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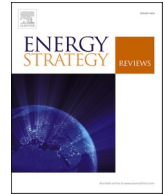
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# Tracing the trajectories of energy intensity, environmental tax revenues, and environmental neutrality in major European economies

Fayyaz Ahmad<sup>a</sup>, Nabila Abid<sup>b,\*</sup>, Junaid Aftab<sup>c</sup>, Aamir Javed<sup>d</sup>

<sup>a</sup> School of Economics, Lanzhou University, Lanzhou, 730000, Gansu, China

<sup>b</sup> EM Normandie Business School, Métis Lab, Le Havre, France

<sup>c</sup> School of Economics and Management, Tongji University, Shanghai, China

<sup>d</sup> Department of Economic Studies, University "G. d'Annunzio" of Chieti-Pescara, Pescara, Italy

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## ABSTRACT

Addressing the urgent challenge of climate change is a paramount global concern, with European economies showcasing commitment through the ambitious European Green Deal, COP, and sustainable development goals. However, the region's reliance on fossil fuels raises questions about the initiatives affecting the environmental neutrality goals in Europe. To find an answer to this, the present study investigates the impact of energy intensity and environmental tax revenues on environmental management efforts in terms of air, water, and waste pollution abatement in Europe by utilizing data spanning 1994 to 2020 for major European economies that held over 95 % of European economic output. The sample is grouped into two panels based on economic growth level. The study employs advanced econometric techniques to perform the preliminary checks, and GMM-PVR is used as the main study model. Aggregate panel findings reveal significant associations between energy intensity, environmental tax revenues, and environmental management. Notably, higher energy intensity is positively linked to increased environmental management activities, reflecting a commitment to address abatement goals and indicating funds are allocated toward pollution mitigation, aligning with Europe's emphasis on sustainability. Foreign direct investment has a negative relationship with environmental management. However, in Panel A, environmental tax revenues, economic growth, and trade openness reveal a negative impact on environmental management, suggesting that intense economic activities surpass the environmental tax revenue efforts to abate pollution, unlike Panel B, which is effective in pollution reduction. The study's policy implications stress enhancing the energy efficiency of economic giants while simultaneously strengthening mechanisms for utilizing environmental tax revenues and reinforcing environmental regulations to align foreign direct investment with sustainable practices. International collaboration is essential to ensure trade relations align with environmental goals, contributing to global efforts to combat climate change.

## 1. Introduction

Since the onset of the industrial revolution, energy has played an essential role as a fundamental input in addressing basic necessities and achieving economic developmental objectives. However, the extensive ecological consequences stemming from energy-related decisions have led to significant global environmental challenges [1], such as air and water pollution, deforestation, and the occurrence of extreme weather conditions (Abid et al., 2021; [2,3]). The elevated levels of human-induced emissions are anticipated unless there is a substantial shift in the global economy towards alternative energy sources, characterized by widespread adoption of more efficient modifications in the

structure of economic activities [4]. A crucial approach to decreasing detrimental emissions and global energy usage is by lowering energy intensity (EI) [5]. EI addresses several concerns, such as reducing greenhouse gas emissions and enhancing energy security [6]. EI is used to measure a country's energy efficiency, and promoting energy efficiency is crucial for achieving the strategic objectives of sustainable development (SDGs) [7,8]. Europe's stated energy policies are determined to attain an annual average improvement of 2.4 % in EI by the year 2030. Concurrently, the existing improvement rates fall significantly below the anticipated levels necessary to achieve the objectives outlined in SDG 7.3 [9] (see Figs. 1 and 2).

Since its inception, energy has been a significant factor in Europe and

\* Corresponding author.

E-mail addresses: [fayyaz@lzu.edu.cn](mailto:fayyaz@lzu.edu.cn) (F. Ahmad), [Nabid@em-normandie.fr](mailto:Nabid@em-normandie.fr) (N. Abid), [junaidaftab05@gmail.com](mailto:junaidaftab05@gmail.com) (J. Aftab), [aamir.javed@unich.it](mailto:aamir.javed@unich.it) (A. Javed).

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has emerged as a subject of frequent discussion within the European political agenda. This engagement has resulted in extensive legislative documents that specifically tackle energy policy security, economic, environmental, and climate dimensions [12]. One of the ongoing initiatives within Europe aimed at addressing energy challenges is the Energy Commission [13], which has delineated priorities and principles to confront issues pertaining to the improvement of energy efficiency, actions against climate change, and innovation in clean energy. All members of Europe are contending with challenges posed by climate change, pollution, and overuse of fossil fuels, therefore directing a concerted effort to reconfigure their energy frameworks. In a bid to accelerate this transition, the union has implemented an ambitious initiative known as the European Green Deal, accelerated plans to achieve objectives outlined in the 2030 agenda for sustainable development [14–16]. The establishment of the energy union in Europe is also regarded as a pivotal policy initiative that provides the framework for a crucial transformation in the European energy system. This initiative facilitates the transition towards environmental neutrality to foster long-term sustainability and promote climate protection [17].

Regardless of how complex and controversial the current portrayal of the energy debate may be, almost everybody agrees that there is an urgent need for intensive environmental initiatives and frameworks [18, 19] to ensure environmental neutrality. Among these policies, various tax policy measures, such as environmental taxes (ET), emerge as a pivotal fiscal policy instrument, impacting resource consumption or emission levels through escalating prices for goods with detrimental environmental effects. Environmental tax is delineated by a base linked to "a physical unit with demonstrated adverse environmental impacts, such as a liter of petrol or a passenger flight" [20]. ET generates government revenues that can be directed toward addressing environmental issues and incentivizing taxpayers to enhance production for social or economic objectives. The taxes are classified into four main categories: energy, transport, pollution, and resource. Energy taxes refer to charges imposed on the production and consumption of energy goods, including gasoline, diesel, natural gas, and electricity. Transportation taxes are charged on automobiles, vessels, and aircraft that utilize publicly maintained roadways, waterways, and airports. Pollution taxes encompass charges imposed on the release or expulsion of detrimental chemicals into the environment, encompassing both toxic gases and liquids [20,21]. In 2020, the ET amassed by European governments was about 299.9 billion euros, representing 2.2 % of the cumulative economic output. When scrutinizing each classification of environmental taxes separately, a substantial proportion (77.2 %) of total revenues in 2020 and energy taxes contributed substantially (77.2 % of total revenues), far outpacing transportation charges (19.1 %) and pollution and

resource taxes (3.7 %) [11].

EI and ET are strongly linked to environmental management efforts, and the European approach recognizes environmental management as a cornerstone of sustainable development [22,23]. To bolster the ongoing battle against pollution and position itself to process EI, the European Council took a significant step in October 2014. During this time, the 2030 Climate and Energy Framework was formally approved by the Council, establishing a binding goal for the European Union to reduce domestic greenhouse gas emissions by at least 40 % from 1990 levels by 2030 [24]. Besides 2030, looking towards 2050, Europe envisions becoming the world's first climate-neutral continent. The challenge lies in setting these long-term objectives and implementing immediate measures that lay the groundwork for the transformative changes needed in the decades ahead [25]. At the same time, the European commission has set ambitious targets and outlined comprehensive strategies; however, the efficacy of these policies depends on the actual execution and enforcement at both the European and member-state levels [26]. There is a need to focus on effective policy implementation, invest in innovation and infrastructure, and foster collaboration among member states. Additionally, periodic assessments and policy adjustments based on real-world outcomes can ensure that the region remains on track to meet its 2030 and 2050 environmental goals.

Based on the ambitious environmental goals, this paper investigates whether EI and ET contribute to environmental management in the largest European economies [see Appendix] in the presence of non-environmental variables, e.g., economic growth (EG), foreign direct investment (FDI) and trade openness (TO). The investigation aligns with the objectives of the EU Green Deal and 2030 agenda [27], Sustainable Development Goals [28], and COP targets [29]. The analysis considers the period from 1994 to 2020, contingent upon data availability. The selection of these economies is driven by Europe's position as the third-largest global economic context, representing one-sixth of global trade. The chosen countries collectively account for over 90 % of the European GDP, with just five countries: Germany, the UK, France, Italy, and Spain, contributing more than 83.75 % to the region's economic output. Notably, "these economies, with GDPs of Germany (\$4 trillion), the UK (\$3.4 trillion), France (\$2.7 trillion), Italy (\$1.9 trillion), and Spain (\$1.4 trillion)", play a pivotal role in environmental advocacy and participate in major global environmental initiatives. In alignment with the paper's objective, our research question is: To what extent do EI and ET either stimulate or inhibit environmental management efforts in European economic giants?

