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Harmonizing Sustainability Goals: Empirical Insights into Climate Change Mitigation and Circular Economy Strategies in Selected European Countries with SDG13 Framework

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Abstract: Global efforts to harmonize the sustainable development goals (SDGs) focus on understanding the nexus between carbon dioxide emissions (CO_2) and the circular economy (CE). This study aims to capture variations in carbon emission performance behavior across different European countries, considering their economic performance, population density, material footprint, and circularity rate. The analysis utilizes panel data for 14 EU countries during the period between 2000 and 2020, specifically in relation to their performance within the SDG13 Framework. Empirical analysis employs Ordinary Least Squares, Fixed Effects and Fully Modified Least Squares techniques. The findings suggest that countries with a higher efficiency in utilizing materials within a circular economy framework and higher population density tend to exhibit lower levels of climate change mitigation. Conversely, an increased material footprint corresponds to higher CO_2 emissions. This aligns with the circular economy's emphasis on minimizing resource extraction through promoting reuse, recycling, and remanufacturing. A comprehensive understanding of the CO_2-CE nexus is essential for formulating effective policies aligning circularity performance with the SDG13 framework.

Keywords: carbon dioxide emissions; circular economy; SDG13; panel data

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1. Introduction

Worldwide endeavors to combat climate change and transition towards more sustainable economic practices center around understanding the complex link between CO_2 and CE. The European Commission's reports confirm the European Union's action plan to achieve sustainable development, emphasizing circularity in the consumption and production process [1,2]. Within this context, the EU has prioritized the transition from a linear economy to a CE, aiming to achieve most of the 17 SDGs [3]. Recent studies have confirmed the significant correlations between the adoption of CE practices and SDG13 targets [4–6].

The existing literature extensively establishes the connection between carbon emissions and gross domestic product [7,8], as well as between carbon emissions and population density [9,10]. Other studies delve into the overall carbon footprint associated with material consumption [11,12]. Understanding the CO_2–CE nexus is essential for policymakers, researchers, and businesses dedicated to environmentally responsible strategies [13]. While many studies underscore the importance of circularity in climate change mitigation, their findings are contradictory. The empirical examination of the impact of the CE on CO_2 indicators, considering recycling rates, reuse, and waste management, has yielded various results [6,14–16]. The CE is intricately linked to climate change in its promotion of the efficient use and reuse of materials, thereby lowering the energy consumption and greenhouse gas emissions associated with resource extraction, transportation, and manufacturing processes. By conserving resources, the CE contributes to mitigating climate change. In a CE model, waste is minimized through strategies such as recycling, remanufacturing, and refurbishing. By extending the lifespan of products and materials, the need for producing new goods from scratch is reduced. This means lower demand for raw materials and energy-intensive manufacturing processes, resulting in reduced greenhouse gas emissions. This shift away from fossil fuels helps decarbonize energy systems, a significant factor in climate change mitigation. Certain CE practices, like reforestation and sustainable land management, can also enhance carbon storage in forests and soils. Additionally, considering the entire lifecycle of products and services, the CE aims to optimize resource flows and minimize negative environmental impacts. This systemic approach helps build more resilient economies and societies capable of coping with climate change challenges.

To the best of the authors' knowledge, no empirical studies have examined the CE–CO_2 nexus by using the circular material use rate (CMU) as the independent variable and employing panel data for EU countries. To address this gap, the empirical analysis aims to capture variations in carbon emission performance behavior across different European countries, considering not only their economic performance (GDP) and population density (DENS), but also their material footprint (MF) and circular material use rate (CMU). Econometric techniques, including Ordinary Least Squares (OLS), Fixed Effects (FE), Random Effects (RE), and Fully Modified Least Squares (FMOLS), are applied to understand the relationship between these variables and CO_2 emissions. For the purpose of our study, panel data for 14 selected EU countries for the period 2000–2020 are chosen based on their performance within the SDG13 Framework. More precisely, data are selected for EU countries that are top performers, considering their greenhouse gas emissions in comparison to the EU limits for 2020. A comprehensive understanding of the CO_2–CMU nexus is pivotal for establishing effective policies that harmonize circularity performance with environmental sustainability.

The subsequent sections of the paper are as follows: Section 2 provides a review of prior empirical research on the relationship between the independent variables and carbon emissions. Section 3 presents the data and methodology employed in the empirical analysis, while Sections 4 and 5 present and discuss the empirical findings, respectively. Section 6 concludes the paper, offering policy implications and suggesting further research.

2. Literature Review

The intricate link between carbon dioxide emissions and gross domestic product is central in environmental economics and climate change research. This nexus encapsulates the complex dynamics between economic development and environmental consequences [7,8,17]. Traditional rapid economic growth has often been associated with an increase in CO_2 emissions, attributed to heightened industrial activities and increased energy use [18,19]. The Environmental Kuznets Curve (EKC) hypothesis posits a potential reversal of this trend, suggesting that further economic growth could reduce CO_2 emissions as nations adopt cleaner technologies and environmental policies [20]. However, empirical evidence on the precise nature of this relationship is diverse, with some studies supporting the EKC's inverted U-shaped curve and others proposing a positive linear correlation between GDP and CO_2 emissions [21]. Recent research, considering global economic changes and the impact of international trade, has added complexity to this nexus, underscoring the necessity for diverse analyses considering diverse economic structures [22]. Other studies have found that the relationship might be represented by an N-shaped EKC, implying that environmental degradation will rise again beyond a certain income level [23,24].

Exploring the CO_2–population density nexus involves considering various intricate factors that influence carbon dioxide (emissions in densely populated areas). In regions with higher population density, increased energy demands, industrial activities, and transportation needs may contribute to elevated CO_2 emissions [25]. However, the relationship is multifaceted, as densely populated areas may also exhibit characteristics of greater efficiency, technological innovation, and a proclivity for sustainable urban practices [26]. The Environmental Kuznets Curve (EKC) hypothesis, often applied to understand the relationship between economic development and CO_2 emissions, suggests that the impact of population density on CO_2 emissions may follow a similar pattern, initially escalating and subsequently diminishing with increased levels of development and urbanization [9,10,27]. Recent research considering urban planning strategies, technological advancements, and policy interventions has added further complexity to this nexus [28,29].

The nexus between CO_2 emissions and material footprint is a focal point in contemporary discussions on sustainable development and environmental assessment. The material footprint, which signifies the total amount of raw materials extracted and used by a country, incorporates both domestic extraction and imported materials [30,31]. The activities involved in the extraction, production, and utilization of materials often contribute significantly to CO_2 emissions through energy-intensive activities. A high material footprint is commonly linked with increased energy consumption and greenhouse gas emissions, thus making a notable contribution to climate change [32]. Conversely, reducing material consumption and enhancing resource efficiency can potentially mitigate CO_2 emissions [33]. Striking a balance between economic development and resource sustainability is essential to tackle the interconnected challenges of climate change and resource depletion, highlighting the significance of the nexus between CO_2 emissions and material footprint. A shift towards a circular economy, prioritizing recycling, reuse, and sustainable material management, is a promising strategy able to decouple economic growth from environmental degradation and diminish the overall carbon footprint associated with material consumption [11,12].

The limited empirical literature on the relationship between circular economy indicators and CO_2 emissions is characterized by conflicting evidence. While some studies suggest that a reduction in CO_2 emissions is associated with circular economy practices, others find no compelling evidence of such a nexus. Advocates assert that the principles of the circular economy, which prioritize recycling, reuse, and waste reduction, can significantly lower CO_2 emissions [34–40]. Studies suggest that implementing effective recycling methods and adopting innovative waste management practices within the circular economy framework may lead to decreased carbon emissions compared to traditional linear production and consumption models [15,41,42]. Conversely, skeptics argue that the impact of circular economy practices on CO_2 emissions is not universally conclusive and depends on various factors, such as the efficiency of recycling technologies and industry-specific measures [43–47].

3. Materials and Methods

3.1. Sample

Our empirical study encompasses a dataset involving 14 European Union (EU) countries over the period from 2000 to 2020. The data selection is based on mapping the EU countries that demonstrate top performance in greenhouse gas (GHG) emissions, aligning with the EU's set limits for 2020 (https://www.greenmatch.co.uk/). These countries are as follows: "Bulgaria, Croatia, Czechia, Greece, Hungary, Italy, Lithuania, Malta, Portugal, Romania, Slovak Republic, Slovenia, Spain and United Kingdom".

