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THE IMPACT OF THE USE OF BIOFUELS ON CO_2 EMISSIONS AT THE LEVEL OF EUROPEAN COUNTRIES FROM THE PERSPECTIVE OF ABSOLUTE DECOUPLING

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Abstract

Decoupling economic growth from CO_2 emissions completely is still a key goal of sustainability programs. According to the current research, nations with faster energy transitions and advanced technologies typically see a sharper decoupling, meaning that real GDP growth is attained without a rise in greenhouse gas emissions. This indicates that the economy is moving in the right direction. This study emphasized the various viewpoints on the dynamics of CO_2 emissions and the interplay between political, economic, and energy issues in European nations between 2021 and 2023. Both external and internal variables—such as the pandemic, energy crises, and geopolitical conflicts—have had a significant impact on CO_2 emissions. Internal elements include national policies and economic dynamics. Emissions variations have been significantly impacted by these world events, underscoring the weaknesses and adaptability of country economies. During pandemic limitations, emissions temporarily decreased in tourism-oriented nations like Malta, Italy, and Spain; however, as economic activity resumed, emissions increased. In contrast, economies focused on heavy industry, such as Poland and Germany, had a different response, driven by reliance on traditional energy sectors and the pace of the energy transition. An essential indicator for evaluating economic sustainability is the ratio between CO_2 emissions and real GDP.
In this context, the purpose of the work was to analyze and evaluate the evolution of CO_2 emissions in relation to the economic growth recorded by European countries, in the period 2021 - 2023, in the conditions of the need for energy transition and the existence of crises such as energy, the Covid-19 pandemic or geopolitical conflicts. Also, determining the degree of decoupling between CO_2 emissions and GDP growth had the objective of highlighting the differences between advanced economies and those in transition. The data that were the basis of the analysis were given by Eurostat, but also by a rich specialized literature represented by articles and scientific research. To carry out the research, we used a combination of statistical and economic methods (descriptive indicators, growth or decline rates, statistical correlations, etc.), but also graphical methods for data visualization. The research confirms that developed countries are performing better due to advanced technologies and faster transition to renewable energy sources. However, countries in transition, which are struggling due to older infrastructure and limited resources, need additional support to achieve their climate goals. Although biofuels are an important component in the transition to cleaner energy sources, their effect on reducing total emissions remains modest. Their impact is often masked by factors such as electrification policies, the adoption of renewables and the overall structure of the energy mix. To better understand the contribution of biofuels, a segmentation by economic sectors such as transport and industry is needed, which future research aims to address. In conclusion, monitoring fluctuations in CO_2 emissions and correlating them with economic and energy factors remains essential to assess progress towards climate neutrality. Country-specific policies and support for economies in transition will play a critical role in achieving global climate goals.

Key words: *biofuels, absolute decoupling, sustainable development, CO_2 emissions, GDP*

INTRODUCTION

The circular economy represents a new economic model that promotes the efficient use of resources by reducing waste, extending the life of products and recycling materials at the end of their life cycle [20, 21]. This model contrasts strongly with the traditional linear economy, which follows the principle of "extract, produce, consume and discard" [4, 16]. Globally, the transition to a circular economy is closely linked to efforts to combat climate change, reduce the consumption of natural resources and reduce environmental pollution [5, 7, 24].

The circular economy is crucial to maximizing the usage of resources needed for renewable technologies in the context of the shift to renewable energy sources [22]. By reusing materials from used equipment and prolonging their life, the circular economy can lessen reliance on primary resources [13]. To meet the targets of the Paris Agreement to keep global warming to 1.5°C over pre-industrial levels, a substantial shift in the world's energy mix is required, with a focus on renewable energy sources like solar, wind, hydropower, and bioenergy.

International and national legislation, technical advancements, and social pressures are some of the variables that impact the circular economy's global context [14, 15, 31]. With the adoption of the European Green Pact and the Action Plan for the Circular Economy, which seeks to attain carbon neutrality by 2050, the European Union is a pioneer in advancing the circular economy [1, 2, 25]. Strategies to promote the shift to a circular economy are also being implemented in other nations and regions, including China, Japan, and Canada.

