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GREEN FISCAL POLICY AND GREEN FINANCE IN MITIGATING ENVIRONMENTAL DETERIORATION IN CENTRAL EUROPEAN REGIONS

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Abstract. Environmental deterioration has intensified across Central Europe as rapid economic expansion continues to rely heavily on resource extraction, fossil fuel consumption, and industrial emissions. This growing ecological pressure has renewed interest in policy instruments capable of steering regions toward sustainable development. Motivated by these concerns, this investigation assessed how green fiscal policy (GFP), green finance (GRF), patent applications (PAP), renewable energy (REN), and natural resource rent (NAR) influence carbon emissions (CAR) in 13 Central European economies with data from 1990–2022. The analysis applies a series of diagnostics followed by the Cross Sectionally Augmented Autoregressive Distributed Lag (CS ARDL) model, supported by FMOLS robustness and Dumitrescu–Hurlin causality tests. The results reveal that GFP, GRF, and REN significantly reduce carbon emissions in both the short and long run. Conversely, NAR and PAP unexpectedly appreciate emissions, depicting inefficiencies in resource governance and the limited environmental orientation of current innovation activities. The D&H causality illustrated both unidirectional and bidirectional causality among the variables. These findings imply that Central European economies can accelerate their transition toward ecological sustainability by strengthening carbon pricing mechanisms, renewable energy investment, restructuring green finance portfolios to low carbon technologies, and enforcing sustainable resource extraction practices for long term carbon neutrality.

Keywords: green fiscal policy, natural resource rent, patent application, renewable resources, green finance, CS-ARDL.

JEL Classification: Q41, Q58, Q32, O53.

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1. Introduction

Recent anthropogenetic practices have increased the global environmental damages and influenced the global weather patterns (Li et al., 2023; Sampene et al., 2024). The global ecosystem continues to inspect the catalysts associated with sustainable ecological quality. To mitigate the affiliation between environmental externalities and sustainable economies, serval organizations have developed policy frameworks such as the EU green deal, the Paris conference on climate change, and other regional environmental deterioration strategies (Khaddage-Soboh et al., 2023). Reducing the region's carbon footprint and increasing its

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worldwide competitiveness are two outcomes of the shift toward a greener economy. The Central European regions have recently seen a surge in their economic progress by industries leading to appreciation in energy utilization (Bozatli & Akca, 2023; Fatima et al., 2026). As a result of this, there has also been an appreciation in the ecological footprint within the Central European communities. The government in these regions has recently directed industries to change or adopt more energy-friendly product development or green and eco-innovative processes and products that are friendly to the environment (Ameer et al., 2024; Wu et al., 2024). The ecological modernization model has recently been described as the novel approach to meeting the zero emissions targets and achieving the sustainable development community. As encapsulated in the ecological modernization theory, effect of green fiscal policy, green innovation, patent applications, and renewable energy to depreciate environmental externalities in Central European communities was be evaluated.

Recent literature has shown that negative environmental externalities can be reduced through different parameters such as green fiscal policies, patent application, green finance, renewable energy, and natural resource rent (Zhou et al., 2023; Abbas et al., 2023). According to the EU Commission book guidelines (2001, as cited in European Environment Agency, 2016), environmental taxes come in the form of energy tax, transport tax, and pollution and resources tax (hence, environmental taxes are referred to as green fiscal policy). The EU revenue from green fiscal policy accounted for 2.2 percent of economic progress with a sum of 331.3b in revenue (Figure 1). Liu et al. (2023) investigated the ecological quality of advanced regions using environmental taxes. The findings demonstrated that green fiscal policy had a material affiliation with achieving ecosystem quality. Yin et al. (2024) and Antohi et al., (2026) established in their evaluation that carbon taxes and green taxes were found to appreciate the adoption of renewable energy in developed regions than emerging communities. The outcome set to expound that green fiscal policies affect both demand and supply side of the economy. Affirming to this was the investigation in Italy on the influence of green finance, green fiscal policy, and renewable energy utilization on ecological externalities (Dogan et al., 2023). The empirical outcome established that green fiscal policy leads to an increased in the adoption of renewable energies such as wind, solar, and hydro.

The UNEP report 2020 and COP21 have indicated that emissions mitigation strategies signed by the various regions will not be met by 2030 and that climate damage is expected to be appreciated to 2.60^{c}. Li et al. (2023) explored ecological footprints within 152 communities across developed and emerging regions. Employing the econometric approaches of the quantile model, which accounts for linear and non-linear data curation. The findings established that natural resource rent had no material affiliation with ecological quality. The article's conclusion emphasizes that instituting green fiscal policy can achieve mitigation within the region. Likewise, green funding, fiscal policy, and ecological taxes were found to have a favourable effect on mitigating environmental externalities (Yan et al., 2023). Resource abundance in developing communities (Masi et al., 2024) examined sixty-two regions. The results show that developing communities with weak political institutions turn to have appreciation in ecological damage with resource abundance. As displayed in Figure 1, various green fiscal policies are adopted to mitigate environmental externalities in European regions. The highlighted literary works have demonstrated that green fiscal policy (GFP), green finance

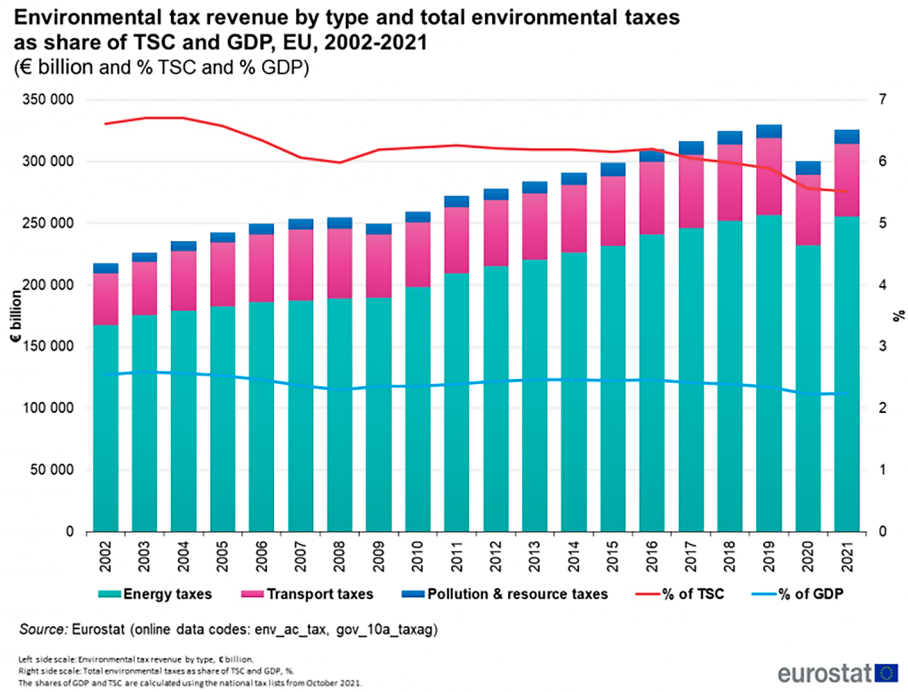


Figure 1. Environmental taxes trend (source: Eurostat, 2025)

(GRF), natural resources rent (NAR), patent application (PAP), and renewable energy (REN) investigation are scant in development and emerging communities. Hence, we explored the Central European communities, as these communities are considered the most polluting regions in Europe. Expect for Germany, which has strict green fiscal policy on environmental externalities; the rest of the regions policies are loose, which makes industrial production continue to increase in polluting activities. Additionally, governments, institutions, and researchers are still battling on the proper way to mitigate environmental damage and their effects on the ecosystem. The investigation was explored on key questions. 1. Whether green fiscal policy can help to mitigate carbon emissions in Central European communities? 2. Can green finance and patents speed the process of reaching zero carbon neutrality? 3. Whether there exists a bi- or unit-directional affiliation between GFP, GRF, PAP, NAR, and REN on CAR in the short or long run in Central European communities.

