

Central European sustainable economy: The role of green finance, technological innovation, and circular economy

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Abstract: The European Green Deal has clarified the need to evaluate the factors affecting the ecological footprint and find strategies to reduce their impact. The study evaluates the correlation between green finance, technological innovation, circular economy, urbanization, energy consumption, economic progress, and ecological footprint. It analyzes data from Central European communities from 1990 to 2022, using robust econometric evaluations, including common correlated effect mean group (CCEMG) and augmented mean group (AMG) models, along with an initial examination of cross-sectional dependence, unit roots, cointegration, and slope heterogeneity. The findings highlight that a reduction in ecological footprints can be achieved through technological innovation, green finance, and a circular economy. In contrast, energy consumption, urbanization, and economic development tend to increase the ecological footprint. Advanced models such as fully modified ordinary least square (FMOLS) and Driscoll and Kraay (DSK) support these findings. The causality analysis revealed the unidirectional and bidirectional relationship between variables. Based on these outcomes, the study recommends that Central European countries implement suitable policies to push the transition toward a sustainable economy.

Keywords: Green finance, technological innovation, circular economy, urbanization, economic progress, Central Europe.

JEL: Q01, Q30, Q40, Q55.

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Introduction

With demand exceeding supply and increased environmental depletion, novel strategies are needed to meet the ever-appreciated population demand of individuals and enterprises

(Mukherjee et al., 2023). Institutions, governments, and individuals have called for prudent measures to mitigate the ecological footprint due to the increasing population and limited resources (Cheng et al., 2024; Rodríguez-Reb'es

et al., 2024). Ecological footprint (EFP) is triggered by different factors, including energy consumption (ENE), urban pollution, deforestation, and sea level depletion. According to the global footprint network, Central European communities require four times the land size needed to meet their ecological footprint (Fig. 1). Germany contributes 4.4986, Czechia 5.0830, Hungary 3.7886, Slovakia 4.1589, Slovenia 4.7899, Poland 4.6867, and Austria 0.25933 to global pollution (Network G.F., 2019). As a result, reducing the footprint caused by anthropogenic activities and global crises has led to the development of various policies, such as the EU Green Deal and the EU circular principle in 2015. The circular economy is a limited model for addressing global waste, energy, and pollution (Almulhim, 2024). In 2015, the EU presented to its member communities its circular economy strategy of eliminating waste and pollution, circular products and materials, and regenerating nature (EU, 2019). Establishing indicates that circularity complements the EU Green Deal by limiting the principle of make-use-disposed linearity.

Numerous academics have demonstrated that a circular economy will help to meet the sustainability progress set by many nations (Yu et al., 2023). Waste-energy is one of the alternative ways to reduce the huge landfill sites around Europe (Halkos & Aslanidis, 2024). They specifically demonstrated waste conversion into energy for production or household consumption. Additionally, waste separation and trade in the EU countries accounted for 50%, part of which is shipped to Vietnam for recycling (Thapa et al., 2024). On the IPAT equation model, Figge and Thorpe (2023) examined different principles to a sustainable level. These include circular economy, operational eco-efficiency, and sufficiency. Central Europe advocates a circular economy and green deals to reduce landfill waste. Exploring the interconnection between circularity and ecological footprint within Central European communities is important. Furthermore, these regions are experiencing rapid economic progress, and there is no doubt that they are investing in innovative procedures. Research and development in technologically innovative ways is an efficient way to depreciate the ecological footprint within the Central European communities (Alina-Petronela et al., 2023; Hao et al., 2023). In Italy, Javed et al. (2023) conducted an empirical evaluation on green technology and ecological footprint

to enhance the quality of the ecosystem. Their findings identify renewable energy and technological innovation (TNI) as the keys to reducing industry footprints. Similarly, Appiah et al. (2023) found that implementing innovation principles in 29 OECD communities between 1990 and 2020 reduced their EFP and improved the quality of the ecosystem. Therefore, evaluating the influence of technological innovation in Central Europe will help improve biocapacity and depreciate the ecosystem footprint.

Nevertheless, the financial strength of a nation determines its development. Green finance (GNF) includes green credit, bonds, and loans, which are tailing towards a sustainable economy (Qing et al., 2024; Yu, 2024). Mohsin et al. (2023) evaluation in Europe demonstrated that communities such as Poland could decrease their emissions footprint by reducing their coal funding. The EU taxonomy has recently addressed the question of what sustainably qualifies for green finance. The European Union's 1 trillion-euro investment to achieve climate neutrality by 2050 is a way to inform governments and investors to invest in sustainable financial assets. Tiwari et al. (2025) conducted a study on the progress of the green economy in the USA between 1990 and 2021. The results showed that financial development had a lower emissions footprint. Similarly, Sampene et al. (2023) investigated the ecological footprint and green finance of South Asian communities. The econometric findings demonstrated that green finance was effective in depreciating ecological footprints. Similar work has confirmed that green finance is important in reducing the ecological footprint (Chen et al., 2024; Sapp, 2024). The Central European communities are no different from other economies in terms of green finance principles.

The increased urban population and resource utilization are causing pollution in Central Europe. According to the EU Report 2022, urban pollution in the European Zone has increased due to industrial and transportation consumption of non-renewable energy sources (Clora & Yu, 2022; Kirat et al., 2024). Addai et al. (2022) evaluated ecological footprint and urbanization in Eastern Europe using various econometric approaches. The findings indicated that urbanization had a bidirectional relationship with ecological footprint. Additionally, Cheng et al. (2024) empirically examined China's provincial dual carbon goals from

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2010 to 2019. The findings indicated that the link between renewable energy innovation was appreciated when urbanization was added as a control variable. By employing the cross-sectional autoregressive distributed lag (CS-ARDL) model on G11 nations. Mehmood (2024) analyzed the influence of urbanization and ecological footing between 1990 and 2020. The results show that urbanization increases environmental depletion in regions. With more industries and individuals moving into urban communities in Central Europe, the demand for natural resources and pollution has increased.

