FIT design requires careful attention to avoid its overestimation as happened in Italy (Bianco et al., 2021).

EI determines a reduction of the emissions in all the sub-periods except for 2010–2014 where it causes a substantial increase of emissions. The period 2010–2014 covers the global economic downturn, therefore there was a substantial reduction of the GDP and of the corresponding variable consumption of energy, but the fixed energy consumption was not proportionally reduced thus its incidence per unit of GDP increased and caused an increase of the EI component.

CF determined a reduction of carbon emissions in all the sub-periods except for 2000–2004. Its trend is linked with the volatility of climatic conditions.

The analysis of GDPPC highlights its impact on the increase of the emissions in all the sub-periods even though with a lower intensity during the 2005–2009 and 2010–2014 periods, which cover the economic downturn. Then PS has a much lower impact with respect to the other indexes; in general, it determines a slight increase of the emissions except for 2010–2014 period where its contribution is slightly negative. This slight reduction is difficult to interpret but it is likely that is linked to the effect of the economic downturn. The analysis in terms of breakdown per country can help to interpret it. Finally, Pop_{27} steadily contributed to the increase of CO_2 since, as shown in Fig. 1(c), except for a few years, it constantly increased by determining a growth in the use of resources.

To complete the analysis, it is necessary to provide a breakdown at EU27 country level since technical, climatic, and socio-economic factors are different, thus different phenomena may arise.

Table 5 highlights the contribution of each country included in EU27. It can be noticed that Germany, Italy, and France have the largest impact and this could be expected since they are the largest countries. Technical factors are the most influential for the emissions reduction. In Germany ES and EI have the largest impact, whereas in Italy CI and ES are the most influential, and finally in France CI and EI are the most relevant. This demonstrates that different countries acted on different parameters to reduce their emissions. The case of Germany is also discussed in (Rogge and Hoffmann, 2010; Hoffmann, 2007). The impact of EU-ETS is analysed in (Rogge and Hoffmann, 2010) and it is underlined how the scheme affected the investment plans of power generators with reference to coal and lignite power plants. These technologies became much less attractive in terms of profitability under the EU-ETS, thus a switch towards are technologies was implemented. Furthermore, EU-ETS represented a driver for small scale investments aimed at reducing carbon emissions in the industry (Hoffmann, 2007). This result can be considered negative from one side since it highlights the absence of a long-term structural strategy, but from the other side allowed to obtain quick and evident results (Hoffmann, 2007).

As for Romania and Poland the most relevant factors are CI and EI. Both the countries massively relied on the utilization of carbon intensive

Table 5
Break-down of carbon emissions (Mt) in the period 1995–2019 for EU 27 countries. Total values referred to EU27 are reported in bold.

Country	CI	ES	EI	CF	GDPPC	PS	Pop_{27}	Total
Belgium	−21	−8	−37	−8	35	8	5	−24,6
Bulgaria	5	−4	−17	−9	25	−8	2	−6,8
Czechia	−2	−10	−50	−21	71	−2	6	−9,4
Denmark	−9	−17	−18	−8	14	3	2	−33,8
Germany	−18	−112	−222	−121	249	−24	38	0−211,1
Estonia	1	−3	−14	−1	14	−2	1	−4,1
Ireland	−9	−4	−40	1	40	11	2	0,0
Greece	−16	−6	−1	−12	13	−2	3	−21,9
Spain	−43	−23	−83	16	76	27	11	−18,7
France	−71	−15	−88	−24	87	25	16	−71,5
Croatia	4	−1	−2	−2	7	−2	0	4,3
Italy	−57	−58	−18	−46	33	1	17	−127,4
Cyprus	0	0	−1	−2	2	2	0	1,3
Latvia	−1	−1	−5	−1	7	−2	0	−1,6
Lithuania	1	−2	−9	−2	12	−3	0	−2,1
Luxembourg	−1	−1	−3	−1	3	3	0	0,9
Hungary	−9	−4	−19	−10	33	−5	2	−11,8
Malta	−1	−0,1	−2	0	1	0	0	−0,8
Netherlands	−11	−10	−60	−19	61	11	8	−20,8
Austria	5	−6	−3	−8	18	3	3	12,7
Poland	−31	−28	−224	−66	315	−21	15	−39,2
Portugal	−11	−5	−17	8	14	−1	2	−9,8
Romania	−22	−9	−59	−16	61	−14	3	−55,2
Slovenia	4	−1	−4	−2	7	0	1	3,8
Slovakia	−2	−3	−23	−6	27	−1	1	−7,0
Finland	−15	−7	−11	−1	14	1	2	−16,3
Sweden	−15	−3	−5	−1	4	1	0	−17,7
EU 27	**−346**	**−342**	**−1035**	**−362**	**1244**	**10**	**143**	**−689**