This research significantly advances the existing body of knowledge and policy frameworks by offering several novel contributions, particularly by bridging critical gaps in the understanding of the interplay

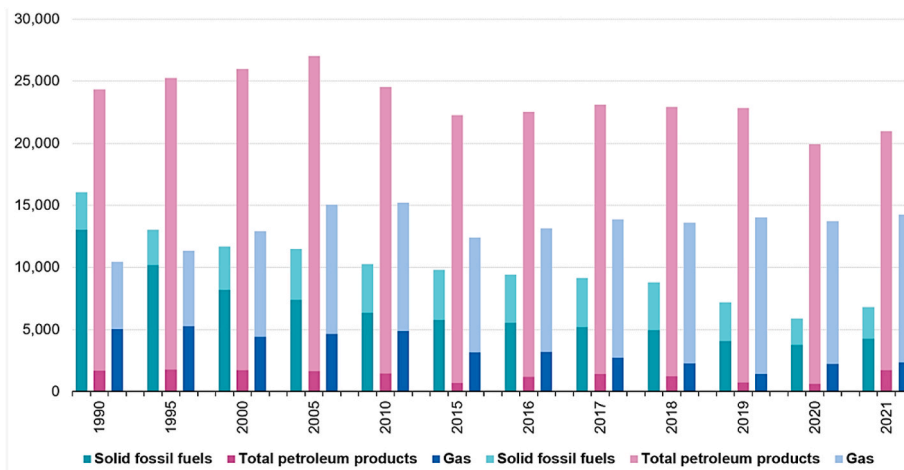


Fig. 1. Energy dependency by fuel in Europe (1990–2021) [10].

between EI and ET within largest and most energy-intensive European economies. While prior studies often focus on EI or ET in isolation, this study is one of the first to investigate their joint impact on environmental management offering a more comprehensive and integrated perspective on how fiscal and energy policies collectively contribute to sustainability and pollution mitigation [30]. The study employs specific environmental management indicators—such as air, water, and waste pollution abatement—to operationalize its analysis. These indicators align with the sustainable development goals and offer concrete metrics to evaluate the effectiveness of EI and ET in achieving environmental management objectives [27]. Another key innovation in this research is the disaggregation of ET into its three core components—energy, transport, and pollution/resource taxes. This nuanced approach enables the identification of differentiated impacts across policy categories, which is essential for designing targeted and effective fiscal interventions [31]. Contextually, the paper focuses on the eleven largest European economies that account for around 90 % approx [32] GDP of the region. Among these economies, five key countries Germany, the UK, France, Italy, and Spain together account for over 83.75 % of European GDP which strengthens sample relevance to Europe’s broader environmental and economic goals, including the Green Deal and the 2030 Agenda. These countries not only contribute significantly to Europe’s economic output but also play a central role in global environmental initiatives, making the findings of this study highly applicable to other high-income, energy-intensive economies [27].

The countries selected for this study are categorized into two panels, with these five nations representing nearly 83.75 % of Panel A and the remaining countries into Panel B. This panel division allows for a more granular examination of the impact of EI and ET, providing detailed insights that go beyond aggregate results. It also facilitates a clearer understanding of how these policies affect pollution management and sustainability within these major economies, offering policymakers a robust framework to design targeted interventions. Methodologically, this study addresses challenges such as heteroscedasticity and cross-sectional dependence using advanced econometric techniques, ensuring that the results are both reliable and robust. These methodological innovations strengthen the study’s findings and provide a solid foundation for deriving effective policy recommendations.

By connecting the empirical results to Europe’s climate neutrality goals for 2050, the EU Green Deal, and the COP targets, this paper offers timely, relevant insights that can guide the transition toward a more sustainable and economically balanced future [28]. Ultimately, this research not only deepens the theoretical understanding of the relationship between EI, ETR, and environmental management, but it also

provides practical policy solutions for guiding major European economies towards environmental neutrality.

The article is structured into different sections. After a brief introduction, the main emphasis is placed on providing an overview of the current body of literature on EI and ET, with a specific emphasis on identifying the gap in the available research. The following part outlines the model, data, and technique used in the study, while the fourth section offers the empirical results. The final portion of the study summarizes the main findings of the research and presents policy suggestions based on those findings.

## 2. Literature review

### 2.1. ET and environmental management

In 1992, OECD introduced the "polluter pays" rule, laying the foundation for the inception of environmental taxes (OECD., 1992). Since the 1980s, developed countries have progressively implemented various environmental taxes, including carbon, energy, and waste taxes [33,34]. ET is frequently used to refer to taxes that are intended to encourage environmental and natural resource conservation rather than only for revenue purposes [21,35]. ET is a prominent environmental policy tool in Europe, which has been progressively adopted by member states since the 1990s in order to address the increasing environmental deterioration [36]. ET is widely recognized as a cost-effective and efficient economic strategy in the fight against climate change. It plays a crucial role in preserving biodiversity, protecting natural resources, mitigating pollution, and addressing climate change. These aspects are essential components of the environmental dimension within the taxation system [37]. ET, when earmarked for environmental protection, has demonstrated increased political acceptability. A study on air passenger tax in Sweden indicates stronger public support when revenue is directed towards boosting the use of biofuels in aviation, compared to alternatives like reducing income tax or funding general welfare services [38]. This finding suggests a greater inclination among the public and government to allocate ET to environmentally focused projects [39].

Several countries, including the United Kingdom, the United States, and India, assign ET to financially support environmental projects and pollution treatment initiatives [34,40,41]. Multiple studies have shown that taxes have a favorable effect on environmental quality, lending credence to the effectiveness of this strategy [13,36,42]. Simultaneously, ET is argued to impact economic performance significantly, emphasizing its role as an instrument that aims to harmonize economic growth with environmental considerations [43]. Such legislative

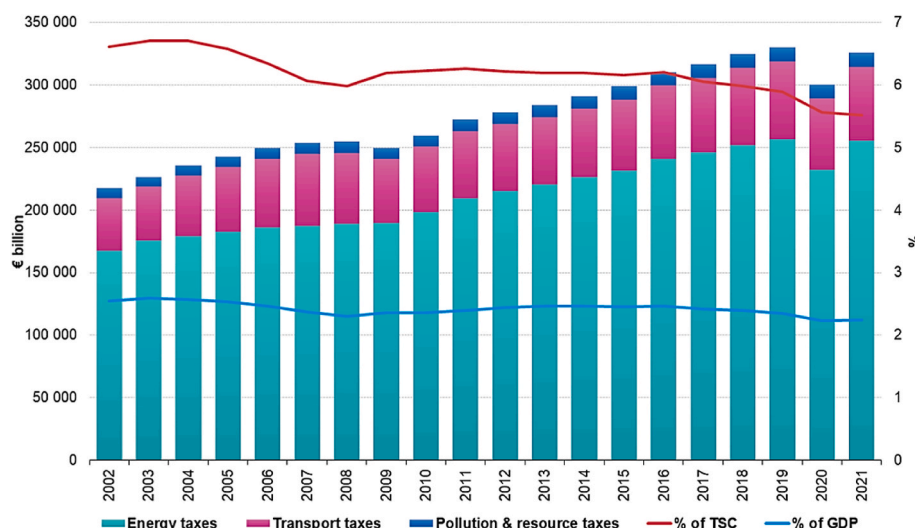


Fig. 2. “Environmental tax revenue by type and total environmental taxes as a share of TSC (total government revenue from taxes) and GDP, EU, 2002–2021 [11]”.

measures are employed to encourage the advancement of eco-friendly equipment, enhance energy effectiveness, and cultivate an environment that is both pristine and conducive to well-being. Miller & Vela [44] conducted an empirical study to assess the effect of environmental taxes on reducing pollution emissions across 50 countries. Utilizing annual data from 1995 to 2010, the study employed cross-sectional dynamic regression techniques to test its central hypothesis. Findings revealed that countries generating higher tax revenues experienced notable decreases in carbon emissions and PM10 particulate matter, along with a reduction in overall energy consumption. Expanding upon this, Vera & Sauma [45] contended that ET contributes to the reduction of carbon emissions in the context of Chile.

Ulucak & Kassouri [46] examined the impacts of taxes associated with the environment on emissions and findings suggest that, at lower degrees of globalization, technologies and taxes related to the environment are associated with heightened CO<sub>2</sub> emissions. Chien et al. [47] investigated the degree of the relationship between environmentally sustainable economic growth and carbon emissions, considering factors such as innovation in the ecological system, environmental levies, and renewable energy. The researchers utilized the QARDL technique, selected for its capacity to elucidate causality patterns across diverse quantiles for various variables. The QARDL estimation results demonstrate that sustainable economic growth, its squared term, and additional indicators notably diminish air pollution over an extended period. Barker et al. [48] examined how internal European policies and efforts contribute to achieving the greenhouse gas reduction goal specified in the Kyoto Protocol. They contended that the efficacy of environmental levies in mitigating carbon emissions is augmented when combined with European policy directives in conjunction with domestic policies.

## 2.2. Energy intensity and environmental management

One of the primary objectives of global efforts to expedite environmental management is the reduction of harmful global emissions aimed at mitigating the adverse effects of worldwide climate change [49]. This endeavour involves a sequential approach encompassing comprehension, regulation, and alleviation of air pollution. Projections of greenhouse gas emissions vary within a given spectrum, contingent upon factors such as social and economic growth, as well as climate and weather policies [6,50,51]. Economic considerations play a pivotal role in furnishing essential information, enhancing the credibility of national commitments, and fortifying assurances for the future. Policymakers and industry stakeholders actively invest in initiatives geared towards combating climate change [52]. In the late 1990s, the international community made great strides toward this objective with the establishment of the Kyoto Protocol. Initiating a collective global effort to minimize the impacts of climate change. Earlier research posits that energy consumption is frequently identified as a primary contributor to environmental pollution [7,53]. A greater number of scholarly works have substantiated the assertion that excessive energy consumption has detrimental effects on the environment [54–56].