The literature has shown unclear relations between energy consumption (ENE), circular economy (CRE), urbanization (UBZ), green finance (GNF), technological innovation (TNI), and economic progress (ECP), with Central Europe not being unique. The following questions are presented: (1) What is the nexus between the EFP and its factors? (2) What, if any, explanations are available for this relationship? This investigation aims to evaluate the impact of various factors on reducing ecological footprints in Central European economies from 1990 to 2022. These factors include energy consumption, circular economy practices, technological innovation, urbanization, and green finance. The Central European economies were chosen due to their under-representation

in environmental climate studies, significant progress in the past two decades, and their role as emerging economies with substantial energy consumption. The V-4 group, including Poland, the Czech Republic, Hungary, Slovakia, and Slovenia, has an expected growth rate of 5% per year, while Central Europe is 6.4% over the next 40 years, narrowing the gap with the V-4 group. Notably, Central European economies account for more than 15.7% of the Eurozone's energy consumption on solid fuels and rank among the top twenty in ecological footprint (Mohsin et al., 2023). These regions have embraced the EU's green deal, circular economy principles, and increased investments in environmental technologies, green finance, and renewable energy. The study employs robust techniques such as the CCEMG and AMG approaches, which address the dearth of empirical studies in this area. In addition, the study investigates the role of CRE, GNF, and innovations in reducing the ecological footprint in the economies of Central Europe. Fig. 1 illustrates the EFP levels in Central European communities.

The study commences with a summary of the previous literature, then proceeds with data and an econometric model, and concludes with empirical findings and policy recommendations.

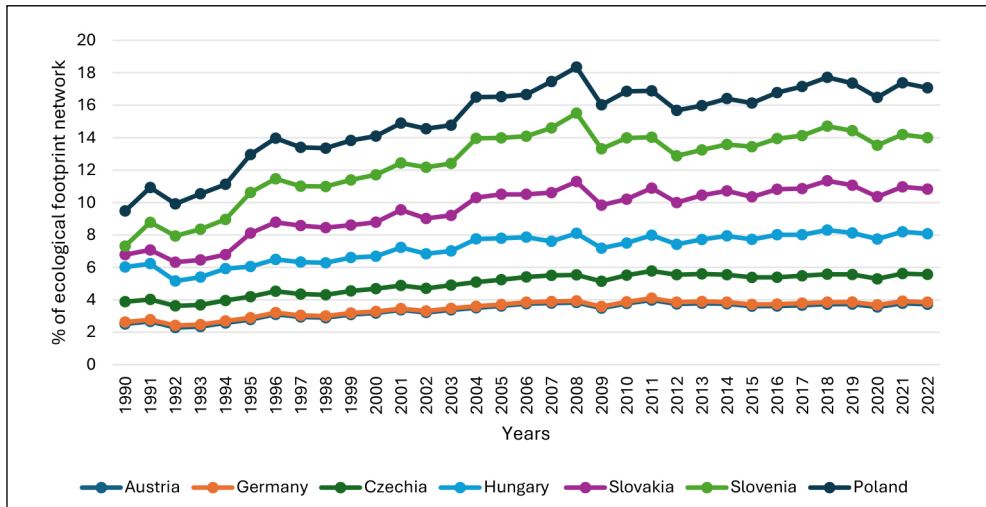


Fig. 1: EFP levels in Central European regions

Source: Global footprint network report (2023)

1 Theoretical background

1.1 Circular economy and ecological footprint

Given the volume of waste associated with a linear economy and the depreciation in nations' biocapacity, the desire to employ a more sustainable approach is necessary to reduce industrial and residential waste (Mukherjee et al., 2023). Yu et al. (2023) evaluated China's green growth policy using the ARDL model. Their findings show a correlation between the adoption of the circular economy and waste trade at 0.15% and 0.07%. Allevi et al. (2021) examine the various approaches to reusing waste within the communities of Lombardy in Italy. The evaluation developed a model to reuse waste to generate electricity and goods. Tauseef et al. (2023) stated that the EFP of the BRICS economies is their high dependency on linear economy principles regarding emissions abatement. However, their carbon footprint has improved following the Paris emission targets policies and the development of innovative approaches. Sauvé et al. (2021) explored blue, grey, and green water sustainability to reduce water contamination in the context of water footprint. Despite the impact of climate change and linear waste from enterprises on the quality and quantity of water exploration, Sauvé et al. (2021) proposed using eco-efficiency, circular economy, and eco-innovation policies to mitigate the water footprint. Meanwhile, Halkos and Aslanidis (2024) studied municipal waste in European communities, examining how enterprises can harness this waste to generate energy. While waste can negatively impact the ecosystem, it can also serve as a valuable resource for producing fertilizer and energy. Solid waste from industrial poultry can be converted into fish feed and other forms of fertilizer. Thapa et al. (2024) suggest that the industrial level can achieve a circular economy through waste trade and management. Yang et al. (2023) have established the principles of industrial ecology.

1.2 Green finance and ecological footprint

Research on GNF has recently emerged in academia due to its impact in alleviating ecological depletion (Mohsin et al., 2023). In emerging economics, Vardar et al. (2023) selected 47 nations to identify the long-run effects of green finance. Their investigation asserts that GNF and renewable energy utilization are the paths to sustainable ecology. From

the point of resource scarcity, Zhang and Chen (2023) asserted in China that green finance and renewable electricity depreciate ecological impact with a bidirectional relationship between the variables. Employing the EKC model, Yu (2024) explored the road to carbon neutrality through natural resource utilization, highlighting natural resources' role in increasing emissions. The results change when green finance is connected to natural resources to mitigate the EFP. In the more polluting economics of South Asia, the principal effect of green finance and biocapacity was evaluated from 1990–2017 on panel analysis. Employing various econometric models and the EKC approach, the results demonstrated that biocapacity appreciates ecological footprint with green finance depreciation factor for EFP (Sampene et al., 2023). Likewise, in the context of Europe, Sun and Rasool (2023) confirm a material effect of green financing in reducing ecological footprint. Khan et al. (2022) indicated that green finance is the answer to the challenge for a nation to trigger economic progress. Furthermore, Qing et al. (2024) established that the Paris climate target can be achieved through green finance. Therefore, we expect that GNF will have an effect on the mitigation of the EFP.