Aligning with the theoretical discourse discussed previously and the study's objectives, the specified structure of the empirical models (1) and (2) are specified as follows:

$$log(y_{it}) = \beta_0 + \beta_1\, log(x_{it}) + \beta_2\, log(k_{it}) + \varepsilon_{it} \quad (1)$$

$$log(y_{it}) = \delta_0 + \delta_1\, log(x_{it}) + \delta_2\, log(\lambda_{it}) + u_{it} \quad (2)$$

where y represents the CO_2 emissions in metric tons per capita in country *i* at time *t* where a higher value signifies a low environmental quality; x denotes the GDP per capita in constant 2015 USD (GDP), representing the level of economic activity in country *i* at time *t*; λ incorporates other variables influencing environmental quality, specifically population density (DENS), material footprint (MF), and the circular material use rate (CMU); and k incorporates those variables with the exclusion of the circularity rate to estimate the impact of circular economy progress on the convergence with the EU objectives related to limiting CO_2 emissions. The coefficients to be estimated are represented by β_i and δ_i, where β_0 and δ_0 represent the constant coefficients. The error term is represented by ε_{it} and u_{it}.

3.2. Measures

3.2.1. Dependent Variable

In the current analysis, CO_2 emissions expressed in metric tons per capita serve as the dependent variable, providing valuable insights into the average individual contribution to total emissions in the examined countries. The data are sourced from the World Bank, available in the World Development Indicators database. Figure 1 illustrates the evolution of CO_2 emissions, offering evidence for the variations in CO_2 emission levels across the top-performing EU countries. In 2020, Malta emerged as the leading nation among 14 EU countries, with the lowest CO_2 emissions levels (3.13). Despite facing challenges due to its small size and limited resources, Malta has proactively invested in renewable energy sources. The country is exploring innovative solutions, such as offshore wind farms, to further reduce its CO_2 emissions levels [48]. Portugal (3.78) has been a frontrunner in renewable energy, particularly wind and solar. Policies promoting clean energy and energy efficiency have significantly contributed to a decline in GHG emissions [49].

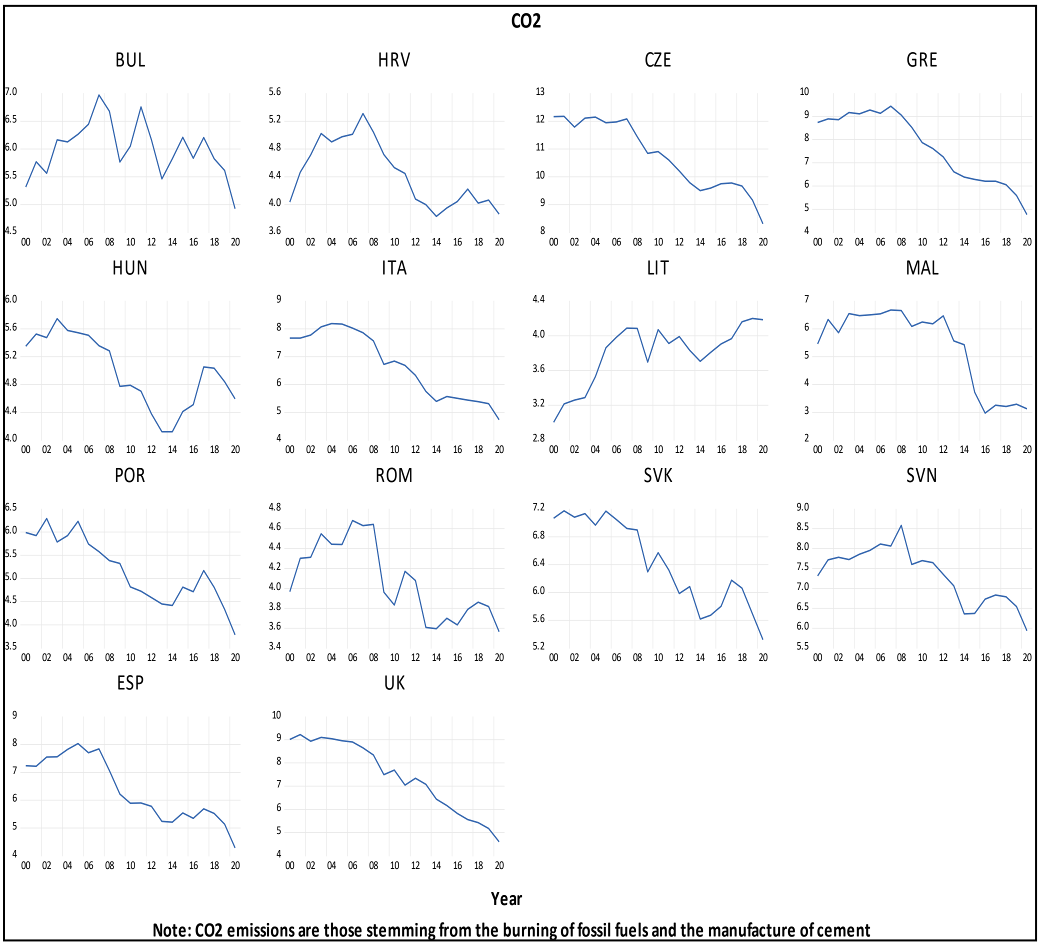


Figure 1. CO_2 emissions levels, Source(s): World Bank, Created by authors.

Romania (3.56) is actively reducing its reliance on coal and increasing the share of renewables in its energy mix [50]. Greece (4.77) is undertaking efforts to transition to a low-carbon economy by increasing the share of renewables [51], while Hungary (4.59) has implemented measures to improve energy efficiency and decrease its reliance on fossil fuels [52]. The United Kingdom (4.60) has made substantial progress in reducing coal usage and increasing the share of renewables [53]. Conversely, Czechia (8.30), Slovenia (5.93), and the Slovak Republic (5.32) exhibit the highest levels among the examined countries. However, Czechia has witnessed a decline in GHG emissions in recent years due to a shift towards cleaner energy sources [54]. Investments in nuclear energy and renewable projects significantly reduce the carbon footprint [55].

3.2.2. Independent Variables

The GDP per capita (constant 2015 USD) and Population Density (people per sq. km of land area) are sourced from the World Bank, specifically from the World Development Indicators database. Material Footprint (tons per capita) and the Circular Material Use Rate are obtained from Eurostat, available in the Circular Economy Indicators database.

The term GDP per capita is employed to test distinct relationships with CO_2 emissions. Figure 2 represents the progression of GDP per capita in constant 2015 USD, providing insights into the growth levels observed across the surveyed EU countries. Focusing on outliers in 2020, Bulgaria (7963.69) and Croatia (13,048.74) emerge as among the lowest-performing countries, while the UK (42098.60) and Spain (24,785.44) exhibit the highest GDP per capita values. This suggests that these countries may manifest distinctive patterns in terms of their economic growth and CO_2 emissions. However, the higher GDP per capita in the UK and Spain could be associated with an initial increase in CO_2 emissions followed by a subsequent decline, aligning with the theoretical concept of a U-shaped relationship [27]. Actual relationships can be influenced by various factors, including population density [56], material footprint [57], and the circular transition of each country [58].