EI is the ratio of a country's energy use to its gross domestic product. Improvements in EI are attributed to various factors, such as the transition from industrial to service-oriented economies, shifts within industries toward less energy-intensive practices, closure of inefficient units, and the implementation of energy-competent technologies [17]. This measurement reflects a country's energy efficiency and signifies its technological progress [57–59]. EI surpasses the mere quantification of energy consumption. Paradoxically, as a nation or region undergoes economic growth characterized by technological advancements and industrial structure shifts that reduce energy intensity, it concurrently experiences heightened environmental pollution. This intricate relationship underscores the multifaceted dynamics between economic development, technological evolution, and their environmental implications (Aydin and Esen, Ö., 2018; [60]). In the past two decades, numerous countries globally have made substantial endeavours to

diminish energy usage (per unit of output) and the release of pollutants into the air, water, and soil—either in absolute terms or on a per capita basis. Prominent agreements such as the Kyoto Protocol [61], the Copenhagen negotiations (2009) [62], and the European Climate and Energy Package [63] exemplify well-known initiatives designed to establish sustainable targets for energy consumption and pollution levels over time, transcending national boundaries. Numerous studies have examined EI, specifically focusing on sectorial and regional shifts within individual economies. In the study by Dogan et al. [64], the authors analyze the effects of technological advancements, international policies, and national regulations on energy transitions and the reduction of greenhouse gas emissions. Their findings underscored the pivotal role that technology and international agreements, such as the Kyoto Protocol, play in driving energy shifts in the G-7 nations. Technological innovations were shown to significantly decrease carbon emissions, while the Kyoto Protocol's impact on national energy policies helped accelerate the move toward more sustainable energy sources.

The study referenced by Voigt et al. [65] scrutinized EI in 40 major economies, utilizing data spanning from 1995 to 2007, indicating that alterations in the industry composition led to a decline in energy intensity. Concurrently, global improvements in EI were attributed to technological advancements. Examining transition countries, specifically Central and Eastern Europe, Cornillie & Fankhauser [66] explored the primary drivers behind the reduction in EI from 1992 to 1998. Their results underscored the influence of economic sectors on changes in energy intensity, revealing a decline in the industrial sector's EI, while structural changes promoted an increase. Additionally, Awais et al. [67] used the ARDL model to support their claim that EI was associated with CO<sub>2</sub> emissions in the US from 1985 to 2017. According to the results, higher EI levels are associated with more pollution. Meanwhile, Rahman et al. [68] looked at 25 developing economies from 1990 to 2018 and found that EI had a beneficial impact on EI in the long run. Furthermore, Yu et al. [69] looked at how Renewable Energy affected EI using the dynamic threshold regression model. According to the findings, there is a notable 2.2 % drop in EI for every 10 % rise in RE, which might have an effect on the carbon intensity level. Moreover, Arroyo & Miguel [70] examined the evolution of Ecuador's EI and CO<sub>2</sub> emissions from the year 2000 to the year 2030. The study used the system dynamics model to predict that by 2030, energy efficiency will have improved and renewable energy use will have changed, leading to less CO<sub>2</sub> emissions and more.

## 2.3. Research gap

In 2019, European nations took a pioneering stance by committing to achieving net-zero greenhouse gas emissions well before 2050. In line with these commitments, European governments introduced the "Fit for 55 policy agenda" in 2021 [71]. To effectuate this transformative shift, diverse mitigation tools, including environmental taxation and technological advancements, have been introduced to curtail the process of environmental degradation [72]. According to the EU directive "A Clean Planet for all" (Wurlod & Noailly, 2018), implementing environmental tax schemes and revised subsidy structures plays a pivotal role in achieving the target of environmental neutrality. Despite certain accomplishments, Europe recognizes that the current achievements are insufficient to propel the process forward. European economies is at the forefront of global efforts to combat climate change and drive the economic transition toward more sustainable investments, as evidenced by various ongoing initiatives [73]. On the other hand, in 2021, the gross available energy in the European increased by 6.0 % compared to 2020. Oil remained the primary energy source, with a 5.3 % increase, followed by natural gas, with a 4.0 % increase, as everyday life relies on energy services. European economies faces challenges in securing sustainable and affordable energy while reducing reliance on fossil fuels. Energy efficiency, productivity, and consumption reduction are vital for a secure and competitive energy system. In general, economic growth

correlates with a decrease in energy intensity. However, exceptions exist, such as in 2020, when the final EI increased despite GDP growth falling below 2 %. This anomaly is attributed to factors like non-GDP-dependent final consumption. The year 2009 deviated from the trend due to deep structural changes in energy-intensive industries [74,75].

Given the discrepancies highlighted earlier between anticipated and actual data, the empirical assessment of the influence of ET and EI on environmental management within major European economies lacks a conclusive stance. This study aims to address this gap by establishing the association between these variables and forecasting their long-term relationship. The objective is to provide nuanced policy recommendations and contribute valuable insights to the academic discourse. This research endeavors to bridge the existing gaps in understanding and provide a more comprehensive perspective on the intricate dynamics between ET, EI, and environmental management in significant European economies.

### 3. Model, data, and methodology

#### 3.1. Sample and data processing

The study examines the impact of EI and ET on environmental management in the largest European economies [Appendix] in the presence of economic growth, foreign direct investment, and trade openness for utilizing data from 1994 to 2020. The choice of data is subject to the availability of data on all study variables for the selected sample. The sample economies collectively constitute over 90 % of the European GDP, with just five nations contributing 13.4 trillion out of the total 16 trillion European GDP. Specifically, “Germany holds \$4 trillion, the UK \$3.4 trillion, France \$2.7 trillion, Italy \$1.9 trillion, and Spain \$1.4 trillion,” constituting 83.75 % of the entire economic output [32, 76]. These European economies are also among the major advocates for environmental protection and are part of the largest world’s environmental initiatives, e.g., the Paris Agreement [77], EU Green Deal [27], Sustainable Development Goals [28], and COP meetings [78]. We divided these countries into two panels. Panel A includes the five countries mentioned above that comprise nearly 83.75 % of the European GDP, and Panel B includes the rest of the European economic giants making the major remaining portion of Europe’s GDP [32]. Following data collection, normalization procedures are applied, leading to the formulation of indexes for environmental management and ET.

This study focuses on the following model:

$$EM_{it} = f(EI_{it}, ET_{it}, EG_{it}, Fdi_{it}, To_{it}) \tag{1}$$

##### 3.1.1. Dependent variable

Environmental management involves the strategic and systematic management of diverse environmental factors with the aim of alleviating detrimental effects on the ecosystem [79]. Proficient environmental management is crucial in preserving ecosystems and minimizing anthropogenic damage to the environment, thereby contributing to the creation of a sustainable and healthier planet for succeeding generations [35,80]. This study measures environmental management as “Air pollution abatement that includes SO<sub>2</sub>, NO<sub>2</sub>, PM emissions from combustion plants, and emissions from motor vehicles.” “Water pollution abatement involves the treatment of water and wastewater, fertilizers from wastewater, and oil pollutant clean-up. The last one is “waste management, which is a crucial aspect that includes solid waste collection, from material recovery, recycling and re-use, fertilizers from waste, incineration and energy recovery, and also from waste management that is not elsewhere classified” [31].

##### 3.1.2. Independent variables

This study categorizes environmental taxes into three distinct types: (1) total environmental taxes, (2) energy taxes, and (3) transport taxes.

These categories are delineated as a percentage of Gross Domestic Product (% of GDP) and the overall total tax revenue [21,31].

(2) EI is a significant factor in shaping economic prospects and influencing environmental management efforts to abate pollution [50]. A notable paradox emerges, wherein heightened economic growth, driven by increased output and consumption, exacerbates environmental unsustainability. This trend is often fuelled by elevated consumption of non-renewable fossil fuels, contributing to environmental degradation, potential loss of ecological assets, and global warming concerns [2]. In this paper, EI is measured as a metric for primary energy consumption, expressed in MJ/\$2017 PPP GDP [12] (see Fig. 3).

##### 3.1.3. Control variables

We have used an analytical framework aligning with the perspective of Dogru et al. [81], who argued that various non-environmental factors significantly influence the outcomes of environmental management initiatives. We have considered several control variables, such as FDI [54,82], trade openness (Abid et al., 2021; [83]), and economic growth in our framework. The variables are described in Table 1, and the methodology map is provided in Fig. 4.