1.3 Technological innovation and ecological footprint

Governments and policy communities have been concerned with adopting and investing in technological innovation to improve environmental quality (Rodríguez-Reb'es et al., 2024). Literature has established the effect of TNI on EFP reduction and increasing the biocapacity of nations. In China, Sun et al. (2024) evaluated the petrochemical enterprises and their investments in technology structures. Their study concludes that technological innovation is a catalyst causing an increase in environmental depletion. This happens when environmental governance moderates it. Hassan (2023) examined South Africa due to its status as a prominent coal mining country. From 1981 to 2017, the econometric findings of the FMOLS indicated that the environmental impact significantly diminished as coal exploitation was integrated with technological advancements. This finding is corroborated by the investigation of Bekun (2024) on net zero carbon and technological innovation between 1975 and 2020 in South Africa. Particularly with

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UNSDG13, the empirical results demonstrated that technological innovation mitigates short-term and long-term carbon emissions. Furthermore, Kirat et al. (2024) expounds the effect of climate changes and environmental externalities on data curation of 111 regions. The outcome of the investigation established that the European community's energy consumption was affiliated with temperature diseases. Employing the ARDL model in the US, Tiwari et al. (2025) explored technological innovation and ecological footprint. The estimates indicated that, in the long run, environmental pollution influenced the deprivation of ecosystems. Affirming this research, twenty-seven European communities, plus the UK and Switzerland, were analyzed by Clora and Yu (2024). They indicated that to mitigate carbon emissions and carbon leakage, these regions should adopt technological innovation approaches and techniques.

1.4 Urbanization and ecological footprint

The rapid pace of urban development has put pressure on the biocapacity within Central European communities (Quito et al., 2023). Chen et al. (2022) delves into 110 economics on the effects of UBZ on EFP. The empirical results pointed out that urbanization is a catalyst for ecological footprint. They recommended that nations with high human capital manage their environmental depletion better. According to Sahoo and Sethi's (2022) investigation of new industrial communities, technological

innovation in urban areas appreciates the quality of the environment. This is possible when economic progress hinges on innovation, research, and development policies. Additionally, the environmental Kuznets curve (EKC) model of economic progress is tied to urban pollution. This was affirmed in the investigation of Mehmood (2024) in G11 states. The econometric test demonstrated that urbanization and economic progress impact the ecosystem partners. In the context of MENA regions, Satari Yuzbashkandi et al. (2023) evaluation of panel data from 1990–2019 on urbanization and ecological footprint highlighted that urbanization is not the cause of depreciation in biocapacity leading ecological footprint. Meanwhile, Toth and Sebova (2024) employed the SLR technique to investigate the influence of environmental externalities in Kosice population bias. This finding is corroborated by the results from Africa by Ekeocha (2021) on the connection between urbanization, economic progress, and ecological footprint. They identify an N-shaped distribution within low-income regions. This phenomenon was attributed to the disparity in income levels. Furthermore, Khan et al. (2023) established that urbanization did not affect the ecological footprint in India. Diversified studies have identified an effect of urbanization on the EFP. Addai et al. (2022) Eastern Europe, and Arif et al. (2023) Pakistan. According to the investigations above, urbanization adversely contributes to ecological footprints, and smart urbanization is the next novelty.

Tab. 1: Variables definition – Part 1

Variables	Proxy	Definition	Reference
Ecological footprint	<i>EFP</i>	Ecological footprint in global hectares (gha) per person	https://data.footprintnetwork.org/
Green finance	<i>GNF</i>	GRF measures environmental product protection by residents	OECD
Circular economy	<i>CRE</i>	Waste recycling technologies, industry value addition	https://databank.worldbank.org/reports.aspx?sou+rewards-development-indicators
Technological innovation	<i>TNI</i>	Measured with % of all technologies	OECD
Energy consumption	<i>ENE</i>	Percentage of oil, gas, fossil fuel (non-renewables)	https://databank.worldbank.org/reports.aspx?sourceworld-development-indicators

Tab. 1: Variables definition – Part 2

Variables	Proxy	Definition	Reference
Urbanization	UBZ	Percentage of urban total population	https://databank.worldbank.org/reports.aspx?sou+rewards-development-indicators
Economic progress	ECP	GDP (constant USD – 2015)	https://databank.worldbank.org/reports.aspx?sou+rewards-development-indicators

Source: own

2 Methodology

The evaluation employed panel data from various verified databases, including the World Bank, Global Footprint Network, and OECD, for the period 1990–2022. The research has established that ecological footprint is associated with increased economic progress in the early stages but declined in the long run with development and changes from non-renewable to adopting renewable energy. However, these are not the only factors contributing to ecological footprint appreciation within the Central European communities. Urbanization signs have been confirmed by Ekeocha et al. (2021). Technological innovation and circular economy assessment by Yang et al. (2023) demonstrated a negative nexus with ecological footprint. Previous articles have recommended green finance to help mitigate ecological footprint and appreciation of biocapacity. Central Europe was selected as it forms about 35.5% of the European region of 27 communities. The ecological footprint within these regions accounted for four times the biocapacity available. Tab. 1 presents the variables definition, measurement, and sources employed for the research.

2.1 Econometric model

The evaluation employed various econometric models that have been verified previously (Ekeocha et al., 2021). We developed our model to present the link between *CRE*, *GNF*, *TNI*, *ENE*, *UBZ*, and *ECP* on *EFP*.