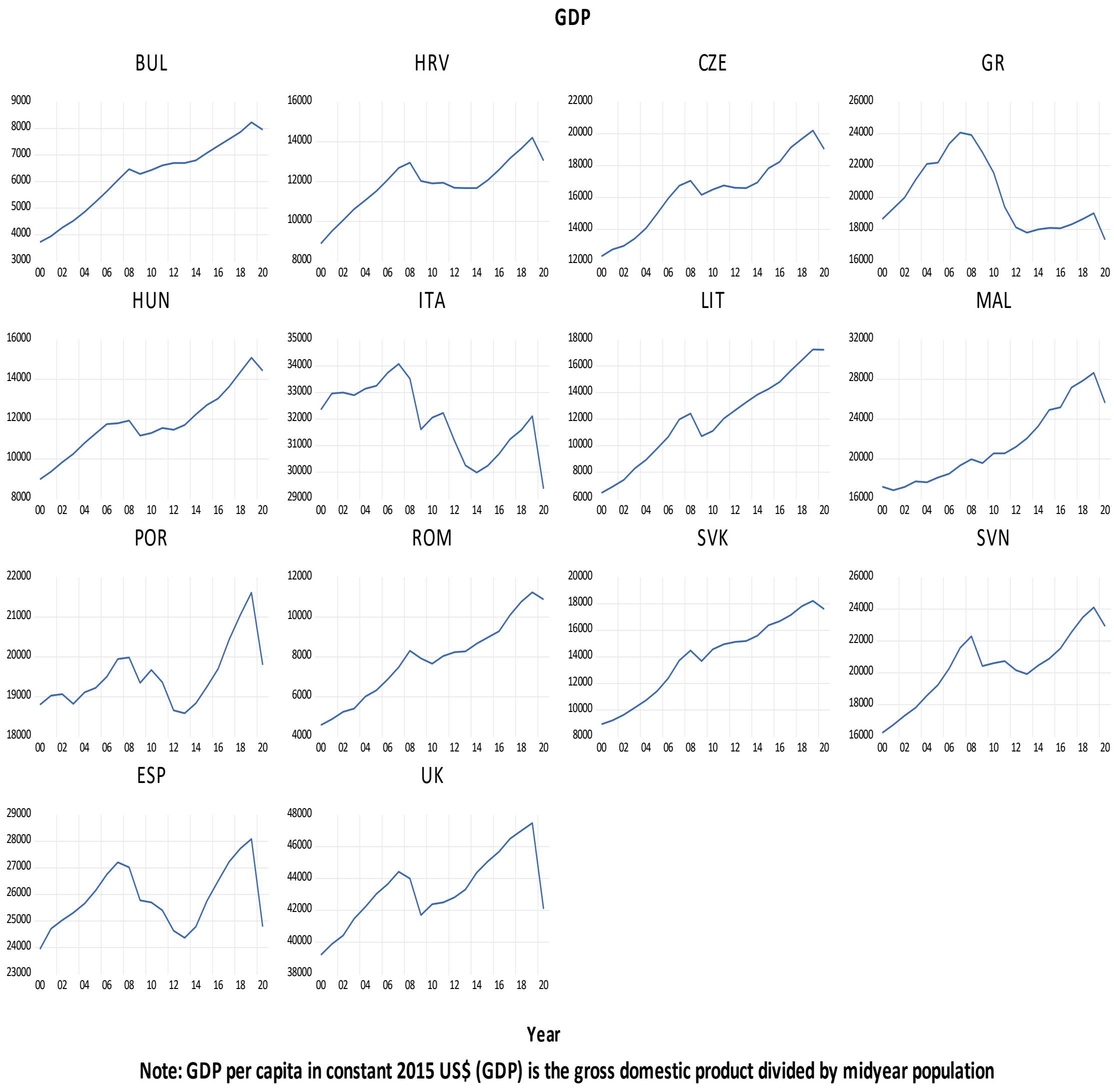


Figure 2. GDP per capita (constant 2015 USD), Source(s): World Bank, Created by authors.

Population density is useful for examining relationships with CO_2 emissions as it enables an assessment of how the concentration of people in a specific area may influence environmental outcomes. A higher population density has the potential to contribute to increased energy consumption, industrial activities, and transportation demands, thereby influencing the overall carbon footprint. Malta stands out as the most densely populated area (1610.41), while Lithuania (44.63), Bulgaria (63.87), and Croatia (72.33) are among the least densely populated areas in the EU (Figure 3).

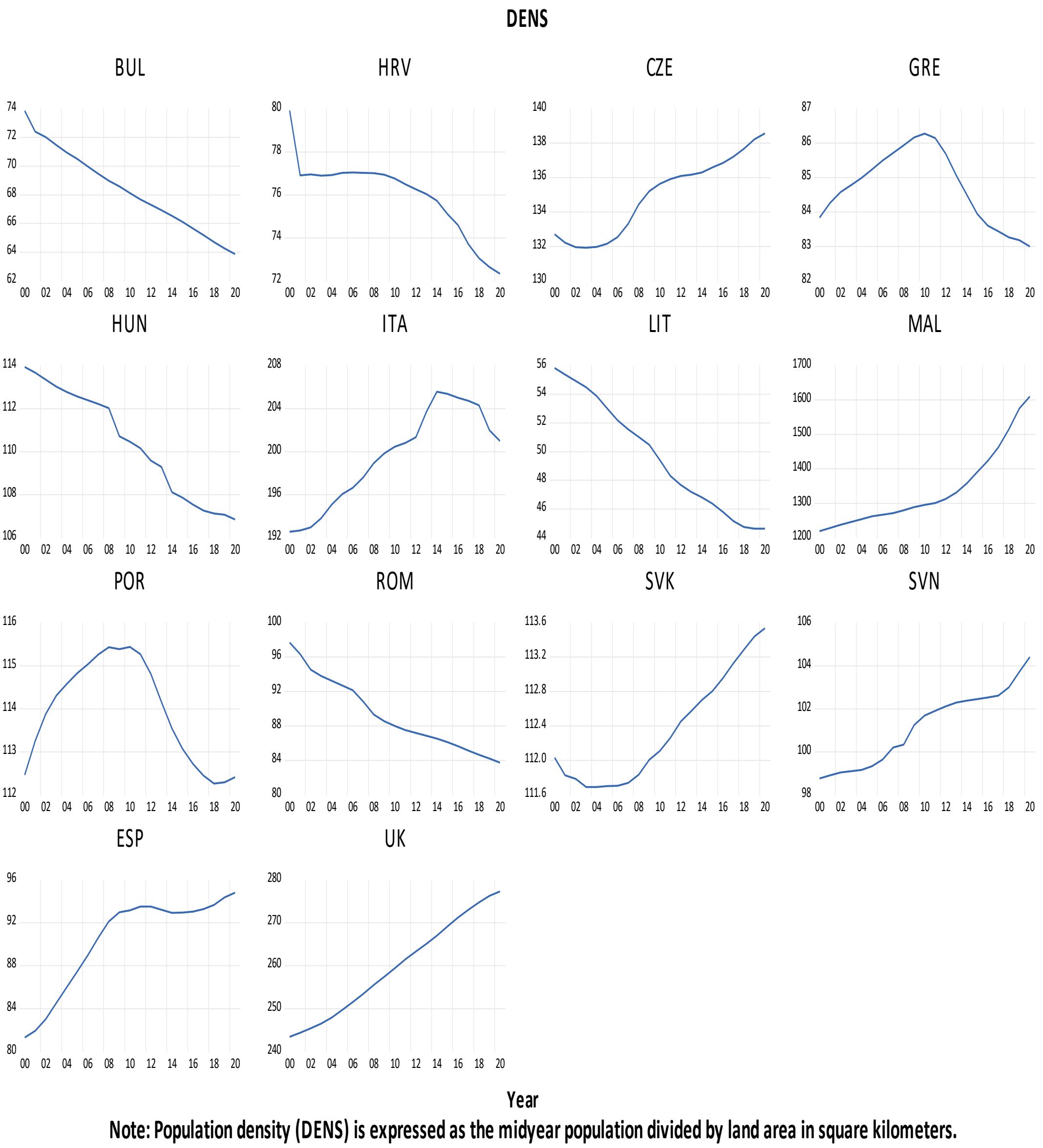


Figure 3. Population density (people per sq. km of land area), Source(s): World Bank, Created by authors.

Material footprint refers to the total quantity of raw materials used to meet a country's demands, encompassing both renewable and non-renewable resources. It serves as a valuable metric for examining associations with CO_2 emissions since the extraction, processing, and transportation of materials contribute to carbon emissions. Understanding the material footprint allows for a comprehensive analysis of a country's environmental impact. Examining the outliers in 2020 reveals that Bulgaria (20.68), Lithuania (21.68), and Romania (30.40) exhibit the highest levels of material footprint (Figure 4). This finding is intriguing, particularly considering Lithuania's smaller size compared to the others, where one might expect a relatively lower material footprint. Romania, with its diverse economy encompassing manufacturing, agriculture, and services, and Bulgaria, an emerging economy with mining industries and agriculture, showcase higher material footprints. Contributing factors include population size, industrial activity, and consumption patterns. In contrast, Spain (10.04), Italy (10.23), and Greece (11.44) present lower material footprint values. This observation is noteworthy, particularly given Italy's industrial base and consumption rates.