local coal and lignite, thus a decrease in CI shows a variation in the energy mix towards more sustainable fuels. Furthermore, both the energy systems were characterized by energy inefficiency due to old systems, often coming from the Soviet period. The relevant impact of EI shows that the countries implemented energy efficiency policies by updating their energy infrastructures. Finally, ES and EI are the most influential factors in Denmark, which demonstrates a focus on the development of renewables and on the promotion of energy efficiency policies.

The diversity of strategies and approaches can be explained with the different energy, productive and social systems available in the different EU countries (Fernández González et al., 2014a).

5.2. Decoupling analysis

Decoupling effort indexes for all the EU 27 countries and EU 27 overall are reported in Table 6.

It can be highlighted a strong decoupling status for EU 27 overall. This means that the economy is expanding – i.e., GDP is growing – while carbon emissions are reducing.

This confirms that policy initiatives implemented in the period 1995–2019 were successful in limiting the CO_2 emissions without affecting the economic growth. If the individual countries are analysed, two decoupling statuses can be noticed, namely strong decoupling in twenty-one countries and weak decoupling in six countries. The six countries characterized by a weak decoupling, in which both GDP and CO_2 emissions grow but at different speed, with the latter being slower, are Ireland, Croatia, Cyprus, Luxemburg, Austria, and Slovenia. The decomposition of the decoupling index allows to understand which are the main motivations for such a trend. In particular, for all these six countries the most relevant parameter is ε_{GDPPC}. This means that carbon emissions due to the spending capacity are hampering the transition to a strong decoupling status in these countries. For all the EU 27 countries ε_{GDPPC} is positive and comprised between 0.26 in Sweden and 1.19 in Croatia, but for twenty-one countries the other parameters compensate the effect and permit to achieve the Strong Decoupling status. Instead, in Croatia and Slovenia ε_{CI} is also positive, respectively equal to 0.69 and 0.41, which highlights a positive elasticity of carbon emissions due to the carbon intensity of fossil fuels with respect to GDP. Namely, these two countries have a carbon intensive energy mix and energy consumption is elastic to the GDP.

If EU 27 overall is analysed, it can be noticed that the decoupling indexes associated to the technical factors strongly contribute to attain the Strong Decoupling status. A similar observation can be also done for the climatic factor. On the contrary, socio-economic factors have an opposite direction, but the decoupling indexes connected with technical factors prevail.

This confirms that EU policies – focused on the decarbonization of energy mix, increase of renewables, and promotion of energy efficiency – had a positive impact in supporting the decoupling between economic growth and carbon emissions. Instead, the distribution of population, the increase in population, and, more substantially, the increase in GDPPC are positively coupled to CO_2 emissions. This demonstrates that an increase of resource consumption (e.g., increased consumption of goods and services due to higher population or higher spending capacity) leads to an increase of CO_2 emissions. Thus, it can be said that EU 27 economy is still coupled to carbon emissions and technical and policy measures should be implemented to support the decoupling in all the economic sectors.