The conclusion on the findings from this study make contribution and new novelty to literary work and theoretical approach of the ecological modernization model. The finding from the econometric modelling illustrated that green fiscal policy served as a material influence on the development of policy strategy to depreciate carbon emissions and environmental externalities in Central European communities. Again, the evaluation makes a significant highlight of the green finance strategy to reduce the current environmental deterioration among the communities through directing the funding to industries with minimal ecological impacts. Additionally, the findings have revealed the material benefits enterprises can gain by adopting renewable energy for energy consumption. Therefore, the investigation will assist

Central European and similar communities in initiating measures to reduce emission levels and provide sustainable recommendations. The investigation sourced data from verified websites for the period 1990–2022. To make comprehensive policy suggestions, the data will be evaluated for normality and outliners with second generation models. The econometric model of the CS-ARDL technique was employed as it is more robust to both linear and nonlinear data structures. The D&H causality was utilized to check the affiliation between variables of co-movement in the long term.

The reminder of the assessment is as follows, literature review, method, results presentation, and discussions of the empirical findings. It ends with conclusion and policy suggestions.

2. Literature review assessment

This section of the investigation covers the theoretical context, review of literatures works, research gaps, and the contribution of the study.

2.1. Theoretical context: Ecological Modernisation Theory (EMT)

A comprehensive theoretical framework for comprehending how contemporary economies can concurrently pursue economic development and environmental sustainability through institutional reform, technological innovation, and structural transformation. EMT, which has its roots in the writings (Jänicke & Jörgens, 2023), contend that environmental deterioration is not a necessary byproduct of industrialisation. Instead, societies can "ecologically modernise" their production systems and lessen ecological stresses while retaining economic competitiveness by intentional governmental interventions, market restructuring, and technological advancements. EMT provides a strong framework for understanding how fiscal, financial, technological, and resource-based mechanisms affect carbon emissions in the Central European region, which is marked by fast industrial restructuring, diverse environmental regulations, and differing institutional capacity. According to EMT, internalising environmental externalities is mostly dependent on environmental policy measures, especially fiscal ones like carbon taxes, pollution levies, and environmental fees. Green fiscal policy promotes industry modernisation and adoption of cleaner technology by raising the cost of polluting activities and rewarding eco-efficient manufacturing (Du & Li, 2024; Khaddage Soboh et al., 2023). The conversion of financial systems into agents of ecological change is a fundamental tenet of EMT. According to Mol and Spaargaren (2000) market-based processes are becoming more and more important in modern environmental governance, as financial institutions provide cash to eco-friendly ventures. Green financing mobilises private funding for clean technology, low-carbon sectors, and renewable energy through green bonds, green credit, and sustainability-linked investments (Abbas et al., 2023; Mehboob et al., 2024). According to EMT, Central Europe's ecological modernisation trajectory will be strengthened by growing green financial flows. EMT assumes that institutional reform and technical advancement can make the utilisation of natural resources sustainable. However, resource rents may worsen environmental deterioration when extraction methods are ineffective or governance mechanisms are

inadequate (Masi et al., 2024; Nwani & Adams, 2021). A key component of EMT's ecological transformation vision is innovation. A society's technological ability to create environmentally friendly solutions is reflected in patents, especially green patents. But EMT also recognises that not every invention is focused on the environment. Patenting activities may not result in environmental gains when traditional, carbon-intensive technologies continue to dominate innovation systems (Ghorbal et al., 2022; Oyebanji et al., 2022). The analysis emphasises how Central Europe might attain ecological sustainability through coordinated legislative, financial, and technical reforms by placing the study within EMT.

2.2. Green fiscal policy and carbon emission affiliation

The Central European communities are battling with continued issues of environmental damage resulting from household and industrial activities. This has been elucidated in the development of various policies to mitigate environmental damage (Antohi et al., 2026; Fatima et al., 2026). One such policy initiative is Europe's Green Deal policy, which aims to achieve a more clean and sustainable ecological quality (European Commission, 2015). An empirical investigation has demonstrated that different policies could help move closer to net zero environmental deterioration. Du and Li (2024) explored carbon tax and its implication on the ecosystem in thirteen Asian regions. The results established that 1% appreciation in carbon taxes reduced environmental externalities from extraction by 0.16%. In the Netherlands, Bozatli and Akca (2024) employed the Fourier ARDL approach to illustrate the influence of load capacity and government effectiveness to mitigate emissions levels. The findings presented a favorable effect of utilizing resource taxes to decrease environmental deterioration. This was an affirmant of the investigation by Khaddage-Soboh et al. (2023) evaluation of G-seven communities. The assessment demonstrated the material effect of employing environmental taxes and strict institutional policy to mitigate emissions. Li et al. (2023) evaluation of production emissions among OECD countries identified in their estimation that at middle and higher quantiles environmental taxes had material significance in appreciating environmental quality. Similar research was undertaken by Kafeel et al. (2024) on OECD States stepping to the novel era of green innovation. The empirical outcomes expound that the carbon tax served as a mediating component on the affiliation between green innovation and environmental externalities. Communities within the Central European regions have initiated positive green fiscal policies to depreciate their ecological footprint levels. Ameer et al. (2024) assessed E-seven economics utilizing the MMQR and data curation between 1990–2020. The results depicted a bidirectional affiliation between environmental taxes and ecological damage. In a global context, Zhu et al. (2023) examined fifty-one communities moving towards net zero emissions. The findings from the articles demonstrated that environment tax and renewable energy are the material protocols to depreciate ecological damage. Further empirical literary evidence has established the possibility of employing green fiscal policies to mitigate environmental externalities. Wu et al. (2024) China – carbon tax; Dogan et al. (2023): European Union – energy tax; Fang and Liu (2026a): China – fiscal and financial green policy and Aydin and Bozatli (2023): OECD – environmental taxes.