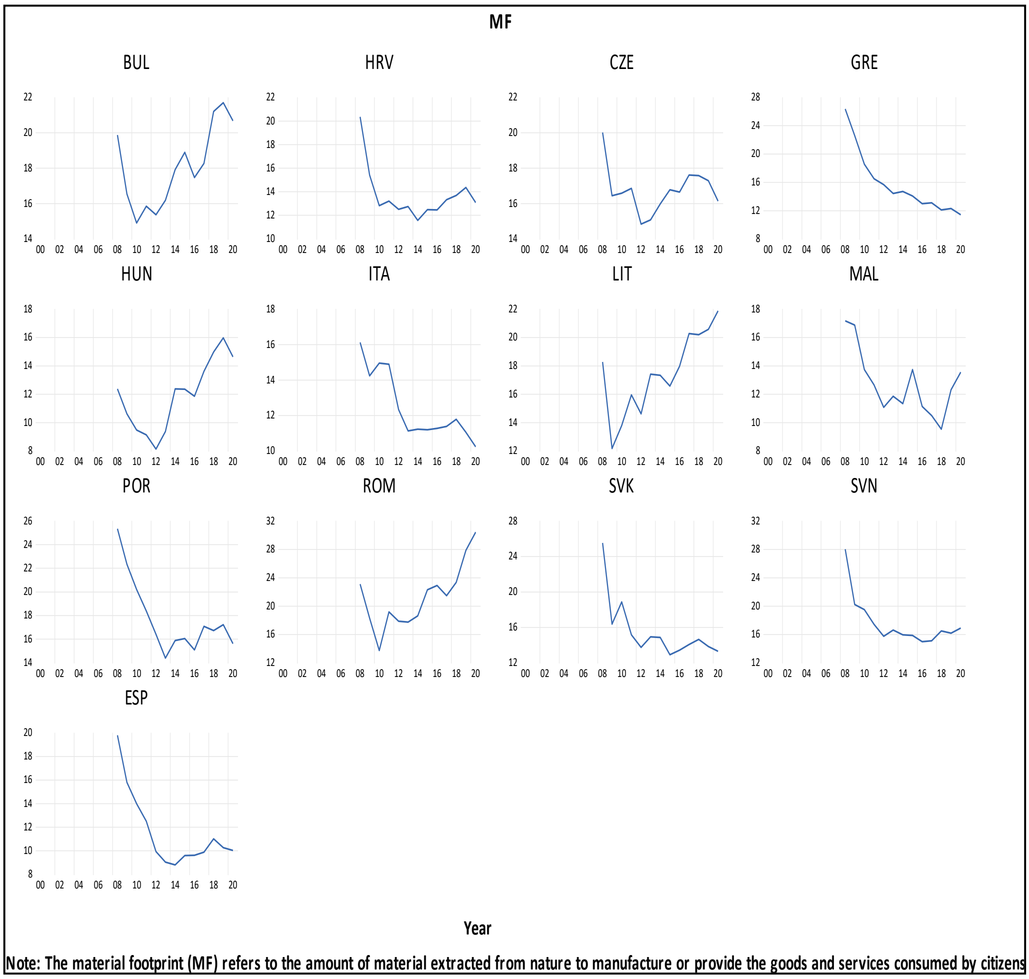
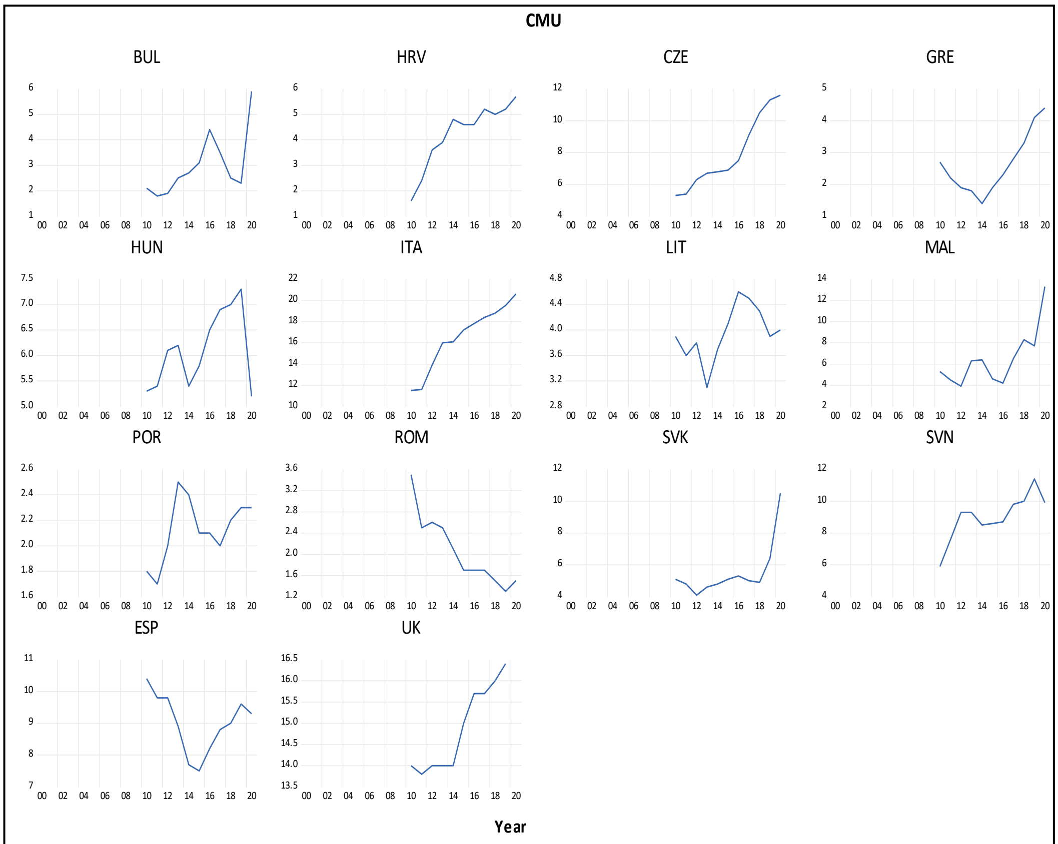


Figure 4. Material Footprint (tons per capita), Source(s): Eurostat, Created by authors.

Figure 5 illustrates the evolution of circularity rates, offering insights into variations in waste collection for recovery practices across the studied countries. The circular material use rate is useful for examining its relationship with CO_2 emissions and assessing a country's efficiency in utilizing materials within a circular economy framework [37]. A higher circularity rate indicates improved resource efficiency, suggesting a reduced need for raw materials and lower CO_2 emissions. Conversely, a lower circularity rate suggests a more linear, wasteful approach, characterized by increased resource consumption and emissions [59]. Among the top performers, Italy (19.5) and UK (16.4) showcase superior circularity rates, attributed to effective recycling incentives and regulations, a commitment to sustainability through investments in eco-friendly practices and technologies, and active engagement in the circular economy. These countries' effective resource management practices in manufacturing and production processes position them above the EU average. Conversely, Romania (1.3) and Portugal (2.3) exhibit the lowest circularity rates, underscoring the need to prioritize circular practices [60]. Enhancing the efficiency of waste management systems and increasing the awareness and adoption of sustainable and circular consumption practices among the population are crucial for addressing these lower circularity rates. Emulating countries that have demonstrated improvements in waste collection methods can assist other EU nations in ensuring the proper disposal of electronic waste, preventing its accumulation in landfills.



Note: CMU is expressed as the share of material resources used which came from recycled waste materials, thus saving extractions of primary raw materials

Figure 5. Circular Material Use Rate, Source(s): Eurostat, Created by authors.

3.3. Methods

The application of logarithmic transformation to variables ensures that the coefficients represent constant elasticities. Various methods, including Ordinary Least Squares (OLS), Fixed Effects (FE), Random Effects (RE), and Fully Modified Least Squares (FMOLS), are applied to understand the relationship between these variables and CO_2 emissions spanning the period from 2000 to 2020. Key details about these variables are summarized in Table 1. Descriptive statistics reveal that the standard deviations of CO_2, MF, and CMU are close to their respective means, indicating low variability. Conversely, the standard deviations of GDP and DENS exhibit considerable divergence from their means. Examining the minimum and maximum values also shows high variability across the data units. To determine the order of integration for the series, standard unit root tests (ADF tests) are employed [61]. Subsequently, Kao statistics are utilized for a panel cointegration analysis to assess potential long-term relationships among the variables across the sample countries [62]. The identification of cointegration confirms statistical support for Equations (1) and (2) across the entire panel. Given the same order of integration among variables and the rejection of the null hypothesis by the Breusch–Pagan test [63], conclusions based on FE can be drawn.