Two of the best methods to lower greenhouse gas (GHG) emissions and slow down climate change are recycling waste and producing biofuel. Global warming and climate change are caused by GHG emissions, primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N2O). Recycling helps cut down on the need to extract basic natural resources, which in turn lowers emissions from raw material extraction, transportation, and processing [23, 26, 28].

Recycling materials, such as metals, glass, plastic and paper, contributes to reducing emissions by saving the energy needed to produce new materials [3, 32]. In addition, recycling reduces the amount of waste that ends up in landfills, where the decomposition of organic waste generates methane, a greenhouse gas 25 times stronger than CO_2.

Biofuels (bioethanol, biodiesel, biogas) are renewable energy sources that can replace traditional fossil fuels such as oil, coal and natural gas [6]. Biofuel production uses biological raw materials such as agricultural residues, organic waste, vegetable oils and energy crops. The use of biofuels reduces net GHG emissions, because the CO2 emissions resulting from their combustion are partially offset by the absorption of CO2 by the plants used as raw materials [19, 27]. In addition to reducing emissions, biofuel production can also contribute to the efficient management of organic waste, turning a waste stream into a valuable resource. This can reduce dependence on fossil fuel imports while creating jobs and boosting the local economy [30].

The idea of "absolute decoupling"—which characterizes the situation where an economy raises its GDP without correspondingly growing its use of natural resources and its environmental impact—is closely associated with the circular economy notion.

[12, 18]. Absolute decoupling is an essential goal for long-term sustainability, as natural resources are finite and environmental pressures continue to increase due to overconsumption.

In a traditional economy, economic growth is closely linked to increased resource consumption. However, to achieve full decoupling, it is necessary to adopt policies and technologies that improve resource efficiency, promote the circular economy and stimulate innovation in renewable energies [11, 29].

Absolute decoupling can be achieved through several mechanisms, including: resource efficiency, renewable energy and circular economy. Increasing the efficiency of resource use through advanced technologies and optimized processes. The transition to renewable energy sources reduces the dependence on fossil fuels and the impact on the environment [17, 23]. Thus, recycling, reusing and extending the life of products reduce the need to extract natural resources.

However, absolute decoupling remains an ambitious and difficult goal to achieve on a global scale. Progress is often limited by factors such as population growth, increased demand for products and services, and technological barriers, and achieving full decoupling requires a concerted global effort involving governments, the private sector, civil society and citizens.

In this context, the purpose of the paper is to analyze the relationship between economic growth and CO_2 emissions, highlighting the impact of energy transition, national or European policies, as well as external factors on economic sustainability and the efficient use of resources at the level of European countries.

MATERIALS AND METHODS

This research aims to analyze CO_2 emissions and other relevant economic and energy factors for the period 2021-2023, using a combination of statistical and economic methods. The methodology describes the steps and tools used to assess the growth/decrease rates of CO_2 emissions, the analysis of the relationships between GDP and greenhouse gas emissions, and the correlations between biofuel consumption and emission intensity. Data on CO_2 emissions were collected from Eurostat databases, for the period 2021-2023. The annual evolution of emissions was determined by calculating the increase/decrease rate, using the standard percentage formula. This provides a clear insight into variations over time, highlighting positive or negative trends. The results are contextualized in relation to economic and social events, such as the global energy crisis or emission reduction measures adopted at European level. For a detailed understanding of greenhouse gas emissions, descriptive statistical indicators such as mean, median, standard deviation, minimum and maximum value, and coefficient of variation were calculated to provide a complete picture of emissions distribution and volatility.

To analyze the differences between GDP/capita compared to the EU average, the data were adjusted to the purchasing power parity (PPP) and were compared to the EU average. The differences were calculated annually, highlighting the economic gaps between the analyzed country and European standards. Bar graphs have been used to visually represent the variations between GDP/capita and the EU average, which allows a quick interpretation of economic progress or stagnation in the analyzed period.

