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Reducing transport sector CO_2 emissions patterns: Environmental technologies and renewable energy

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A R T I C L E I N F O

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Sustainable growth

A B S T R A C T

The research explores the impact of environmental technologies and renewable energy on carbon dioxide (CO_2) emissions from the EU transportation sector (2007–2020). Utilizing panel corrected standard error and feasible generalized least squares methods, the study uncovers key drivers influencing declining CO_2 emissions. The results reveal a significant and variable effect of environmental technologies and renewable energy on CO_2 emissions in the EU transport sector, emphasizing the positive correlation between increased renewable energy adoption and emission reduction. This underscores the necessity for heightened EU investment in sustainable transport infrastructure and clean energy solutions, encompassing initiatives like electric vehicles, hydrogen fuel cells, and biofuels. The study further recommends promoting renewable energy sources for transport systems, aligning with the broader goals of the European Green Deal and the EU Climate Law. Additionally, the research provides essential insights into policy implications, emphasizing a multifaceted approach including comprehensive strategies for cleaner transportation, innovation, and education to accelerate the transition towards sustainable practices in the EU.

1. Introduction

The EU countries have articulated ambitious goals to become a carbon-neutral region, reflecting their commitment to combatting climate change and setting an example on the global stage (Pudryk et al., 2023; Prokopenko and Miśkiewicz, 2020; Karnowski and Miśkiewicz, 2021; Trushkina, 2019; Dzwigol, 2021b). This aspiration not only addresses environmental concerns but also intersects with pressing issues related to globalization, as it underscores the EU's determination to play a leadership role in promoting sustainable practices worldwide (Kharazishvili and Kwilinski, 2022; Szczepańska-Woszczyna et al., 2022; Karnowski and Rzońca, 2023). Additionally, these goals highlight the convergence of macroeconomic policies (Moskalenko et al., 2022a, 2022b; Kwilinski et al., 2022; Dźwigoł, 2021) EU member states, signaling a collective commitment to green growth, technological innovation, and fostering economic resilience in the face of global challenges. In this case, EU has been developed and implemented the regulations for different sectors (Polcyn et al., 2022; Melnychenko, 2019; Kharazishvili and Kwilinski, 2022; Stępień et al., 2023; Letunovska et al., 2023; Miśkiewicz et al., 2023). Considering the last report of the European Environment Agency (2023), the transport sector is one of the biggest polluters and producers of CO_2. It requires to activate the EU forces to transform transport sector from tradition (with highest negative impact on the environment) to green development. The scholars (Dzwigol et al., 2023; Kwilinski et al., 2022, 2023a, 2023b; Hussain et al., 2021) underlined that it could be achieved via environmental technologies and renewable energy. However, Wicker et al. (2021) outlined that environmental technologies and renewable energy sources in the transport sector is prohibitively expensive. Sharma and Aiyejina (2010) also concluded that implementation of renewable systems in transport sector is prohibited expensive. In addition, Kahia et al. (2020) show that scale of renewable energy should be massive to compensate the positive impact of economic growth on environmental degradation. Furthermore, Kany et al. (2022) and Gulagi et al. (2021) show it does not the feasibility of transitioning to renewable energy in all aspects of transportation, particularly in aviation and long-haul freight sectors. At the same time, the studies (Shan et al., 2021; Habiba et al., 2022; Godil et al., 2021) show that environmental technologies and renewable energy sources play a crucial role in reducing CO_2 emissions in the transport sector by offering cleaner and more sustainable

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alternatives to conventional fossil fuel-based transportation. Omri and Saidi (2022) outline the bidirectional connection between CO_2 emissions and both renewable and non-renewable energy in both short and long-term perspectives. Environmental technologies and renewable energy solutions often contribute to improve energy efficiency in transportation (Wen et al., 2022). Furthermore, the past studies (Kwilinski et al., 2023c; Dzwigol et al., 2020; Trzeciak et al., 2022) empirically confirmed that digitalization boosts the transformation of transport sector to green development with improving energy efficiency. Dhahri et al. (2024) outline that digitalization is conducive to sustainable development of all economic sector. At the same time, the digitalization requires appropriate knowledge (Kwilinski, 2019; Miśkiewicz, 2019; Kwilinski et al., 2020), competencies (Dzwigol, 2019, 2020; Szczepańska-Woszczyna et al., 2022; Szczepańska-Woszczyna and Gatnar, 2022) and infrastructure and management instruments (Dzwigol, 2021a, 2022; Dzwigol et al., 2020; Dźwigoł and Trzeciak, 2023). Khurshid et al. (2023d) indicated that carbon pricing proves effective in the short term, achieving long-term sustainability requires a focus on green innovation and stringent environmental policies.

In this case, analyzing CO_2 emissions patterns in the transport sector using environmental technologies and renewable energy is crucial for mitigating climate change and setting effective emission reduction targets. It allows formulating targeted policies, allocating resources efficiently, and foster technological innovation. Additionally, it develops options for improving air quality, enhances energy security, and offers economic opportunities while demonstrating global leadership in addressing climate challenges. Ultimately, it leads to a more sustainable, resilient, and environmentally just transportation system.

This paper makes significant contributions to filling the existing scientific gaps in the theoretical understanding of the decline in CO_2 emissions from the transport sector in several ways. First and foremost, the study enriches the literature on CO_2 emissions from the transport sector by delving into the specific determinants behind emissions reduction within the European Union (EU) region. While there is a substantial body of research on CO_2 emissions in the transport sector, much of it tends to concentrate on broader or global perspectives, often overlooking the unique dynamics and policy implications within the EU. The EU has set ambitious targets to significantly reduce greenhouse gas emissions, with specific focus on the transport sector, which is a major contributor to carbon emissions. By understanding the patterns and determinants of CO_2 emissions reduction, EU policymakers can tailor their strategies to effectively address the unique challenges and opportunities within the region. This knowledge is essential for crafting informed policies that align with the EU's broader environmental goals, such as those outlined in the European Green Deal and the EU Climate Law. Thus, this paper seeks to provide a more comprehensive analysis, offering insights that are particularly relevant to the EU's environmental policies and initiatives aimed at reducing emissions from transportation. Furthermore, this research makes a notable contribution to the literature on the sustainable economy by placing a specific emphasis on the Environmental Kuznets Curve (EKC) theory. In addition to this theoretical framework, the study employs analytical techniques such as Partial Least Squares Cointegration Estimation and Feasible Generalized Least Squares (FGLS) analyses. These methods are instrumental in not only identifying but also quantifying the pivotal roles played by renewable energy sources and environmental technologies in the reduction of CO_2 emissions stemming from the transport sector. By incorporating EKC theory and applying these rigorous analytical tools, this study offers a nuanced and comprehensive exploration of the complex relationship between economic development, environmental sustainability, and the adoption of green technologies, thus advancing understanding of sustainable economic practices and policies.