Table 1. Summary statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
CO_2	143	5.50	1.66	2.97	10.90
GDP	143	17,819.24	6683.10	6433.64	32,229.46
DENS	143	203.40	354.40	44.62	1610.41
MF	143	14.99	3.68	8.13	30.40
CMU	143	6.04	4.14	1.30	20.60

4. Results

4.1. Regression Analysis

Table 2 presents the long-run coefficient estimates obtained by applying Fixed Effects and FMOLS models. The regression model (1) with FE is presented in Equation (3). Significance at the 1% level is estimated, with 92% of the variability in CO_2 emissions explained by the chosen explanatory variables, affirming their suitability. The estimated GDP coefficient implies that a 1% increase in GDP per capita results in a 0.66% reduction in CO_2 emissions. Higher material footprint levels are associated with increased environmental degradation, while conversely, population density negatively correlates with CO_2 emissions. The significant negative impact of population density and the positive effect of material footprint indicate the strong influence of these factors on the relationship between economic growth and CO_2 emissions in EU countries.

$$\log(CO_2) = 13.22 - 0.66 \log(GDP) - 1.34 \log(DENS) + 0.46 \log(MF) \quad (3)$$

Table 2. Regression results. Dependent variable: CO_2 emissions levels.

	Model 1		Model 2	
Variable	**FE**	**FMOLS**	**FE**	**FMOLS**
Constant	13.22		15.13	
GDP/capita	−0.66 *** (0.08)	−0.69 *** (0.11)	−0.60 *** (0.11)	−0.69 *** (0.16)
Population Density	−1.34 *** (0.26)	−1.35 *** (0.36)	−1.76 *** (0.30)	−1.73 *** (0.39)
Material Footprint	0.46 *** (0.05)	0.49 *** (0.08)	0.32 *** (0.07)	0.42 *** (0.11)
Circularity Rate			−0.09 *** (0.03)	−0.10 ** (0.04)
R2	0.91	0.91	0.92	0.92
F-statistic	101.18 ***		85.03 ***	

** 5% level of significance. *** 1% level of significance. Numbers in parentheses represent standard errors.

Equation (4) reveals the regression results for model (1) with FMOLS. Higher economic growth leads to lower environmental degradation. The negative impact of population density on CO_2 emissions implies that well-planned urban development can lead to more efficient resource use, reduced energy consumption, and lower per capita emissions. The positive correlation between material footprint and CO_2 emissions may indicate a shift towards a circular economy. EU countries actively promote circular economy practices, emphasizing efficient material use and waste reduction, and contributing to reduced emissions associated with production and consumption. Nevertheless, these results diverge from those of the empirical study presented in [16], which found that, in the long run, a 1% increase in MF leads to a 0.62% reduction in CO_2 emissions across 15 EU countries. The observed changes in the relationship between GDP and CO_2 emissions may reflect the influence of significant investments in green technologies within the EU. These technologies, supported by policies promoting renewable energy and sustainable practices, have the potential to reduce carbon emissions even with ongoing GDP growth.

$$\log(CO_2) = -0.69 \log(GDP) - 1.35 \log(DENS) + 0.49 \log(MF) \quad (4)$$

4.2. Regression Analysis on Model 2

A recurring challenge in the existing literature is the limited availability of short-span data on circular economy indicators and the absence of a suitable identification strategy to address endogeneity concerns. To address this gap, this study utilizes an extensive panel dataset covering European countries from 2000 to 2020. The research aims to bridge divergent perspectives within the literature regarding the relationship between CE and CO_2 emissions. One school of thought asserts that CE decreases CO_2 emissions [13,34,35], leading to notable reductions in CO_2 emissions in countries implementing circular policies. Conversely, another strand suggests that CE lacks a substantial impact on CO_2 emissions. Specifically, research indicates that chemical recycling technology is ineffective in mitigating CO_2 emissions [44]. For China and Nigeria, increased energy efficiency in mining and extraction sectors did not lead to measurable CO_2 emission reductions [43]. An examination of municipal waste recycling and renewable energy's impact on environmental sustainability found no significant relationship between recycling rates and CO_2 in EU member states from 2004 to 2017 [25].

The regression model (2) with FE is presented in Equation (5). The model is statistically significant at a 1% level, explaining 92% of the variability in CO_2 emissions per capita with selected explanatory variables. A 1% increase in GDP results in a 0.60% decrease in CO_2 emissions. High efforts in waste recovery are associated with lower CO_2 emission levels; conversely, a higher material footprint is linked to increased CO_2 emissions. The observed negative relationship between GDP and CO_2 emissions could indicate a shift in the environmental consequences of economic growth for EU countries. Considering the negative relationship between population density and CO_2 emissions, the positive relationship between material footprint and CO_2 emissions and the negative relationship between circular material use rate and CO_2 emissions for EU countries, resulting in a negative relationship between GDP and CO_2 emissions, suggests a significant transformation in the dynamics of the association between economic factors and carbon dioxide emissions.

The negative relationship between population density and CO_2 emissions implies that sustainable urbanization practices in EU countries are achieving notable reductions in per capita emissions in densely populated areas. The positive relationship between material footprint and CO_2 emissions indicates that, as material consumption increases, so do carbon emissions, aligning with the environmental impact of resource extraction, production, and consumption patterns. The negative relationship between the circular material use rate and CO_2 emissions suggests that adopting circular economy practices, which emphasize efficient material use and waste reduction, contributes to mitigating carbon emissions. This finding contrasts with the empirical study, which focused on Ghana and identified a long-term positive correlation between CE and CO_2 emissions, attributed to potential rebound effects [64]. However, it is consistent with a study of 15 EU countries for the period 2000–2015, concluding that CE indicators, such as resource productivity and municipal waste recycling, tend to reduce CO_2 emissions [16]. It also corresponds with research indicating that a 1% increase in the recycling rate of municipal waste resulted in a 0.06% decrease in CO_2 emissions across 29 EU countries from 2000 to 2020 [37]. Additionally, the results complement an empirical study that found the effect of CMU on CO_2 emissions to be insignificant for 27 EU countries during the period of 2010–2017 [15].

$$\log(CO_2) = 15.13 - 0.60 \log(GDP) - 1.76 \log(DENS) + 0.32 \log(MF) - 0.09 \log(CMU) \quad (5)$$

In Equation (6), the regression results for model (2) with FMOLS are revealed. The evolving relationships highlight the impact of policies prioritizing sustainable urban development, circular economy initiatives, and responsible resource management. These shifts may also be attributed to adopting green technologies and environmentally friendly practices, reflecting a commitment to reducing the carbon intensity of economic activities. The move towards a negative relationship between GDP and CO_2 emissions could be influenced by the increased integration of renewable energy sources into the energy mix. EU countries focusing on clean energy may be experiencing a decoupling of economic growth from carbon emissions through sustainable energy practices.

Sustainable urban development is likely to be further supported by the implementation of green building standards. The efforts of EU countries to construct environmentally friendly buildings contribute to reduced energy consumption, resulting in lower carbon emissions in densely populated areas. The observed changes in consumer behavior towards sustainability and increased environmental awareness also contribute to these relationships. Consumers' choices, when aligned with sustainability principles, influence overall carbon emissions. Collaboration among EU countries on environmental initiatives and adherence to international sustainability goals play a pivotal role in shaping these relationships. The collective commitment to shared environmental objectives contributes to positive shifts in the dynamics between economic growth and carbon emissions.

$$\log(CO_2) = -0.69 \log(GDP) - 1.73 \log(DENS) + 0.42 \log(MF) - 0.10 \log(CMU) \quad (6)$$

5. Discussion

The findings underscore that national recycling efforts are associated with lower CO_2 emissions, while an increased material footprint corresponds to higher CO_2 emissions. The results align with the empirical studies conducted by [33], emphasizing that a high material footprint is often linked to increased CO_2 emissions. The negative correlation observed between a country's economic growth and CO_2 implies that eco-friendly urban planning, circular material utilization, and conscientious consumption have become more evident in higher-income countries. These results are in line with [20], highlighting that further economic growth can reduce CO_2 emissions as countries adopt cleaner technologies and implement environmental policies. This study emphasizes the crucial role of sustainable urbanization practices in reducing per capita emissions in densely populated areas. The environmental impacts of resource acquisition, manufacturing, and product usage are deemed paramount. These findings are consistent with [26], emphasizing that technological innovation and a propensity for sustainable urban practices are significant drivers behind the negative correlation between population density and per capita emissions. Adopting circular economy practices substantially contributes to mitigating carbon emissions through judicious material use and waste reduction. These results are consistent with the studies conducted by [34,35,37,38], highlighting that CE principles can substantially reduce CO_2 emissions.