To analyse the dynamic evolution of the decoupling, five temporal sub-periods of five years are considered, namely 1995–1999, 2000–2004, 2005–2009, 2010–2014, and 2015–2019. Fig. 3 shows the decoupling index and status for the whole EU 27.

The figure highlights that the decoupling status is substantially stable during the considered sub-periods, only in the time block 2000–2004 the status was Weak Decoupling, but it can be observed that the climatic factor had a relevant role in weaking the decoupling relationship. Climatic factor played an important role also in the following periods, e.g., 2010–2014, where it contributed considerably to the attainment of the Strong Decoupling and counterbalanced the impact of energy intensity. The 2010–2014 period is quite specific since it includes the global economic downturn and a partial recovery. Being a period characterized by turbulence, the instability is reflected in the decoupling indexes.

It can be noticed that the energy intensity decoupling index is largely

Table 6
Decomposition of decoupling Index for the EU 27 countries in the period 1995–2019. Total values referred to EU27 are reported in bold.

Country	ε_{CI}	ε_{ES}	ε_{EI}	ε_{CF}	ε_{GDPPC}	ε_{PS}	ε_{Pop27}	E	Type
Belgium	−0,30	−0,11	−0,54	−0,11	0,51	0,12	0,08	−0,36	SD
Bulgaria	0,19	−0,16	−0,64	−0,33	0,93	−0,30	0,06	−0,25	SD
Czechia	−0,02	−0,10	−0,47	−0,20	0,66	−0,02	0,05	−0,09	SD
Denmark	−0,29	−0,54	−0,58	−0,24	0,43	0,09	0,07	−1,06	SD
Germany	−0,05	−0,32	−0,63	−0,34	0,70	−0,07	0,11	−0,59	SD
Estonia	0,02	−0,10	−0,55	−0,04	0,56	−0,07	0,03	−0,16	SD
Ireland	−0,08	−0,04	−0,37	0,01	0,37	0,10	0,02	0,00	WD
Greece	−0,89	−0,36	−0,08	−0,69	0,71	−0,12	0,20	−1,25	SD
Spain	−0,28	−0,15	−0,54	0,11	0,49	0,17	0,07	−0,12	SD
France	−0,41	−0,09	−0,51	−0,14	0,50	0,14	0,09	−0,41	SD
Croatia	0,69	−0,11	−0,33	−0,43	1,19	−0,32	0,09	0,78	WD
Italy	−0,87	−0,89	−0,27	−0,71	0,50	0,02	0,26	−1,96	SD
Cyprus	0,00	−0,09	−0,14	−0,31	0,43	0,30	0,06	0,24	WD
Latvia	−0,06	−0,11	−0,46	−0,07	0,69	−0,18	0,03	−0,16	SD
Lithuania	0,04	−0,09	−0,51	−0,09	0,66	−0,17	0,03	−0,12	SD
Luxembourg	−0,13	−0,05	−0,33	−0,09	0,33	0,32	0,04	0,09	WD
Hungary	−0,19	−0,08	−0,40	−0,21	0,70	−0,11	0,05	−0,25	SD
Malta	−0,26	−0,03	−0,45	0,02	0,36	0,12	0,03	−0,22	SD
Netherlands	−0,10	−0,10	−0,55	−0,18	0,56	0,10	0,07	−0,19	SD
Austria	0,20	−0,23	−0,09	−0,30	0,67	0,13	0,10	0,46	WD
Poland	−0,06	−0,05	−0,40	−0,12	0,57	−0,04	0,03	−0,07	SD
Portugal	−0,54	−0,26	−0,84	0,40	0,69	−0,05	0,11	−0,49	SD
Romania	−0,20	−0,09	−0,53	−0,14	0,56	−0,13	0,03	−0,50	SD
Slovenia	0,41	−0,12	−0,47	−0,24	0,78	0,00	0,06	0,42	WD
Slovakia	−0,05	−0,07	−0,47	−0,11	0,54	−0,02	0,03	−0,14	SD
Finland	−0,53	−0,24	−0,38	−0,04	0,51	0,04	0,06	−0,59	SD
Sweden	−0,87	−0,16	−0,32	−0,04	0,26	0,06	0,03	−1,04	SD
EU 27	**−0,20**	**−0,20**	**−0,61**	**−0,21**	**0,73**	**0,01**	**0,08**	**−0,40**	**SD**