#### 3.2. Estimation model

The study has utilized a unique statistical methodology called GMM-PVR (generalized method of moment panel vector auto-regression) to get optimal findings and generate valuable insights for environmental strategies. The latest progress in the GMM-PVAR approach has arisen from the integration of several expansions. Sigmund & Ferstl [88] expanded upon the first difference GMM estimator initially proposed by Anderson & Hsiao [89], Arellano & Bond [90], and [91]), as well as the system GMM estimator introduced by Blundell & Bond [92]. Sigmund & Ferstl [88] developed an extended version of the PVAR model by including several lags of endogenous variables, weakly exogenous factors, strictly exogenous variables, and fixed effects to determine the structural form of the GMM-PVAR. The pursuit of alternatives to the Ordinary Least Squares (OLS) methods persisted due to the potential presence of Nickell bias within OLS models, as identified by Nickell [93]. The Generalized Method of Moments (GMM) estimators gained

**Table 1**  
Variables description.

Variables	Measurement	Symbol	Source
Environmental Management [index]	Air pollution abatement “a) Emissions abatement from SO <sub>x</sub> , NO <sub>x</sub> , PM emissions from combustion plants; b) emissions from motor vehicles.” Water pollution abatement “a) Water and wastewater treatment, b) Fertilizers from wastewater, c) Oil spill and pollutant clean-up” Waste management “a) Solid waste collection, b) Material recovery, recycling and re-use, c) Fertilizers from waste, d) Incineration and energy recovery, e) Waste management – Not elsewhere classified”	EM	[31].
Energy intensity	“MJ/\$2017 PPP GDP”	EI	[84]
Environmental tax revenues [index]	a) total environmental taxes b) energy taxes c) transport taxes “Each defined as % of GDP and also as a share of overall total tax revenue.”	ET	[85]
Economic growth	Gross domestic product per capita (constant 2015 US\$)	EG	[86]
Foreign direct investment	Net inflows % of GDP	FDI	[86]
Trade openness	% of GDP	TO	[87]

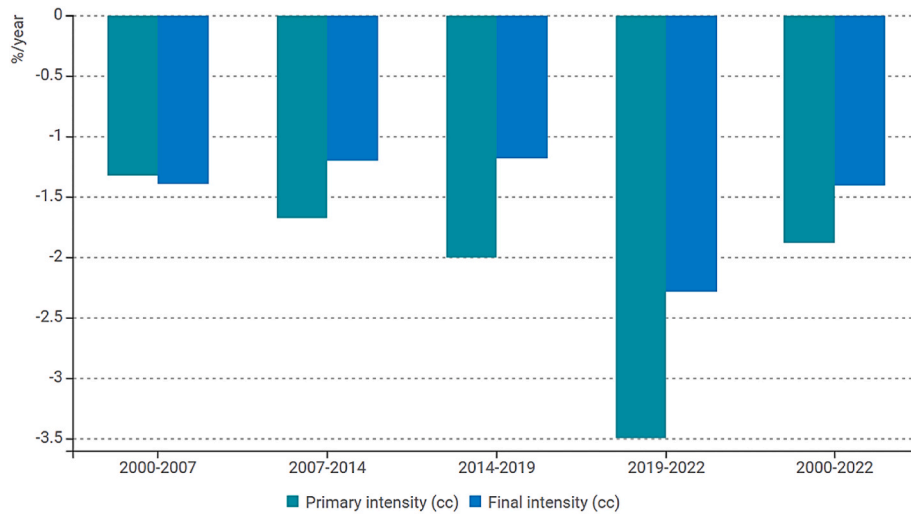


Fig. 3. Primary and final energy intensities trends in the Europe [75].

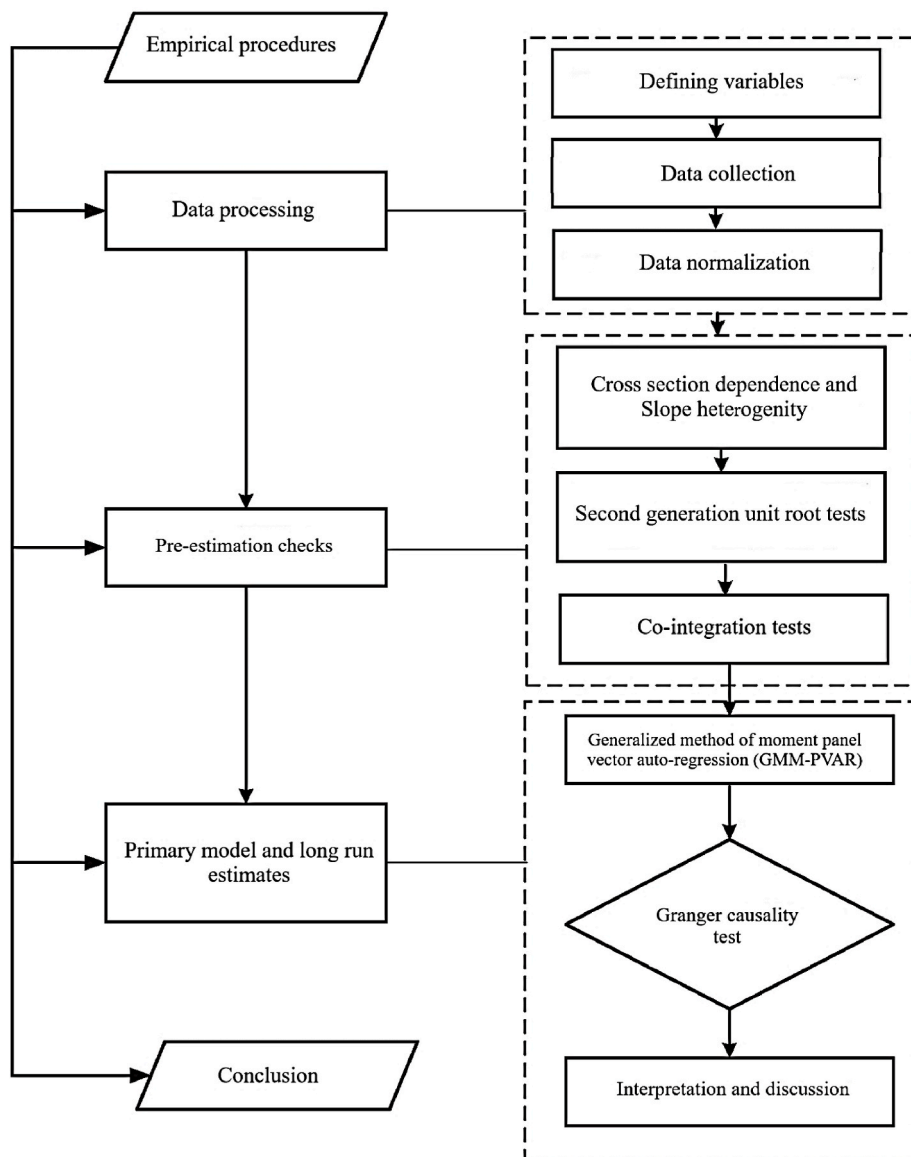


Fig. 4. Methodology map.

recognition in econometrics after being introduced by Hansen (1982). GMM is valued for its ability to produce more reliable estimations, especially when traditional OLS methods encounter challenges due to Nickell bias.

Within GMM, two primary variants stand out: the first difference GMM estimator, proposed by Arellano & Bond [90] and earlier by Holtz-Eakin et al. [91], and the system GMM estimator, pioneered by Blundell & Bond [92]. The key difference lies in the utilization of additional moment conditions in the system GMM estimator [88]. These supplementary conditions are instrumental in enhancing the accuracy of estimations in econometric models, particularly in situations where standard methods might prove inadequate due to various biases.

The computational representation of the GMM PVR model is as follows:

$$\alpha_{i,t} = \beta_i + \sum_{q=1}^p R_q \delta_{i,t-1} + \chi v_{i,t} + \omega y_{i,t} + \varepsilon_{i,t} \quad (2)$$

In equation (2) above,  $\delta_{i,t-1}$  denotes the  $m \times 1$  vector of endogenous variables for the  $i_{th}$  cross-sectional unit at time  $t$ ,  $v_{i,t}$  is the  $r \times 1$  vector of predetermined variables which may be potentially correlated with their previous error terms,  $y_{i,t}$  refers to the strictly exogenous variables which are independent of the error terms and  $\varepsilon_{i,t}$  is the error term that is independently and identically distributed for all  $i$  and  $t$ . Sigmund & Ferstl [88] made advancements by expanding and altering the time gaps of the endogenous, weakly exogenous, and strictly exogenous variables, building upon Binder et al.'s [94] estimator. To fulfill the initial differential requirements, we must employ the forward orthogonal transformation, or simply put, the first difference. Hence, by employing either the first difference or the forward orthogonal transformation, Equation (3) model was developed in the following manner.

$$\Delta \alpha_{i,t} = \beta_i + \sum_{q=1}^p R_q \Delta \delta_{i,t-1} + \chi \Delta v_{i,t} + \omega \Delta y_{i,t} + \Delta \varepsilon_{i,t} \quad (3)$$

The assessment of the stability within the PVAR framework involves evaluating the modulus of each eigenvalue derived from the model. If all eigenvalues fall within the unit circle (values are strictly less than one), it indicates that the PVAR meets the stability criterion. Furthermore, endogeneity represents a fundamental issue in panel data models, leading to biased and inconsistent estimators. To address this endogeneity concern, numerous scholarly articles have adopted the GMM framework. The GMM-PVAR model constructs a set of equations where all variables are considered endogenous. Consequently, this approach effectively addresses the issue of endogeneity. Moreover, it allows for the assessment of the impact of a single exogenous shock by employing orthogonalized responses while safeguarding the other covariates from external shocks [88]. Additionally, various other research works have employed the GMM-PVAR model as part of their methodology, among other approaches utilized [64,95,96].