The initial model was developed as:

$$EFP = f(TNI, GNF, CRE, UBZ, ENE, ECP) \quad (1)$$

The variables were changed to the logarithm form to have a favorable econometric approach suitable for the analysis. According to Sampene et al. (2023). Equation (2) presents the technique.

$$\ln ECF_{it} = \lambda_0 + \lambda_1 \ln TNI_{it} + \lambda_2 \ln ENE_{it} + \lambda_3 \ln GNF_{it} + \lambda_4 \ln UBZ_{it} + \lambda_5 \ln CRE_{it} + \lambda_6 \ln ECP_{it} + \varepsilon_{it} \quad (2)$$

where: \ln – log form; *EFP* – ecological footprint; *TNI* – technological innovation; *GNF* – green finance; *CRE* – circular economy; *UBZ* – urbanization; *ENE* – energy utilization; *ECP* – economic progress; coefficients of $\lambda_1 - \lambda_6$. The slope is coined as λ_0 with the error assessment given by ε_{it} ; t – the period 1990–2022; and i – Central European communities.

Cross-sectional dependence and slope heterogeneity test

Panel data analysis is susceptible to biased interpretations and inaccurate statistical results when cross-sectional dependence (CSD) is overlooked or neglected. In panel data analysis, obtaining reliable and unbiased estimates necessitates identifying and correcting CSD. Research findings and policy recommendations may be compromised if this dependency is overlooked, perhaps leading to inaccurate conclusions about the relationships between the variables (Adebayo et al., 2023; Sampene et al., 2024).

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

Next, the slope homogeneity was evaluated to identify the independent variables across time and groups. When investigating whether or not slopes are homogeneous, this evaluation is crucial since it sheds light on how stable the nexus is under different circumstances. When using panel data studies to make predictions or propose policies, it is essential to understand if the slopes are consistent. This is

particularly true when the connections between variables may alter over time or between dimensions. Equations (4–5) present the function of the slope homogeneity test (SHT).

$$\bar{\Delta}SHT = (N)^{\frac{1}{2}}(2K)^{-\frac{1}{2}} \left(\frac{1}{N} \bar{S} - K \right) \quad (4)$$

$$\bar{\Delta}ASHT = (N)^{\frac{1}{2}} \left(\frac{2k(T-k-1)^{-\frac{1}{2}}}{T+1} \right) \left(\frac{1}{N} \bar{S} - K \right) \quad (5)$$

where: $\bar{\Delta}SHT$ denotes the delta of the slope and $\bar{\Delta}ASHT$ presents the adjusted SHT.

Unit root test

Panel root evaluation is fundamental in panel data analysis to ensure the order and the stationarity of the construct. In the econometric approach common augmented dickey-fuller (CADF) and cross-sectional augmented impesaran-shin (CIPS) tests are considered to check for issues of cross-sectional in the data. The utilization of the test expounds to the next appropriate evaluation.

$$CADF = \gamma x_{it} = \alpha_{it} + \beta_{it-1} + \delta_i T + \sum_{j=1}^N \gamma_{ij} Y_{X_{it-j}} + \varepsilon_{it} \quad (6)$$

where: γ – the disparities among the indicators; X_{it} – the variables assessed in this research.

$$CIPS = \frac{1}{N} \sum_{i=1}^N \varphi_i(N, T) \quad (7)$$

where: N – the research period; T – the cross-sections among the indicators.

Cointegration test

The Westerlund (2007) cointegration test, formulated for panel data, facilitates the examination of long-term connections between variables. Cointegration is essential in time series evaluation, signifying a shared stochastic tendency among variables. The Westerlund (2007) test for panel data includes cross-sectional dependence, which lets you examine whether a set of variables has a cointegrating connection. This is especially useful for analyzing economic phenomena with long-term equilibrium

dynamics, as it helps identify persistent co-movements across variables spanning time and various entities. Equations (8–11) demonstrated the cointegration test.

$$G_{\tau} = \frac{1}{N} \sum_{i=1}^N \frac{\eta_i}{S.E(\hat{\eta}_i)} \quad (8)$$

$$G_{\alpha} = \frac{1}{N} \sum_{i=1}^N \frac{T\eta_i}{1 - \sum_{j=1}^k \hat{\eta}_{ij}} \quad (9)$$

$$P_{\tau} = \frac{\hat{\eta}_i}{S.E(\hat{\eta}_i)} \quad (10)$$

$$P_{\alpha} = T\eta_i \quad (11)$$

where: the means for the group statistics is depicted by ($G_a - G$) and the cointegration is denoted by ($P_t - P_a$).

Long-term estimation models

In panel data analysis, the common correlated effects mean group (CCEMG) estimator is a good way to deal with possible CSD. The CCEMG estimator enhances the mean group (MG) estimator by accommodating common correlated effects (Pesaran, 2006). The CCEMG estimator provides superior coefficient estimates compared to conventional MG estimators due to its utilization of data from the entire panel. This renders it particularly advantageous for analyzing economic processes that exhibit interdependence across temporal and spatial dimensions. This strategy enhances our understanding of how prevalent factors influence various units over time. It improves the model's accuracy and mitigates the bias risks associated with neglecting cross-sectional dependence. Designed to address the differences between cross-sectional observations, the augmented mean group (AMG) estimator is a valuable tool for evaluating panel data. The AMG estimator enhances the conventional MG estimator by incorporating individual-specific fixed effects. This addresses unobserved heterogeneity among units, offering a more adaptable and realistic framework for studying panel data. The AMG estimator is particularly useful when analyzing economic phenomena that differ between entities, such as industries or regions. The AMG estimator makes parameter estimates more accurate in panel

data analysis by considering effects specific to time and units. This makes econometric studies stronger and more reliable. Equations (12–13), which express the AMG technique computationally, are based on a two-stage methodology:

Phase I AMG technique:

$$\Delta Y_{it} = \varphi_i + \delta_i \Delta X_{it} + \gamma_i \vartheta_t + \sum_{t=2}^T \theta_i \Delta D_t + \mu_i \quad (12)$$

Phase II of the AMG technique:

$$AMG_{Estimator} = N^{-1} \sum_{i=1}^N \hat{\beta}_i \quad (13)$$

where: φ_i – the intercept, Y_{it} and X_{it} – the evaluated element; ϑ_t – heterogeneous terms having common causes that are not evaluated, Δ – the initial operator of the indicators; time dimension t ; and μ_{it} – the model’s stochastic error term.