Economic efficiency was assessed by the ratio of real GDP to CO_2 emissions, using inflation-adjusted GDP. A higher ratio reflects a lower economic intensity of emissions, which indicates a more efficient use of resources. The analysis also included the identification of economic sectors that contribute significantly to economic efficiency, comparing this evolution with other European Union member countries. Data on biofuel consumption (expressed in tonnes of oil equivalent) were analyzed to determine increasing or decreasing trends over the period. The segmentation of consumption by sector (transport, industry) allowed the identification of areas where biofuels have the greatest impact. Reducing reliance on fossil fuels and assessing the switch to renewable energy sources require this analysis. The Pearson correlation coefficient was used to examine the relationships among CO_2 emissions, emission intensity, and biofuel consumption. Because of this, it was feasible to gauge how strongly the variables were related to one another, classifying the correlations as weak, moderate, or strong based on the coefficient's value. The analysis was completed by testing the statistical significance of the correlations, to verify the validity of the results obtained.

Research tools and limitations

The research relied on the use of tools such as Microsoft Excel, Python and R, which facilitated statistical analysis and visual representation of data. The limitations of the methodology include the quality and availability of data for the analyzed period, as well as the impact of exogenous factors (public policies, economic crises), which can influence the interpretation of the results.

RESULTS AND DISCUSSIONS

In the framework of international climate commitments like the Paris Agreement and the European Green Deal, analyzing data sets that enable both the identification of trends in CO_2 emissions and the comparison of nations' energy transition performances is necessary for the development of sustainable policies as well as the assessment of the success of the steps taken to achieve climate neutrality by 2050 at the level of the European Union. Also, monitoring the effects of public policy measures on emissions, such as the implementation of renewable energies, increasing energy efficiency or reducing fossil fuel consumption, are useful tools in this endeavor. The analysis of annual emissions of carbon dioxide (CO_2) for the member states of the European Union (EU-27), as well as for other relevant countries, in the period 2014-2023 allowed us to examine the annual rates of increase or decrease in emissions leading to the identification periods of progress or regression in reducing pollution, comparing average emissions to assess the positioning of each country in relation to the EU average, but also detecting anomalies and determining factors on them. The data set included both countries with mature economies, such as Germany, France and Italy, as well as emerging economies from the Central and Eastern European region, such as Poland, Romania or Bulgaria. Non-EU countries, such as Norway, Switzerland, Serbia and Turkey, were also included, in order to obtain a broad perspective on the dynamics of emissions in Europe. This information is an integral part of a data set that tracks the accounts of atmospheric emissions, being classified according to economic activities NACE Rev. 2, being expressed in tons of carbon dioxide (CO_2) (Table 1).

Table 1. Growth/decrease rates of CO_2 emissions in Europe

Country	Growth 2019/2020	Growth 2020/2021	Growth 2021/2022	Growth 2022/2023
European Union 27 countries (from 2020)	-12.20	7.88	-0.31	-9.33
Germany	-12.56	9.04	0.85	-12.23
Poland	-5.76	11.53	-3.78	-8.72
Italy	-11.43	9.45	2.73	-8.26
France	-12.69	9.26	-1.68	-7.83
Spain	-18.44	8.37	4.92	-8.03
Netherlands	-12.64	1.54	-4.68	-7.43
Czechia	-11.45	7.05	0.58	-11.89
Belgium	-8.45	1.59	-4.06	-7.15
Denmark	-14.23	14.01	-8.73	-2.84
Romania	-5.83	3.39	-6.65	-6.24
Norway	-10.09	-4.19	1.97	-7.29
Greece	-15.46	0.72	-6.46	-14.19
Austria	-12.59	5.78	2.38	-3.13
Ireland	-31.04	8.30	24.46	-0.70
Hungary	-7.98	1.71	-1.08	-8.83
Portugal	-17.04	-1.63	5.36	-11.35
Bulgaria	-14.35	16.52	11.74	-30.65
Sweden	-13.53	7.49	-2.28	-3.58
Finland	-16.80	0.30	1.57	-12.93
Slovakia	-10.00	15.59	-12.63	-0.71
Lithuania	11.61	1.50	-7.16	-2.73
Croatia	-5.49	1.75	0.64	-6.88
Slovenia	-4.66	-1.64	-10.28	-5.58
Estonia	-28.93	13.65	15.10	-24.30
Latvia	-20.52	6.16	-1.31	1.53
Luxembourg	-10.71	0.42	-6.96	-3.77
Cyprus	-2.56	-0.99	1.66	0.35
Iceland	-21.35	0.71	27.57	11.61
Malta	-11.48	25.22	22.79	1.06
Switzerland	-20.03	6.02	3.21	-100.00
Serbia	2.06	-3.61	0.59	-100.00
Türkiye	1.00	10.77	-3.69	-100.00

Source: own processing [8].

