Carbon and Energy Intensity of the USA and Germany. A LMDI Decomposition Approach and Decoupling Analysis.

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Abstract

The present study investigates the driving factors of energy and carbon intensity of the great economies of the USA and Germany, being two economies with different structures and dependencies on energy while they are among the world's economic and geopolitical leading players. Both Decoupling and Decomposition Analysis are applied to identify and rank factors defining Carbon and Energy Intensity during the period from 2000 to 2017, with the so-called financial crisis being within this period. The decoupling analysis denotes that these advanced economies should enhance their decoupling efforts, while decomposition analysis confirms the leading role of energy intensity in CO₂ emissions, next the income and the energy mix emerge as important factors with population trend to be an additional factor only in the USA. Finally, conclusions and relevant policy suggestions are presented.

Keywords: LMDI decomposition analysis, CO₂ emissions, energy intensity, decoupling effect, scenario analysis, the United States, Germany.

1. Introduction

Trends of CO₂ emissions as well as of carbon intensity of the economy are of prominent importance within the frameworks of contemporary economies and energy policies. CO₂ emissions and carbon intensity are the outcome of several factors including the efficient use of energy, energy mix (fossil fuels versus renewables), and growth trends and structure, income level and population. The evolution and ranking of the driving forces of CO₂ emissions is an issue of scientific and policy importance. The present study attempts an investigation over the Carbon and Energy Intensity of the great economies of the USA and Germany attempting to identify the key driving forces.

The international literature proves that the driving forces of economic and demographic growth, geopolitical changes, international trade and western society's lifestyle are inducing high energy consumption and coupling between growth and CO₂ emissions (Hatzigeorgiou et al., 2008). Various methods have been developed to evaluate and rank the factors driving energy consumption and CO₂ emissions, including the Index Decomposition Analysis (IDA) methodology (Ang, 1999; Wang et al., 2018) and decoupling analysis (Tapio, 2005). The present article investigates the driving forces behind the trends of the energy-related CO₂ emissions in Germany and in the United States of America (USA) from 2000 to 2017. The paper attempts a decomposition analysis by means of the Logarithmic Mean Divisia Index (LMDI) method while combining it with a set of decoupling indexes. The leading role of these two advanced economies in the continents of America and Europe, their different structures and evolutionary trajectories as well as different mixtures of energy and climate policies induced the comparison between these two giant economies with tremendous influence at the global scale.

For the USA, a number of studies investigate the driving factors of CO₂ emissions. Vinuya et al. (2010) analyzed the trends of CO₂ emissions for the USA economy employing the LMDI technique. The authors concluded that the decline of energy intensity was the causal effect for the reduction of CO₂ emissions. Baldwin and Wing (2013) studied the spatiotemporal evolution of CO₂ emissions for the USA economy employing a permutation of Kaya identity, over the period 1963–2008. The results denoted that energy efficiency improvement and compositional shifts were the causal factors for the decrease of CO₂ emissions.

Shahiduzzaman and Layton (2017) analyzed the feasibility of the Greenhouse Gases (GHGs) target for 2025, employing the additive LMDI technique. Their analysis indicated that Gross Domestic Product (GDP) and Population effects were the main contributors on the increase of total CO₂ emissions for the years 2000-2014, while Energy Intensity had the biggest negative contribution.

Wang et al. (2018) compared CO₂ emissions in the China and the USA by an LMDI approach combined with a decoupling analysis of CO₂ emissions from economic growth. The study showed that the main reasons for the decrease of CO₂ emissions in China and the USA are income and population effects followed by the energy intensity and the energy mix effects. Jiang et al. (2019), based on Cobb-Douglas (C-D) production function and LMDI technique, examine the evolution of CO₂ emissions in the USA. The study quantified the impact of the technological status on CO₂ emissions for the USA. Song et al. (2019) established a two-dimensional model for the relationship between economic development and CO₂ emissions in China and the USA. The methodology was based on Tapio (2005) decoupling index and Environmental Kuznets Curve (EKC) for 1965-2016. The results depicted that strong decoupling has not achieved. Wang et al. (2020) implied an aggregate and sectoral decomposition analysis of CO₂ emissions for the USA over 1997-2016. The study resulted that the main influencing factor is the scale effect (income and population), while the technology effect (energy intensity and emission coefficient) is the key driving force in mitigating emissions.

Regarding the case of Germany, the studies on the identification of the driving forces of CO₂ emissions are numerous. Bhattacharyya and Matsumura (2010) analyzed the decline of greenhouse gas emissions in European Union (EU) over the period 1990-2007, employing the LMDI decomposition technique. Their paper revealed that the reduction of the energy intensity in the EU-15 is attributable to significant improvements by large emitters such as Germany and the UK. Gonzalez et al. (2014) suggested environmental and energy strategies in order to control CO₂ emissions using LMDI technique, in the EU-27. The results signified the negative impact of the energy intensity and fuel mix effects and the positive impact of the population, income and emission factor for the change of the CO₂ emissions.