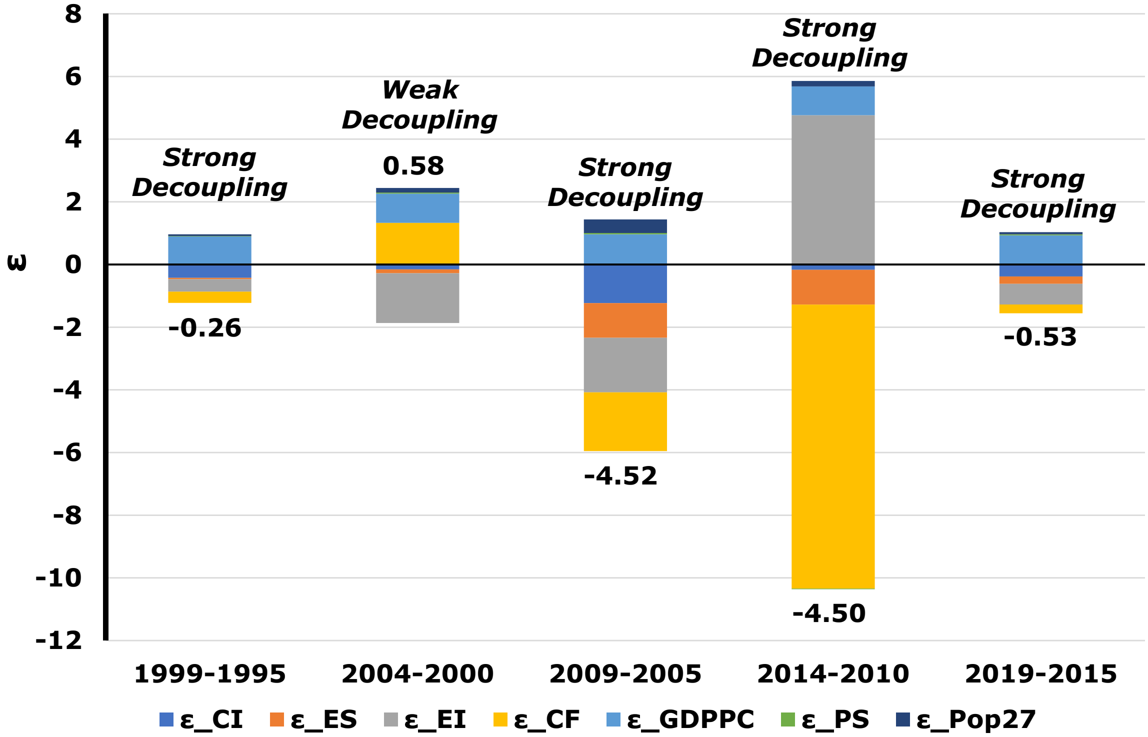


Fig. 3. Decoupling index and decoupling status for EU 27. The contribution of all the decomposition parameters to the decoupling is illustrated.

positive and characterized by END status, e.g., both carbon emissions and GDP increased. This can be ascribed to the rebound effect consequent to the downturn period.

Table 7 highlights the decoupling index and status for all the EU 27 countries. Different decoupling status can be identified during the considered sub-periods in each country. In the last period, 2015–2019, 19 countries are characterized by the Strong Decoupling status, among these all the largest EU countries such as Germany, France, Italy, and Spain. The countries which highlight a status other than Strong Decoupling are relatively small in size. This explains the overall Strong Decoupling status at EU 27 level.