CO_2 emissions resulting from the burning of fossil fuels and the manufacture of cement are identified as significant contributors to climate change. These activities release substantial amounts of carbon dioxide into the atmosphere, contributing to the greenhouse effect and global warming [25,34,39]. Concurrently, the CMU is a key indicator for evaluating the circularity of an economy. It measures the extent to which materials are recycled, reused, or recovered within the economic system, reducing the need for extracting and consuming virgin raw materials.

The CMU decreases when a country heavily relies on the extraction of virgin resources, leading to a higher demand for raw materials and potentially increasing associated CO_2 emissions. To enhance the CMU and reduce CO_2 emissions, prioritizing effective waste collection systems is crucial. By improving waste management infrastructure, promoting recycling and recovery practices, and encouraging sustainable consumption patterns, countries can increase their CMU and reduce their reliance on carbon-intensive activities [15,39]. This, in turn, contributes to the mitigation of climate change by minimizing the need for extracting new raw materials and reducing the emissions associated with their production and disposal. For instance, repairing or refurbishing products, instead of discarding and replacing them, avoids the energy-intensive manufacturing of new products and directly reduces CO_2 emissions.

Remanufacturing electronic devices can save energy compared to producing new devices, leading to lower CO_2 emissions in manufacturing. In construction, utilizing recycled materials instead of raw materials significantly reduces the CO_2 emissions produced by demolished structures, minimizing the carbon footprint linked to material extraction [34,39].

In this study, potential rebound effects can be explored by examining how changes in behavior and policies counteract initially achieved positive environmental impacts. If circular economy efforts lead to the perception that waste disposal issues are adequately addressed, individuals and businesses might become less cautious about reducing overall consumption or adopting further waste reduction practices. For instance, a city implementing circular economy initiatives, like a recycling program, might witness increased consumption as residents believe their recycling efforts absolve them of responsibility. This could result in a rise in overall resource use, potentially offsetting the emissions saved through recycling. People might develop a false sense of accomplishment after participating in recycling, leading to increased resource consumption due to reduced guilt or perceived environmental responsibility.

The relation between a country's economic growth and CO_2 emissions suggests that, as countries reach higher levels of economic growth, there is a risk that the perceived benefits of eco-friendly practices might lead to satisfaction, potentially resulting in a relaxation of stringent environmental regulations. Rebound effects might occur if the benefits of economic growth at higher income levels cause people to neglect the environmental priorities that were initially emphasized. A country achieving high economic development may also prioritize industries with higher carbon footprints due to perceived economic benefits, resulting in increased emissions despite initial efforts to implement sustainable practices. However, in our study, high economic growth is negatively associated with environmental degradation within European countries. Decoupling effects may be evident as countries become more affluent, and air pollution may decrease.

6. Conclusions

This study investigates the long-term relationship among CO_2 emissions, GDP per capita, population density, material footprint, and the circularity rate. It focuses on the top 14 greenhouse gas emitters within EU countries from 2000 to 2020. The empirical results suggest that countries demonstrating higher efficiency in material use within a circular economy framework and with regard to population density tend to exhibit lower levels of CO_2 emissions. Conversely, an increase in the material footprint is associated with increased environmental degradation. This aligns with the priorities of the circular economy, which are to minimize resource extraction through the promotion of reuse, recycling, and remanufacturing. By extending the life cycle of products and materials, countries can reduce the need to extract raw materials associated with higher CO_2 emissions levels. Circular economy practices, particularly recycling, generally require less energy than extracting and processing virgin materials, contributing to energy conservation and a diminished carbon footprint. In a circular economy, the emphasis on remanufacturing and recycling often reduces reliance on the energy-intensive traditional manufacturing processes that contribute to CO_2 emissions. The use of recycled materials in manufacturing results in lower emissions compared to goods from raw materials. However, the effectiveness of such practices relies on supportive policies including tax incentives, extended producer responsibility programs, and regulations promoting sustainable manufacturing and consumption.

The study also shows a negative association between a country's economic growth and CO_2 emissions. This finding implies that as economies expand, CO_2 emissions decrease. Economic growth is also associated with shifts in consumption patterns, such as service-oriented economies with a lower carbon intensity than manufacturing and heavy industry. Advanced economies often drive technological innovations, leading to breakthroughs in energy technology, transportation, and industrial processes that contribute to reduced carbon emissions.

Governments are advised to implement emission reduction strategies that focus on investments in cleaner technologies, thus promoting energy efficiency and enforcing industry emission standards. Policymakers can also encourage the research and development of green technologies to address the challenges associated with emissions during economic growth. Strengthening and enforcing environmental regulations become crucial during phases of rapid economic growth. Regulations should target industries with high carbon emissions and promote the adoption of best practices for material footprint reduction. The adoption of carbon pricing mechanisms, such as carbon taxes or cap-and-trade systems, can incentivize businesses to reduce their footprint and help internalize the environmental costs of carbon emissions. Recognizing the transnational nature of economic activities, countries should collaborate on international initiatives, sharing best practices and joint efforts to achieve common environmental goals.

The finding that countries with a higher population density tend to exhibit lower CO_2 emissions levels can be attributed to the fact that a higher population density often result in more compact urban environments. In such settings, there is a greater potential for efficient land use, reduced sprawl, and shorter commuting distances. Compact urban planning promotes public transportation, walking, and cycling, significantly reducing the overall carbon emissions associated with transportation. Countries with a higher population density are more inclined to invest in and support robust public transportation systems. Well-developed public transit networks can diminish reliance on individual car travel, resulting in lower emissions per capita. Additionally, higher population density can facilitate economies of scale in infrastructure development, such as energy-efficient buildings, district heating, and waste management systems. These efficiencies can contribute to lower per capita energy consumption and emissions. In densely populated areas, individuals often benefit from improved access to services, amenities, and job opportunities in close proximity. Therefore, it is crucial to prioritize the development of efficient and accessible public transportation systems to minimize dependence on individual car travel, while simultaneously enforcing energy efficiency standards for buildings and infrastructure. Implementing education and awareness campaigns to promote sustainable practices and behaviors among residents in densely populated areas is also a positive step.

While this study provides valuable insights, it is essential to acknowledge its limitations and identify opportunities for future research. This study relies on panel data from 14 EU countries, capturing only the top-performing EU countries based on their greenhouse gas emissions compared to the EU limits for 2020. Expanding the analysis to include low-performing countries could enhance the generalizability of the findings. This study also focuses on economic performance, population density, material footprint, and the circularity rate as independent variables for carbon emission performance. However, factors such as policy frameworks, technological advancements, or cultural aspects could influence the relationship between circular economy practices and carbon emissions. Exploring these additional factors could provide a more comprehensive understanding of the carbon emission performance behavior across different countries.

Future research could investigate the factors influencing individuals' perceptions of environmental responsibility, considering the impact of circular economy initiatives and recycling programs on attitudes and behaviors. Additionally, assessing the effectiveness of policy interventions in preventing rebound effects, with a specific focus on mitigating potential complacency and fostering sustained environmental benefits, is crucial. This study stresses the importance of formulating effective policies that successfully integrate circular economy practices with the SDG13 framework. Exploring potential synergies and trade-offs between circularity and other sustainable development goals could inform policy decisions in a broader context. This study examines carbon emission performance at the country level, but conducting sector-specific analyses could provide insights into the carbon emission behavior within different industries and sectors. This could help identify sector-specific strategies and interventions for promoting circularity and reducing carbon emissions. While this study employs quantitative techniques, conducting qualitative research, such as interviews or case studies, could offer deeper insights into the mechanisms and drivers behind the observed relationships. Understanding the underlying motivations, barriers, and enablers for circular economy practices and their impact on carbon emissions could be valuable for policymakers and practitioners. Future studies could also comprehensively analyze circular city models, emphasizing the potential challenges and unintended consequences associated with successful endeavors to reduce per capita emissions.