2.3. Green finance and carbon emission affiliation

The affiliation between green funding and regional carbon emissions in Europe is attracting more and more attention. Communities are more concerned with the financial partner of their investment and its affiliation with the quality of the environment (Sun et al., 2022). Green finance initiatives come in the form of green credit, green loans, and green investment for enterprises. Sadiq et al. (2023) empirical evaluation of BRICS communities between 2001 and 2020 indicated that green finance, innovation, and environmental damage taxes depreciate emission levels. Likewise, Chu (2024) examined high-income regions through the econometric model of quantile regression. The outcome illustrated that green funding and ecological taxes had material influence on CAR reduction in the regions. In the context of China, Abbas et al. (2023) evaluate renewable energy financing to mitigate China environmental emissions levels. The findings demonstrated that financing through green finance and environmental taxes caused an appreciation REN by 0.137 and 0.428, respectively. Additionally, Mehboob et al. (2024) investigated green finance through ARDL simulation approaches between 1990 and 2020. The empirical outcome outlines a long-run affiliation between GRF, eco-taxes, and geopolitical issues on environmental issues. A similar outcome was identified in literary works in China (Wang et al., 2023). The Central European communities, like Germany, have implemented stringent green finance policies to direct investment into renewable energies with low rates and simple processes for such investment. This was affirmed in the literary works of Deng et al. (2024), Transformation of green finance in advanced regions. The assessment outcome demonstrated that green finance had a material influence on greenhouse gas emissions depreciation. Highlights from literature evaluation have expounded on the favourable affiliation between GRF and renewable technology in energy in abatement of CAR (Nhuong et al., 2025; Chin et al., 2024; Udeagha & Muchapondwa, 2023a).

2.4. Natural resource abundance and carbon emissions affiliation

The nexus between NAR and CAR has garnered increasing attention in recent years. Voumik et al. (2023) look at five emerging economies in South Asia to determine the affiliation between NAR and carbon emissions. The STIRPAT approach was modelled to evaluate the long- and short-run effects of the CS-ARDL for the period 1972–2021. The empirical investigation demonstrated that NAR reduces carbon emissions. In the developed economy of the USA, Huang et al. (2021) explore the relationship between NAR, financial development, and urbanisation and CO_2 emissions. The results from the QARDL illustrate a unidirectional nexus between NAR and carbon emissions. In the context of the provinces in China, Shen et al. (2021) examined NAR, energy usage, and carbon emissions for the period 1995–2017. Employing the CS-ARDL as an analytical estimator, the findings established that natural resource rent had a material influence on carbon emissions. Examining the case of oil-producing nations, Xie et al. (2024) assessed the impact of natural resource rent on carbon emissions between 1990 and 2021. Their findings revealed a nuanced relationship, suggesting that the level of environmental stringency in exploring forests, lumbering, and other ecosystems is crucial. From a global and continental perspective, Bosah et al. (2023) evaluate the nexus between NAR and carbon emissions to achieve sustainability development goals and zero

carbon neutrality. Using panel data analysis, the researchers found that the relationship was neutral, bidirectional, and unidirectional across continents. Focusing on the role of institutional quality, Nwani and Adams (2021) conducted a cross-country analysis to understand how NAR influences carbon emissions. The study illustrated that countries with weak institutions tend to exhibit a stronger material affiliation between resource rent and carbon emissions. Similar investigations have revealed a material influence between NAR and carbon emissions. Agboola et al. (2021) research in G7 countries and Tufail et al. (2021) research in OECD countries. While Udeagha and Muchapondwa (2023b) research in BRICS region exhibited an inverse correlation between NAR and CAR.

2.5. Patent application and carbon emissions nexus

Patent application is found to account for decrease in environmental pollutions (Ghorbal et al., 2022; Pu et al., 2025). Their research in South Korea and China demonstrated that, theoretically investment in innovative development products reduce carbon emissions. Likewise, Fu et al. (2023) investigated provincial patents in China through green technology innovation and its effect of carbon emission. The evaluation illustrated that between 2010–2019 six provinces that were assessed had a favourable reducing effect on carbon emissions. In the context of OPEC communities, Aziz et al. (2023) examined patent rights and carbon emission effects. The findings illustrated that nations with patent applications reduced their emissions rate compared to adoption of renewable energies. In Spain, Oyebanji et al. (2022) employed the ARDL approach and empirically tested the affiliation of environmental technology on sustainable practices. The results show that patent rights in the adoption of environmental technology help to decrease carbon emissions. However, Milindi and Inglesi-Lotz (2022) research on six different income groups of nations on the link between progress in technology and carbon emissions. The analysis of sub and full panel data demonstrated that patent rights had an immaterial nexus to decreasing carbon emissions. Recent studies in Europe by Abban et al. (2023) assessed patent application in achieving the Europeans net zero emissions by 2050. The fixed effect results depicted that mitigating carbon emission is achieved through patent and renewable energies. Liu et al. (2023) presented in their article in China that, movement to net zero emission target is through home patent or foreign patent with improvement in innovation. However, Chen et al. (2026) explored innovation in line with corporate physical investment within 11 Asian communities. The findings from the econometric model of GMM depicted the green innovation in the form of patent application appreciate boost enterprise investment leading to environmental sustainability. Again, Hu et al. (2023) research in the public health in China on patent right to curb carbon emission after 2001. The findings demonstrate that regional polices on patent application decrease emissions.

2.6. Renewable energy and carbon emissions affiliation

Environmental deterioration catalysed by the utilization of non-renewable energies has been a major concern for Central European communities. Javed et al. (2023) explored the energy utilization pattern in the European region of Italy. The econometric approach of dynamic simulation ARDL was employed, and the empirical outcome demonstrated that renewable energy

had a material affiliation with carbon emission depreciation. Likewise, Zhou et al. (2023) assess the United Kingdom's ecological footprint and renewable energy from data curation between 1995Q1 and 2018Q4. The wavelet analysis illustration reveals a negative correlation between the variables. Yin et al. (2024) conducted a detailed analysis of thirty-eight communities, concluding that advanced regions are more adept at managing their environmental damage than emerging regions. In the context of OECD states, Kafeel et al. (2024) investigated the influencing effects of REN utilization and green innovation on the quality of the ecosystem. The empirical results highlighted that REN and innovation cause a depreciation in environmental deterioration. Ahmed and Pata (2024) also use the MMQR method to investigate the factors that influence ecological sustainability among the top ten emitters. The results show that factors like ecological levies and renewable energy decrease the emissions volumes. Similarly, Shayanmehr et al. (2023) assessed the top leading regions in the race for renewable energy utilization. The article experiment presented a significant quantile from 25–90% on environmental taxes and renewable to ecological deterioration mitigation. Ameer et al. (2024) indicated in their research that E7 regions can reduce their ecological damage through proper policy on renewable energy utilization to cease the volumes from parasite emissions. Wu et al. (2024) research in China established that China's appreciation in renewable energy is because of investment directed to mitigate the ecological footprint. Literary work has demonstrated that due to the unpredicted atmospheric conditions, it is appropriate for regions to adopt REN. Abbas et al. (2023) renewable energy in China; Aydin and Bozatli (2023) ten most renewable energy in OECD communities; Dogan et al. (2023) European Union energy path; and Zhu et al. (2023) fifty-one states from emerging and developed regions.