The paper has the following structure: Section 2 – exploring the theoretical background on linking between transport sector CO_2 emissions, environmental technologies and renewable energy; Section 3 – identifying the methodology and instruments for checking the research hypotheses; Section 4 – explain the empirical results of investigation; Section 5 – comparison analysis of the obtained findings with the precious investigations; Section 6 – summarizing the core results of the investigation, policy implication and recommendation, limitation and further directions for investigations.

2. Literature review

2.1. The relationship between gross domestic product (GDP) and CO_2 emissions from the transport sector

Developed nations tend to have higher GDPs and lower emissions per unit of economic output due to cleaner technologies and more efficient infrastructure (Liu et al., 2022; Arefieva et al., 2021; Li et al., 2022). Liu et al. (2023) and Raihan et al. (2022) outline that understanding this relationship between GDP and CO_2 emissions is essential for countries aiming to balance economic growth with environmental sustainability. It highlights the possibility of "decoupling" economic prosperity from environmental harm, a key goal in the pursuit of sustainable development. The studies (Solaymani, 2022; Dzwigol et al., 2021; Kharazishvili et al., 2020) support the traditional hypothesis that GDP growth lead to increasing the CO_2 emissions. Thus, the intensification of industrial activity, growth of urbanization, and consumer demand for transportation services contribute to higher CO_2 emissions. Latif et al. (2023) indicate that the traditional EKC suggests that as a country's income initially rises, environmental degradation worsens, but beyond a certain income level, environmental quality begins to improve. In other words, there's an initial increase in pollution as countries industrialize, followed by a decline as they become wealthier and can afford cleaner technologies and better environmental regulations. At the same time, Awan et al. (2022) outline that traditional EKC hypothesis don't work in the long-run term. Based on the empirical results they justified the N-shape EKC hypothesis for the transport sector. Furthermore, the urbanization provokes the growth of CO_2 emissions from transport sector, whereas innovation alleviates CO_2 emissions from transportation. Guo et al. (2020) confirm the U-shape relations between GDP and CO_2 emissions from transportation in China. However, this impact is different depends on regions. Based on the abovementioned results the following hypothesis is checked:

H1. There is an inverted U-shaped relationship between GDP and CO_2 emissions from the transport sector.

2.2. Role of environmental technologies in declining transport sector CO_2 emissions

The global challenge of reducing carbon dioxide (CO_2) emissions has prompted businesses to explore innovative solutions, and one promising avenue is the integration of open innovation dynamics into their business models. Open innovation involves collaborating with external partners, including customers, suppliers, and other stakeholders, to co-create value (Shaukat et al., 2023). In the context of the transport sector, embracing open innovation can lead to novel approaches that significantly contribute to the reduction of CO_2 emissions (Chesbrough, 2012; Lotfi et al., 2023). Integrating open innovation dynamics into the business models of companies in the transport sector presents a strategic opportunity to address the urgent challenge of reducing CO_2 emissions (Lee and Roh, 2023; Pedersen, 2020). By fostering collaborative ecosystems, embracing technology platforms, co-creating with customers, promoting open-source innovation, and advocating for supportive regulations, businesses can drive positive environmental outcomes while remaining competitive in an evolving market (Trombadore et al., 2020). The business model outlined here serves as a blueprint for organizations seeking to play a crucial role in shaping a more sustainable future for the transportation industry.

Environmental technologies are pivotal in the ongoing efforts to reduce CO_2 emissions stemming from the transport sector (Nederveen et al., 2003; Hickman et al., 2009; Zhang et al., 2013; Borysova and Monastyrskyi, 2019; Borysova et al., 2019; Khurshid et al., 2023a). Kahia et al. (2023) confirmed that growth of environmental technologies was conducive to declining of CO_2 emissions in long-term. In the face of pressing climate change and environmental challenges, these innovative technologies are taking center stage, transforming the transport into more sustainable future. Shahzad et al. (2022) and Luo et al. (2023) outline that their roles are multifaceted, encompassing a wide range of strategies to curtail emissions and improve the environmental performance of the transportation systems. Razzaq et al. (2021) outline that green innovations, encompassing environmentally friendly technologies and practices, play a pivotal role in mitigating carbon emissions, particularly in nations with high levels of emissions. These innovations encompass a range of solutions, from renewable energy sources and energy-efficient systems to carbon capture technologies. Their primary purpose is to reduce the environmental impact and carbon footprint of industries and economies. By adopting green innovations, a country with substantial emissions can effectively lower its carbon emissions, contributing to global efforts to combat climate change and transition toward a more sustainable and environmentally responsible future. The inherent goal of green innovations is to facilitate a significant reduction in carbon emissions, aligning with the broader aim of achieving a greener and sustainable development. Khan and Khurshid (2022) conformed that short-term time and spectral correlation between circular economy, emissions, and technological innovation, with circular economy leading technological innovation in the short term, and emissions leading technology innovation in the short term, indicating the importance of infrastructure development and business models in shaping these dynamics. In addition, Khurshid et al. (2022) outline that eco-patents contribute to decreasing carbon dioxide emissions, the study highlights the significant impact of environmental policies and taxes. The role of small and medium-sized enterprises (SMEs) in open innovation within the context of environmental technologies and renewable energy is a subject that has garnered increasing attention in academic literature (Brunswicker and Van de Vrande, 2014; Skordoulis et al., 2020). SMEs, often characterized by their flexibility and agility, play a vital role in fostering innovation ecosystems (Lepore et al., 2023). In their study, Passaro et al. (2023) undertake a systematic literature review with a specific focus on revealing the determinants of eco-innovation within small and medium-sized enterprises (SMEs), while also exploring the intricate relationships among these factors. The outcomes of this thorough review significantly enhance understanding of the elements that have been empirically validated as pivotal for SMEs in the realm of eco-innovation implementation. Additionally, the research underscores the pressing need for the development of tailored policies aimed at addressing the specific requirements identified within the SME sector pertaining to the successful implementation of eco-innovations. Kurniawati et al. (2022) find a positive correlation between innovativeness and sustainability performance, emphasizing the constructive impact of innovativeness on organizational sustainability. Additionally, the study reveals a positive association between inbound open innovation and innovativeness. Organizational factors contributing to this relationship include competence mapping and network position, both identified as positive influencers on inbound open innovation. Moreover, knowledge-related factors play a significant role, with the appropriation of knowledge output, connective capacity, inventive capacity, and innovative capacity all showcasing positive effects on inbound open innovation in the organizational context. In their study, Phonthanukitithaworn et al. (2023) elucidate the complex interplay among enterprise innovative maturity, the orientation of small- and medium-sized enterprises (SMEs) towards sustainability principles, and the enhancement of their involvement in sustainable development for improved business efficiency. Through the utilization of structural equation modeling rooted in second-order factor analysis, the researchers underscore the critical role played by intellectual capital within SMEs. This aspect proves instrumental in nurturing opportunity recognition and facilitating the emergence of open sustainability innovation. To maximize effectiveness, the authors emphasize the importance of strategically aligning sustainability-oriented initiatives and an open innovation strategy within SMEs. Moreover, Carrasco-Carvajal et al. (2023) found that effective management of intellectual property is crucial for SMEs to participate meaningfully in open innovation processes. The review suggests that understanding the strategies employed by SMEs to protect intellectual property while engaging in collaborative initiatives is essential for fostering a conducive environment for sustainable innovation.