### 3.3. Preliminary analysis

Building upon the framework established by Dogan et al. [64], we have conducted our empirical investigation by adhering to the following stages. Firstly, we tackled the issue of cross-sectional dependency (CD) and subsequently verified the stationarity of the study variables. Following this, we examined the long-term relationships using cointegration tests. Afterward, we utilized the innovative GMM-PVAR methodology to estimate the long-term elasticities of the explanatory variables. Lastly, we performed a causality test. Given the utilization of panel data in this investigation, there exists a notable likelihood of interdependency among the different cross-sections. CD introduces inaccuracies in computations, contradicting the data and distorting the relationships between variables. Such dependencies can significantly impact the selection of suitable statistical models in subsequent stages

[97]. Neglecting this potentiality could yield misleading and biased outcomes [98]. Consequently, the research delved into assessing CD by employing statistical tests proposed by Breusch and Pagan [99] and Pesaran [100,101]. These tests are instrumental in examining the presence and extent of CD within panel data analysis. The Pesaran-CD test specifically evaluates cross-sectional dependence, while the Breusch and Pagan-LM test scrutinizes the presence of heteroscedasticity in panel data models. The following equations denote Breusch's, Pagan-LM's, and Pesaran's tests, respectively.

$$\mathcal{L}M = \sqrt{\frac{2\mathbb{T}}{\hat{N}(\hat{N}-1)}} \left( \sum_{j=1}^{\hat{N}} \sum_{i=j+1}^{\hat{N}} p_{ji} \right) \frac{\mathbb{T}^{-\mathcal{L}} p_{ji}^2 - \check{E}(\mathbb{T}^{-\mathcal{L}}) p_{ji}^2}{\text{var}(\mathbb{T}^{-\mathcal{L}}) p_{ji}^2} \quad (4)$$

$$\mathcal{E}D = \sqrt{\frac{2\mathbb{T}}{\hat{N}(\hat{N}-1)}} \left( \sum_{j=1}^{\hat{N}} \sum_{i=j+1}^{\hat{N}} p_{ji} \right) \quad (5)$$

In the CD and LM equations, the symbol  $\hat{N}$  represents the individual dimension,  $\mathbb{T}$  stands for the time dimension,  $\mathcal{k}$  signifies the number of variables in the sectional mode,  $\check{E}$  denotes expectation, and  $p_{ji}^2$  signifies the pairwise correlation residual derived from linear regression. In both the LM and CD tests, the null hypothesis assumes the independence of cross-sectional units.

Following this, we checked the dataset for variables with potential stationarity issues. The research used Pesaran's cross-sectionally enhanced IPS (CIPS), a second-generation unit root test [102]. These tests exhibit higher sensitivity and superior capabilities in averting inaccurate results [103]. Bai and Carrion-I-Silvestre [102] test, considers both non-stationarity and CSD problems and addresses structural breaks in panel data and various other concerns pertaining to panel data analysis. Following is the CIPS mathematical equation:

$$\Delta Y_{ij} = \varepsilon_i + J_i Y_{ij-1} + K_{j-1} + \sum_{q=0}^p \gamma_{iq} \Delta \omega_{i-j} \sum_{q=1}^p \delta_{iq} \Delta Y_{ij} L_{ij} i = 1, 2 \dots n \quad (6)$$

Within the provided equation,  $\varepsilon_i$  denotes the deterministic term,  $J_i, K_j, L_i$  represent coefficients,  $Y$  signifies the cross-sectional mean, and  $p$  stands for the lag order in the test. Equation (6) aids in constructing the CIPS test equation, presented as follows:

$$CIPS = \frac{1}{\hat{N}} \sum_{j=1}^{\mathcal{K}} CADF_j \quad (7)$$

The homogeneity in slope coefficients was assessed using the well-regarded Pesaran and Yamagata [104] test for assessing slope heterogeneity, an advancement from the Swamy [105] test. The Pesaran and Yamagata [104] test offers enhanced reliability by presenting ordinary and adjusted slope heterogeneity measures. This test proves more efficient compared to the standard heterogeneity test, which poses issues with small cross-sections and extended timeframes where cross-sectional dependency is not considered. The equations for Pesaran and Yamagata [104] slope heterogeneity test are provided below.

$$\Delta_{ab} = (\hat{N})^{1/2} \bar{I}(2k)^{-1/2} \left( \frac{1}{\hat{N}} \right) \hat{S} - k \quad \text{for small sample} \quad (8)$$

$$\Delta_{abd} = (\hat{N})^{1/2} \left( \frac{2k(\mathbb{T}-k-1)}{\mathbb{T}+1} \right)^{-1/2} \left( \frac{1}{\hat{N}} \hat{S} - 2k \right) \quad \text{for large sample} \quad (9)$$

In the given equation,  $S$  denotes the Swamy t-statistics,  $N$  represents the count of cross-sections, and  $k$  signifies the number of explanatory variables. The term  $\Delta_{ab}$  is indicative of assessing the homogeneity of the slope coefficient. Moving to equation (iv),  $\Delta_{abd}$  corresponds to the adjusted slope coefficient of homogeneity.

The third procedural step involves confirming the presence of a long-run cointegrating relationship among the model variables. Following the verification of the stationary properties of the variables, the study

employed Westerlund & Edgerton’s [106] cointegration test. The panel cointegration test proposed by Westerlund & Edgerton [106] addresses concerns related to CD, slope homogeneity, and correlated error terms.

$$\alpha_i(\mathcal{L})\Delta \mathcal{Y}_{1i} = \xi_{1i} + \xi_{2i}\dagger + \alpha_i(\mathcal{Y}_{it-1} - \mathcal{B}_i\mathcal{Y}_{it-1} + \lambda_i(\mathcal{L})^{\prime\prime\prime} + e_{it} \quad (10)$$

In the preceding equation,  $\xi_{1i}$  is expressed as  $\alpha_i(1)\mu_{2i} - \alpha_i\mu_{1i} + \alpha_i\mu_{2i}$  and  $\xi_{2i} = -\alpha_i\mu_{2i}$  and  $\alpha_i$  represents the cointegration vector associated with the variables Y and X. The term  $\mathcal{B}_i$  signifies the coefficient of the error correction term. The test statistics are illustrated as follows,

$$G_{\tau} = \frac{1}{\mathcal{N}} \sum_{i=1}^{\mathcal{N}} \frac{\alpha'_i}{SE(\alpha'_i)} \quad (10.1)$$

$$G_{\alpha} = \frac{1}{\mathcal{N}} \sum_{i=1}^{\mathcal{N}} \frac{\mathcal{F}\alpha'_i}{\alpha'_i(1)} \quad (10.2)$$

$$\mathcal{P}_{\tau} = \frac{\alpha'}{SE(\alpha')} \quad (10.3)$$

$$\mathcal{P}_{\alpha} = \frac{\mathcal{P}_{\alpha}}{\mathcal{F}} \quad (10.4)$$

Similarly, we have used Banerjee & Carrion-i-Silvestre [107] cointegration results at the cross-sectional level, which allows for accurate estimation of cross-sectional dependence, accommodating varying strengths of statistics, stationarity or non-stationarity concerns and effectively managing slope heterogeneity and potentially misleading parameters within panel data.

Finally, the study employed the Granger causality test proposed by Engle and Granger [108] to investigate the potential impact of study variables on each other in the future and discern the direction of their relationship. With a unit root of I(1) and evidence of cointegration in the underlying time series, the causality test determines if the variables will show long-term reciprocal interactions. The following are the equations that are used in the causality test:

$$\begin{aligned} \Delta EI_t &= \varepsilon_{1\alpha} + \sum_{\alpha=1}^{\delta} \varepsilon_{1,1\gamma\alpha} \Delta EI_{t-\alpha} + \sum_{\alpha=1}^{\delta} \varepsilon_{1,2\gamma\alpha} \Delta ET_{t-\alpha} + \sum_{\alpha=1}^{\delta} \theta_{1,3\gamma\alpha} \Delta EM_{t-\alpha} \\ &+ \sum_{\alpha=1}^{\delta} \theta_{1,4\gamma\alpha} \Delta EG_{t-\alpha} + \sum_{\alpha=1}^{\delta} \theta_{1,5\gamma\alpha} \Delta FDI_{t-\alpha} + \sum_{\alpha=1}^{\delta} \theta_{1,6\gamma\alpha} \Delta TO_{t-\alpha} \\ &+ \xi_{1\gamma} ECT_{t-1} + \varphi_{\gamma t} \end{aligned} \quad (11)$$

$$\begin{aligned} \Delta ET_t &= \varepsilon_{1\alpha} + \Delta ET_{t-\alpha} + \sum_{\alpha=1}^{\delta} \varepsilon_{1,2\gamma\alpha} \Delta EI_{t-\alpha} + \sum_{\alpha=1}^{\delta} \theta_{1,3\gamma\alpha} \Delta EM_{t-\alpha} \\ &+ \sum_{\alpha=1}^{\delta} \theta_{1,4\gamma\alpha} \Delta EG_{t-\alpha} + \sum_{\alpha=1}^{\delta} \theta_{1,5\gamma\alpha} \Delta FDI_{t-\alpha} + \sum_{\alpha=1}^{\delta} \theta_{1,6\gamma\alpha} \Delta TO_{t-\alpha} \\ &+ \xi_{1\gamma} ECT_{t-1} + \varphi_{\gamma t} \end{aligned} \quad (12)$$

$$\begin{aligned} \Delta EM_t &= \varepsilon_{1\alpha} + \sum_{\alpha=1}^{\delta} \varepsilon_{1,1\gamma\alpha} \Delta EI_{t-\alpha} + \sum_{\alpha=1}^{\delta} \varepsilon_{1,2\gamma\alpha} \Delta ET_{t-\alpha} + \sum_{\alpha=1}^{\delta} \theta_{1,3\gamma\alpha} \Delta EM_{t-\alpha} \\ &+ \sum_{\alpha=1}^{\delta} \theta_{1,4\gamma\alpha} \Delta EG_{t-\alpha} + \sum_{\alpha=1}^{\delta} \theta_{1,5\gamma\alpha} \Delta FDI_{t-\alpha} + \sum_{\alpha=1}^{\delta} \theta_{1,6\gamma\alpha} \Delta TO_{t-\alpha} \\ &+ \xi_{1\gamma} ECT_{t-1} + \varphi_{\gamma t} \end{aligned} \quad (13)$$

$$ECT_{\gamma t} = \beta_{1\gamma} EI_{\gamma t} + \beta_{2\gamma} ET_{\gamma t} + \beta_{3\gamma} EM_{\gamma t} + \beta_{4\gamma} FDI_{\gamma t} + \beta_{5\gamma} EG_{\gamma t} + \beta_{6\gamma} TO_{\gamma t} \quad (14)$$

$\varepsilon$  denotes the random error term,  $\Delta$  represents the first-order difference operator, and ECT stands for the error correction term. The Error Correction Term (ECT) generally falls within the range of 0 to  $-2$ , providing insights into the enduring correlation between variables.