As mentioned above, the period 2010–2014 is peculiar to analyse. It can be noticed that seven countries, including Italy and Spain, show a Recessive Decoupling status, which means a reduction of the emissions

Table 7
Decoupling index and decoupling status in the considered sub-periods for EU 27 countries.

Country	1995–1999		2000–2004		2005–2009		2010–2014		2015–2019	
	Index	Type	Index	Type	Index	Type	Index	Type	Index	Type
Belgium	−0,06	SD	0,19	WD	−3,06	SD	−3,55	SD	−0,09	SD
Bulgaria	1,90	RD	1,13	EC	−0,32	SD	0,19	WD	−1,24	SD
Czechia	−2,44	SD	0,12	WD	−0,87	SD	−4,02	SD	1,16	ED
Denmark	−0,44	SD	0,16	WD	9,60	RD	−5,74	SD	−0,68	SD
Germany	−0,67	SD	0,51	WD	−6,07	SD	−0,89	SD	−1,46	SD
Estonia	−0,77	SD	0,52	WD	7,21	RD	1,15	EC	−0,67	SD
Ireland	0,31	WD	0,04	WD	−67,59	SD	−0,97	SD	−0,21	SD
Greece	0,89	EC	0,30	WD	−2,08	SD	0,92	RD	−3,10	SD
Spain	0,76	WD	1,22	END	−4,42	SD	2,93	RD	−0,75	SD
France	0,41	WD	−0,65	SD	−4,47	SD	−3,52	SD	−0,60	SD
Croatia	3,36	END	1,08	EC	−1,46	SD	6,02	RD	−0,08	SD
Italy	0,59	WD	1,08	EC	5,43	RD	5,31	RD	−1,38	SD
Cyprus	1,08	EC	0,39	WD	0,43	WD	1,40	RD	0,25	WD
Latvia	−3,24	SD	−2,84	SD	91,98	END	2,39	END	−1,46	SD
Lithuania	−1,93	SD	7,25	END	−10,22	SD	1,79	END	3,55	END
Luxembourg	−0,57	SD	2,88	END	−1,04	SD	−1,78	SD	0,48	WD
Hungary	0,76	WD	−0,05	SD	8,21	RD	−2,89	SD	0,39	WD
Malta	0,63	WD	2,08	END	−0,45	SD	−0,27	SD	−0,14	SD
Netherlands	−0,08	SD	1,14	EC	−0,73	SD	−7,11	SD	−0,69	SD
Austria	−0,77	SD	5,64	END	−1,63	SD	−2,26	SD	0,22	WD
Poland	−0,66	SD	−0,22	SD	0,14	WD	−0,75	SD	0,37	WD
Portugal	1,01	EC	0,15	WD	−31,51	SD	2,08	RD	−0,74	SD
Romania	10,94	RD	0,62	WD	−1,32	SD	−0,68	SD	−0,23	SD
Slovenia	−0,51	SD	0,50	WD	−0,94	SD	−448,67	SND	−0,13	SD
Slovakia	−0,21	SD	0,37	WD	−0,86	SD	−1,97	SD	−0,12	SD
Finland	−0,13	SD	1,76	END	−26,14	SD	235,62	RD	0,84	EC
Sweden	−2,55	SD	8,98	END	−17,41	SD	−9,56	SD	−5,37	SD
EU 27	−0,26	SD	0,58	WD	−4,52	SD	−4,50	SD	−0,53	SD

and GDP. This can be ascribed to the economic downturn which determined a reduction of economic activities and consequently of the emissions. In the following period all these countries moved from the Recessive Decoupling to the Strong Decoupling or Weak Decoupling status except for Finland, which moved to the Expansive Coupling status, probably due to a rebound effect after the crisis.

6. Conclusions

The present paper employees the LMDI additive decomposition and Tapio's decoupling method for analysing the factors affecting carbon emissions in EU 27. A seven indexes identity is developed to study the driving forces determining carbon emissions. Indexes are grouped to highlight the effect of technical, climatic, and socio-economic parameters. The analysis is developed over a period of 25 years, namely from 1995 up to 2019.