2.7. Research gaps and contributions

Extensive inspection has examined the determinants of environmental sustainability, the existing literature presents fragmented and often contradictory evidence regarding the roles of GFP, GRF, NAR, PAP, and REN in mitigating carbon emissions. Prior studies report mixed outcomes: while some find that green fiscal policy, green finance, and renewable energy significantly reduce environmental deterioration (Du & Li, 2024; Dogan et al., 2023; Udeagha & Ngepah, 2023), others identify weak or inconsistent effects depending on regional characteristics, methodological choices, and data periods (Liu et al., 2023; Mehboob et al., 2024). Similarly, the nexus between natural resource rent and carbon emissions remains inconclusive, with studies reporting negative, positive, or neutral affiliation across different contexts (Voumik et al., 2023; Shen et al., 2021; Bosah et al., 2023). A second gap concerns the limited empirical focus on Central European communities, despite their high pollution intensity and heterogeneous environmental policy frameworks. Except for Germany, which maintains strict environmental taxation, many Central European regions operate under relatively weak green fiscal and regulatory structures, contributing to rising ecological footprints (Ameer et al., 2024; Bozatli & Akca, 2023). Yet, few studies have systematically assessed how fiscal instruments, green finance mechanisms, innovation capacity, and resource exploitation jointly influence environmental outcomes in this region. Third, although patent applications and green innovation are increasingly recognized as critical drivers of ecological modernization, their environmental effectiveness remains ambiguous. Some studies show that patenting activity reduces

emissions (Ghorbal et al., 2022; Oyebanji et al., 2022), while others find insignificant or even adverse effects depending on the type of innovation and institutional environment (Milindi & Inglesi-Lotz, 2022). This inconsistency highlights the need for region-specific evidence, particularly in transitioning economies where innovation systems are unevenly developed. Fourth, the literature has not sufficiently addressed the directionality and dynamic interactions among green fiscal policy, green finance, natural resource rent, patent applications, renewable energy, and carbon emissions. Many studies rely on first-generation estimators that do not account for cross-sectional dependence or slope heterogeneity, potentially biasing long-run estimates (Khaddage-Soboh et al., 2023; Sampene et al., 2024). As a result, the causal pathways through which these variables influence environmental quality remain unclear. Finally, few studies employ second-generation econometric techniques, such as the CS-ARDL model and Dumitrescu–Hurlin causality tests, which are more appropriate for panels characterized by interdependence and structural heterogeneity. Recent evidence suggests that these models yield more robust and policy-relevant insights (Bozatli & Akca, 2023; Takyi et al., 2024), yet their application remains limited in the context of Central Europe.

To address these gaps, the present investigation contributes by a) Providing the first integrated assessment of green fiscal policy, green finance, natural resource rent, patent applications, and renewable energy on carbon emissions in 13 Central European economies from 1990–2022. b) Applying robust second-generation econometric techniques (CS-ARDL, FMOLS, and Dumitrescu–Hurlin causality) to capture long-run dynamics, cross-sectional dependence, and causal directionality. c) Clarifying contradictory findings in prior studies by offering region-specific evidence on how fiscal, financial, technological, and resource-based factors jointly shape environmental outcomes. d) Advancing the ecological modernization framework by demonstrating how policy instruments, financial mechanisms, and innovation systems interact to influence carbon neutrality pathways in transitioning European economies. This refined approach fills a significant empirical void and provides actionable insights for policymakers seeking to balance economic growth with environmental sustainability.

3. Method and material

3.1. Data sources and variable inspection

The issues of environmental externalities on the ecosystem quality imply several factors, including ecological footprints. To investigate the environmental deterioration of Central European communities, carbon emissions were employed as the parameter. Figure 2 illustrates the methodological approach and road map of the research. However, there are other factors that influence the environmental quality of Central Europe, which are the concern for this research, including green fiscal policy, natural resource rent, patent applications, green finance, and renewable energy. Through the lens of EMT, which highlights the role of institutional reform, technological upgrading, and market-based mechanisms in reducing environmental degradation, the selection of GFP, GRF, NAR, REN, and PAP are theoretically justified. These factors also mirror the extensive body of empirical research (Udeagha & Muchapondwa, 2023a; Takyi et al., 2024) demonstrating that key factors influencing carbon emissions in both developed and developing nations include resource governance, innovation systems, green financial flows, fiscal incentives, and the adoption of renewable energy.

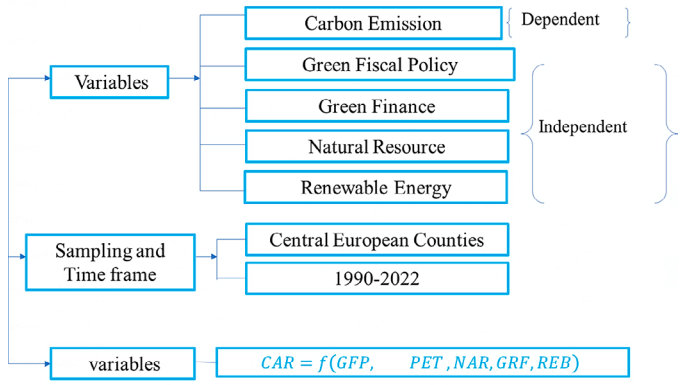


Figure 2. Methodological evaluation approach

As a result, their inclusion offers a thorough analytical framework for evaluating how Central European economies might move toward ecological sustainability via coordinated financial, technological, and regulatory routes. We developed the econometric functions as follows:

$$CAR = f\left(GFP,\ REN,\ NAR,\ GRF,\ PAP\right). \tag{1}$$

The econometric model is transformed to its logarithm form to make the variables in a uniform order to carry out the necessary preliminary test. The next step shows the equation.

$$CAR = f\left(lnGFP, lnREN, lnNAR, lnGRF, lnPAP\right). \tag{2}$$

To have comprehensive and robust results, we employed a balance panel data curation between 1990–2022 for Central European communities (Table 1). Empirical evaluation has demonstrated that carbon emissions can be measured in different edge depending on the database and methodologies (Nhuong et al., 2025). To guarantee transparency and material errors, all variables utilised in this investigation were obtained from explicitly defined and publicly accessible sources. Carbon emissions (CAR), green fiscal policy (GFP),

Table 1. Variables evaluations, data sources, and counties

	Source	Acronyms	Measurement Unit
Carbon emission	WDI	CAR	Kilotons (kt)
Green fiscal policy	WDI	GFP	Total percentage of GDP
Patent application	WDI	PAP	Patent application (non-resident + resident)
Natural resource abundance	WDI	NAR	Natural resource rent (% of GDP)
Green finance	OECD	GRF	Total percentage of green credit to private enterprises
Renewable energy	WDI	REN	Total percentage of energy utilization
Data sources: WDI-World development indicator (https://data.worldbank.org/indicator), OECD (https://stats.oecd.org/), Eurostat (https://ec.europa.eu/eurostat/).			

List of Central European regions

Poland	Czechia	Austria1	Slovakia	Switzerland	Germany
Croatia	Lithuania	Serbia	Slovenia	Hungary	Bulgaria Romania

natural resource rent (NAR), and patent applications (PAP) were sourced from the World Development Indicators (WDI) database of the World Bank, which offers standardised annual environmental and macroeconomic indicators for all Central European economies. Renewable energy consumption (REN), defined as the proportion of renewable energy in total final energy usage, was obtained from the WDI Energy and Extractives dataset, which aggregates standardised energy information supplied by national statistical offices. Green finance (GRF), characterised as the proportion of green credit allocated to private firms, was derived from the OECD Green Growth Indicators and augmented with data from national central bank financial stability reports for countries with insufficient OECD coverage. The country selection was done through Eurostat classification.