Rodrigues et al. (2023) and Grace et al. (2023) and environmental technologies are facilitating the adoption of electric buses, trams, and trains, all of which produce lower emissions and improve air quality in urban areas. These sustainable modes of transportation provide a green alternative to private car use. Palit et al. (2022) and Shah et al. (2021) underlined that the influence of environmental technologies extends to smart transportation solutions, which include traffic management systems, real-time navigation apps, and autonomous vehicles. These innovations optimize routes, reduce congestion, and minimize idling, ultimately leading to more fuel-efficient journeys and a noticeable reduction in CO_2 emissions (Massar et al., 2021; Brych et al., 2021; Fontaras et al., 2017). Wang et al. (2020) proves that CO_2 emissions from transport sector is defer from region of Belt and Road countries and have a spatial effect. The scholars confirm that green innovations and environmental patent allow declining CO_2 emissions from transport sector. Using Global Malmquist-Luenberger (GML) index and Slack Based Measure (SBM) Zeng et al. (2022) confirms that green technologies spatial spillover and nonlinear effects on CO_2 emissions from transport sector. Considering mentioned above the following hypothesis is outlined:

H2. Higher patent activity in environment-related technologies is associated with lower CO_2 emissions.

2.3. *Renewable energy and CO_2 emissions from the transport sector*

Renewable energy sources, such as wind, solar, and hydroelectric power, serve as a clean and sustainable energy supply for electric vehicles (Mwasilu et al., 2014; Yuksel and Kaygusuz, 2011; Barman et al., 2023). Chu and Meisen (2011) proves that renewable energy technologies produce minimal or zero direct CO_2 emissions during electricity generation, positioning them as a greener alternative to fossil fuels. Omri et al. (2023) revealed the importance of effective policies to reduce emissions in secondary and tertiary economic sectors by promoting the use of renewable energy. The crucial role of renewable energy in mitigating climate changes also was highlited by Boubaker and Omri (2022). Choi et al. (2018) explains that as the proportion of renewables in the energy mix expands, the environmental benefits of electrical vehicles adoption become even more pronounced. Furthermore, the renewable energy could be directed toward powering the charging infrastructure for electric public transportation, yielding further emissions reductions. Additionally, the utilization of renewable energy sources throughout the electric vehicle manufacturing process and supply chain could significantly lower the carbon footprint associated with the production of electric vehicles when compared to traditional internal combustion engine vehicles. The studies (P. Li et al., 2022; F. Li et al., 2022; Günther et al., 2015; Xia et al., 2022) show that it's not only the vehicles themselves but also the entire ecosystem of EVs that benefits from this cleaner energy source. The integration of renewable energy in the transport sector allows reducing dependence on imported fossil fuels, bolstering energy security, and the creation of jobs within the renewable energy sector (Raihan et al., 2023; Wang et al., 2022). Using the STIRPAT model Murshed et al. (2022) confirms the hypothesis that enhancing renewable electricity led to declining CO_2 emissions generated from Argentina's transportation sectors. Zahoor et al. (2023)

confirm that enhancing of renewable energies boost the achievement targets of CO_2 declining from transport sector in China. Based on EKC theory and applying Granger causality test, Azlina et al. (2014) proved the similar conclusion for Malaysia. However, Sovacool and Hirsh (2009) and Muradov and Veziroğlu (2008) outline that considering the emissions associated with manufacturing batteries or producing hydrogen, the carbon savings of these vehicles may not be as substantial as proponents claim. Based on the abovementioned analysis the following hypothesis is checked:

H3. Greater utilization of renewable energy sources is negatively correlated with CO_2 emissions.

3. Materials and methods

The first proposed hypothesis was assessed based on the model that adopted the Environmental Kuznets Curve (EKC) theory (Kharazishvili et al., 2020; Dzwigol et al., 2021; Kahia et al., 2021; Solaymani, 2022).

$$CO_{2_{it}} = a_{11} + \beta_{11}GDP_{it} + \beta_{12}GDP^2{}_{it} + \beta_{13}X_{it} + \varepsilon_{it} \quad (1)$$

where $CO_{2_{it}}$ – carbon emissions from transport sector in country i at period t; GDP_{it} – Gross Domestic Product per capita in country i at period t; β_{11}, β_{12} and β_{13} – the search coefficients of the model; X_{it} – control variables; a_{11} – the constant of the model; ε_{it} – the error term.