#### 4. Results interpretations

The descriptive statistics and the result of the correlation analysis are presented in Table 2. There’s moderate variability in environmental management measures, EI (2859.573) displays a significantly wider spread of values, reflecting pronounced disparities among regions. ET (0.463444), on the other hand, depicts very minimal variability, indicating a more consistent pattern across the European nations in terms of income generated from environmental taxes. The strong positive correlation coefficient (0.781) indicates a robust relationship between environmental management and EI. This correlation suggests that higher EI tends to correspond with higher levels of environmental management initiatives. There is a strong positive correlation between environmental management and ET (0.624). This positive correlation indicates that higher ETs are associated with stronger environmental management initiatives. A positive correlation exists between environmental management and EG (0.585). This suggests a tendency for improved environmental management to be somewhat associated with higher economic growth rates. There is a relatively weak positive correlation between environmental management and FDI (0.289), which suggests a mild tendency for increased levels of FDI to be associated with enhanced environmental management practices.

In time series analysis, it is crucial to determine whether the data series is stationary or possesses a unit root. The present study utilizes several CD tests, which are essential econometric techniques to determine the most appropriate tests for stationarity, long-run cointegration, long-run estimation, and causality. Table 3 presents the results of three important CD tests, namely Breusch and Pagan [99], Pesaran [109], and Pesaran (2005). The CD test shows that all the variables are stationary at a 5 % significance level, indicating the presence of cross-sectional dependence among the panels. These outcomes are taken into account when conducting subsequent panel unit root tests. In cross-section dependence scenarios, the initial generation unit root tests may introduce uncertainty and predispose the estimations to biases. According to Pesaran and Yamagata [104], slope heterogeneity tests hold importance in panel data analysis by uncovering variations in relationships between variables across diverse subgroups or time periods. This is beneficial for pinpointing factors influencing policy effectiveness and crafting more targeted interventions. The results in Table 3 from the slope heterogeneity test indicate both models hold statistical significance at the 0.01 level. This signifies substantial diversity in independent variable coefficients among various data subgroups, revealing the existence of slope heterogeneity. Such variations may arise due to differences in coefficients of independent variables across subgroups or time periods.

Following the assessment of CSD, the subsequent phase involves analyzing the data’s unit root characteristics or stationarity properties utilizing Pesaran [100] and Bai and Carrion-I-Silvestre [102] unit root tests. These tests offer significant theoretical and empirical insights into their implications when dealing with CSD presence, slope heterogeneity, and structural breaks. As indicated in Table 4, the Pesaran unit root test results affirm the stationarity of all variables at their levels. Nevertheless, it does not incorporate considerations for structural breaks within the data. Nonetheless, the outcomes from Bai and Carrion-I-Silvestre’s [102] cointegration test refute the null hypothesis of data stationarity at levels. This confirms the existence of a unit root in all model variables when incorporating structural changes, as assessed by the  $Pm$  and  $P$  statistics found in the lower segment of Table 4.

The subsequent stage entails exploring the connections between variables via cointegration before predicting long-run coefficients (Table 5). This research employs the Westerlund (2007) test to assess the cointegration among EM, EI, ET, EG, FDI, and TO. The outcomes from the Westerlund (2007) test dismiss the null hypothesis, indicating "no cointegration." Both group-based and panel-based statistics demonstrate significance at a 5 % level. These findings imply that, in the long term, EFP, GTI, ET, REN, HDI, FDI, EG, and TO are cointegrated.

The study employed the cointegration analysis method by Banerjee

**Table 2**  
Descriptive statistics.

	EM	EI	ET	EG	FDI	TO
Mean	1567.525	3478.405	2.604293	23933.37	19430.35	49.28136
Median	1115.685	2489.933	2.659800	7974.000	14683.31	50.23207
Maximum	7053.778	11610.72	3.673263	212911.0	62907.27	72.00055
Minimum	312.4241	422.5826	1.726856	917.0000	5341.696	23.49944
Std. Dev.	1278.344	2859.573	0.463444	38029.75	13050.44	12.34654
EM	1					
EI	0.781	1				
ET	0.624	-0.585	1			
EG	0.585	0.844	0.591	1		
FDI	0.289	0.562	0.259	0.732	1	
TO	-0.064	0.093	0.168	0.458	-0.057	1

**Table 3**  
Cross-sectional dependence results.

Variables	Breusch-Pagan LM	Pesaran Scaled LM	Pesaran CD
EM	201.527**	44.263**	26.49**
EI	170.225**	39.336**	14.67**
ET	115.385**	31.551**	10.37**
EG	319.349**	53.163**	31.38**
FDI	135.749**	34.485**	11.29**
TO	88.371**	21.364**	8.57**

Slope homogeneity test		
Models	$\bar{\Delta}$ (p value)	$\bar{\Delta}_{adjusted}$ (p value)
Model 1	10.17* (0.000)	9.89* (0.000)
Model 2	9.88*** (0.000)	9.17*** (0.000)

Note: \*\* indicate 1 % significance level.  
Note: \*\*\*, \*\*, and \* refer to the level of significance at 1 %, 5 %, and 10 %, respectively, whereas the values in parentheses contain P-values.

**Table 4**  
Results of Unit root test with & without structural break Pesaran [100].

Variables	Level I (0)		First Difference I (1)	
	CIPS	M – CIPS	CIPS	M – CIPS
EM	-4.715***	-7.027**	-	-
EI	-3.213***	-4.191**	-	-
ET	-3.130***	-5.063**	-	-
EG	-5.074***	-8.152**	-	-
FDI	-4.252***	-6.238**	-	-
TO	-5.156**	-4.081**	-	-

Bai and Carrion-i-Silvestre [102]						
	Z	P <sub>m</sub>	P	Z	P <sub>m</sub>	P
EM	0.167	0.233	15.185	-5.056***	4.794***	59.432***
EI	0.274	0.161	19.042	-3.156***	4.035***	70.384***
ET	0.184	0.323	16.158	-5.153***	5.384***	68.458***
EG	0.249	0.178	22.172	-4.702***	5.053***	73.385***
FDI	0.195	0.236	19.113	-7.189***	4.174***	59.194***
TO	0.238	0.161	24.138	-3.952***	5.163***	67.736***

Note: “The significance level is determined by 1, 5, and 10 % indicated through \*\*\*, \*\*, and \*, respectively”.

**Table 5**  
Westerlund cointegration results.

Statistics	Value	Z-value	P-value
Gt	-4.162	-2.872	0.001
Ga	-8.385	-4.289	0.000
Pt	-10.36	-3.755	0.000
Pa	-14.81	-7.172	0.000

Note: \*\*\* indicates 1 % significance level.

& Carrion-i-Silvestre [107], considering three distinct scenarios: no deterministic elements, inclusion of a constant, and inclusion of a trend. Table 6 displays the findings for cointegration across various countries under these three conditions. The statistical results refuted the null hypothesis (H0), which assumes no cointegration, and instead supported the alternative hypothesis, indicating the existence of a long-term cointegrating relationship among the model variables for both the full dataset and each specific economy analyzed.

The study utilized the GMM-PVAR methodology to investigate the relationship among EM, EI, ET, EG, FDI, and TO in European economic giants. The aggregate results are presented in Table 7, and individual panel results are also presented in Table 7. The stability condition evaluation shows that the eigenvalue absolute values are less than one, which means that the PVAR follows the stability requirement, as shown in Fig. 5. All modeled series, including the PVAR system, must be rationalized according to this criterion. Accordingly, the GMM-PVAR estimates, as shown in Table 7, are considered consistent and credible.