3.2. Model assumptions and theoretical paradigm

In the push for sustainability within the Central European community, the instrument of green fiscal policy has been considered a significant tool to reduce carbon emission. These policy tools include carbon tax, environmental tax, and subsidies for funding renewable energy. Specifically, eco-friendly products and processes benefit the ecosystem. It is, therefore, inevitable that green fiscal policy is a significant component to mitigate ecological deterioration; its application is overlapped. From this hypothesis $\delta_1 = \frac{\partial GFP_{i,t}}{\partial CAR_{i,t}} < 0$. According to empirical literature, natural resource rent affects environmental externalities inversely (Voumik et al., 2023; Agboola et al., 2021). For the long-term sustainability of Central European communities, this variable is employed in the model to mitigate carbon emissions. Therefore, we denote natural resources rent as a negative as displayed $\delta_2 = \frac{\partial NAR_{i,t}}{\partial CAR_{i,t}} < 0$. Recently, green finance has become one of the components when it comes to factors to adopt to reduce ecological footprint. Attention is growing to the nexus between GRF and regional carbon emissions in Europe. Theoretically, green finance has an immaterial affiliation with carbon emissions (Mehboob et al., 2024; Deng et al., 2024). Hence, we hypothesize that green finance will have a negative sign as illustrated $\delta_3 = \frac{\partial GRF_{i,t}}{\partial CAR_{i,t}} < 0$. Moreover, the presumption of patent application and carbon emissions affiliation in literary works estimates that regions that employed patent application move closer to their net zero emission compared to their other counterparts (Oyebanji et al., 2022; Hu et al., 2023). From the enormous inspection presented we coined an inverse nexus. $\delta_4 = \frac{\partial PAP_{i,t}}{\partial CAR_{i,t}} < 0$. Furthermore, REN in the form of hydro, wind, solar, and nuclear energy is considered a favorable energy utilization compared to natural gas, coal, and other non-renewable energy sources. Yin et al. (2024) affirms that regions that are advanced turned to manage their environmental damage compared to emerging regions by adopting renewable energies. We have a negative association with carbon emission. $\delta_5 = \frac{\partial REN_{i,t}}{\partial CAR_{i,t}} < 0$.

3.3. Preliminary tests

3.3.1. Cross sectional dependence (CSD)

To begin with the econometric evaluation and inspection of the variables, we follow the literature work of (Sampene et al., 2024). In the initial step, we assessed CSD as the data curation spun through many years. The key findings indicate that there is no significant correlation among the variables. Central European regions are interlinked in terms of trade, share of technology, culture, and other social facilities, which may lead to cross-sectional dependence in the data. This scenario helps reduce bias and distorted outcomes. By reference to Pesaran (2004), the cross-sectional test was developed:

$$CSD = \sqrt{\frac{2T}{M(M-1)}}\left(\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\sigma_{ij}^{t}\right). \tag{3}$$

3.3.2. Slope heterogeneity

The slop heterogeneity was employed to improve and decrease the cross-sectional environment of the outcome and to elaborate on the slop coefficient of the variables' results. In order to analyze this slope parameter, the econometric method in Equations (4)–(5) was created.

$$\tilde{\Delta}\mathrm{SHT} = (M)^{\frac{1}{2}}(2K)^{\frac{-1}{2}}\left(\frac{1}{M}(\tilde{S}-K)\right); \tag{4}$$

$$\tilde{\Delta}\mathrm{ASHT} = (M)^{\frac{1}{2}}\left(\left(\frac{2k(T-k-1)}{T+1}\right)^{\frac{-1}{2}}\right)\left(\frac{1}{M}(\tilde{S}-K)\right). \tag{5}$$

3.3.3. Unit root

In reference to Pesaran (2007), the core to panel data analysis are panel unit root assessment like CADF and CIPS. The purpose of this assessment is to see if the variables being studied remain constant over all the time points in the cross-section (Khaddage-Soboh et al., 2023; Du & Li, 2024). The below function $Equ\,6-CADF$ and $Equ\,7-CIPS$ was outlined to test the stationarity of the variables of carbon emission, green fiscal policy, natural resource rent, green finance, patent application, and renewable energy across Central European communities.

$$CADF = \gamma x_{it} = \alpha_{it} + \beta_{it-1} + \delta_I T + \sum_{j=1}^{M}\gamma_{ij}\gamma x_{it-j} + \varepsilon_{it}; \tag{6}$$

$$CIPS = \frac{1}{M}\sum_{i=1}^{M}\varphi_i(M,T). \tag{7}$$

3.3.4. Panel cointegration

To verify the long-run movement exitance between the variables after establishing the stationarity, the two most employed cointegrations in literary work were utilized. The cointegration evaluation of Westerlund (2007) technique was employed to establish the long-run equilibrium affiliation of the variables of CAR, GFP, GRF, NAR, PAP, and REN. The Westerlund evaluation $\left(\text{Eqs.}\,(8)-(11)\right)$ accounts for the delimitation of affiliated with CSD and slop heterogeneity among the variables.

$$G_{\tau} = \frac{1}{M}\sum_{i=1}^{M}\frac{\eta_i}{S.E(\widehat{\eta_i})}; \tag{8}$$

$$G_{a} = \frac{1}{M}\sum_{i=1}^{M}\frac{T\eta_i}{1-\sum_{j=1}^{k}\widehat{\eta_{ij}}}; \tag{9}$$

$$P_{\tau} = \frac{\widehat{\eta_i}}{S.E(\widehat{\eta_i})}; \tag{10}$$

$$P_{a} = T\eta_i. \tag{11}$$

The group estimation was $(G_T - G_a)$ and the co-integration is $(P_T - P_a)$.

3.4. Regression advocate

The CS-ARDL model is a superior approach compared to other models because it effectively handles the complex issues that often arise in panel data analysis, leading to more reliable and accurate results (Du and Li, 2024). The CS-ARDL model by Chudik and Pesaran (2015) is specifically designed to handle the issue of CSD in panel data analysis. CSD occurs when the units in a panel dataset are correlated with each other, which can lead to biased and inconsistent outcomes if not properly addressed. The CS-ARDL model can account for slope heterogeneity, where the affiliation between variables may differ across cross-sectional units (Takyi et al., 2024; Sampene et al., 2024). This feature is crucial, as heterogeneity is common in panel data settings. Also, the CS-ARDL model allows for the assessment of both short-run and long-run affiliation between variables. The CS-ARDL approach can be incorporated when the variables have a mixed order of integration, i.e., some are I (0) and others are I (1). This research evaluation employed the CS-ARDL approach on the variables of CAR, GFP, REN, GRF, NAR, and PAP for Central European regions. The empirical econometric model is presented below.

$$\Delta CAR_{it} = \varphi_{it} + \sum_{j=1}^{n}\varphi_{it}\, CAR_{i,t=j} + \sum_{j=0}^{n}\grave{}\varphi_{it}\, X_{i,t=j} + \sum_{j=0}^{1}\grave{}\varphi_{it}\, \bar{Z}_{i,t=j} + \mu_{it}. \tag{12}$$

$\bar{Z}_t = \left(\Delta CAR_{it}, \bar{Z}_t\right)$ Comprises the CST mean average and its components X_{it} Exhibit the distinctiveness of individual independent variables GFP, REN, GRF, NAR, and PAP.