Following the studies (Godil et al., 2021; Jebli et al., 2020; Amin et al., 2020), the regression model for exploring the effect of renewable energy on reducing CO_2 emissions from transport sector was specified as follows:

$$CO_{2_{it}} = a_{21} + \beta_{21}GDP_{it} + \beta_{22}GDP^2{}_{it} + \beta_{23}RE_{it} + \beta_{24}X_{it} + \varepsilon_{it} \quad (2)$$

where RE_{it} – renewable energy in country i at period t; β_{21}, β_{22} and β_{23} – the search coefficients of the model; a_{21} – the constant of the model; ε_{it} – the error term.

Incorporating variable RE into the EKC model (1) helps to discern the trajectory of a country's ongoing energy transition and its impact on both economic growth and environmental sustainability. To examine the conditional role of environmental technologies in declining transport sector CO_2 emissions, according to Alataş (2022) and Ahmed et al. (2020), the following model was specified:

$$CO_{2_{it}} = a_{31} + \beta_{31}RD_{it} + \beta_{22}RD^2{}_{it} + \beta_{23}X_{it} + \varepsilon_{it} \quad (3)$$

where RD_{it} – renewable energy in country i at period t; β_{21}, β_{22} and β_{23} – the search coefficients of the model; a_{21} – the constant of the model; ε_{it} – the error term.

Industry value-added (% of GDP) and Urban population (% of total Population) were taken as control variables in models (1)-(3). Industry Value-Added (IND) indicates the relative contribution of the industrial sector to the overall economy (Pelkki and Sherman, 2020; Tsang et al., 2008). The transport sector encompasses various activities such as road, rail, air, and maritime transportation, all of which rely heavily on industrial production for the manufacturing of vehicles, infrastructure, and fuel. Consequently, any fluctuations in the industrial sector can have ripple effects on the transport industry, impacting its emissions, energy consumption, and overall sustainability. Urbanization is a multifaceted phenomenon with wide-ranging implications (Lee et al., 2023; Gierałtowska et al., 2022). As people migrate from rural to urban areas in search of better economic opportunities, improved living standards, and access to essential services, the urban population's share of the total population tends to rise. This shift can be indicative of societal progress, as urban areas often offer better access to education, healthcare (Omri and Kahia, 2024), and employment opportunities. However, the urbanization trend also presents unique challenges. As urban populations grow, so do demands for housing, infrastructure, and resources. This can strain urban environments, leading to issues such as congestion, pollution, and increased pressure on natural resources.

All data in models (1)-(3) were transformed into logarithms to stabilize the variance of the errors in a regression model and make it more homoscedastic, which is an important assumption in regression analysis. The study utilized panel data for the EU countries over the period of 2007–2020. The data for analysis was compiled from Crippa et al. (2022), World Data Bank (2023), Eurostat (2023), European Environmental Agency (2023). The descriptive statistics of the chosen variables are presented in Table 1.

The descriptive statistics provide a comprehensive overview of the central tendencies, variabilities, and extreme values within the dataset, aiding in understanding the distribution and characteristics of the variables under consideration. The mean CO_2 emissions of approximately 32.33 suggest the average carbon dioxide emissions across the observed entities. Similarly, the mean GDP of around 35,150.09 reflects the average economic output. Standard deviation (SD) values indicate the extent of variability or dispersion in the data. A higher standard deviation suggests greater variability. For instance, the standard deviation of 41.33 for CO_2 emissions indicates significant variability in emissions levels among the entities, while a standard deviation of 23,354.75 for GDP suggests considerable disparities in economic output. The minimum CO_2 value of 2.13 represents the entity with the lowest carbon emissions, while a minimum GDP value of 8214.08 indicates the smallest economy. Conversely, the maximum (Max) values reveal the entities with the highest recorded values. For instance, a maximum CO_2 value of 163.49 represents the entity with the highest carbon emissions, while a maximum GDP value of 123,678.70 units signifies the largest economy. Figure 1 demonstrates the varying levels of CO_2 emissions in EU countries during the period from 2007 to 2020. The countries with the highest CO_2 emissions were France, Germany, Italy, Poland, and Spain. However, France, Germany, Italy, and Spain have started to reduce CO_2 emissions in the transportation sector since 2018.

To empirically examine the models (1)-(3) involves in the initial step checking the panel data for the presence of heteroscedasticity, autocorrelation, and cross-sectional dependence, as these factors can lead to inefficient and misleading results. To assess heteroscedasticity and autocorrelation, modified Wald tests for group-wise heteroscedasticity and Wooldridge tests for autocorrelation (Canarella, 2008; Rahman and Alam, 2022) in panel data were employed. Additionally, Pesaran's test for cross-sectional independence (Pesaran, 2015) was conducted to evaluate the presence of cross-sectional dependence. In the subsequent step, this study employed Partial Least Squares Cointegration Estimation (PSCE) to rigorously test and validate hypotheses H1-H3. In the context of panel data involving multiple variables, particularly those representing economic and environmental factors, multicollinearity is a common concern. PSCE's proficiency in addressing this issue enhances the reliability of the analysis. Given the intricate interplay between environmental and economic factors, PSCE's flexibility in capturing nonlinear dynamics proves valuable in enhancing understanding of these complex relationships. To assess robustness and ensure the reliability of the findings, various tests were conducted. These included considerations for country- and year-effects, along with lag methods and the application of Feasible Generalized Least Squares (FGLS). This meticulous approach factors in variations across countries and years, temporal dependencies, and potential heteroscedasticity, contributing to a nuanced and comprehensive exploration of the research question.

Table 1
The descriptive statistics of the selected variables.