The CCE-MG technique is the next archetypal estimator we employed since it is a reliable and consistent estimator. The robustness of no affiliation structural weakness, the serial connection between the series, and unexplained common elements are all considered by the CC-MG (Kapetanios et al., 2011). Equation (14) provides an algebraic expression for the CCE-MG:

$$Y_{it} = \alpha_{1i} + \beta_i X_{it} + \theta_i n_{it} + \mu_{it} \quad (14)$$

where: Y_{it} and X_{it} are shown as observed variables; α_{1i} – the definite group effect; β_i – the steep of cross-sectional estimators, indicates the unidentified common component that loads with θ_i heterogeneous and μ_{it} depicts the model’s probabilistic error term.

Equation (15) represents the enhanced approach with a mean CSD of the described and unknown parameters:

$$Y_{it} = \alpha_{1i} + \beta_i Z_{it} + \varphi_i \bar{y}_{it} + \bar{z}_{it} + \theta_i n_{it} + \mu_{it} \quad (15)$$

This regression was computed using the ordinary least squares approach for each cross-section. Equation (16) provides a rigorous solution for estimating the country-wise co-efficient used by linear models:

$$CCEMG = N^{-1} \sum_{i=1}^N \hat{\theta}_i \quad (16)$$

Robustness analysis

Driscoll and Kraay (1998) proposed the standard error estimating method in panel data analysis, which offers a robustness test, particularly when using the CCEMG and AMG estimators. However, the accuracy of their parameter estimates depends on the validity of the assumed covariance structure. The DSK evaluation provides a diagnostic tool to demonstrate the sensitivity of results to potential misspecifications in the covariance structure. By incorporating these standard errors into the evaluation, researchers can gain insights into their estimates’ robustness and improve their findings’ reliability. As a way to make panel data analyses more rigorous, the DSK approach tests how stable the results are under different assumptions about the covariance structure. This makes sure that the econometric conclusions are more solid and reliable.

As a result of the earlier discussion, the analysis utilized the ordinary least squares method to estimate the DSK equations, as designated in Equation (17).

$$y_{it} = x'_{it-1} \beta + z_{it} \gamma + \mu_{it} \quad (17)$$

$i = 1, \dots, N, t = 1, \dots, T$

where: y_{it} – the explanatory variable (*EFPI*); x'_{it} – the regressors (*TNI, GNF, CRE, ENE, UBZ, ECP*). In addition, μ – the error term of the function; i – the Central European communities; t – the period for the research.

Panel causality test

The investigation employs the panel Granger causality test Dumitrescu and Hurlin (2012) to evaluate the link. The DH test becomes even more important when error terms are cross-sectionally dependent. Furthermore, in heterogeneous and balanced panels, the DH 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 DH Granger causality test is based on the premise that there is no causal interaction between the variables.

$$Y_{it} = \alpha_i + \sum_{m=1}^M \psi_i^m Y_{i(m-t)} + \sum_{m=1}^M \lambda_i^m Z_{i(m-t)} \quad (18)$$

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where: m – the segment of the lag;
 ψ_i^m – the model's autoregressive parameters.

3 Results

3.1 Descriptive and correlation evaluation

The descriptive evaluation is explored to assess the variables' initial match for the econometric analysis (Tab. 2). The results demonstrated that economic progress had the highest average mean

(26.078). Urbanization mean value is 15.812. The results implied that 15.8% of Central European communities live in urban areas. The other variables had the following mean values: technological innovation (5.977), circular economy (8.496), energy consumption (0.864), and ecological footprint (0.417). The variables had negative and positive skewness with their kurtosis and Jarque bera distributed.

Tab. 2: Descriptive evaluation

	<i>EFP</i>	<i>TNI</i>	<i>GNF</i>	<i>UBZ</i>	<i>ENE</i>	<i>CRE</i>	<i>ECP</i>
Mean	0.417	5.977	2.662	15.812	0.864	8.496	26.078
Median	0.861	5.648	2.543	15.734	0.851	8.352	25.885
Maximum	1.438	10.062	4.605	17.990	1.261	10.896	28.921
Minimum	-2.553	0.100	-0.083	13.820	-0.377	6.329	23.997
Std. dev.	1.131	2.174	0.711	1.234	0.206	1.201	1.365
Skewness	-1.734	0.110	0.840	0.236	-1.176	0.602	0.706
Kurtosis	4.473	2.153	4.976	2.314	10.139	2.598	2.670
Jarque-Bera	136.769	7.373	64.816	6.671	543.942	15.512	20.248
Probability	0.000	0.025	0.000	0.035	0.000	0.000	0.000
Observations	231	231	231	231	231	231	231

Source: own

3.2 Cross-sectional evaluation and slope heterogeneity

We use cross-section and slope heterogeneity to check the independence of the indicators

explored in this research. Tab. 3 presents the outcomes from Breusch-Pagan, bias-corrected scaled, and Pesaran, along with their significance. The distribution exhibits independence

Tab. 3: Cross-sectional evaluation and slope heterogeneity

	Breusch-Pagan_{LM}	Bias-corrected scaled_{LM}	Pesaran_{LM}
lnEFP	289.454***	41.423***	41.314***
lnTNI	385.529***	52.081***	51.972***
lnGNF	142.865***	33.738***	33.447**
lnUBZ	386.188***	56.349***	56.240***
lnENE	297.732***	42.395***	42.281***
lnCRE	132.769***	16.166***	16.056***
lnECP	307.953***	44.277***	44.168***
Slope homogeneity	Test statistics		
$\hat{\Lambda}$	28.536***		
$\hat{\Lambda}_{adjusted}$	32.704***		

Note: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$ indicate the significance levels.