3.5. Granger causality

The panel granger causality test by Dumitrescu and Hurlin (2012) is employed in the investigation to realize the affiliation. When error terms are CSD, the D&H estimator becomes even more important. Furthermore, in heterogeneous and balanced panels, the D&H is applicable when the duration is longer than the cross-section units. In contrast to the alternative hypothesis, which supports the existence of a causal nexus in the archetype, the null hypothesis of the D&H granger causality estimator is based on the premise that there is no causal interaction among the constructs.

$$Y_{it} = \alpha_i + \sum_{m=1}^{M} \psi_i^m, Y_{i(m-t)} + \sum_{m=1}^{M} \lambda_i^m, Z_{i(m-t)}. \quad (13)$$

Such that m illustrates the segment of the lag, ψ_i^m displays the model's autoregressive parameters.

4. Empirical results

Table 2 displayed the descriptive and variance inflation factor evaluation for the variables under investigation within the Central European regions. The findings revealed both positive and negative mean coefficients among the variables. The highest standard deviation was patent application and the lowest was green fiscal policy, indicating both high and low volatility within the variables studied. Again, the Jarque-Bera and p. values show that the constructs are not normally distributed. Therefore, the null hypothesis estimation of normal distribution is opposed. The multicollinearity of the variables was verified through VIF. The results revealed that all the variables are within the threshold values of less than 5.

Table 2. Descriptive statistics

	CAR	GFP	REN	NAR	GRF	PAP
Mean	4.886	1.243	1.119	–0.410	1.665	2.676
Maximum	6.053	1.446	1.554	0.757	2.231	4.370
Minimum	3.979	0.866	0.258	–2.095	0.932	0.699
Std. Dev.	0.473	0.124	0.309	0.578	0.263	0.914
Skewness	0.781	–1.018	–0.859	–0.844	0.010	0.126
Kurtosis	3.091	3.444	2.956	3.655	2.647	1.999
Jarque-Bera	29.41	45.40	33.68	36.96	19.81	65.81
Probability	0.000	0.025	0.000	0.035	0.005	0.000
Obs.	429	429	429	429	429	429
	VIF	1/VIF				
GFP	1.63	0.596				
REN	1.18	0.851				
NAR	2.05	0.487				
GRF	2.03	0.492				
PAP	1.08	0.923				

4.1. Cross sectional dependence (CSD)

The results of the CSD evaluation as displayed in Table 3 indicated that Central European communities are interdependent on each other. Implying that when there is a shock in one region, the effect is easy to transfer to the other Central European regions. Again, the conclusion of the null hypothesis of no slope heterogeneity was opposed.

Table 3. Cross sectional dependence

Variables	Breusch-Pagan LM	Bias-corrected scaled LM	Pesaran LM
GFP	112.247 [a]	41.423 [a]	41.314 [a]
REN	164.597 [a]	52.081 [a]	51.972 [a]
NAR	142.865 [a]	75.258 [a]	44.923 [a]
GRF	86.152 [a]	46.845 [a]	56.741 [a]
PAP	37.953 [a]	24.111 [a]	22.547 [a]
Slope Homogeneity	Test Statistics		
$\hat{\Delta}$	28.536 [a]		
$\hat{\Delta}_{adjusted}$	32.704 [a]		

Note: [a] signifies at 1% significance level.

4.2. Panel unit root

The outcome of the stationarity estimations employed in this investigation are encapsulated in Table 4. Initially, not all the test results coefficients and p-values were deemed significant based on the panel unit root tests (CADF and CIPS). The results indicate that the variable was stationary in the first level, leading to the opposing of the unit root null hypothesis of non-stationarity. This series seems to adhere to the I (1) unit root methodology constructed on the data.

Table 4. Panel unit root

Series	CADF		CIPS	
	Level	First Difference	Level	First Difference
CAR	–1.197	–2.440 [a]	–1.620	–4.767 [a]
GFP	–2.254 [b]	–2.722 [a]	–2.532 [a]	–5.019 [a]
REN	–2.147	–3.230 [a]	–1.854	–5.198 [a]
NAR	–2.077	–3.627 [a]	–2.595 [a]	–5.567 [a]
GRF	–2.219 [b]	–2.837 [a]	–2.567 [a]	–5.016 [a]
PAP	–2.834 [a]	–3.842 [a]	–2.613 [a]	–5.285 [a]

Note: [a] indicates 1%, [b] indicates 5%.

4.3. Panel cointegration evaluation

To determine the long-run affiliation among the variables within Central European region, Westerlund (2007) panel cointegration was employed. The findings in Table 5 highlight a 1% significance value for G_T ant P_T establishing the presence of cointegration and rejecting the null hypothesis of no presence of cointegration. Therefore, as recommended by Takyi et al. (2024) the long-run econometric evaluation of CS-ARDL was applied to the variables.

Table 5. Panel cointegration evaluation

Test	Statistics	P-value
*G*τ	–7.241 [a]	0.014
Ga	1.385	0.545
*P*τ	–6.754 [a]	0.000
Pa	1.422	0.654

Note: [a] signifies at 1% significance level.

4.4. CS-ARDL evaluation and discussions

The econometric analytical outcome of CS-ARDL is presented in Table 6 with short- and long-term effects. The speed at which Central European regions can develop green fiscal policies, invest in renewable energy, and direct finance to cleaner and greener projects is at –0.784. ECT (–1) represents the shift from short-term to long-term depreciation of carbon emission levels. With the EU Green Deal project and circular economy initiatives, Central European regions will be able to meet SDG 13 by 2030. The investigation outline in Table 6 indicated that green fiscal policy had a negative affiliation with carbon emissions within the Central European communities. Empirically, a 1% rise in green fiscal policy resulted in a 34.9% depreciation in carbon emissions as it is observed in the long term. The effect is low in the short term, with a 1% change leading to 18.6%. The implication is that enterprises in the short term may take time to readjust to green fiscal policy to reduce carbon emissions in the Central European regions in transition to a more sustainable economy. However, in the long-term, industries in Central European communities may employ renewable energy in production and invest in technological innovation to moderate the consumption of fossil fuels. Similarly, REN had an inverse material relationship with CAR in the short and long term as depicted in Table 6. The effect is high in the long term –0.601 and –0.192 respectively. The findings revealed that, when Central European States adopt renewable energy strategies including wind, biofuel, solar, and hydro they will be able to depreciate their emissions levels and shift to more sustainable cleaner ecosystems.

With reference to the nexus between NAR and CAR within Central European communities, the CS-ARDL technique established a positive material affiliation between NAR and CAR. The outcome implies that a percentage upsurge in natural resources leads to 0.138 and 0.502 in short and long term respectively. The findings highlighted that as natural resources increase, it will have a corresponding appreciation in carbon emissions in Central European regions. Furthermore, green finance had a negative significant efficacious nexus with carbon emissions in the short and long term. With a 1% uprise in green finance development linked to a coefficient figure of –0.343 and –0.542 in the short and long term respectively. Green finance has recently been discussed as the policy direction to net zero emission and meeting the SDG 13 (Sun et al., 2022). The research findings demonstrated a long-term nexus among green financing, eco taxes, and geopolitical factors concerning environmental damage. Finally, the investigation diagnosis test shows an R square and adjusted R square Coefficient values of 79.45 and 77.12 establishing how well the endogenous variable is explain by the exogenous variables.