Stats	CO_2	GDP	RE	RD	Urban	IND
Mean	32.33	35150.09	16.10	269.12	71.86	14.97
SD	41.33	23354.75	9.85	583.68	12.72	4.95
Min	2.13	8214.08	2.83	0.00	51.98	4.55
Max	163.49	123678.70	43.96	3335.60	98.08	34.90

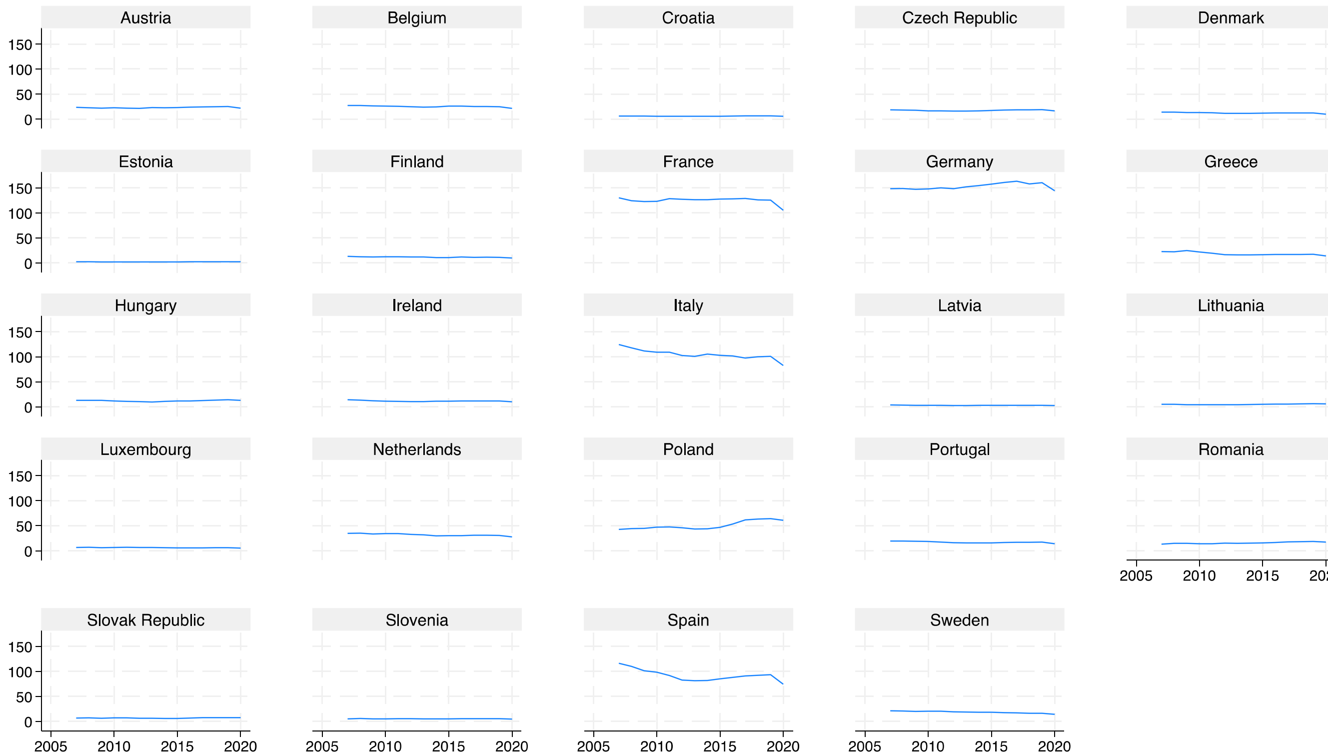

Fig. 1. Average of CO_2 emissions by transport.

4. Results

The results of the heteroscedasticity and autocorrelation tests (Table 2) reveal significant findings with low p-values, indicating the presence of issues related to heteroscedasticity and autocorrelation in the empirical data across all three models (represented by Models 1, 2, and 3).

The Modified Wald test shows high test statistics (301.93, 186.49, and 800.20) and associated p-values close to zero, signifying that the variance of the error term (residuals) is not consistent across different groups or entities in the analyzed panel data. The Wooldridge test reports elevated test statistics (87.62, 67.48, and 83.41) and very low p-values, indicating the presence of serial correlation or autocorrelation in the residuals of analyzed models. Heteroscedasticity and autocorrelation can affect the reliability of the regression estimates, potentially leading to biased or inefficient parameter estimates. Addressing these statistical challenges may require the use of heteroscedasticity-robust standard errors, panel data models that account for autocorrelation, and further diagnostic checks to ensure the accuracy and validity of the regression results.

The empirical findings from Pesaran's test of cross-sectional independence reveal strong evidence of significant cross-sectional dependence in all three models (Table 3).

This outcome is substantiated by the low p-values of 0.00 accompanying relatively high-test statistics of 20.496, 21.338, and 16.278 for the respective models. Cross-sectional dependence indicates that the entities or observations in the analyzed panel data are not independent but rather influenced by common factors or interactions that systematically affect multiple entities simultaneously.

Table 3
The empirical results of testing for cross-sectional dependence.

Test	(1)		(2)		(3)	
	GDP		Renewable Energy		Environment-related technologies	
	Test Statistic	p-Value	Test Statistic	p-Value	Test Statistic	p-Value
Pesaran's test of cross-sectional independence	20.496	0.00	21.338	0.00	16.278	0.00

The outputs of PSCE are shown in Table 4. Considering the empirical results for Model 1 and 2, GDP shows a statistically significant positive relationship with CO_2 emissions, indicating that as GDP increases, so do emissions from transportation. However, this effect is mitigated by the negative coefficient for GDP^2 suggesting a nonlinear relationship. Initially, economic growth leads to rising emissions, but beyond a certain point, further growth is linked to emission reduction, indicative of an inverted U-shaped pattern. It allows confirming research Hypothesis 1.

Additionally, urbanization is found to have a significant positive

Table 2
The results of heteroscedasticity and autocorrelation tests.

Test	(1)		(2)		(3)	
	GDP		Renewable Energy		Environment-related technologies	
	Test Statistic	p-Value	Test Statistic	p-Value	Test Statistic	p-Value
Modified Wald test for group-wise heteroscedasticity	301.93	0.00	186.49	0.00	800.20	0.00
Wooldridge test for autocorrelation in panel data	87.62	0.00	67.48	0.00	83.41	0.00

Table 4
The outputs of Partial Least Squares Cointegration Estimation (PSCE) analyses.