The decomposition and decoupling analysis lead to the following main conclusions:

- Technical factors, namely carbon intensity of fossil fuels, energy consumption structure, and energy intensity, contributed to the reduction of carbon emissions in EU 27 with the major contribution of the energy intensity effect. This can be interpreted as the result of the successful implementation of EU policies aimed to decarbonize the fossil fuel mix, to promote the renewables, and to push energy efficiency. Technical factors also supported the decoupling between CO_2 emissions and GDP and allowed to reach the Strong Decoupling status.
- The role of the climatic factor is highlighted by showing its contribution to the reduction of carbon emissions due to the lower amount of fossil fuels used for heating during the winter season. The climatic factor also contributed to the Strong Decoupling status. On the other hand, this cannot be interpreted as a stable trend since weather conditions are volatile. Furthermore, it cannot be even considered as a “positive” contribution because the trend of increasing temperature during the winter season may be seen as an effect of global warming. The reduction of energy consumption for heating in winter should be also compared with the increase in energy consumption for summer air-conditioning, however at the moment there are not enough data available to develop this comparison.
- Socio-economic factors are responsible for the increase of carbon emissions, especially the growth of GDP per capita. This means that at an increase of the economic output and of the spending capacity corresponds to an increase of carbon emissions, thus the production and utilization of goods and services is still coupled to CO_2 emissions. To invert this trend, it is necessary to introduce technical innovations and policies aimed at reducing carbon emissions also in sectors other than energy and carbon intensive productions.

In this study the focus is on the decomposition and decoupling of CO_2 emissions at macro level, i.e., EU 27 and corresponding countries, without analysing the industrial sub-sectors. This represents a future research path to explore for understanding the most critical sectors hampering the reduction of CO_2 emissions and a stronger decoupling.

CRediT authorship contribution statement

Vincenzo Bianco: Conceptualization, Methodology, Writing Original Draft, Writing - Reviewing and Editing.
Furio Cascetta: Conceptualization, Methodology, Writing Original Draft, Writing - Reviewing and Editing.
Sergio Nardini: Conceptualization, Methodology, Writing Original Draft, Writing - Reviewing and Editing.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

Appendix A

Table A1
Data type and indication of the Eurostat database code containing the data.

Data type	Eurostat database code
Carbon emissions	*env_air_gge*
Population	*demo_pjan*
GDP	*nama_10_gdp*
Energy consumption	*nrg_bal_s*
HDDs	*nrg_chdd_a*

References

Akdoğan, T., Erkara, E., Mert, B., Hiçyılmaz, B., Alataş, S., Karakaya, E., 2023. Understanding material and energy use in the processes of decoupling CO_2 emissions from economic growth. Environ. Sci. Pollut. Res. 30, 80863–80883.
Alolo, M., Azevedo, A., El Kalak, I., 2020. The effect of the feed-in-system policy on renewable energy investments: evidence from the EU countries. Energy Econ. 92, 104998.
Ang, B.W., 2004. Decomposition analysis for policymaking in energy: which is the preferred method? Energy Policy 32, 1131–1139.
Ang, B.W., 2005. The LMDI approach to decomposition analysis: a practical guide. Energy Policy 33 (7), 867–871.
Ang, B.W., 2015. LMDI decomposition approach: a guide for implementation. Energy Policy 86, 233–238.
Bel, G., Joseph, S., 2018. Climate change mitigation and the role of technological change: impact on selected headline targets of Europe's 2020 climate and energy package. Renew. Sustain. Energy Rev. 82 (3), 3798–3807.
Bhattacharyya, S.C., Matsumura, W., 2010. Changes in the GHG emission intensity in EU-15: lessons from a decomposition analysis. Energy 35 (8), 3315–3322.
Bianco, V., Scarpa, F., Tagliafico, L.A., 2014. Analysis and future outlook of natural gas consumption in the Italian residential sector. Energ. Conver. Manage. 87, 754–764.
Bianco, V., Scarpa, F., Tagliafico, L.A., 2015. Current situation and future perspectives of European natural gas sector. Front. Energy 9 (1), 1–6.
Bianco, V., Casetta, F., Nardini, S., 2021. Analysis of technology diffusion policies for renewable energy. The case of the Italian solar photovoltaic sector. Sustain. Energy Technol. Assess. 46, 101250.
Chen, J., Wang, P., Cui, L., Huang, S., Song, M., 2018. Decomposition and decoupling analysis of CO_2 emissions in OECD. Appl. Energy 231, 937–950.
Cheng, S., Wang, P., Chen, B., Fan, W., 2022. Decoupling and decomposition analysis of CO_2 emissions from government spending in China. Energy 243, 122741.