Most countries saw significant reductions in emissions in 2020, caused by the global restrictions imposed by the pandemic. Reduced mobility, closing down of industries and declining consumption of fossil energy were the main driving factors. Ireland (-31.04%) and Estonia (-28.93%) had the biggest declines, due to their economy's dependence on sectors directly affected by the pandemic, such as international transport and heavy industry. The year 2021 was characterized by an economic recovery, which led to increases in emissions in some countries. Malta (+25.22%) exemplifies this trend, as the reopening of the tourism sector and the resumption of economic activities have led to a more intensive use of energy. However, in most countries, increases were moderate, reflecting a slow transition to pre-pandemic recovery. In 2022, the increase in emissions in countries such as Iceland (+27.57%) was due to the expansion of industrial activities, such as the extraction and processing of natural resources. On the other hand, stricter climate policies have helped keep emissions under control in many other EU member states. The energy crisis generated by the war in Ukraine has led some countries to temporarily return to the use of fossil fuels, but accompanied by the transition to renewable sources. In 2023, Bulgaria (-30.65%), reported significant reductions in emissions, caused by the transition to cleaner energy sources, but also by the reduction of industrial activities. The total decreases reported for Switzerland, Serbia and Turkey (-100%) are due to the way of reporting, not real phenomena (Table 1).

Average emission values indicate a general downward trend in most of the analyzed countries, due to continuous efforts to reduce emissions through the implementation of climate policies and the transition to renewable energy sources. The differences between the average and the median emphasize an asymmetric distribution of emissions, depending on the categories of industries, countries with more developed industries having emissions well above the average. The large standard deviation for each year indicates significant variations between the analyzed countries, which, in addition to the major structural differences in the economies, are also due to the energy mix of each country. The large difference between the maximum and minimum values reflects the inequality in terms of responsibility for emissions between countries, which underlines the importance of differentiated support for countries with emerging economies, but also the need for more coherent and coordinated policies to achieve climate neutrality at the EU level (Table 2).

Table 2. Descriptive statistical analysis of greenhouse gas emissions (2019-2023) (tons)

Year	Mean	Median	Standard Deviation	Minimum	Maximum
2019	161366346.3	42352944.61	426537404.2	2244158.71	2439651928
2020	143079283.8	35444347.82	375130918.2	1986561.15	2141996586
2021	154258252.9	41128466.51	405376356	2487478.71	2310736492
2022	153519502.9	43562540.39	404037969.4	3054450.56	2303466818
2023	128195808.6	32283670.91	366021667.7	0	2088657365

Source: own processing [8].

Starting from the fact that the analysis of the relationship between CO_2 emissions and GDP offers an important perspective on economic sustainability and the impact of economic development on the environment, this second indicator was also analyzed. However, this relationship is not a linear one and may vary depending on the level of economic development, energy mix and technological efficiency. For emerging economies, GDP growth is associated with high emissions due to reliance on polluting industries and fossil fuels. In contrast, developed countries show lower emission intensity per unit of GDP, reflecting the transition to renewable energy sources, strict climate policies and advanced technologies.

Table 3. The difference between GDP/capita in European countries compared to the EU average (%)