Table 6. CS-ARDL evaluation

Variable	Short Run			Long Run		
	Co-efficient	Stand. err	p-value	Co-efficient	Stand. err	p-value
GFP	–0.186 [a]	–0.775	0.000	–0.349 [a]	0.496	0.004
REN	–0.192 [a]	–0.802	0.000	–0.601 [a]	0.438	0.000
NAR	0.138 [a]	0.825	0.003	0.502 [a]	0.117	0.000
GRF	–0.343 [a]	0.947	0.000	–0.542 [a]	0.021	0.000
PAP	0.524 [a]	0.210	0.000	0.768 [a]	0.590	0.000
ECT (–1)	–0.784 [a]	0.122	0.000			
Diagnostics test						
Modified Wald test	Heteroskedasticity	255.641	0.891			
Woodridge test	Autocorrection	201.645	0.345			
Jarcque Bera test	Normality	7.895	0.075			
F-statis	Goodness of fit	44.251	0.000			
	R-square	0.79				
	Adj. R-square	0.77				

Note: [a] signifies at 1% significance level.

4.5. Robustness Assessment (FMOLS)

To validate CS-ARDL estimation, the FMOLS was employed as present in Table 7 on the variables of GFP, REN, NAR, GRF, and PAP long-run affiliation with CAR. The outcome revealed a negative relationship between GFP, GRF, and REN on CAR. In contrast, a positive affiliation was identified in NAR and PAP on CAR. The significance affirms the sturdiness of the CS-ARDL estimation.

Table 7. Robustness assessment (FMOLS)

Variables	Co-efficient	Stand. err	p-value
GFP	–0.489	0.218	0.001
REN	–0.217	0.062	0.000
NAR	0.662	0.052	0.000
GRF	–0.582	0.074	0.000
PAP	0.353	0.122	0.000
Diagnostics test			
R-squared	0.903	Mean dep. Variable	4.883
Adjusted R-squared	0.899	SD dep. Variable	0.473
S.E. of regression	0.150	Sum squared resid	8.985
Long-run Variance	0.331		

4.6. Panel granger causality

As encapsulated in Table 8 and Figure 3 , the D-H model presented the causality affiliation between the variables from the analysis. The outcome illustrated that carbon emission had a unidirectional nexus with green fiscal policy. This implies that significant policy initiative on GFP will lead to the depreciation in carbon emission. Previous literary work has reported similar outcomes (Ameer et al., 2024; Dogan et al., 2023). Again, the D-H causality approach established a unidirectional relationship between carbon emission and renewable energy among Central European communities. The estimation indicated that, when regions continue with their EU green deal in the shift to renewable energy it will lead to reduction in environmental damage. The findings align with Ameer et al. (2024), who showed in their research that E7 regions can mitigate ecological harm by effective policies on renewable energy consumption to reduce emissions significantly. The D-H causality evaluation revealed the bidirectional causation between NAR and CAR. This study indicates that CAR and NAR are synergistic. Natural resources are a material for the sustainability of Central European communities. Takyi et al. (2024) in Visegrad regions and Sampene et al. (2024) Mercosur economics are prior studies that demonstrated close results, and our finding contributes to that body of evidence. Also, the D&H test indicated a unidirectional causal link between green financing and CAR. The unidirectional causal relationship between these indicators indicates that enhancing and executing CAR is facilitated by augmenting investment in GRF. This was confirmed in the literary works of Deng et al. (2024), about the transformation of green finance in advanced communities. The evaluation results indicated that green finance significantly impacted the reduction of greenhouse gas emissions. Finally, Table 7 presented evaluation of bidirectional causality between patent application and carbon emission within the investigated regions. The outcome illustrated that mutually PAP and carbon emission co-move in the two-way direction. Milindi and Inglesi-Lotz (2022) investigate the relationship between technological advancement and carbon emissions across six distinct income categories of nations. The examination of both sub and full panel data revealed that patent rights had an insignificant nexus with the reduction of carbon emissions.

Table 8. D&H evaluation

Null Hypothesis:	W-Stat.	Z-Stat.	Prob.	Decision
CAR ⇎ GFP	1.153	0.389	0.697	Unidirectional
GFP ⇎ CAR	8.830 [a]	19.963	0.000	
CAR ⇎ REN	1.835 [a]	2.129	0.033	Unidirectional
REN ⇎ CAR	1.301	0.764	0.445	
CAR ⇎ NAR	2.012 [a]	2.580	0.000	Bidirectional
NAR ⇎ CAR	1.668 [a]	1.702	0.008	
CAR ⇎ GRF	1.291	0.741	0.457	Unidirectional
GRF ⇎ CAR	2.161 [a]	2.960	0.003	
CAR ⇎ PAP	2.196 [a]	3.049	0.002	Bidirectional
PAP ⇎ CAR	3.667 [a]	6.799	0.000	

Note: [a] signifies at 1% significance level.

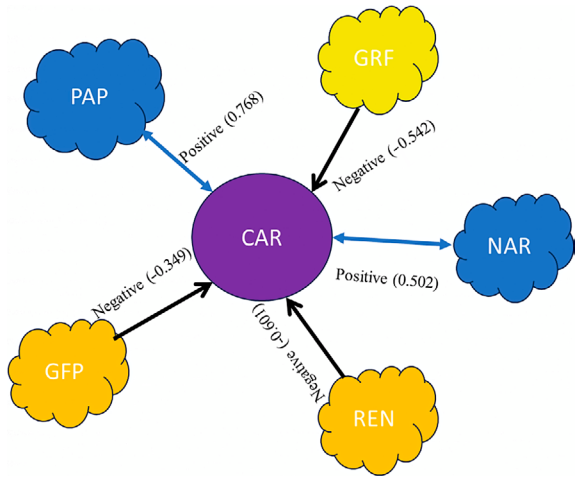


Figure 3. Causality assessment

5. Discussion of empirical findings

The CS-ARDL results in Table 6 show that green fiscal policy significantly reduces carbon emissions in both the short and long run. This finding aligns with earlier studies demonstrating that environmental taxes, carbon levies, and pollution-based fiscal instruments effectively mitigate ecological deterioration (Du & Li, 2024; Khaddage-Soboh et al., 2023; Fang & Liu, 2026b). The negative coefficient confirms that fiscal interventions in Central Europe though unevenly implemented are functioning as intended by incentivizing cleaner production and discouraging fossil-fuel-intensive activities. This outcome is consistent with evidence from OECD and EU regions, where green fiscal measures have been shown to enhance environmental quality (Bozatli & Akca, 2024; Dogan et al., 2023). The results therefore reinforce the ecological modernization argument that fiscal tools are essential for steering industries toward low-carbon pathways.