The aggregate panel result shows that EI shares a positive and statistically significant relationship ( $\beta = 0.334$ ) with EM, implying that increased EI will increase environmental management efforts to abate air, water, and waste pollution. The results contradict the findings of [110], whose findings suggested that EI is the major cause of environmental degradation. Our results also imply that the European countries with higher EI can emphasize managing environmental concerns more, potentially due to higher awareness or regulations regarding energy consumption and its environmental impact. ET also displays a positive and statistically significant association ( $\beta = 0.147$ ) with EM. This indicates that these European countries tend to allocate revenue funds generated through environmental taxes towards environmental management activities to combat and lessen pollution. The results also align with the region’s emphasis on environmental sustainability, where European governments might utilize such revenues to support green

**Table 6**  
Banerjee & Carrion-i-Silvestre [107] cointegration analysis.

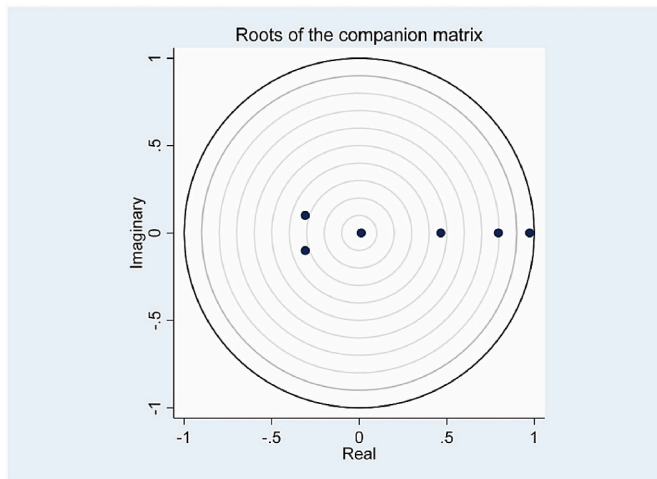
Panel DV: EM	Panel No deterministic specification	With constant	With trend
Full Sample	-6.316***	-5.434***	-6.736***
<b>Panel 1</b>			
UK	-4.168***	-4.547***	-5.534***
Germany	-4.194***	-3.546***	-4.104***
France	-3.601***	-3.716***	-4.429***
Italy	-3.636***	-3.791***	-4.534***
Spain	-5.369***	-4.418***	-5.635***
<b>Panel 2</b>			
Netherlands	-5.539***	-4.014***	-3.874***
Poland	-5.421***	-4.635***	-5.747***
Sweden	-4.316***	-4.676***	-4.521***
Belgium	-5.143***	-5.553***	-5.485***
Ireland	-5.045***	-4.014***	-4.874***
Austria	-4.344***	-4.739***	-4.265***

Note: \*\*\*, \*\* & \* explain the level of significance at 1 %, 5 %, and 10 %, respectively, whereas the values are in parentheses contains P-values.

**Table 7**  
GMM-PVR estimates.

Variable	Aggregate Panel	Aggregate Panel 95 % Conf. Interval	Panel A	Panel A 95 % Conf. Interval	Panel B	Panel B 95 % Conf. Interval
EM(-1)	0.438*** (2.741)	[0.365, 4.97]	0.547*** (2.341)	[0.735, 0.846]	0.365*** (5.0214)	[0.587, 0.982]
EI	0.334** (9.732)	[0.373, 3.76]	-0.286*** (-0.591)	[0.104, 0.183]	0.165*** (-3.83)	[0.462, 0.621]
ET	0.147*** (4.742)	[0.156, 4.49]	-0.331*** (3.122)	[0.215, 0.458]	0.231** (5.125)	[0.102, 0.163]
EG	0.162** (5.734)	[-0.141, 2.37]	0.167** (5.245)	[0.313, 0.554]	0.143** (4.264)	[0.428, 0.572]
FDI	-0.439*** (6.12)	[0.175, 2.45]	0.167** (5.245)	[0.313, 0.554]	0.143** (4.264)	[0.428, 0.572]
TO	0.638** (7.018)	[0.3487, 1.32]	-0.041** (4.224)	[0.015, 0.029]	0.088* (0.343)	[0.053, 0.084]

Note: “This table shows the results of GMM - PVAR estimates for the panel with environmental management as the dependent variable. The figures in parentheses are t-values. \*\*\*, \*\*, and \* show statistical significance at the 1 %, 5 % and 10 % level”.



**Fig. 5.** Stability check.

initiatives, eco-friendly technologies, or conservation programs. The results aggregate and align with findings of [111,112].

EG results show a positive and statistically significant correlation ( $\beta = 0.162$ ) with environmental management, suggesting that stronger economies in Europe often invest more in EM. This positive relationship highlights that economically prosperous countries within the region might prioritize environmental conservation and regulations, possibly due to higher resources and capabilities to invest in sustainable practices [54,113,114]. FDI indicating a negative and statistically significant relationship ( $\beta = -0.439$ ) with environmental management implies that increased foreign direct investment might potentially hinder environmental management efforts within European countries. This could be due to concerns regarding environmental regulations being relaxed to attract investments, leading to potential environmental degradation in certain cases [115,116]. TO exhibiting a significantly positive association ( $\beta = 0.6385$ ) with environmental management suggests that European nations imply that increased international trade encourages adopting environmentally sustainable practices and regulations, possibly due to pressure from international agreements or markets prioritizing environmental standards. The results are supported by Ref. [117,118], who reveal that TO improves high-growth countries' environmental conditions.

GMM-PVR results for Panel A and Panel B are presented in Table 7. Panel A countries include the UK, Germany, France, Italy, and Spain, which constitute more than 70 % of the EG of Europe [32], and the remaining countries are the Netherlands, Poland, Sweden, Belgium, Ireland, and Austria, together both panel countries constitute 100 % of European EG Ref. [76]. The foremost reason to explore these panels separately is rooted in the fact that panel A countries not only hold approximately 70 % of Europe's EG, but the intense economic activities of these high-growth countries are also responsible for rising emission levels of the region [119]. The result of Panel A shows that EI exhibits a significantly positive relationship ( $\beta = 0.547$ ) with environmental

management, and given the significance of these nations in terms of EG, the significant relationship indicates their increased efforts in managing environmental concerns stemming from higher energy usage. The results contradict the findings of Chen et al. (2018), who suggested that EI is the major cause of rising air pollution, but the study was conducted in lower and middle-income economies. ET displays a negative and statistically significant relationship ( $\beta = -0.286$ ) with EM, which suggests that despite the generation of revenues from ET, there might be challenges or inefficiencies in utilizing these funds effectively for environmental management initiatives to abate air, water, and waste pollution. EG exhibits a negative and statistically significant correlation ( $\beta = -0.331$ ) with environmental management in these major European economies, implying that rapid EG could potentially increase air pollution in these countries [120]. This growth is often fuelled by industries that heavily rely on conventional and often polluting energy sources, such as coal, oil, and gas. The more intensive the economic activities, the higher the reliance on these fossil fuels, which can lead to heightened environmental degradation, including air and water pollution and greenhouse gas emissions [121]. FDI displays a positive and statistically significant impact ( $\beta = 0.167$ ) on EM. It implies that countries receiving higher FDI might also witness increased efforts in EM. This could be due to foreign investors demanding compliance with environmental standards or host countries aiming to enhance environmental regulations to attract investments. TO shows a negative and statistically significant relationship ( $\beta = -0.041$ ) with EM, implying that while TO brings economic benefits, it could also pose challenges for environmental policies and sustainability efforts.

The Panel B results show that EI exhibits a significantly positive relationship ( $\beta = 0.365$ ) with EM. However, the association between EI and environmental management in panel B is moderately weaker compared to panel A, where the coefficient was higher. ET coefficient ( $\beta = 0.165$ ) is similar to the findings in panel A; the relationship remains positive; however, in this case, it is stronger in panel B. This implies that in Panel B countries, higher ET are more decisively associated with enhanced environmental management efforts than in Panel A. Despite a slightly weaker coefficient compared to panel A, the positive relationship between EG and environmental management ( $\beta = 0.231$ ) still indicates that as economic growth occurs, there is a propensity for these countries to direct efforts toward environmental management. FDI relationship ( $\beta = 0.143$ ) with environmental management is slightly weaker than panel A's. This suggests that in these specific countries of panel B, higher FDI contributes positively to environmental management, yet to a lesser extent than observed in panel A. TO and environmental management ( $\beta = 0.088$ ) relationship suggests that in this subset of countries, increased TO might have a more modest impact on environmental management compared to the larger panel A.