Ward et al. (2016) established a simple model based on IPAT equation questioning the possibility of Decoupling of GDP growth from environmental impacts, for selected countries. The model showed that GDP growth cannot be decoupled from energy use. Cohen et al. (2018) evince the existence of decoupling between GHG emissions and economic growth using a simple trend/cycle decomposition for Germany (1990-2014). Sadorsky (2020) studied the driving factors of energy-related CO₂ emissions in the time of financial crisis, applying the LMDI technique. The decrease in energy intensity was the key driver behind declining CO₂ emissions, while an increase in GDP was the biggest force enlarging CO₂ emissions. Haein et al. (2020) used the LMDI technique for decomposing CO₂ emissions from electricity generation, employing a comparative analysis of 36 OECD countries. The study proved that the improvement in electricity intensity (ELI), calculated as electricity generation per GDP (EL/GDP), and the decrease in the share of thermal generation were the main effects for the reduction of CO₂ emissions.

Other scholars, in recent papers, focused on the evolution of GHGs for China as a large economy, by means of decomposition or/and decoupling analysis (Fatima et al., 2019; Yang et al., 2020; Zhang et al., 2020; Hu et al., 2021).

Contributing to the above-mentioned literature with new evidence, the objective of this article is to evaluate and analyze the energy and CO₂ intensity of the USA and Germany, an issue with high policy relevance. Remarkably, the GDP of German economy accounted for 24.07% of the EU (The World Bank Group, 2020). In 2018, the global share of CO₂ emissions for USA is 14.7% (IEA, 2020a) and the USA GDP accounted for 21.54% of the global GDP (The World Bank Group, 2020). Although a number of past studies have concentrated on CO₂ emissions and economic output for various countries, a comparative analysis of driving factors for energy-related CO₂ emissions between the two major economies, USA and Germany, is not widely presented in the energy literature. The proposed analysis could provide valuable insight in existent and future energy and environmental policies of the two economies.

First, we conduct a descriptive and structural comparative analysis between the two economies, delineating their energy status and we set a baseline scenario, examining whether the recent emission targets of the two economies are attainable. Next, we are employing a set of decoupling indexes to explore the linkage between the energy-related CO₂ emissions and economic growth. Finally, we are applying robust LMDI techniques in order to rank and quantify the driving forces leading CO₂ emissions. The period under investigation is from 2000 to 2017.

Regarding the environmental policies, Germany follows the Climate Action Law (the German first national climate law) which has been included in German government coalition's 2030 climate package. In accordance with the above the targets are a reduction in greenhouse gas emissions up to 55% by 2030 and to become greenhouse gas neutral by 2050. Those objectives have been inspired for the respective EU policies (BMWI, 2019; European Commission, 2020a). On the other hand, the target of the USA economy is to reduce CO₂ emissions by 26-28% in 2025 compared to 2005¹, as submitted to the UNFCCC (United Nations Framework Convention on Climate Change).

The main energy and climate policy targets of the two countries for the study period 1990-2017 are summarized in the Table 1:

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¹<https://www4.unfccc.int/sites/submissions/indc/Submission%20Pages/submissions.aspx>

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Milestone Regulations (1990 – 2017)**Germany**

1990: Federal government committed to reduce carbon dioxide emissions to 25% below 1990 levels by 2005. (First Initiative, 1990) Also, Germany agreed that by 2020, GHG emissions would drop 40% from 1990 levels (Bailey and Rupp, 2004).

1999: Germany signed the Kyoto Protocol and has committed to reduce its emissions to 21% below 1990 levels between 2008 and 2012 (Telli et al., 2020).

2007: The parliament of the EU approved the following goals for the year 2020^{2,3}:
-20% cut in greenhouse gas emissions (from 1990 levels)
-20% of EU energy from renewables
-20% improvement in energy efficiency.

2010: The updated government targets are to reduce total emissions by at least 40% by 2020 and at least 55% by 2030, compared with 1990 levels (2010 Energy Concept) (IEA, 2020b).

2011: German government announced the Energiewende (energy transformation) and decided to reduce the amount of fossil fuels from 80% of energy supply to 20% by 2050 (Lu et al., 2020).

2016: Germany follows the European Council agreement submitted to UNFCCC for a reduction in GHG within the EU of at least 40% by 2030, compared with 1990 (BMUB, 2016).

The USA

1990: Under the UNFCCC, the USA committed to the voluntary goal of holding greenhouse gas emissions at the end of the 1990s decade to their 1990 levels (Blodgett et al., 2002).

1997: In the 1997 Kyoto Protocol to the UNFCCC, the USA participated in negotiations that ended with agreement on further reductions that could become legally binding (Blodgett et al., 2002).

2002: The Administration rejected the Kyoto Protocol. The goal is to reduce GHG intensity by 18% over the next 10 years through voluntary activities, which means that the 183 metric tons of carbon emissions (MMTCE) per million dollars of GDP that the United States is emitting in 2002 would fall to 151 MMTCE per million dollars of GDP in 2012 (Blodgett et al., 2002).

2014: USA's target as submitted to the UNFCCC, aims at reducing CO₂ emissions by 26-28% in 2025 compared to 2005⁴.

2017: Under the Paris Agreement, the USA. promised to achieve a reduction of about 25% by 2025 compared with 2005 levels^{5,6} (2016). The next year, it announced the USA. with drawal from the Paris Agreement⁷. In 2021, the USA rejoined the Paris Agreement⁸.