The empirical results indicate that green finance exerts a significant negative effect on carbon emissions, suggesting that increased green credit allocation, sustainable investment portfolios, and environmentally oriented financial instruments contribute to emission reduction. This aligns with findings from BRICS, China, and high-income regions, where green finance has been shown to promote renewable energy adoption and reduce environmental externalities (Abbas et al., 2023; Chu, 2024; Mehboob et al., 2024). The Central European context appears to follow a similar trajectory: financial institutions are gradually integrating environmental criteria into lending decisions, thereby directing capital toward cleaner technologies. This supports the broader literature that positions green finance as a catalyst for ecological sustainability (Nhuong et al., 2025; Chin et al., 2024; Wang et al., 2023).

The CS-ARDL estimates confirm a strong negative relationship between renewable energy consumption and carbon emissions, indicating that increased reliance on wind, solar, hydro, and other renewable sources significantly improve environmental quality. This finding is consistent with empirical evidence from Italy, the United Kingdom, OECD countries, and

emerging economies, where renewable energy has consistently been linked to reductions in ecological footprints (Javed et al., 2023; Zhou et al., 2023; Kafeel et al., 2024). The results also support Yin et al. (2024), who argue that advanced regions with higher renewable energy penetration are better positioned to manage environmental degradation. For Central Europe, the results highlight the importance of accelerating renewable energy investments to achieve long-term carbon neutrality.

Contrary to theoretical expectations, the CS-ARDL results reveal a positive and significant relationship between natural resource rent and carbon emissions, indicating that resource-rich Central European economies experience higher environmental degradation. Regions such as Poland, Hungary, and Slovakia depend on coal resources which has a direct linked with environmental deterioration. This outcome aligns with studies showing that weak institutional frameworks and unsustainable extraction practices can amplify ecological damage in resource-dependent regions (Masi et al., 2024; Nwani & Adams, 2021). Similar findings have been reported in China and global panels, where natural resource exploitation has been associated with increased emissions when environmental governance is insufficient (Shen et al., 2021; Bosah et al., 2023). The results suggest that Central Europe may be experiencing a form of "resource-driven pollution," where economic gains from resource rents are not accompanied by adequate environmental safeguards.

The empirical findings show that patent applications unexpectedly increase carbon emissions, contradicting the theoretical expectation that innovation should reduce environmental harm. This result suggests that the majority of patents in Central Europe may not be environmentally oriented or that innovation activities are still dominated by conventional, carbon-intensive technologies. Similar mixed or insignificant effects have been reported in studies examining the environmental impact of technological progress across different income groups and regions (Milindi & Inglesi-Lotz, 2022). While some research shows that green patents reduce emissions (Ghorbal et al., 2022; Oyebanji et al., 2022), the positive coefficient in this study indicates that Central Europe has not yet achieved a strong alignment between innovation systems and environmental sustainability. This highlights the need for targeted policies that promote green innovation, rather than general patenting activity.

6. Policy, conclusions, limitations, and future investigation directions

6.1. Policy suggestions

The escalation in natural resource utilization, population appreciation, and growth in economic development has called for a prudent approach to deprecating the external deterioration on the environment. The research places emphasis on the material effect of green fiscal policy, natural resource rent, renewable energy, and patent applications on carbon emissions among Central European regions. The empirical findings highlight several actionable policy pathways for Central European economies seeking to reduce carbon emissions and strengthen environmental sustainability. First, governments should intensify the implementation of green fiscal policies, particularly through carbon taxes, pollution levies, and targeted environmental taxation. These measures can incentivize industries to adopt cleaner technologies and reduce

reliance on fossil-fuel-intensive production processes. Second, the results demonstrate the importance of expanding green finance portfolios. Policymakers should encourage financial institutions to increase green credit allocation, lower financing barriers for environmentally friendly enterprises, and integrate sustainability criteria into lending decisions. Strengthening green bond markets and offering fiscal incentives for green investments can further accelerate the transition toward low-carbon development. Third, the positive environmental role of renewable energy suggests that Central European governments must scale up investments in renewable energy infrastructure, including wind, solar, hydro, and biomass. Policies that support grid modernization, renewable energy subsidies, and cross-border energy cooperation will enhance energy security while reducing emissions. Fourth, the unexpected positive relationship between patent applications and carbon emissions indicates that innovation systems require stronger environmental orientation. Governments should promote green innovation by offering tax credits, research grants, and intellectual property incentives specifically tied to eco-friendly technologies. Strengthening collaboration between universities, research institutions, and industry can also improve the environmental relevance of technological development. Finally, the positive association between natural resource rent and emissions suggests the need for stricter governance of resource extraction. Policies should focus on sustainable resource management, transparent reporting, and environmental compliance frameworks to ensure that resource exploitation does not exacerbate ecological degradation.

The evaluation contributes to ecological modernization theory (EMT) which posits that economic progress and environmental protection can be harmonized via technological innovation, institutional reform, and market-based mechanisms. Applying EMT to green fiscal policy in Central Europe provides material significance in achieving carbon neutrality and employing sustainable economic development. This study extends EMT by highlighting how GFP, GRF, NAR, PAP, and REN serve as mechanisms to decouple economic progress from environmental degradation. The integration of these variables highlights the theory's premise that ecological objectives are achievable within the framework of advanced private enterprises when supported by initiative-taking policies and technological progress.

6.2. Conclusion

This study examined the influence of green fiscal policy, green finance, patent applications, renewable energy, and natural resource rent on carbon emissions across 13 Central European economies from 1990 to 2022. Employing second-generation econometric techniques including the CS-ARDL model, FMOLS robustness checks, and Dumitrescu–Hurlin causality tests, the analysis provides robust evidence on the long-run and short-run dynamics among these variables. The findings reveal that green fiscal policy, green finance, and renewable energy significantly reduce carbon emissions, confirming their significant role in advancing ecological modernization. Conversely, natural resource rent and patent applications increase emissions, suggesting inefficiencies in resource governance and the limited environmental orientation of current innovation activities. The causality results further demonstrate unidirectional causality from green fiscal policy, green finance, and renewable energy to carbon emissions, while natural resource rent and patent applications exhibit bidirectional causality with emissions. Overall, the study contributes to the literature by offering region-specific insights into the

environmental performance of Central European economies and by demonstrating the importance of integrating fiscal, financial, technological, and resource-based strategies to achieve long-term sustainability.

6.3. Limitations and future research directions

Although the study provides valuable empirical insights, several limitations offer opportunities for future research. First, the analysis relies on aggregate national-level data, which may mask sector-specific variations in environmental performance. Future studies could employ firm-level or industry-level datasets to capture micro-level dynamics. Second, the study focuses on five key determinants of environmental quality. Additional variables such as institutional quality, environmental regulation stringency, digitalization, or trade openness may further enrich the understanding of carbon emission drivers in Central Europe. Third, the study uses annual panel data, which may not fully capture short-term fluctuations or seasonal variations in emissions and energy use. Future research could incorporate quarterly or monthly data where available. Fourth, while the CS-ARDL and D&H causality models provide robust long-run insights, future studies could apply nonlinear, machine-learning, or spatial econometric approaches to explore complex interactions, threshold effects, and spatial spillovers across neighbouring countries. Finally, future research could extend the analysis to comparative regional studies, examining how Central Europe differs from Western Europe, the Balkans, or emerging economies in terms of green policy effectiveness and environmental outcomes.

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Conflict of interests

The authors declare no conflict of interest.

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