Variables	(1)		(2)		(3)	
	GDP		Renewable Energy		Environment-related technologies	
	coefficient	p-value	coefficient	p-value	coefficient	p-value
GDP	9.343	0.000	7.67	0.00	–	–
GDP^2	-0.451	0.000	-0.37	0.00	–	–
RE	–	–	-0.28	0.00	–	–
RD	–	–	–	–	-0.08	0.01
RD^2	–	–	–	–	0.06	0.00
Urban	1.192	0.000	1.61	0.00	0.60	0.02
IND	0.234	0.000	0.34	0.00	0.01	0.89
Constant	-51.235	0.000	-43.91	0.00	4.53	0.00
R-squared	0.895		0.839		0.798	
Observations	336		336		336	

correlation with CO_2 emissions from transport, as urban areas experience increased transport-related emissions with population growth. Industrialization also plays a role, with a positive coefficient indicating that industrial activities contribute to higher emissions from the transport sector. In Model 2, the results allow confirming hypothesis 3 that a higher utilization of renewable energy sources exhibits a statistically significant negative correlation with CO_2 emissions from transport sector. In simpler terms, increased use of renewables tends to be associated with lower transport-related emissions. The findings for Model 3 show that the coefficient for RD is statistically significant with a p-value of 0.01. This suggests that environment-related technologies have a negative relationship with CO_2 emissions from the transport sector. In other words, as RD increases, there tends to be a reduction in transport-related CO_2 emissions. However, the coefficient for RD^2 is statistically significant with a p-value of 0.00. The positive sign of this coefficient indicates a nonlinear relationship between RD and CO_2 emissions from transportation. Initially, as RD grows, CO_2 emissions tend to decrease, but beyond a certain point, further RD growth leads to an increase in CO_2 emissions. This implies a U-shaped relationship between RD and CO_2 emissions from transport sector.

The empirical results from the robustness test shown in Table 5. Thus, for GDP, Models 1 and 2 reveal statistically significant positive impacts on CO_2 emissions from transport sector with coefficients of 11.26 and 8.58, respectively, and p-values of 0.00. Additionally, the introduction of the squared term GDP^2 shows a nonlinear, inversely proportional relationship in both models. Renewable Energy (RE) in Model 2 exhibits a negative impact on CO_2 emissions from transport sector, signified by a coefficient of − 0.25 and a p-value of 0.00.

Model 3 assesses RD and its squared term RD^2, uncovering a nonlinear positive relationship with CO_2 emissions from transport sector through RD^2 with a coefficient of 0.05 and a p-value of 0.00. Urbanization (Urban) consistently demonstrates a positive influence on CO_2 emissions from transport sector across all three models with statistically significant coefficients and p-values of 0.00. IND exhibits a positive impact on CO_2 emissions from transport sector in Models 1 and 2. Furthermore, the presence of year- country-effects enhances the models by accounting for time-specific and country-specific factors. The robust R-squared values (0.940, 0.881, and 0.871) underscore the effectiveness of these models in elucidating a substantial portion of the variance in the dependent variables.

The empirical results from the robustness test, which incorporates lagged variables (Table 6), showed that lagged GDP displays statistically significant positive effects on CO_2 form transport sector in both Models 1 and 2, indicated by coefficients of 8.49 and 6.42, respectively (p-values of 0.00). The squared term of lagged GDP exhibits negative coefficients, implying non-linear relationships between lagged GDP and the dependent variables (CO_2 form transport), with diminishing effects as lagged GDP increases. Lagged RE negatively impacts on CO_2 form transport, with a coefficient of − 0.29 and a p-value of 0.00 in model (2). The growth of lagged RE by 1 point led to declining CO_2 form transport by of 0.29.

Model 3 explores the impact of lagged RD and its squared term on CO_2 from transport, uncovering a nonlinear positive relationship through RD^2. Urbanization consistently demonstrates a positive influence with statistical significance in all models, while Industrialization is not statistically significant in Model 3.

The empirical results obtained from the robustness test conducted using Feasible Generalized Least Squares (Table 7) confirm that GDP has a statistically significant positive impact on CO_2 emissions from transport in Models 1 and 2, as evidenced by coefficients of 17.03 and 19.53, respectively, and p-values of 0.00. At the same time, the GDP^2 negatively effect on CO_2 from transport sector in Models 1 and 2 which confirm Hypothesis 1, that there is an inverted U-shaped relationship between GDP and CO_2 emissions from the transport sector.

Table 5
The empirical results of robustness test by country- and year-effects.

Variables	(1)		(2)		(3)	
	GDP		Renewable Energy		Environment-related technologies	
	coefficient	p-value	coefficient	p-value	coefficient	p-value
GDP	11.26	0.00	8.58	0.00	–	–
GDP^2	-0.54	0.00	-0.42	0.00	–	–
RE	–	–	-0.25	0.00	–	–
RD	–	–	–	–	-0.05	0.42
RD^2	–	–	–	–	0.05	0.00
Urban	1.72	0.00	1.46	0.00	0.95	0.00
IND	0.32	0.00	0.25	0.00	-0.04	0.61
Constant	-30.53	0.02	-39.92	0.02	5.28	0.00
Year-effects	Yes		Yes		Yes	
Country-effects	Yes		Yes		Yes	
R-squared	0.940		0.881		0.871	
Observations	336		336		336	

Table 6
The empirical results of robustness test considering the lag.

Variables	(1) GDP		(2) Renewable Energy		(3) Environment-related technologies	
	coefficient	p-value	coefficient	p-value	coefficient	p-value
l.GDP	8.49	0.00	6.42	0.00	–	–
$l.GDP^2$	-0.41	0.00	-0.31	0.00	–	–
l.RE	–	–	-0.29	0.00	–	–
l.RD	–	–	–	–	-0.05	0.04
$l.RD^2$	–	–	–	–	0.05	0.00
Urban	1.38	0.00	1.73	0.00	0.57	0.02
IND	0.27	0.00	0.43	0.00	0.00	0.99
Constant	-47.43	0.00	-38.09	0.00	3.95	0.00
R-squared	0.881		0.815		0.857	
Observations	312		312		312	

Table 7
The empirical results of robustness Feasible Generalized Least Squares (FGLS).