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183 *Table 1. Emission Goals for the USA and Germany (1990-2017).*

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185 As we can see in Table 1 the policy regulations for Germany usually set a strict target in
186 order to achieve a significant reduction of the CO₂ emissions in the future. On the other
187 hand, the USA energy and environmental policy set a more achievable target for the
188 reduction of CO₂ emissions, although they have several commitment gaps in this attempt
189 because of their Administration changes over time.

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191 In addition, these two economies are among the largest carbon-emitting countries in the
192 world (15,7% of global CO₂ emissions in 2020) as stated in recent COP26, the aim of keeping

²https://ec.europa.eu/clima/policies/strategies/2020_en

³<https://www.eea.europa.eu/themes/climate/trends-and-projections-in-europe/trends-and-projections-in-europe-2017/overall-progress-towards-the-european>

⁴<https://www4.unfccc.int/sites/submissions/indc/Submission%20Pages/submissions.aspx>

⁵<https://unfccc.int/node/61231>

⁶<https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>

⁷<https://www.state.gov/on-the-u-s-withdrawal-from-the-paris-agreement/>

⁸<https://www.state.gov/the-united-states-officially-rejoins-the-paris-agreement/>

alive the goals of Paris Agreement. Consequently, their environmental and energy status is of great interest to be studied in depth.

The remainder of the paper is organized as follows: Section 2 & 3 present the methodology used and the data analysis, respectively. Results and discussion are described in Section 4. Section 5 summarizes the conclusions.

2. Methods

We conduct a Decoupling Analysis between energy-related CO₂ emissions (*C*) and economic growth for the USA and Germany. Decoupling CO₂ emissions with economic development is essential for environmental management.

We estimate the Decoupling Index (*DI*) for the standard *C/GDP* ratio:

$$DI_{GDP} = \frac{\Delta(C)}{\Delta(GDP)} = \frac{(C_t - C_{t-1})/C_{t-1}}{(GDP_t - GDP_{t-1})/GDP_{t-1}} \quad (1)$$

and we estimate the DI for the *C/Income* ratio:

$$DI_{Inc} = \frac{\Delta(C)}{\Delta(Income)} = \frac{(C_t - C_{t-1})/C_{t-1}}{(Income_t - Income_{t-1})/Income_{t-1}} \quad (2)$$

We also set the $EI_{GDP} = E/GDP$ and $EI_{Inc} = E/Income$ energy intensity ratios. The $CI_{Inc} = C/Income$ carbon intensity ratio is proposed as an indicator that approximates better than the $CI_{GDP} = C/GDP$ ratio the real-world properties of production. In accordance with the existing literature, the indexes DI_{Inc} and CI_{Inc} denote weaker decoupling trends than the DI_{GDP} and CI_{GDP} respectively (Bithas and Kalimeris, 2013; Bithas and Kalimeris, 2018). The categorization of the decoupling states is based on the study of Tapio (2005).

Time series Decomposition Analysis is employed to assess the evolution of the decomposition factors during the 2000-2017, in the USA and Germany. LMDI technique is applied to determine and rank the causal effects leading the trends of CO₂ emissions in a comparative basis. This technique has emerged as the most preferred IDA technique among researchers and analysts for ease of formulation and simplicity sake. Moreover, LMDI technique is extensively utilized because results in incomplete decomposition and gives zero residual term (Hatzigeorgiou et al., 2008; Yasmeeen et al., 2020).

The following variables are defined for each year:

<i>i</i>	fuel type (coal, oil, natural gas, renewable resources)
<i>E_i</i>	energy consumption of fuel type <i>i</i> (Mtoe)
<i>E</i>	total energy consumption (Mtoe)
<i>C</i>	total CO ₂ emissions (MtCO ₂)
<i>C_i</i>	CO ₂ emissions from fuel type <i>i</i> (MtCO ₂)

Y GDP (million 2010US\$ for Germany/ million 2012US\$ for the USA)
 P Population (in million people)

The energy-related CO₂ emissions (C) are given by the Equation:

$$C = \sum_{i=0}^4 I S_i P Inc F_i = \sum_{i=0}^4 \left(\frac{E}{GDP} \right) \left(\frac{E_i}{E} \right) P \left(\frac{GDP}{P} \right) \left(\frac{C_i}{E_i} \right) \quad (3)$$

Where

$$\circ \text{ Energy Intensity as } I = \frac{E}{GDP} \quad (4)$$

$$\circ \text{ Energy Structure as } S_i = \frac{E_i}{E} \quad (5)$$

$$\circ \text{ Income as } Inc = \frac{GDP}{P} \quad (6)$$

$$\circ \text{ Emission factor as } F_i = \frac{C_i}{E_i} \quad (7)$$

$$\circ \text{ Population as } P \quad (8)$$

In additive LMDI technique, the difference in CO₂ emission levels between two years can be expressed in MtCO₂ as follows:

$$\Delta C_{tot} = \Delta C_p + \Delta C_{inc} + \Delta C_{int} + \Delta C_f + \Delta C_s = C_T - C_0 \quad (9)$$

where ΔC_{tot} is the change of total CO₂ emissions.