Country	2019	2020	2021	2022	2023
Euro area - 19 countries	6	5	5	5	5
Euro area – 20 countries	5	4	4	4	4
European Union - 27 countries	0	0	0	0	0
Albania	-70	-70	-69	-66	-64
Austria	24	23	21	23	20
Belgium	17	18	17	19	18
Bosnia and Herzegovina	-68	-67	-67	-66	-64
Bulgaria	-45	-43	-40	-38	-36
Croatia	-33	-34	-30	-28	-24
Cyprus	-7	-9	-6	-2	-3
Czechia	-5	-4	-8	-11	-10
Denmark	25	32	34	35	25
Estonia	-16	-15	-15	-16	-20
Finland	7	12	9	7	5
France	5	4	1	-2	-1
Germany	22	23	20	18	16
Greece	-34	-38	-36	-33	-31
Hungary	-27	-25	-25	-23	-23
Iceland	28	20	22	32	35
Ireland	90	105	126	138	113
Italy	-4	-7	-4	-2	-2
Japan	-12	-11	-15	-17	-15
Latvia	-34	-31	-29	-31	-30
Lithuania	-17	-13	-12	-12	-13
Luxembourg	149	156	160	152	137
Malta	6	5	9	5	7
Montenegro	-50	-56	-54	-51	-49
Netherlands	28	31	32	34	33
North Macedonia	-58	-58	-57	-58	-59
Norway	46	41	71	114	71
Poland	-26	-21	-21	-22	-23
Portugal	-23	-25	-26	-23	-19
Romania	-31	-28	-28	-26	-22
Serbia	-58	-56	-55	-54	-51
Slovakia	-30	-26	-26	-29	-26
Slovenia	-13	-12	-12	-11	-8
Spain	-9	-17	-15	-12	-9
Sweden	17	21	21	15	14
Switzerland	52	53	56	59	54
Türkiye	-41	-40	-40	-32	-28
United Kingdom	3	1	-2	2	-1

Source: own processing [9, 10].

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However, this relationship is not a linear one and may vary depending on the level of economic development, energy mix and technological efficiency. For emerging economies, GDP growth is associated with high emissions due to reliance on polluting industries and fossil fuels. In contrast, developed countries show lower emission intensity per unit of GDP, reflecting the transition to renewable energy sources, strict climate policies and advanced technologies (Table 3).

Countries such as Luxembourg (+149 → +137) and Ireland (+90 → +113), although with strong economies, competitive industries and advanced services, or Ireland had accelerated growth due to the attraction of foreign investment. Eastern European and

Balkan countries such as Romania (-31 → -22) and Bulgaria (-45 → -36) had a slow convergence towards the EU average, supported by moderate economic growth and European funds. France and Italy have values close to 0, due to stable economies, but no major progress. The slight decline in Luxembourg and Denmark remains within normal limits for advanced economies. Economic convergence is evident for Eastern Europe, but gaps persist in regions such as the Western Balkans (-70 Albania, -64 Bosnia), highlighting the need for structural reforms and investment (Table 3).

Table 4. The ratio between CO_2 emissions and real GDP

Country	2019	2020	2021	2022	2023
Euro area - 19 countries	1.06	1.05	1.05	1.05	1.05
Euro area – 20 countries	1.05	1.04	1.04	1.04	1.04
European Union - 27 countries	1	1	1	1	1
Albania	0.3	0.3	0.31	0.34	0.36
Austria	1.24	1.23	1.21	1.23	1.2
Belgium	1.17	1.18	1.17	1.19	1.18
Bosnia and Herzegovina	0.32	0.33	0.33	0.34	0.36
Bulgaria	0.55	0.57	0.6	0.62	0.64
Croatia	0.67	0.66	0.7	0.72	0.76
Cyprus	0.93	0.91	0.94	0.98	0.97
Czechia	0.95	0.96	0.92	0.89	0.9
Denmark	1.25	1.32	1.34	1.35	1.25
Estonia	0.84	0.85	0.85	0.84	0.8
Finland	1.07	1.12	1.09	1.07	1.05
France	1.05	1.04	1.01	0.98	0.99
Germany	1.22	1.23	1.2	1.18	1.16
Greece	0.66	0.62	0.64	0.67	0.69
Hungary	0.73	0.75	0.75	0.77	0.77
Iceland	1.28	1.2	1.22	1.32	1.35
Ireland	1.9	2.05	2.26	2.38	2.13
Italy	0.96	0.93	0.96	0.98	0.98
Japan	0.88	0.89	0.85	0.83	0.85
Latvia	0.66	0.69	0.71	0.69	0.7
Lithuania	0.83	0.87	0.88	0.88	0.87
Luxembourg	2.49	2.56	2.6	2.52	2.37
Malta	1.06	1.05	1.09	1.05	1.07
Montenegro	0.5	0.44	0.46	0.49	0.51
Netherlands	1.28	1.31	1.32	1.34	1.33
North Macedonia	0.42	0.42	0.43	0.42	0.41
Norway	1.46	1.41	1.71	2.14	1.71
Poland	0.74	0.79	0.79	0.78	0.77
Portugal	0.77	0.75	0.74	0.77	0.81
Romania	0.69	0.72	0.72	0.74	0.78
Serbia	0.42	0.44	0.45	0.46	0.49
Slovakia	0.7	0.74	0.74	0.71	0.74
Slovenia	0.87	0.88	0.88	0.89	0.92
Spain	0.91	0.83	0.85	0.88	0.91
Sweden	1.17	1.21	1.21	1.15	1.14
Switzerland	1.52	1.53	1.56	1.59	1.54
Türkiye	0.59	0.6	0.6	0.68	0.72
United Kingdom	1.03	1.01	0.98	1.02	0.99