Variables	(1) GDP		(2) Renewable Energy		(3) Environment-related technologies	
	coefficient	p-value	coefficient	p-value	coefficient	p-value
GDP	17.03	0.00	19.53	0.00	–	–
GDP^2	-0.81	0.00	-0.93	0.00	–	–
RE	–	–	-0.44	0.00	–	–
RD	–	–	–	–	-0.35	0.00
RD^2	–	–	–	–	0.02	0.00
Urban	1.39	0.00	1.11	0.00	1.77	0.00
IND	0.43	0.00	0.41	0.00	0.35	0.00
Constant	-93.38	0.00	-103.56	0.00	9.53	0.00
Wald chi2	146032.30	0.00	23397.57	0.00	27839.15	0.00
Observations	336		336		336	

Model 2 indicates that Renewable Energy (RE) has a significant negative influence on CO_2 emissions from transport sector, as denoted by a coefficient of − 0.44 and a p-value of 0.00. It allows confirming hypothesis 3, that renewable energy sources are negatively correlated with CO_2 emissions. In Model 3, patent activity in environment-related technologies has statistically significant negative impact on CO_2 emissions from transport sector which does not confirm H2 – higher patent activity in environment-related technologies is associated with lower CO_2 emissions. RD^2 exhibit a statistically significant positive relationship with CO_2. It means, that not all environment-related technologies could be implemented in the transport sector which allow declining CO_2 emissions from transport sector. Urbanization (Urban) consistently displays a positive effect on the dependent variables across all models, while IND positively impacts CO_2 emissions from transport sector.

The positive association between GDP and CO_2 emissions, with a nuanced nonlinear pattern, emphasizes the need for sustainable economic growth. This aligns well with the European Green Deal's emphasis on circular economies and biodiversity, offering a practical roadmap to harmonize economic development with environmental objectives outlined in the EU Climate Law. Identifying urbanization and industrialization as contributors to CO_2 emissions highlights the need for eco-friendly urban and industrial practices. This aligns with the European Green Deal, emphasizing policies to reduce emissions associated with urbanization and industrial activities. Insights into environment-related technologies (RD) and CO_2 emissions offer practical guidance for fostering eco-friendly innovations. This aligns with the European Green Deal's focus on innovation and sustainability, urging businesses and researchers to strike a balance between technological growth and emissions reduction. Incorporating these insights into EU policies and initiatives will contribute to achieving specific targets, such as carbon neutrality by 2050, outlined in the European Green Deal and the EU Climate Law. Additionally, these findings can inform the development and implementation of broader strategies, such as the Sustainable Development Goals (SDGs) and the EU's 2030 Agenda, ensuring a comprehensive approach to addressing climate change and promoting sustainable practices across various sectors.

5. Discussion

The results of PSCE and FGLS allow confirming the research hypothesis that GDP and CO_2 emissions from the transport sector has the U-shaped relationship. It means that GDP initially increases, the CO_2 emissions from its transport sector tend to rise as well by: 9.34 (Model 1) and 7.67 (Model 2) in PSCE; 17.03 (Model 1) and 19.53 (Model 2) in FGLS. However, as the GDP continues to grow beyond a certain point, CO_2 emissions start to decrease by: 0.451 (Model 1) and 0.37 (Model 2) in PSCE; 0.81 (Model 1) and 0.93 (Model 2) in FGLS. The similar conclusions on U-shaped relationship between GDP and CO_2 emissions from the transport sector were obtained by the past studies (Gulagi et al., 2021; Godil et al., 2021; Kwilinski et al., 2023c; Guo et al., 2020). The U-shaped relationship implies that economic growth is not inherently tied to an increase in CO_2 emissions from the transport sector. Instead, it suggests that with the right policies, technological advancements, and societal changes, it is possible to decouple economic growth from rising emissions, ultimately leading to a more sustainable and environmentally friendly transportation system.

It should be noted that extending of renewable energy sources allow declining CO_2 emissions from the transport sector which is coherent to the conclusions of the priory studies (Polcyn et al., 2022; Dzwigol et al., 2023; Mwasilu et al., 2014; Yuksel and Kaygusuz, 2011; Barman et al., 2023; Chu and Meisen, 2011; Choi et al., 2018; Li et al., 2022). It means that as EU increases its use of renewable energy, there is a corresponding decrease in the emissions of carbon dioxide associated with energy production. In simpler terms, as renewable energy sources like solar, wind, hydro, and geothermal power are more extensively adopted and integrated into the energy mix, the amount of CO_2 emitted into the atmosphere due to energy generation tends to decrease.

The research findings show that environment-related technologies and CO_2 emissions from transport sector has the U-shaped relationship. It is controversial to the studies (Nederveen et al., 2003; Hickman et al., 2009; Zhang et al., 2013; Rodrigues et al., 2023; Grace et al., 2023) which confirm that environment-related technologies negative effect on CO_2 emissions from transport. Khurshid et al. (2023c) outlined that the introduction of new technologies in transportation exerts a limiting influence on demand, transport activities, and overall emissions over both extended and immediate timeframes. Considering the obtained results in this study, at the first stage the environment-related technologies allow declining CO_2 emissions from transport sector by: 0.08 (PSCE) and 0.35 (FGLS). However, as the adoption and implementation of environment-related technologies continue to grow and expand, there is a point at which CO_2 emissions begin to increase again. This signifies that beyond a certain threshold or level of technology adoption, CO_2 emissions from the transport sector start to rise by: 0.0.06 (PSCE) and 0.02 (FGLS).

The U-shaped relationship suggests that there is an optimal level of technology adoption in the transport sector where CO_2 emissions are minimized. Initially, as greener technologies are introduced, emissions decline. Yet, as technology adoption reaches a certain point, other factors or unintended consequences may come into play, causing emissions to increase. Possible explanations for the upward trend in emissions at the later stage of technology adoption could include factors like increased energy demand due to a larger fleet of vehicles or a shift to energy-intensive transportation modes. It highlights the complexity of managing emissions reductions while promoting technological innovation in the transport sector and the importance of carefully monitoring and adjusting policies as technology adoption evolves.