The relevant formulae for the decomposition factors are as follows:

$$\Delta C_p = \sum_{i=1}^4 \frac{(C_{i,T} - C_{i,0})}{\ln(C_{i,T}/C_{i,0})} \ln \left(\frac{P_T}{P_0} \right) \quad (10)$$

$$\Delta C_{inc} = \sum_{i=1}^4 \frac{(C_{i,T} - C_{i,0})}{\ln(C_{i,T}/C_{i,0})} \ln \left(\frac{Inc_T}{Inc_0} \right) \quad (11)$$

$$\Delta C_{int} = \sum_{i=1}^4 \frac{(C_{i,T} - C_{i,0})}{\ln(C_{i,T}/C_{i,0})} \ln \left(\frac{I_T}{I_0} \right) \quad (12)$$

$$\Delta C_f = \sum_{i=1}^4 \frac{(C_{i,T} - C_{i,0})}{\ln(C_{i,T}/C_{i,0})} \ln \left(\frac{F_{i,T}}{F_{i,0}} \right) \quad (13)$$

$$\Delta C_s = \sum_{i=1}^4 \frac{(C_{i,T} - C_{i,0})}{\ln(C_{i,T}/C_{i,0})} \ln \left(\frac{S_{i,T}}{S_{i,0}} \right) \quad (14)$$

where ΔC_p is the change of population, ΔC_{inc} the change of income, ΔC_{int} the change of the energy intensity, ΔC_f the change of the emission factor and ΔC_s the change of the energy structure.

In multiplicative LMDI technique, the change scheme is:

$$D_{tot} = D_p D_{inc} D_{int} D_f D_s = C_T / C_0 \quad (15)$$

where D_{tot} is the change of total CO₂.

The relevant formulae for the decomposition factors are as follows:

$$D_p = \exp \left(\sum_{i=1}^4 \frac{(C_{i,T} - C_{i,0}) / (\ln C_{i,T} - \ln C_{i,0})}{(C_T - C_0) / (\ln C_T - \ln C_0)} \ln \left(\frac{P_T}{P_0} \right) \right) \quad (16)$$

$$D_{inc} = \exp \left(\sum_{i=1}^4 \frac{(C_{i,T} - C_{i,0}) / (\ln C_{i,T} - \ln C_{i,0})}{(C_T - C_0) / (\ln C_T - \ln C_0)} \ln \left(\frac{Inc_T}{Inc_0} \right) \right) \quad (17)$$

$$D_{int} = \exp \left(\sum_{i=1}^4 \frac{(C_{i,T} - C_{i,0}) / (\ln C_{i,T} - \ln C_{i,0})}{(C_T - C_0) / (\ln C_T - \ln C_0)} \ln \left(\frac{I_T}{I_0} \right) \right) \quad (18)$$

$$D_f = \exp \left(\sum_{i=1}^4 \frac{(C_{i,T} - C_{i,0}) / (\ln C_{i,T} - \ln C_{i,0})}{(C_T - C_0) / (\ln C_T - \ln C_0)} \ln \left(\frac{F_{i,T}}{F_{i,0}} \right) \right) \quad (19)$$

$$D_s = \exp \left(\sum_{i=1}^4 \frac{(C_{i,T} - C_{i,0}) / (\ln C_{i,T} - \ln C_{i,0})}{(C_T - C_0) / (\ln C_T - \ln C_0)} \ln \left(\frac{S_{i,T}}{S_{i,0}} \right) \right) \quad (20)$$

where D_p is the change of population, D_{inc} the change of income, D_{int} the change of the energy intensity, D_f the change of the emission factor and D_s the change of the energy structure.

3. Data and Analysis

3.1 Data comparison for the economies of the USA and Germany

The trends of the key variables of our study are presented in Figures S1-S6 in the supplementary information file. Figures S1 and S2 indicates the trends of the main fuels in energy consumption: oil, natural gas, renewable resources and coal, with data drawn from the International Energy Agency (IEA, 2020a). The share of nuclear energy is negligible for the two economies. Electricity is not considered to be a separate fuel; it is taken into account via the original fossil fuels that are utilized to produce electricity (Hatzigeorgiou et al., 2010). Renewable resources for Germany present a remarkable increase by 220% through the last 17 years, while in the USA the increase of renewables is approximately 52%. The share of oil, the fuel with the largest energy consumption, declines for both Germany (-17.5%) and the USA (-6.7%).

To estimate CO₂ emissions from primary fuel consumption we adopted the OECD emission coefficients (IPCC, 2006), depicted in Table S1 in the supplementary information file. Energy-related CO₂ emissions follow significant fluctuations (Fig.S3), with remarkable decrease for the 2006-2007 time period in Germany and 2007-2009 in the USA. Remarkably, these time periods coincide with the onset of the financial crisis.

The World Bank Open Data are adopted for the aggregate values of Germany's GDP (The World Bank Group, 2020), while the GDP of the USA is based on data from Bureau of Economic Analysis (BEA, 2020). An upward trend of GDP for both countries is shown in Fig.S4, with the exception of the 2007-2009 time period; GDP for Germany declined by 5% while for the USA economy declined by 8%.