Source: own processing [9, 10].

The ratio of CO_2 emissions to real GDP shows a general stability in the EU-27 (~1) over the period 2019-2023, reflecting a moderate decoupling between economic growth and CO_2 emissions due to climate policies. Countries with high ratios (Luxembourg, Ireland, Norway) have advanced economies with high energy consumption. Countries with low ratios (Romania, Bulgaria, Serbia) have lower energy efficiency. France and Germany reduced the ratio through green technologies, while Romania and Portugal registered increases, they did not succeed in an efficient energy transition. There is therefore a need to accelerate the transition to renewables, support countries in transition and integrate decarbonisation policies to improve economic sustainability (Table 4).

Table 5. Biofuel consumption in the period 2021-2023 (Mtep)

Country	2021	2022	2023
European Union - 27 countries (from 2020)	1.674	1.748	1.833
Belgium	2	2.2	1.7
Bulgaria	1.5	1.7	1.2
Czechia	1.2	1.2	1.5
Denmark	1.8	1.7	1.5
Germany	1.4	1.4	1.3
Estonia	1.8	1.3	2.4
Ireland	1.6	1.9	1
Greece	1	0.9	2.3
Spain	1.8	1.7	2.3
France	1.9	2.1	0
Croatia	1.3	0.3	1.5
Italy	1.3	1.3	1.4
Cyprus	1.5	1.4	0
Latvia	1.1	0.4	2.1
Lithuania	2.1	2.1	4.2
Luxembourg	3.7	3.9	1.8
Hungary	1.4	1.6	2
Malta	1.8	1.9	1.5
Netherlands	1.3	1.4	1.9
Austria	1.5	1.5	1.5
Poland	1.4	1.6	2
Portugal	2	1.9	2.1
Romania	1.9	2.3	2
Slovenia	2.1	1.6	1.6
Slovakia	1.3	1.5	2.3
Finland	2.5	2.2	4.6
Sweden	4.1	4.9	
Iceland	0.9	0.7	1.8
Norway	1.7	1.7	
Serbia	0	0	

Source: own processing [9, 10].

The consumption of biofuels in the European Union (average of 27 countries) increased gradually, from 1,674% in 2021 to 1,833% in 2023, indicating a general trend of adoption. Sweden and Finland are the countries that recorded high values, with Sweden reaching a peak of 4.9% in 2022 and Finland 4.6% in 2023. Luxembourg and Lithuania also have a high consumption of biofuels, although they have significant fluctuations during the analyzed period. The data shows a general increase in biofuel consumption in Europe, with discrepancies between northern and southern countries. Countries with high consumption can be good practice examples for promoting renewable sources (Table 5).

Table 6. Correlation coefficients between biofuel consumption, CO_2 emissions and emission intensity (2021-2023)

Year	CO2 vs Biofuel	CO2 Intensity vs Biofuel
2021	-0.042885704	-0.057648879
2022	-0.00089963	-0.011070211
2023	-0.058024703	-0.049987424

Source: own processing.