6. Conclusions

The results of investigation allow confirming all research hypothesis that GDP and CO_2 emissions from the transport sector had U-shaped relationship, extending renewable energy sources and patent activity in environment-related technologies allow declining CO_2 emissions from transport sector. The coefficients obtained from Partial Least Squares Cointegration Estimation (PSCE) and Feasible Generalized Least Squares (FGLS) were 0.08 and 0.35, respectively. Nevertheless, with the ongoing increase and integration of environment-related technologies, there reaches a critical juncture where carbon dioxide (CO2) emissions begin to rise once more. This indicates that beyond a specific threshold or degree of technology adoption, CO_2 emissions from the transportation sector start to increase by 0.06 (PSCE) and 0.02 (FGLS). Considering the finding the following policy implication for EU countries could be outlined to extend the environment-related technologies:

1. EU countries should adopt an extensive approach to transition towards cleaner transportation options. In addition to setting ambitious targets for renewable energy adoption in the transport sector, they should diversify their renewable energy sources, promote intermodal connectivity, and implement incentive programs for consumers and businesses to invest in electric and low-emission vehicles (Dzwigol et al., 2023; Kwilinski et al., 2023a, 2023b, 2023c). Collaboration with the private sector, extending infrastructure to rural areas, investing in research and development, and launching public awareness campaigns are essential elements of this approach. Local governments should also support electric mobility within urban areas, and green public procurement policies should prioritize clean vehicles for government fleets. Furthermore, ensuring the resilience of renewable energy and electric vehicle infrastructure is crucial. By adopting these measures, EU countries could create a supportive ecosystem that not only meets renewable energy goals but also promotes inclusive and sustainable mobility for all citizens (Kwilinski et al., 2022b, 2023d).
2. To bolster innovation and the deployment of environment-related technologies in the transport sector, EU countries should continue adopt a comprehensive set of policies and initiatives. Omri et al. (2022) and Kahia et al. (2022) confirmed that effective governance, particularly in economic and institutional aspects allow extending the renewable energy among all sectors and decline the CO_2 emissions. In addition to offering tax incentives (Khurshid et al., 2023b) for research and development, EU governments should intensify grant programs and funding opportunities to support research projects in eco-friendly technologies (Karnowski and Miśkiewicz, 2021; Polcyn et al., 2022; S. Wang et al., 2022; X. Wang et al., 2022; Miśkiewicz et al., 2022; Hens et al., 2019; Borysova, and Monastyrskyi, 2018). Encouraging public-private partnerships allow expedite technology development, while technology incubators, accelerators, and regulatory sandboxes can nurture startups and innovations. Cross-sector collaboration and international research cooperation should be promoted to leverage diverse expertise, and innovation challenges and competitions could incentivize creative solutions. Environmental technology clusters concentrate resources and expertise, and clear frameworks for assessing environmental impact should be established. These measures collectively create an ecosystem that fosters innovation, accelerates the deployment of green technologies, and positions the EU as a global leader in sustainable transportation solutions (Miśkiewicz et al., 2022; Hens et al., 2019; Borysova, and Monastyrskyi, 2018; Khurshid, and Deng, 2021).
3. To promote eco-friendly transportation and renewable energy adoption, EU countries should take a multifaceted approach to education and awareness. In addition to public awareness campaigns, tailored education efforts should address diverse demographic groups and integrate sustainability into school curricula. Community engagement initiatives and interactive online platforms empower citizens to make informed choices. Collaboration with environmental organizations and industry training programs amplify awareness efforts, while policy workshops and demonstration projects facilitate informed decision-making among policymakers and professionals. Ongoing education is crucial, and public-private partnerships support these initiatives (Trzeciak et al., 2022; Kwilinski, 2019; Miśkiewicz, 2019; Kwilinski et al., 2020). By adopting this comprehensive approach, EU countries could build an informed and engaged society, accelerating the shift towards sustainable transportation and renewable energy solutions.
4. Governments should introduce policies that encourage businesses to adopt business models with open innovation dynamics, promoting knowledge-sharing, and collaborative problem-solving (Chaurasia et al., 2020; Crupi et al., 2021; Gurca et al., 2021). Financial incentives, grants, and tax breaks can be tailored to reward sustainable practices and the development of eco-friendly technologies. Open innovation engineering offers a structured approach to designing and implementing innovations (Barham et al., 2020; Obradović et al., 2021). Policymakers should advocate for the incorporation of engineering methodologies that prioritize sustainability and emissions reduction. Establishing standards and certification processes specific to open innovation engineering practices can guide businesses in achieving environmentally responsible outcomes. Effective management of open innovation is crucial for its success. Policymakers should consider initiatives that facilitate the efficient flow of information and collaboration among diverse stakeholders. Supportive regulations can encourage businesses to embrace open innovation as a strategic tool for addressing environmental challenges in the transport sector.

Despite the valuable findings, this study has a few limitations which could be consider in the further investigations. It is necessary to extend the object of investigation by adding other countries (such as the USA, China) which allow compare the results and increasing validity of the results. Thus, considering the studies (Dacko-Pikiewicz, 2019; Dementyev et al., 2021; Dzwigol, 2019a, 2019b, Dzwigol et al., 2020, 2023, Kwilinski et al., 2020a, 2020b, 2022, 2022a; Letunovska et al., 2022; Trushkina et al., 2020) digitalization provokes changes not only in macrolevel, however in microlevel by changing structure of entrepreneurship and logistics' companies. Besides, new green technologies require the appropriate level of education (Dzwigol, 2020, 2022, 2023; Dzwigol et al., 2020; Zhanibek et al., 2022) which could boost the reorientation of transport sector using the latest green innovations and digital technologies. At the time, it is necessary to consider the government efficiency in the further investigations which allow explain the role of quality of institutions, voice and accountability, political stability, corruption, rule of law in declining carbon dioxide emissions from transport sector.

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CRediT authorship contribution statement

Aleksy Kwilinski: Conceptualization, Methodology, Validation, Investigation, Data curation, Writing original Draft preparation, Review and editing, Visualization, Supervision, Funding acquisition. Oleksii Lyulyov: Conceptualization, Methodology, Validation, Investigation, Data curation, Writing original Draft preparation, Review and editing, Visualization, Supervision, Funding acquisition. Tetyana Pimonenko: Conceptualization, Methodology, Validation, Investigation, Data curation, Writing original Draft preparation, Review and editing, Visualization, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors (Aleksy Kwilinski, Oleksii Lyulyov, Tetyana Pimonenko) declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper (Reducing transport sector CO_2 emissions patterns: environmental technologies and renewable energy).

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