Source: own

due to its high significance. In addition, the sloping heterogeneity depicts the nexus between the indicators and their dependent variables. The $\hat{\Delta}$ and $\hat{\Delta}$ adjusted highlights the favorable levels of independent and dependent affiliation across the variables.

3.3 Unit root assessment

Examining the variables of technological innovation, circular economy, urbanization,

economic progress, energy utilization, and ecological footprint holds significant importance due to their sloping heterogeneity and cross-section dependence. We used the CIPS and CADF approach, as shown in Tab. 4, to determine the stationarity of the indicators. We calculated the estimates at the first level, ensuring a 1% significance level. The results of literary works by Bekun (2024) for South Africa confirmed a unit root at the first level.

Tab. 4: Unit root assessment

Series	CIPS		CADF	
	Level	First difference	Level	First difference
<i>lnEFP</i>	-1.120	-8.470***	-1.486	-5.070***
<i>lnTNI</i>	1.179	-10.776***	1.650	-10.498***
<i>lnGNF</i>	1.421	-7.458***	-1.786	-6.781***
<i>lnUBZ</i>	-0.897	-7.216***	1.558	-13.554***
<i>lnENE</i>	-1.213	10.149***	1.127	11.216***
<i>lnCRE</i>	-1.326	-8.246***	1.489	9.109***
<i>lnECP</i>	0.850	-14.277***	0.861	-12.742***

Source: own

3.4 Cointegration assessment

The investigation undergoes a cointegration evaluation of Westerlund's assessment to confine a long-term relation between technological innovation, circular economy, economic progress, green finance, urbanization, and ecological footprint between Central

European countries (Tab. 5). The cointegration coefficient and *p*-values *G_t* and *P_t* established a cointegration relationship and long-term nexus within the variables for the research period. In Asia, Ahakwa et al. (2023) and Eastern Europe, Addai et al. (2022) align with these results.

Tab. 5: Cointegration assessment

Test	Statistics	<i>p</i> -value
<i>G_t</i>	-6.954***	0.001
<i>G_a</i>	-1.112	0.831
<i>P_t</i>	-9.946***	0.000
<i>P_a</i>	-1.472	0.654
Variance ratio	161.866***	0.000

Source: own

3.5 Long-term estimation

Tab. 6 presents an estimate of the CCEMG and AMG models to explore the nexus between technological innovation, economic progress, circular economy, urbanization, and green finance on the *EFP* in Central Europe. The findings revealed that technological innovation, circular economy, and green finance decelerate ecological footprint, with a percentage change in these variables econtributing to a reduction in ecological damage by 0.782, 0.303, and 0.355, respectively. However, *UBZ*, *ENE*,

and economic progress accelerated environmental deterioration, with a 1% change contributing to values of 0.883, 0.601, and 0.652 under the CCEMG approach. Likewise, AMG results align with CCEMG estimates with minor changes in coefficient values. This indicates that an increase or decrease in these variables aligns more closely with the *EFP* over the long term. The diagnosis outcome of *R*-squares adjusted *R*-squares, and the *F*-statistics affirmed that the independent variable explained the dependent variable favorably under both models.

Tab. 6: Long-term evaluation

Variable	CCEMG		AMG	
	Coefficient	Std. error	Coefficient	Std. error
<i>lnTNI</i>	-0.782***	0.029	-0.407***	0.043
<i>lnGNF</i>	-0.355***	0.068	-0.116***	0.053
<i>lnUBZ</i>	0.883***	0.163	0.428***	0.104
<i>lnENE</i>	0.601***	0.266	0.590***	0.697
<i>lnCRE</i>	-0.303***	0.204	-0.734***	0.255
<i>lnECP</i>	0.652***	0.092	0.683***	0.235
Constant	8.796***	2.190	14.936***	3.283
Diagnostic test				
<i>R</i> -squared	0.869		0.854	
Adjusted <i>R</i> -squared	0.861		0.845	
SE of regression	0.658		0.715	
Sum squared resid	97.190		96.135	
Log-likelihood	-227.781		-235.090	
<i>F</i> -statistic	75.759		87.644	
Prob(<i>F</i> -statistic)	0.000		0.000	

Source: own

3.6 Robustness test

In Tab. 7, two econometric models were employed to test the robustness of the empirical outcome from Tab. 6. The FMOLS and DSK estimators were considered following Ahakwa et al. (2023) which served as a reliability check. The estimates and coefficients affirmed

the previous results that technological innovation, green finance, and circular economy exhibited a positive effect on the ecological footprint within Central European communities. Likewise, energy consumption, economic progress, and urbanization negatively impacted the ecological footprint.

Tab. 7: FMOLS and DSK evaluation

Variable	FMOLS model		DSK model	
	Coefficient	p-value	Coefficient	p-value
lnTNI	-0.775***	0.000	-0.953***	0.004
lnGNF	-0.802***	0.000	-0.862***	0.000
lnUBZ	0.825***	0.003	0.785***	0.000
lnENE	0.947***	0.000	0.931***	0.000
lnCRE	-0.702***	0.001	-0.597***	0.000
lnECP	0.525***	0.000	0.783***	0.000

Note: *** depicts significant coefficient at 1%, ** 5% and * 10%, respectively.

Source: own

3.7 Causality test

We evaluated the causality approach of D&H to assess the impact of *TNI*, *CRE*, *ENE*, *GNF*, *UBZ*, and *ECP* on *EFP* in the Central European region. The D&H principle outlines the long-term bidirectional, unidirectional, or no-directional nexus between the indicators. As illustrated in Tab. 8 and Fig. 2, technological innovation had a unidirectional connection with *EFP* in the long term. The evaluation demonstrated that *TNI* depreciates

the speed of ecological footprint within Central Europe. The outcome depicts that policy adoptions toward technological innovation by enterprises and governments will lead to a quality ecosystem. The work of Kirat et al. (2024) affirms these findings. Again, the investigation revealed that green finance had a two-way nexus with ecological damage. The underlying results explained that green finance upsurges or surges ecosystem quality in Central European communities.