The correlation coefficients for the analyzed years indicate an insignificant linear relationship between the consumption of biofuels and CO_2 emissions, which shows that biofuels, although they represent a sustainable alternative, did not have a measurable impact in reducing total emissions at the national level, apart from a partly due to their limited use in the total energy mix, and partly due to the general increase in energy demand, which canceled out the positive effects of biofuels. The correlation between biofuel consumption and emission intensity (CO_2/GDP) is also and emission intensity (CO_2/GDP) is also very low, indicating an indirect and unclear impact of biofuel use on emissions relative to economic performance, which is due to regional and economic discrepancies. Thus countries with high GDP have lower emission intensity due to the general transition to green technologies and economic efficiency, not necessarily due to the use of biofuels (Table 6).

Biofuel consumption increased slightly between 2021 and 2023 in most European countries, but this increase was not correlated with significant reductions in emissions or improvements in emissions intensity.

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The correlation between biofuel consumption CO_2 emissions are deeply influenced by the interplay of internal (politics, economy) and external (pandemics, global crises) factors, and these fluctuations must be monitored to assess progress towards climate neutrality.

CONCLUSIONS

The pandemic, energy crisis and geopolitical conflicts have had a significant impact on emissions fluctuations. Countries with economies oriented towards tourism (Malta, Italy, Spain, etc.) or those oriented towards heavy industry (Poland, Germany, etc.) had different reactions depending on their economic dynamics and energy transition.

The CO_2 emissions/real GDP ratio remains a key indicator of economic sustainability. It is found that developed countries perform better due to advanced technologies, while countries in transition require additional support to achieve climate goals.

Although biofuels play an important role in the energy transition, their effect on total emissions is modest and masked by other factors. Electrification policies, the adoption of renewable sources and the overall energy mix are determinants of reducing emissions and improving emissions intensity. We consider that a segmentation by economic sectors (e.g. transport vs. industry) could establish much more correctly the real impact of biofuels, and that is why we propose such a future analysis.

We consider that although biofuels are a sustainable solution in the energy transition, their extensive use in the European energy mix is limited by several economic, technological, political, social and ecological barriers. Thus, biofuels involve high production costs, especially those of second and third generation, which use agricultural residues or algae. The lack of economies of scale limits their competitiveness with fossil fuels. Subsidies and support policies are often insufficient or geared towards other renewable technologies such as wind and solar energy. In addition, Europe depends on imports of raw materials such as vegetable oils, which increases price volatility and affects supply chains. Technologies associated with biofuels are still immature, especially for older generations. Production and refining require specialized infrastructure, which is underdeveloped in many regions. In addition, the energy density of biofuels is lower than that of fossil fuels, which makes them less attractive for sectors such as heavy transport. The compatibility of biofuels with existing infrastructure is also a challenge, requiring significant investment. Support policies for biofuels are often inconsistent across EU member states, and frequent changes in regulations discourage private investment. In addition, the promotion of biofuels may conflict with other priorities, such as the electrification of transport or the development of hydrogen. First-generation biofuels, criticized for their impact on deforestation and food prices, receive little political support. The ecosystem may be impacted by deforestation and biodiversity loss resulting from the cultivation of raw materials for biofuels. Agricultural resources are scarce, and conflicts arise from the competition between their use for food and energy. Integrated strategies are needed to overcome these obstacles. Investments in research and development can improve the sustainability and efficiency of biofuels from the second and third generations. Their growth would be aided by the EU's adoption of a unitary regulatory framework, and their incorporation into a varied energy mix would enable their application in industries like heavy transportation and aviation where alternatives are challenging to execute. Increasing societal acceptance, however, requires public education and the fight against unfavorable stereotypes.

In conclusion, tracking changes in CO_2 emissions and how they relate to energy and economic variables is still crucial for evaluating the advancement of climate neutrality. Biofuels can help with the energy shift in certain industries, like transportation, but their contribution to complete decoupling is minimal. However, the overall energy mix and related policies have a big impact on their efficiency. Therefore, it is necessary to evaluate their effects within the framework of a comprehensive plan that incorporates electrification and the use of renewable energy sources.

At the same time, lowering emission intensity (CO_2/GDP) is essential for sustainable development, and policies that support energy efficiency and technical innovation are strongly related to this goal. In addition to lowering their emissions, nations that include renewable energy sources and implement active decoupling strategies lay the groundwork for long-term, steady economic growth.

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