All data for Population (Fig.S5) are retrieved from World Bank Open Data⁹. The population in the USA increases linearly, while Germany's population remains approximately constant, with a slightly decrease from 2009 to 2011. An upward trend in income is observed in both countries, similar to GDP (Fig.S6).

Summarizing all the above-mentioned facts, Table 2 depicts the physiology of the two economies and the analogy of their key variables for the years 2000 (a) and 2017 (b).

<i>a. Key variables - 2000</i>	<i>USA</i>	<i>Germany</i>	<i>USA/Germany</i>
Energy Consumption (Mtoe)	1.546,3	231,4	6,7
CO₂ emissions (MtCO ₂)	3.411,8	515,5	6,6
GDP (million 2010 US\$)	12.620.268,4	3.118.322,5	4,0
Population (million people)	282,2	82,2	3,4
Income (2010 US\$)	44.721,0	37.935,8	1,2

<i>b. Key variables - 2017</i>	<i>USA</i>	<i>Germany</i>	<i>USA/Germany</i>
Energy Consumption (Mtoe)	1.520,5	227,0	6,7
CO₂ emissions (MtCO ₂)	3.163,3	447,6	7,1
GDP (million 2010 US\$)	17.348.626,6	3.878.004,0	4,5
Population (million people)	325,1	82,7	3,9
Income (2010 US\$)	53.364,0	46.892,4	1,1

Table 2. The physiology of the USA and German economies for the years 2000 (a) and 2017 (b).

Although the aggregate energy consumption for the two economies remains stable (USA/Germany = 6.7), the respective analogy for CO₂ emissions increased from 6.6 to 7.1

⁹<https://data.worldbank.org>

(2000-2017). This reflects that German policy measures for decarbonization of the economy are more effective than those of the USA.

In order to examine further the efficiency of the existing environmental policies for both economies, we set a Baseline scenario. For the case of Germany, we attempt to forecast the evolution of CO₂ emissions from 2018 to 2030. The years 1990 and 2030 are the landmarks of the German climate policy. By using historical data for the years 2000-2017, we estimate the average annual rate of CO₂ emissions (- 0.75%) according with the following formulae:

$$\text{Average annual rate of CO}_2 \text{ emissions} = \frac{\sum_{i=1}^N (\text{annual \% change of CO}_2 \text{ emissions})}{N} \quad (21)$$

where N is the number of years.

We assume this rate will persist for the years 2018-2030 and the results are shown to Fig.1a.

Fig. 1a. Forecast results of the German CO₂ emissions.

Adopting the same rationale, we forecast the evolution of CO₂ emissions from 2018 to 2025 for the case of the USA. The average annual rate of change of CO₂ emissions for the years 2018-2025 is equal to -0.41%, as defined by using historical data for the years 2000-2017. The results for the CO₂ emissions levels are demonstrated in Fig.1b.

Figure 1b. Forecast results of the USA CO₂ emissions.

The forecast results imply that CO₂ emissions targets cannot be achieved under the baseline scenario for both economies: the German economy remains apart by 52.8% from the 2030 optimistic target, while the USA by 18.7% from the 2025 emission levels.

3.2 Data for Structural Analysis in the USA and Germany

In this subsection we perform a descriptive structural analysis for the USA and Germany economy. The following sectors are selected according to the EIA (U.S Energy Information Administration, 2020a) approach:

- **Residential sector:** Utilities - Household consumption
- **Commercial sector:** Private Services (Financial, Business, Educational, Health & Food Services) & Government Services
- **Industrial sector:** Agriculture, Mining, Construction & Manufacturing
- **Transportation sector:** Transportation & Warehousing

Fig.2 presents the Energy Consumption per sector for Germany (2a) and the USA (2b). The data are retrieved from IEA (IEA, 2020a).

Fig. 2a. Percentage (%) of Energy Consumption for the sectors of the German economy (2000 and 2017)

Fig. 2b. Percentage (%) of Energy Consumption for the sectors of the USA economy (2000 and 2017)

In 2000, the Industrial sector is responsible for 32.3% of the energy use of the German economy. After 17 years, the Industrial sector is responsible for 27.2% of the energy use. For the USA, the share of industrial sector has a reduction of 2.4% (2000-2017).

Fig.3 depicts the GDP per sector for Germany (3a) and the USA (3b). The data are retrieved from Eurostat (European Commission, 2020b) and BEA (2020), respectively.

Fig. 3a. Percentage (%) of GDP for the sectors of the German economy (2000 and 2017)

Fig. 3b. Percentage (%) of GDP for the sectors of the USA economy (2000 and 2017)

Figure 3a denotes that the structure of the German economy remains almost stable during the study period. Regarding the structure of the USA economy, the Commercial sector contributes the most value added in 2000 and 2017, while the GDP share for Industrial sector is down over 6.5% from 2000 to 2017. These changes demonstrate the USA's "turning point" as a service-oriented economy in accordance with the relevant literature (Yao et al., 2015; van Neuss, 2019). The share of residential sector is negligible for the two economies.

434 Fig.4a presents the Energy Intensity per sector for the German economy.

435
436
437 *Fig.4a. Energy Intensity per sector in Germany from 2000 to 2017 (indexed 2000=100).*

439 As can be seen, energy intensity trends for Commercial sector have been gradually
440 decreasing since 2000. The energy intensity for the Industrial sector presents fluctuations
441 with a total decreasing trend (-34% in the period 2000-2017), underlining the de-
442 industrialization effect.