Tab. 8: D&H evaluation

Null hypothesis	W-stat.	Z-stat.	Prob.	Decision
<i>TNI</i> ⇔ <i>EFP</i>	2.171	0.004	0.996	
<i>EFP</i> ⇔ <i>TIN</i>	20.188***	20.243	0.000	Unidirectional
<i>ENE</i> ⇔ <i>EFP</i>	12.5467***	7.426	0.000	
<i>EFP</i> ⇔ <i>ENE</i>	10.058**	8.245	0.011	Bidirectional
<i>GNF</i> ⇔ <i>EFP</i>	1.464	0.788	0.430	
<i>EFP</i> ⇔ <i>GFN</i>	8.172***	6.746	0.002	Unidirectional
<i>CRE</i> ⇔ <i>EFP</i>	1.578	0.660	0.508	
<i>EFP</i> ⇔ <i>CRE</i>	11.485***	3.270	0.756	Unidirectional
<i>UBZ</i> ⇔ <i>ECF</i>	7.439**	0.305	0.020	
<i>EFP</i> ⇔ <i>UBZ</i>	10.311**	4.148	0.000	Bidirectional
<i>ECP</i> ⇔ <i>EFP</i>	1.819	0.225	0.550	
<i>EFP</i> ⇔ <i>ECP</i>	8.295***	0.744	0.4565	Bidirectional

Note: *EFP* – ecological footprint; *TNI* – technological innovation; *CRE* – circular economy; *UBZ* – urbanization; *ENE* – energy consumption; *ECP* – economic progress.

Source: own

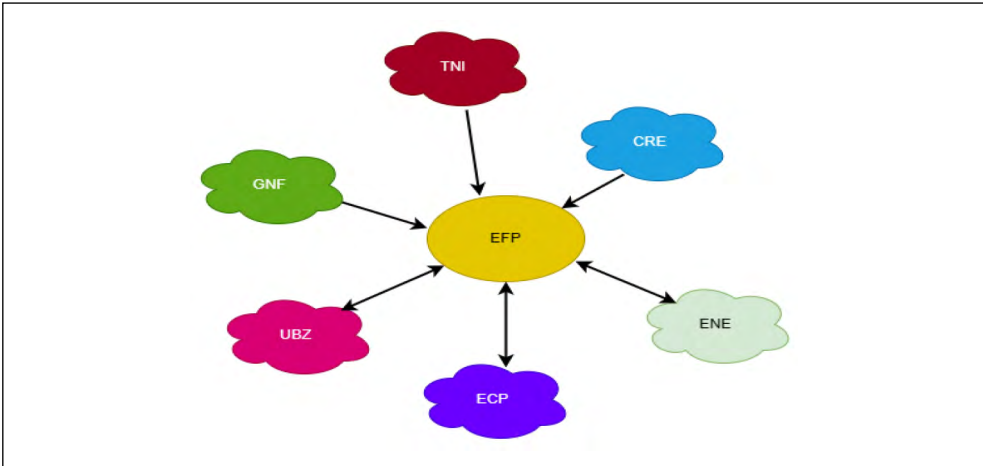


Fig. 2: Causality evaluation

Source: own

4 Discussions

The highlighted findings from the CCEMG and AMG models indicated that technological innovation had a negative link with ecological footprint, with -0.775 and 0.953 , respectively, within the Central European communities. The results attested to the improvement of green technological innovation investments, such as electric automobiles. The European Union deals with principles to forge and transit to a more sustainable community. On the path to UNSDG-13, Bekun (2024) explored South African technological innovation methodologies to mitigate ecological deterioration. The investigation's findings confirm that technological advancement enhances ecosystem quality. Additionally, Saqib et al. (2024) examined ten most polluted and with high ecological footprint quota. The empirical findings demonstrated that innovation deployment in the communities had aligned with a depreciation in greenhouse gas. Conflicting with our estimates, Sun et al. (2024) established that China's recent investment in petrochemical enterprises and adoption of technological innovations had posed an increase in their ecological footprint.

According to empirical estimates, a 1% appreciation in green finance reduces ecological deterioration by -0.355 CCEMG and -0.116 AMG in the Central European regions. The recently adopted green monetary policies (green bonds,

green credit, and green loans) initiatives by the EU central bank government are a signpost to mitigate ecosystem damage. The experiment conducted by Sampene et al. (2023) in South Asian communities, the assessment conducted by Khan et al. (2022) in 26 Asian regions, and the evaluation conducted by Mohsin et al. (2023) in European nations all support the notion that green portfolios can enhance environmental quality. Despite the positive findings, Sun and Rasool (2023) found that these policies in Europe's top 10 green finance regions negatively impact the environment. The article recommended that a proper green finance initiative will reduce environmental deterioration.

With the econometric empirical assessment of urbanization, all the dynamic approaches established an upsurge in ecological footprint with a percentage of 1% shift in urbanization, resulting in 0.833 and 0.428 favorable rises in environmental damage within Central European communities. This outcome is associated with the desire for the population to move from rural enclaves to urban communities in search of white-collar jobs, infrastructure, and a favorable lifestyle. This trend coincides with the rise in urban transport emissions, which are primarily attributed to fossil fuel emissions and road infrastructure. Zhang and Chen (2023) investigation in China illustrated the connection between carbon

emissions and urbanization, affirming that urbanization appreciates China's urban carbon footprint. Similarly, Arif et al. (2023) confirmed in the context of Pakistan that the urban carbon footprint is associated with foreign investment and the establishment of industrial enterprises in urban areas. Contradictory to the estimates, Addai et al. (2022) investigation in Eastern Europe on the affiliation between ecological footprint and urbanization for a period 1998Q4 and 2017Q4. Employing the econometric technique of common correlated effect mean group and the Dumitrescu Hurlin causality, the findings indicated that urbanization appreciate ecological footprint. Also, a bidirectional causality was found between the nexus of urbanization and ecological footprint. Additionally, Tanveer et al. (2024) argued that urbanization improves the quality of ecosystems. An important element in reducing the damaging effect of urbanization could be linked to the awareness-action nexus of Toth and Sebova (2024) in the mitigation context.