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References

1. European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. *Closing the Loop-An EU Action Plan for the Circular Economy. COM/2015/0614 Final.* 2015. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614 (accessed on 10 October 2023).
2. European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Next Steps for a Sustainable European Future European Action for Sustainability. 2016. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52016DC0739&from=ES (accessed on 10 October 2023).
3. Rodríguez-Antón, J.M.; Rubio-Andrada, L.; Celemín-Pedroche, M.S.; Alonso-Almeida, M.M. Analysis of the relations between circular economy and sustainable development goals. *Int. J. Sustain. Dev.* **2019**, *26*, 708–720. [CrossRef]
4. Belmonte-Ureña, L.J.; Plaza-Úbeda, J.A.; Vazquez-Brust, D.; Yakovleva, N. Circular economy, degrowth and green growth as pathways for research on sustainable development goals: A global analysis and future agenda. *Ecol. Econ.* **2021**, *185*, 107050. [CrossRef]
5. Rodríguez-Antón, J.M.; Rubio-Andrada, L.; Celemín-Pedroche, M.S.; Ruíz-Peñalver, S.M. From the circular economy to the sustainable development goals in the European Union: An empirical comparison. *Int. Environ. Agreem. Politics Law. Econ.* **2022**, *22*, 67–95. [CrossRef] [PubMed]
6. Romero-Perdomo, F.; Carvajalino-Umaña, J.D.; Moreno-Gallego, J.L.; Ardila, N.; González-Curbelo, M.Á. Research trends on climate change and circular economy from a knowledge mapping perspective. *Sustainability* **2022**, *14*, 521. [CrossRef]
7. Elfaki, K.E.; Khan, Z.; Kirikkaleli, D.; Khan, N. On the nexus between industrialization and carbon emissions: Evidence from ASEAN+ 3 economies. *Environ. Sci. Pollut. Res.* **2022**, *29*, 31476–31485. [CrossRef] [PubMed]
8. Nguyen, H.T.; Van Nguyen, S.; Dau, V.H.; Le, A.T.H.; Nguyen, K.V.; Nguyen, D.P.; Bui, H.M. The nexus between greenhouse gases, economic growth, energy and trade openness in Vietnam. *Environ. Technol. Innov.* **2022**, *28*, 102912. [CrossRef]
9. Ohlan, R. The impact of population density, energy consumption, economic growth and trade openness on CO_2 emissions in India. *Nat. Hazards* **2015**, *79*, 1409–1428. [CrossRef]
10. Uzair Ali, M.; Gong, Z.; Ali, M.U.; Asmi, F.; Muhammad, R. CO_2 emission, economic development, fossil fuel consumption and population density in India, Pakistan and Bangladesh: A panel investigation. *Int. J. Finance Econ.* **2022**, *27*, 18–31. [CrossRef]
11. Velenturf, A.P.; Purnell, P. Principles for a sustainable circular economy. *Sustain. Prod. Consum.* **2021**, *27*, 1437–1457. [CrossRef]
12. Bherwani, H.; Nair, M.; Niwalkar, A.; Balachandran, D.; Kumar, R. Application of circular economy framework for reducing the impacts of climate change: A case study from India on the evaluation of carbon and materials footprint nexus. *Energy Nexus* **2022**, *5*, 100047. [CrossRef]
13. MacArthur, E. Towards the circular economy. *J. Ind. Ecol.* **2013**, *2*, 23–44. Available online: https://www.werktrends.nl/app/uploads/2015/06/Rapport_McKinsey-Towards_A_Circular_Economy.pdf (accessed on 26 November 2023).

14. Ellen Macarthur Foundation. *Completing the Picture: How the Circular Economy Tackles Climate Change*; Ellen Macarthur Foundation: Cowes, UK, 2019; Volume 1, pp. 1–71.
15. Pao, H.T.; Chen, C.C. The dynamic interaction between circular economy and the environment: Evidence on EU countries. *Waste Manag. Res.* **2022**, *40*, 969–979. [CrossRef] [PubMed]
16. Mongo, M.; Laforest, V.; Belaïd, F.; Tanguy, A. Assessment of the Impact of the Circular Economy on CO_2 Emissions in Europe. *J. Innov. Econ. Manag.* **2021**, I107-29. Available online: https://www.cairn.info/revue-journal-of-innovation-economics-2022-3-page-15.htm (accessed on 26 November 2023). [CrossRef]
17. Halkos, G.E. Environmental Kuznets Curve for sulfur: Evidence using GMM estimation and random coefficient panel data models. *Environ. Dev. Econ.* **2003**, *8*, 581–601. [CrossRef]
18. Tiwari, A.K. Energy consumption, CO_2 emissions and economic growth: Evidence from India. *Int. J. Bus. Econ.* **2011**, *12*, 85–122. [CrossRef]
19. Zaman, K.; Abd-el Moemen, M. Energy consumption, carbon dioxide emissions and economic development: Evaluating alternative and plausible environmental hypothesis for sustainable growth. *Renew. Sustain. Energy Rev.* **2017**, *74*, 1119–1130. [CrossRef]
20. Balsalobre-Lorente, D.; Shahbaz, M.; Ponz-Tienda, J.L.; Cantos-Cantos, J.M. Energy innovation in the environmental Kuznets curve (EKC): A theoretical approach. Carbon footprint and the industrial life cycle: From urban planning to recycling. In *Carbon Footprint and the Industrial Life Cycle*; Springer International Publishing: Berlin/Heidelberg, Germany, 2017; pp. 243–268.
21. Neagu, O. The link between economic complexity and carbon emissions in the European Union countries: A model based on the Environmental Kuznets Curve (EKC) approach. *Sustainability* **2019**, *11*, 4753. [CrossRef]
22. Wang, Q.; Zhang, F. The effects of trade openness on decoupling carbon emissions from economic growth–evidence from 182 countries. *J. Clean. Prod.* **2021**, *279*, 123838. [CrossRef]
23. Zhang, J. Environmental Kuznets curve hypothesis on CO_2 emissions: Evidence for China. *J. Risk Financ. Manag.* **2021**, *14*, 93. [CrossRef]
24. Wang, Q.; Yang, T.; Li, R. Does income inequality reshape the environmental Kuznets curve (EKC) hypothesis? A nonlinear panel data analysis. *Environ. Res.* **2023**, *216*, 114575. [CrossRef]
25. Wang, S.; Liu, X.; Zhou, C.; Hu, J.; Ou, J. Examining the impacts of socioeconomic factors, urban form, and transportation networks on CO_2 emissions in China's megacities. *Appl. Energy* **2017**, *185*, 189–200. [CrossRef]
26. Bibri, S.E.; Krogstie, J. Smart sustainable cities of the future: An extensive interdisciplinary literature review. *Sustain. Cities Soc.* **2017**, *31*, 183–212. [CrossRef]
27. Dinda, S. Environmental Kuznets curve hypothesis: A survey. *Ecol. Econ.* **2004**, *49*, 431–455. [CrossRef]
28. Seto, K.C.; Dhakal, S.; Bigio, A.; Blanco, H.; Carlo Delgado, G.; Dewar, D.; Zwickel, T. *Human Settlements, Infrastructure, and Spatial Planning*; UCLA: Los Angeles, CA, USA, 2014.
29. Ahmad, M.; Jiang, P.; Murshed, M.; Shehzad, K.; Akram, R.; Cui, L.; Khan, Z. Modelling the dynamic linkages between eco-innovation, urbanization, economic growth and ecological footprints for G7 countries: Does financial globalization matter? *Sustain. Cities Soc.* **2021**, *70*, 102881. [CrossRef]
30. Wiedmann, T.O.; Schandl, H.; Moran, D. The footprint of using metals: New metrics of consumption and productivity. *Environ. Econ. Policy Stud.* **2015**, *17*, 369–388. [CrossRef]
31. Wiedmann, T.O.; Schandl, H.; Lenzen, M.; Moran, D.; Suh, S.; West, J.; Kanemoto, K. The material footprint of nations. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 6271–6276. [CrossRef]
32. Schandl, H.; Hatfield-Dodds, S.; Wiedmann, T.; Geschke, A.; Cai, Y.; West, J.; Owen, A. Decoupling global environmental pressure and economic growth: Scenarios for energy use, materials use and carbon emissions. *J. Clean. Prod.* **2016**, *132*, 45–56. [CrossRef]
33. Ekins, P.; Hughes, N.; Brigenzu, S.; Arden Clark, C.; Fischer-Kowalski, M.; Graedel, T.; Westhowk, H. Resource Efficiency: Potential and Economic Implications. 2016. Available online: https://pure.iiasa.ac.at/id/eprint/13813/ (accessed on 26 November 2023).
34. Bianchi, M.; Cordella, M. Does circular economy mitigate the extraction of natural resources? Empirical evidence based on analysis of 28 European economies over the past decade. *Ecol. Econ.* **2023**, *203*, 107607. [CrossRef]
35. Di Maio, F.; Rem, P.C. A robust indicator for promoting circular economy through recycling. *J. Environ. Prot.* **2015**, *6*, 1095–1104. [CrossRef]
36. Geissdoerfer, M.; Morioka, S.N.; de Carvalho, M.M.; Evans, S. Business models and supply chains for the circular economy. *J. Clean. Prod.* **2018**, *190*, 712–721. [CrossRef]
37. Hailemariam, A.; Erdiaw-Kwasie, M.O. Towards a circular economy: Implications for emission reduction and environmental sustainability. *Bus. Strategy Environ.* **2023**, *32*, 1951–1965. [CrossRef]
38. Laurijssen, J.; Marsidi, M.; Westenbroek, A.; Worrell, E.; Faaij, A. Paper and biomass for energy?: The impact of paper recycling on energy and CO_2 emissions. *Resour. Conserv. Recy.* **2010**, *54*, 1208–1218. [CrossRef]
39. Razzaq, A.; Sharif, A.; Najmi, A.; Tseng, M.L.; Lim, M.K. Dynamic and causality interrelationships from municipal solid waste recycling to economic growth, carbon emissions and energy efficiency using a novel bootstrapping autoregressive distributed lag. *Resour. Conserv. Recy.* **2021**, *166*, 105372. [CrossRef]
40. Maldonado-Guzman, G.; Garza-Reyes, J.A. Beyond lean manufacturing and sustainable performance: Are the circular economy practices worth pursuing? *Manag. Environ. Qual.* **2023**, *34*, 1332–1351. [CrossRef]