443
444 Fig.4b shows the Energy Intensity per sector for the USA economy.

446
447 *Fig.4b. Energy Intensity per sector in the USA from 2000 to 2017 (indexed 2000=100).*

448 Decreases in the energy intensity for Transportation and Industrial sectors denote energy
449 efficiency improvements and structural changes in the economy (Tol et al., 2009; Herrendorf
450 et al., 2014; van Neuss, 2019).

451 Section 4 presents the results of our research for the period 2000-2017.

4. Results and Discussion

4.1 Decoupling Analysis of energy-related CO₂ emissions from economic growth

In this section we attempt to interpret the connection between economic growth and energy-related CO₂ emissions by means of a decoupling analysis.

EI as the key index of the link between economy and energy consumption, is often used to assess the energy efficiency of a particular economy, indicating how well the economy converts energy into monetary output (Martínez et al., 2019). Fig. 5a depicts the trends of energy intensity indexes: EI_{GDP} and EI_{Inc.} The declining trends of EI indexes demonstrate the so-called decoupling effect denoting a gradual delinkage of growth from energy use. In addition, the EI_{Inc.} index denotes a weaker decoupling effect in the USA than Germany. The trend is declining for both countries, with relatively small fluctuations.

Fig. 5a. Energy Intensity Indexed for the USA and Germany from 2000 to 2017 (indexed 2000=100).

Fig. 5b shows the trends of the carbon intensity indexes: CI_{GDP} and CI_{Inc.}, for the economies of the USA and Germany.

Fig. 5b. Carbon Intensity indexes for the USA and Germany from 2000 to 2017.

The declining trends of CI_{Inc} index follow similar evolution trajectories with the EI_{Inc} index, denoting also a weaker decoupling effect in the USA than Germany. Although, differentiations occur on the evolution of CI_{GDP} index, denoting a stronger decoupling in Germany than the USA.

Tables 3a and 3b depict the EI_{GDP} , EI_{Inc} , CI_{GDP} and CI_{Inc} indexes for Germany and the USA, respectively. We also calculate the percentage change of the relevant indexes from 2000 to 2017.

Year	EI_{GDP}	EI_{Inc}	CI_{GDP}	CI_{Inc}
2000	0,0742	0,0061	0,000165	0,013592
2017	0,0585	0,0048	0,000115	0,009540
2000-2017 (%)	-21,16%	-21,31%	-30,19%	-29,81%

Table 3a: Carbon intensity and energy intensity comparison for the economy of Germany.

Year	EI_{GDP}	EI_{Inc}	CI_{GDP}	CI_{Inc}
2000	0,1225	0,0174	0,000136	0,038468
2017	0,0876	0,0151	0,000096	0,031327
2000-2017 (%)	-28,49%	-13,22%	-29,33%	-18,56%

Table 3b: Carbon intensity and energy intensity comparison for the economy of the USA.

Table 3a indicates an important difference between carbon intensity indexes and energy intensity indexes; the percentage changes of CI_{GDP} and CI_{Inc} are higher than the respective of the EI_{GDP} and EI_{Inc} . This denotes that Germany is less carbon-intensive economy than energy-intensive.

According to Table 3b, the CI_{GDP} and EI_{GDP} indexes has similar percentage changes through the period 2000-2017 for the USA, in contrast with the income-based indexes. As can be concluded, GDP-based indexes for the case of the USA indicate no significant differentiation between the two types of intensities and tend to decrease considerably faster than income-based indexes.

The decoupling effect is caused by declining carbon intensity (Wu et al., 2005; Wang et al., 2005). We further investigate the decoupling effect following the categorization proposed by various researchers (Watson, 2014; Bachtrögler, 2016). In this concept we examine the impact of financial crisis on the relationship among the energy-environment and economy. The study period is divided into three phases:

- the period before the Great Recession (2000-2007)
- the period of the Great Recession (2007-2013)
- the period after the Great Recession (2013-2017)

Tables 4a and 4b presents the Decoupling states and the percentage changes of Carbon Intensity Indexes for the Germany and the USA respectively.

Time	DI_{GDP}	CI_{GDP}	Decoupling	DI_{Inc}	CI_{Inc}	Decoupling

Period		(%)	state		(%)	state
2000-2007	-1,56	-22,89%	Strong decoupling	-1,57	-22,84%	Strong decoupling
2007-2013	0,60	-1,52%	Weak decoupling	0,39	-3,46%	Weak decoupling
2013-2017	0,02	-8,07%	Weak decoupling	0,02	-5,78%	Weak decoupling

Table 4a. Decoupling Analysis of energy-related CO₂ emissions for 2000-2017 in Germany.

Time Period	DI _{GDP}	CI _{GDP} (%)	Decoupling state	DI _{Inc}	CI _{Inc} (%)	Decoupling state
2000-2007	-0,01	-13,59%	Strong decoupling	-0,02	-7,75%	Strong decoupling
2007-2013	-3,04	-11,95%	Strong decoupling	5,18	-7,61%	Expansive decoupling
2013-2017	0,23	-7,12%	Weak decoupling	0,33	-4,45%	Weak decoupling

Table 4b. Decoupling Analysis of energy-related CO₂ emissions for 2000-2017 in the USA.