Furthermore, *ENE* demonstrated a significant and positive correlation, with *EFP* accounting for 0.601 and 0.590 for every 1% increase in the use of coal, fossil fuels, and gases in Central Europe. This evaluation clarified that due to Central Europe's reliance on non-renewable energy, countries like Poland and Hungary consume a significant amount of coal and fossil fuels, increasing their carbon footprint indices. This empirical study shows that economic growth harmed the ecological footprint, as shown by the coefficients 0.635 and 0.683 for the CCEMG and AMG approaches, respectively. This suggests that a 1% appreciation in economic progress intensifies the *EFP* in Central European regions. The outcome from the investigation corroborates with Baz et al. (2020) employed the nonlinear model to examined ecological footprint in Pakistan between 1971–2014. The findings demonstrated that energy consumption is affiliated with economic growth resulting in carbon footprint rising. Likewise, Qing et al. (2024) confirm a material effect traditional energy consumption on ecological footprint in Pakistan. They established that both in the long and short run oil, coal, and gas had adverse effects on biocapacity.

A circular economy had a favorable affiliation with *EFP* in the long term, with a CCEMS value of -0.303 and an AMG value of -0.734 . Circular economic principles are linked with

waste and food security to diminish ecological footprints in the Central European community. The global food indices for 2019 bring household food waste to sixty-one percent. The findings demonstrated that methodologies like e-waste and recycling, reproduction, and reuse reduce ecological footprints. In line with the evaluations, Almulhim (2024) assessment in Kingdom of Saudi Arabia on the affiliation between circular economy and environmental sustainability. The outcome established that circular economy principles were able to improve the nation's food sector. Likewise, Thapa et al. (2024) corroborated the affirmation that the circular economy paradigm reduces environmental deterioration. The research is not consistent with the works of Figge and Thorpe (2023) and Halkos and Aslanidis (2024). Unsurprisingly, the circular economy had a major impact on ecological footprint depreciation, with these communities integrating the EU green deals and principles into their sustainability target.

Conclusions

The increase in anthropogenic activities on natural resources has motivated the government and researchers to evaluate these ecological damages. The influence of technological innovation, green finance, circular economy, urbanization, and economic progress on ecological footprint is assessed in the Central European communities. The data curation from 1990–2022 was adopted from verified sources to avoid bias. A robust econometric approach was employed to test the data normality and its nexus effect. The cross-sectional dependence and slope heterogeneity were evaluated to estimate the various collinearities. Likewise, the unit root and cointegration accounted for the approach stability and long-run connection between the variables. The study highlighted that *TNI*, *GNF*, and *CRE* positively impacted ecological footprints through CCEMG and AMG estimators, which were confirmed by the FMOLS and DSK approaches. This analysis demonstrates that when Central European communities adopt these measures, their ecological footprint will be reduced. Moreover, the affiliation with the *EFP* highlighted the negative impact of urbanization, economic progress, and energy consumption. In this sense, economic progress is needed to switch to more efficient and renewable energy while not affecting productivity.

Next, the D&H causality was employed to estimate the link between *TNI*, *CRE*, *ENE*, *GNF*, *UBZ*, and *ECP* on ecological footprint. Consistent with econometric approaches evaluations, technological innovation, green finance, and circular economy displayed a unidirectional nexus with ecological footprint within Central Europe regions. The results have induced suggestions to depreciate ecological damage without a reverse effect. On the other hand, urbanization, energy utilization, and *ECP* had a bidirectional nexus with the ecological footprint in the Central European countries. The findings exhibited policy directions to combat environmental deterioration in the Central European communities. Central European countries should invest in research and support industrial enterprises in adopting necessary technologies to mitigate environmental damage. Additionally, tax incentives and policies that facilitate the inflow of technology from neighboring regions to utilize eco-friendly resources should be prioritized in future agendas. Again, green finance had a favorable and significant impact on the ecological footprint. Countries such as Germany, which lead in green finance policies like green credit, green bonds, and green loans play a crucial role in directing investments. Regions like Poland and Slovakia can adopt similar strategies to empower local manufacturers with the necessary capital to invest in energy projects, such as electric vehicles and household energy efficiency, thereby reducing their reliance on coal and fossil fuels. Additionally, circular economy is viewed as the future of resource conservation because it keeps products in circulation and allows them to be reused for various purposes before they eventually end up in landfills. With the EU Green Deal and the municipal waste separation policy set for 2030, Central European communities that implement stringent policies will lower their levels of municipal waste, contributing to a healthier ecosystem and potentially increasing life expectancy. Furthermore, governments could modernize small communities by improving basic facilities and infrastructure to reduce migration to urban areas. Encouraging the private sector to invest in rural development such as opening branches in these regions can help retain young people and prevent them from moving to cities in search of better jobs. Finally, as energy consumption and economic progress go hand

in hand, it is recommended that governments invest in renewable energy sources which are more environmentally friendly. Additionally, policies should encourage households to minimize energy use during times.

Limitation. The study has some specific shortfalls, including the fact that it only includes data from Central Europe. As a result, the findings may not apply to Asian or African communities. Future research should explore regions such as Africa, BRICS nations, Asia, and Oceania. Moreover, various econometric principles and methodologies should be employed to analyze the affiliation between these factors and the ecological footprint.

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