41. Schwarz, A.E.; Ligthart, T.N.; Bizarro, D.G.; De Wild, P.; Vreugdenhil, B.; Van Harmelen, T. Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach. *Waste Manag.* **2021**, *121*, 331–342. [CrossRef] [PubMed]
42. Triguero, A.; Cuerva, M.C.; Saez-Martınez, F.J. Closing the loop through eco-innovation by European firms: Circular economy for sustainable development. *Bus. Strategy Environ.* **2022**, *31*, 2337–2350. [CrossRef]
43. Li, G.; Zakari, A.; Tawiah, V. Energy resource melioration and CO_2 emissions in China and Nigeria: Efficiency and trade perspectives. *Resour. Policy* **2020**, *68*, 101769. [CrossRef]
44. Meys, R.; Frick, F.; Westhues, S.; Sternberg, A.; Klankermayer, J.; Bardow, A. Towards a circular economy for plastic packaging wastes–the environmental potential of chemical recycling. *Resour. Conserv. Recycl.* **2020**, *162*, 105010. [CrossRef]
45. Bayar, Y.; Gavriletea, M.D.; Sauer, S.; Paun, D. Impact of municipal waste recycling and renewable energy consumption on CO_2 emissions across the European Union (EU) member countries. *Sustainability* **2021**, *13*, 656. [CrossRef]
46. Gedam, V.V.; Raut, R.D.; de Sousa Jabbour, A.B.L.; Tanksale, A.N.; Narkhede, B.E. Circular economy practices in a developing economy: Barriers to be defeated. *J. Clean. Prod.* **2021**, *311*, 127670. [CrossRef]
47. Cudjoe, D.; Wang, H.; Zhu, B. Assessment of the potential energy and environmental benefits of solid waste recycling in China. *J. Environ. Manag.* **2021**, *295*, 113072. [CrossRef] [PubMed]
48. Ozturk, I.; Acaravci, A. Energy consumption, CO_2 emissions, economic growth, and foreign trade relationship in Cyprus and Malta. *Energy Sources B Econ. Plan.* **2016**, *11*, 321–327. [CrossRef]
49. Adebayo, T.S.; Oladipupo, S.D.; Adeshola, I.; Rjoub, H. Wavelet analysis of impact of renewable energy consumption and technological innovation on CO_2 emissions: Evidence from Portugal. Environ. *Sci. Pollut. Res.* **2022**, *29*, 23887–23904. [CrossRef] [PubMed]
50. Colesca, S.E.; Ciocoiu, C.N. An overview of the Romanian renewable energy sector. *Renew. Sustain. Energy Rev.* **2013**, *24*, 149–158. [CrossRef]
51. Mondol, J.D.; Koumpetsos, N. Overview of challenges, prospects, environmental impacts and policies for renewable energy and sustainable development in Greece. *Renew. Sustain. Energy Rev.* **2013**, *23*, 431–442. [CrossRef]
52. Bart, I.; Csernus, D.; Sáfián, F. *Analysis of Climate-Energy Policies & Implementation in Hungary*; National Society of Conservationists—Friends of the Earth Hungary: Budapest, Hungary, 2018. Available online: http://eko-unia.org.pl/wp-content/uploads/2018/06/mini-report-1_Hungary.pdf (accessed on 26 November 2023).
53. Fouquet, R.; Pearson, P.J. A thousand years of energy use in the United Kingdom. *Energy J.* **1998**, *19*, 1–41. [CrossRef]
54. Kacperska, E.; Łukasiewicz, K.; Pietrzak, P. Use of renewable energy sources in the European Union and the Visegrad Group countries—Results of cluster analysis. *Energies* **2021**, *14*, 5680. [CrossRef]
55. Karakosta, C.; Pappas, C.; Marinakis, V.; Psarras, J. Renewable energy and nuclear power towards sustainable development: Characteristics and prospects. *Renew. Sustain. Energy Rev.* **2013**, *22*, 187–197. [CrossRef]
56. Boissau, S.; Locatelli, B.; Weber, J. Population and environment relationship: A U-shaped curve hypothesis. In Proceedings of the International Symposium on Sustainable Ecosystem, Chambéry, France, 14–18 March 1999; pp. 125–128. Available online: https://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers20-11/010031878.pdf (accessed on 26 November 2023).
57. Ansari, M.A.; Haider, S.; Khan, N.A. Environmental Kuznets curve revisited: An analysis using ecological and material footprint. *Ecol. Indic.* **2020**, *115*, 106416. [CrossRef]
58. Bonnini, S.; Borghesi, M.; Giacalone, M. Advances on multi sample permutation tests for "V-shaped" and "U-shaped" alternatives with application to circular economy. *Ann. Oper. Res.* **2023**, 1–16.
59. Moraga, G.; Huysveld, S.; Mathieux, F.; Blengini, G.A.; Alaerts, L.; Van Acker, K.; Dewulf, J. Circular economy indicators: What do they measure? *Resour. Conserv. Recycl.* **2019**, *146*, 452–461. [CrossRef] [PubMed]
60. Hondroyiannis, G.; Sardianou, E.; Nikou, V.; Evangelinos, K.; Nikolaou, I. Circular economy and macroeconomic performance: Evidence across 28 European countries. *Ecol. Econ.* **2024**, *215*, 108002. [CrossRef]
61. Pesaran, M.H. A simple panel unit root test in the presence of cross-section dependence. *J. Appl. Econ.* **2007**, *22*, 265–312. [CrossRef]
62. Kao, C. Spurious regression and residual-based tests for cointegration in panel data. *J. Econ.* **1999**, *90*, 1–44. [CrossRef]
63. Pesaran, M.H. General Diagnostic Tests for Cross Section Dependence in Panels. 2004. SSRN 572504. Available online: https://ssrn.com/abstract=572504 (accessed on 25 November 2023).
64. Mawutor, J.K.M.; Sogah, E.; Gborse, F.C. Circular economy and carbon emissions: Threshold effect of quality of governance. *Manag. Environ. Qual.* 2023; *in press*. [CrossRef]