More specifically, in the period before the financial crisis we observe a strong decoupling state for both economies. For the case of Germany, the shift from strong to weak decoupling state happens in the years of the financial crisis (DI_{GDP}=0.6 & DI_{Inc}=0.39, 2007-2013) and remains in that state (DI_{GDP}=0.02 & DI_{Inc}=0.02, 2013-2017), while the USA turns into weak decoupling state after 2013 (DI_{GDP}=0.23 & DI_{Inc}=0.33, 2013-2017). The financial crisis in the USA (2007-2013), resulting in negative CO₂ emission annual growth rates, at -6% and -4% in 2009 and 2012, respectively. These were the lowest rates from 2000 to 2017, indicating that CO₂ emissions declined in line with economic recession (U.S Energy Information Administration, 2020b).

4.2 Application of LMDI technique for DA of energy-related CO₂ emissions in Germany and the USA.

4.2.1 Results of Additive LMDI Decomposition Analysis

We apply a set of LMDI decomposition techniques to interpret the evolution of energy-related CO₂ emissions, the dependent variable of the current study. With this approach we can quantify the effect of each decomposition factor on the evolution of CO₂ emissions.

The results of the decomposition analysis with additive LMDI technique are depicted in Tables 5a and 5b for Germany and the USA, respectively.

Year	ΔC_{inc}	ΔC_{pop}	ΔC_{str}	ΔC_{int}	ΔC_{tot}

2000-2001	7,86	0,87	-2,36	0,22	6,59
2001-2002	-1,89	0,86	-7,73	-6,65	-15,40
2002-2003	-3,87	0,28	-13,94	8,69	-8,85
2003-2004	5,94	-0,11	-7,59	-8,17	-9,93
2004-2005	3,74	-0,27	-6,78	-8,69	-12,01
2005-2006	18,46	-0,54	-2,64	-9,60	5,68
2006-2007	14,10	-0,61	-16,19	-42,40	-45,11
2007-2008	5,13	-0,85	8,70	8,68	21,66
2008-2009	-24,91	-1,12	-4,69	2,38	-28,34
2009-2010	18,71	-0,68	-5,49	9,37	21,92
2010-2011	25,19	-8,19	0,76	-37,53	-19,77
2011-2012	1,00	0,81	-1,24	1,29	1,86
2012-2013	0,68	1,20	2,62	8,54	13,03
2013-2014	7,80	1,82	-1,83	-27,45	-19,67
2014-2015	3,70	3,73	-0,42	0,16	7,17
2015-2016	6,12	3,53	-0,86	-1,75	7,04
2016-2017	9,16	1,66	0,64	-5,33	6,13
2000-2017	96,93	2,40	-59,06	-108,25	-67,98

Table 5a. Factor Decomposition Analysis (Additive LMDI) for Germany, 2000-2017 (unit: MtCO₂).

Year	ΔC_{inc}	ΔC_{pop}	ΔC_{str}	ΔC_{int}	ΔC_{tot}
2000-2001	-34,59	33,64	33,69	-57,53	-24,79
2001-2002	-9,37	31,41	-10,28	-14,05	-2,28
2002-2003	47,10	29,19	-11,74	-41,14	23,42
2003-2004	91,18	31,89	14,12	-60,14	77,05
2004-2005	102,00	31,90	-37,27	-144,17	-47,54
2005-2006	42,52	32,97	-27,77	-85,07	-37,35
2006-2007	33,60	32,37	-31,44	-28,23	6,29
2007-2008	-76,08	31,53	-49,09	-49,94	-143,58
2008-2009	-208,04	27,72	-29,31	10,57	-199,06
2009-2010	74,53	25,93	-1,47	28,26	127,25
2010-2011	44,78	22,71	-44,04	-148,98	-125,52
2011-2012	56,38	22,21	-16,93	-136,29	-74,63
2012-2013	41,90	21,08	-1,86	38,80	99,93
2013-2014	70,07	22,85	1,92	-52,32	42,50
2014-2015	52,33	23,11	8,49	-82,79	1,15
2015-2016	33,92	22,70	-5,40	-44,70	6,53
2016-2017	58,61	20,19	15,70	-72,30	22,20
2000-2017	420,84	463,40	-192,68	-940,01	-248,44

Table 5b. Factor Decomposition Analysis (Additive LMDI) for the USA, 2000-2017 (unit: MtCO₂).

As shown in Table 5a, in Germany, the income effect was the primary factor contributing to the increase of CO₂ emissions during 2000-2017, with the exception of the 2008-2009 time

period. The CO₂ emissions cumulatively increased by 96.93 MtCO₂ because of income growth. The effects of energy intensity (-108.25 MtCO₂) and energy structure (-59.06 MtCO₂) are the critical factors that induce the decrease of emissions during 2000–2017. The federal government (2014) adopted measures for the increase of renewable shares in power generation, modernization of fossil fuel power plants and the development of more co-generation plants (IEA, 2020b). Furthermore, the share of Renewables presents 3.2 times increase from 2000 to 2017 (Fig.S1), contributed to the mitigation of CO₂ emissions. The impact of population effect on CO₂ emissions (2.4 MtCO₂) is positive but weak.