Eurostat. https://ec.europa.eu/35urostat/data/database. (Accessed 12 September 2022).
Fernandez Gonzalez, P., Landajo, M., Presno, M.J., 2014. Multilevel LMDI decomposition of changes in aggregate energy consumption. A cross country analysis in the EU-27. Energy Policy 68, 576–584.
Fernández González, P., Landajo, M., Presno, M.J., 2014a. The driving forces behind changes in CO_2 emission levels in EU-27. Differences between member states. Environ. Sci. Policy 38, 11–16.
Fernández González, P., Landajo, M., Presno, M.J., 2014b. Tracking European Union CO_2 emissions through LMDI (logarithmic-mean Divisia index) decomposition. The activity revaluation approach. Energy 73, 741–750.
Hoffmann, V.H., 2007. EU ETS and investment decisions: the case of the German electricity industry. Eur. Manag. J. 25 (6), 464–474.
Jenner, S., Groba, F., Indvik, J., 2013. Assessing the strength and effectiveness of renewable electricity feed-in tariffs in European Union countries. Energy Policy 52, 385–401.
Karmellos, M., Kopidou, D., Diakoulaki, D., 2016. A decomposition analysis of the driving factors of CO_2 (carbon dioxide) emissions from the power sector in the European Union countries. Energy 94, 680–692.
Karmellos, M., Kosmadakis, V., Dimas, P., Tsakanikas, A., Fylaktos, N., Taliotis, C., Zachariadis, T., 2021. A decomposition and decoupling analysis of carbon dioxide emissions from electricity generation: evidence from the EU-27 and the UK. Energy 231, 120861.
King, A.D., Karoly, D.J., Henley, B.J., 2017. Australian climate extremes at 1.5 C and 2 C of global warming. Nat. Clim. Chang. 7, 412.
Laing, T., Sato, M., Grubb, M., Comberti, C., 2014. The effects and side-effects of the EU emissions trading scheme. WIREs Clim. Change 5, 509–519.
Li, R., Jiang, R., 2020. Investigating effect of R&D investment on decoupling environmental pressure from economic growth in the global top six carbon dioxide emitters. Sci. Total Environ. 740, 140053.
Madaleno, M., Moutinho, V., 2018. Effects decomposition: separation of carbon emissions decoupling and decoupling effort in aggregated EU-15. Environ. Dev. Sustain. 20, S181–S198.
Moutinho, V., Carrizo Moreira, A., Silva, P.M., 2015. The driving forces of change in energy-related CO_2 emissions in Eastern, Western, Northern and Southern Europe: the LMDI approach to decomposition analysis. Renew. Sustain. Energy Rev. 50, 1485–1499.
Moutinho, V., Madaleno, M., Inglesi-Lotzb, R., Dogan, E., 2018. Factors affecting CO_2 emissions in top countries on renewable energies: a LMDI decomposition application. Renew. Sustain. Energy Rev. 90, 605–622.
Ozturk, I., Acaravci, A., 2010. CO_2 emissions, energy consumption and economic growth in Turkey. Renew. Sustain. Energy Rev. 14, 3220–3225. https://doi.org/10.1016/j.rser.2010.07.005.
Pan, X., Guo, S., Xu, H., Tian, M., Pan, X., Chu, J., 2022. China's carbon intensity factor decomposition and carbon emissions decoupling analysis. Energy 239, 122175.
Pani, R., Mukhopadhyay, U., 2010. Identifying the major players behind increasing global carbon dioxide emissions: a decomposition analysis. Environmentalist 30, 183–205.