Table 5b presents the results of the time series LMDI technique for the USA. The first influencing factor to rise emissions is the population effect. This factor eventually contributed to an increase in emissions of 463.40 MtCO₂ from 2000 to 2017. The income effect exhibits substantial variations during the examined period, leading to an overall positive contribution to the increase or energy-related CO₂ emissions (420.84 MtCO₂, 2000-2017). The USA has a mean annual increase in income about 0.8%. The energy intensity effect was the most critical factor decreasing CO₂ emissions. The cumulative effect of energy intensity is near to -940 MtCO₂, while the total change of emissions is -248.44 MtCO₂. Moreover, changes in the energy structure played a significant role in decreasing CO₂ emissions (-192.68 MtCO₂, 2000-2017). The energy mix marked an importance swift from coal (-48%) to Renewables (+52%) from 2000 to 2017.

4.2.2 Comparative evaluation of Results

In this sub-section we analyze the underlying driving forces responsible for the decrease of energy-related CO₂ emissions, on a comparative basis. We apply the Multiplicative LMDI technique to explore and rank contributions of the decomposition factors (Figs.6a-6d).

Income effect

Fig. 6a. Change of energy-related CO₂ emissions due to the Income Effect (Multiplicative LMDI)

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Energy Intensity effect

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Fig.6b. Change of energy-related CO₂ emissions due to the Energy Intensity Effect (Multiplicative LMDI)

Energy Structure effect

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Fig. 6c. Change of energy-related CO₂ emissions due to the Energy Structure Effect (Multiplicative LMDI)

Population effect

Fig. 6d. Change of energy-related CO₂ emissions due to the Population Effect (Multiplicative LMDI)

The most crucial remarks are summarized below:

1. Total CO₂ emissions reduced by 13.8% for German and by 7.3% for the USA, during 2000-2017. The decreasing trends of energy intensity and the substitution of carbon-intensive coal and oil with renewable resources played positive roles in decreasing CO₂ emissions. Although it is not clear the reasons behind the trends in energy intensity they are often attributed to technological advance and a swift of the economy towards services.
2. The energy intensity effect is negative for both economies: the trend for Germany presents a decrease by 21%, where the trend for USA follows a decreasing trend by 25%.
3. The energy structure effect influences CO₂ emissions more in Germany (-12%) than in the USA (-6%) (Fig.6c).
4. The German income effect has greater positive contribution (+24%) than the USA (+14%).
5. The contribution of population effect, although positive in both economics, is infinitesimal in Germany (+0.5%) while strong in the USA (+15%), (Fig.6d).

5. Conclusions

The USA and German economies for the period 2000-2017 present an increasing GDP and Income, with the exception of 2007-2013. For the USA economy, the descriptive data analysis demonstrates the de-industrialization effect. Population increased (15.2%) in the USA while remain stable in Germany.

A decoupling analysis indicate a smoother transition from strong to weak decoupling for the USA. The weak decoupling was found in both Germany and the USA in 2013-2017 denotes that these advanced economies should enhance relevant decoupling efforts in order to move towards to the pre-financial crisis decoupling states. Future decoupling efforts requires “cleaner” energy structure for both economies.

We employ LMDI additive and multiplicative techniques to identify the causal effects on the evolution of energy-related CO₂ emissions. The crucial factor responsible for the decrease of

CO₂ emissions for both economies is energy intensity. Remarkably, the energy intensity of industrial sector is declined by 34% for the German economy and by 12% for the USA economy. This difference once combined with the relative deindustrialization of the USA induces some policy suggestions for the USA whose industrial sector presents a relatively bad emissions performance which induces an inferior CO₂ reduction, almost half from those of Germany. Germany, although increased the share of the industrial sector, reduced more intensively CO₂ emissions, mainly due to the decreasing EI of its industrial sector. This performance of the industrial sector of Germany combined with changes of the energy structure, offset the increased contribution of the income factor which had a much stronger compared to the USA's income.

The impact of the population has been strong in the USA however negligible in Germany. Taking into account that the population in Germany remains almost stable while there a substantially increasing population in the USA where CO₂ emissions indicated a higher increase, there is a strong evidence that CO₂ emissions are the outcome of processes and interactions both within economic and social systems. Natural, economic and social systems are coupled and interdependent. CO₂ analysis, climate and energy policies ought to be envisaged as targeting the coupling of natural, economic and social systems and not isolated. An integrated consideration can be beneficial, effective and supporting in the pursuit of a sustainable economy. The adoption of an integrated approach in the design of energy policy may enrich potentials to reach the newly set ambitious climate targets which seems hard to achieve once past trends prevail, indicated by the baseline scenarios of the present study.

The future research effort should include complementary research on the causal relationship between the driving forces of CO₂ emissions using an econometric analysis. This could provide a holistic approach for a sustainable future, denoting which variables are highly determined by others and leading to specific policy measures.

Statements and Declarations

Ethical Approval - Consent to Participate - Consent to Publish. This article does not contain any studies with human or animal subjects.

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