Papież, M., Śmiech, S., Frodyma, K., 2021. The role of energy policy on the decoupling processes in the European Union countries. J. Clean. Prod. 318, 128484.
Paraschiv, V., Paraschiv, L.S., 2020. Trends of carbon dioxide (CO2) emissions from fossil fuels combustion (coal, gas and oil) in the EU member states from 1960 to 2018. Energy Rep. 6 (8), 237–242.
Perillo, F., Pereira da Silva, P., Cerqueira, P.A., 2022. Decoupling efficiency from electricity intensity: an empirical assessment in the EU. Energy Policy 169, 113171.
Radovanović, M., Filipović, S., Vukadinović, S., Trbojević, M., Podbregar, I., 2022. Decarbonisation of eastern European economies: monitoring, economic, social and security concerns. Energ Sustain. Soc. 12, 16 https://doi.org/10.1186/s13705-022-00342-8.
Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., et al., 2016. Paris agreement climate proposals need a boost to keep warming well below 2 C. Nature 534, 631–639.
Rogge, K.S., Hoffmann, V.H., 2010. The impact of the EU ETS on the sectoral innovation system for power generation technologies – findings for Germany. Energy Policy 38 (12), 7639–7652.
Román-Collado, R., Economidou, M., 2021. The role of energy efficiency in assessing the progress towards the EU energy efficiency targets of 2020: evidence from the European productive sectors. Energy Policy 156, 112441.
Štreimikienė, D., Balezentis, T., 2016. Kaya identity for analysis of the main drivers of GHG emissions and feasibility to implement EU "20–20–20" targets in the Baltic States. Renew. Sustain. Energy Rev. 58, 1108–1113.
Tapio, P., 2005. Towards a theory of decoupling: degrees of decoupling in the EU and case of road traffic in Finland between 1970 and 2001. Transport. Policy 12 (2), 137–151.
The Future of Cooling Opportunities for Energy-efficient Air Conditioning, 2018. IEA. https://iea.blob.core.windows.net/assets/0bb45525-277f-4c9c-8d0c-9c0cb5e7d525/The_Future_of_Cooling.pdf. (Accessed 4 October 2022).
Trotta, G., 2019. Assessing energy efficiency improvements, energy dependence, and CO2 emissions in the European Union using a decomposition method. Energ. Effic. 12, 1873–1890.
Tsai, W.H., Lee, K.C., Liu, J.Y., Lin, H.L., Chou, Y.W., Lin, S.J., 2012. A mixed activity-based costing decision model for green airline fleet planning under the constraints of the European Union Emissions Trading Scheme. Energy 39, 218–226. https://doi.org/10.1016/j.energy.2012.01.027.
Wang, Q., Su, M., 2020. Drivers of decoupling economic growth from carbon emission – an empirical analysis of 192 countries using decoupling model and decomposition method. Environ. Impact Assess. Rev. 81, 106356.
Wang, Q., Su, M., Li, R., 2018. Toward to economic growth without emission growth: the role of urbanization and industrialization in China and India. J. Clean. Prod. 205, 499–511.
Yan, J., Hao, Y., Feng, C., 2021. A race between economic growth and carbon emissions: what play important roles towards global low-carbon development? Energy Econ. 100, 105327.
Zhang, Y.J., Wei, Y.M., 2010. An overview of current research on EU ETS: evidence from its operating mechanism and economic effect. Appl. Energy 87, 1804–1814. https://doi.org/10.1016/j.apenergy.2009.12.019.