The impulse response graph (Fig. 6) reveals that energy intensity exerts a notable and significant short-term effect on environmental management. This influence is most pronounced during the initial three steps, after which it gradually wanes. The findings imply that heightened energy intensity prompts immediate environmental management responses, potentially due to stricter regulations or increased awareness of environmental consequences. However, this influence diminishes and stabilizes around zero by the tenth step, indicating that its effect is

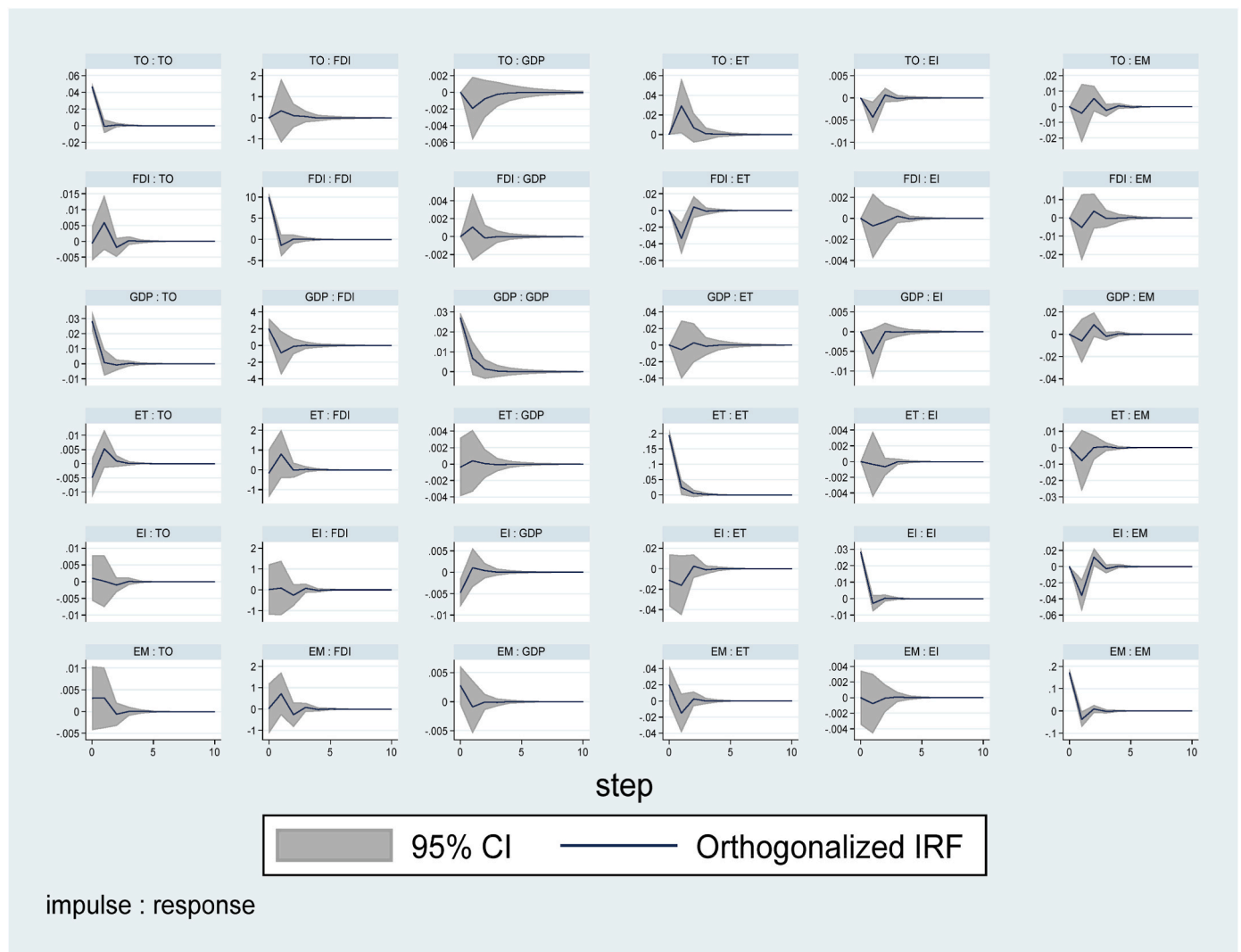


Fig. 6. Impulse-response Functions.

transient.

ET also has a positive impact on environmental management, albeit on a smaller scale. The effect peaks between the third and fourth steps but begins to decline after the fifth step. This pattern suggests that ET contribute positively to environmental management by channeling resources into green initiatives. Nonetheless, the relatively modest effect underscores inefficiencies in effectively utilizing these funds. FDI shows a short-term adverse effect on environmental management, with its impact stabilizing near zero after the fifth step. This observation implies that FDI may temporarily weaken environmental policies, likely due to regulatory concessions or economic strategies aimed at attracting investments. TO, on the other hand, demonstrates a mild but positive and stable influence on environmental management, reaching equilibrium after five steps. This finding suggests that trade openness promotes environmentally sustainable practices, possibly through compliance with international standards and trade agreements. Lastly, GDP exerts a consistent and substantial positive impact on environmental management, peaking early in the observation period. This indicates that economic expansion strengthens environmental management by providing the necessary financial resources to invest in sustainable practices and address environmental challenges effectively.

In the final phase of our analysis, we employed the Engle et al. [108] test to investigate the long-term causal relationship between the variables. The outcomes of the causality analysis are outlined in Table 8,

Table 8  
Granger causality.

Null Hypothesis	F-Statistic	Prob.
EI↔EM	4.941	0.0025
ET↔EM	6.033	0.0014
EG↔EM	5.184	0.0032
FDI↔EM	3.835	0.0241
TO↔EM	2.837	0.0052

indicating a statistically significant causal linkage between EI and environmental management. Within the European framework, this infers that alterations or fluctuations in EI levels precede and potentially shape initiatives related to environmental management. Elevated EI levels might necessitate heightened efforts in environmental management across these European nations. ET and environmental management results imply that greater revenues generated from environmental taxes might stimulate amplified attention and investments in strategies for environmental management. EG and EM's long-term causality indicates that rapid economic growth in these economically powerful countries might necessitate intensified measures of environmental management due to heightened environmental pressures stemming from economic activities. The results also show that FDI would remain an influential factor impacting environmental management in Europe. TO

and environmental management causality also imply that increased TO might prompt adaptation or initiatives in EM approaches.

## 5. Discussion and policy implications

Today, addressing the formidable challenge of combating climate issues stands as one of the foremost tasks confronting global authorities. To accomplish the ambitious EU green deal [27], Sustainable Development Goals (SDG-7) [28], and COP Charter of environmental management [78], European economies are demonstrating their higher commitment. However, just five economies in Europe hold approximately 83.75 % of the region's economic output [76] and are involved in intensive economic activities, and high economic growth often correlates with increased industrial activities, infrastructural development, and overall economic expansion (Abid et al., 2021). Considering that Europe's biggest economies' reliance on fossil fuels continued in 2023 [122], it is important to examine how much EI and Europe's policy instrument, ET, affect the environmental management efforts to abate air, water, and waste pollution. To achieve this goal, we targeted the biggest economies in Europe [Appendix A] that make up over 90 % of Europe's GDP and divided the economies into two panels. Panel A represent 5 countries [see appendix] that holds around 83.75 % of the region's GDP and Panel B includes countries that make up rest of GDP. The targeted economies constitute 15.3 trillion in 16 trillion European economy [76]. The study used extensive econometric techniques and run preliminary checks on data from 1994 to 2020 then applied main GMM-PVR model.

The aggregate results reveal a positive and statistically significant relationship between EI and environmental management in European economic giants. Higher EI demonstrates a positive and statistically significant connection with increased environmental management activities, suggesting a commitment to address air, water, and waste pollution. This inclination may stem from heightened awareness or stringent regulations related to energy consumption and its environmental impact. Our results also imply that the European countries with higher EI can place greater emphasis on managing environmental concerns, potentially due to higher awareness or regulations regarding energy consumption and its environmental impact. ET also shows a positive and statistically significant association with environmental management, indicating that European nations allocate funds generated through environmental taxes toward pollution mitigation efforts. This aligns with the region's emphasis on environmental sustainability, possibly supporting green initiatives or conservation programs. EG exhibits a positive correlation with environmental management, suggesting that economically prosperous countries prioritize environmental conservation, possibly due to greater resources. This positive relationship highlights that economically prosperous countries within the region might prioritize environmental conservation and regulations, possibly due to higher resources and capabilities to invest in sustainable practices. FDI exhibits a negative relationship with environmental management, implying potential hindrance to environmental efforts, while TO shows a positive association with environmental management, suggesting increased international trade encourages environmentally sustainable practices.

Panel A, comprising major European economies, further emphasizes the positive relationship between EI and EM. ET exhibits a negative relationship, raising questions about the effectiveness of utilizing such funds for pollution reduction. EG negatively correlates with EM, suggesting rapid economic growth may increase pollution in major European economies. The results are positively significant, considering Germany is still the biggest emitter in Europe despite high environmental taxes (DuStatist, 2023). The result raises questions on promising layouts of the EU Green Deal and 2030 agenda [27], Sustainable Development Goals (SDG-7) [28], and COP26 targets [29] in the biggest GDP holders in Europe and their strictly applied ET to conserve environmental interest as policy instruments. EG exhibits a negative and statistically significant correlation with environmental management in

these major European economies, implying that rapid EG could potentially increase air pollution in these countries. The more intensive the economic activities, the higher the reliance on these fossil fuels, which can lead to heightened environmental degradation, including air and water pollution and greenhouse gas emissions. Additionally, policy-makers and industries may prioritize short-term economic gains over long-term environmental sustainability in pursuit of economic growth. As a result, environmental initiatives might not receive adequate attention or investment compared to economic development projects. The trade-off between economic growth and environmental conservation becomes more apparent in economies where environmental regulations are less stringent or ineffective. Moreover, the negative relationship might also reflect a lag in policy adjustments or inadequate implementation of sustainable practices in response to economic growth. Panel B results show a moderately weaker relationship between EI and environmental management compared to Panel A. ET's positive relationship with environmental management is stronger in Panel B. EG maintains a positive relationship with environmental management, but FDI's impact is slightly weaker than in Panel A. TO has a more modest impact on environmental management in Panel B. Lastly, the causality test indicates a statistically significant causal linkage between EI and E environmental management, suggesting that alterations in EI levels precede and potentially shape environmental management initiatives in Europe. ET and environmental management results imply that greater revenues from environmental taxes stimulate increased attention and investments in environmental management strategies.

Based on the findings, we have devised the following policy suggestions. First, there is a need for a more targeted approach toward improving energy efficiency that aligns with environmental goals and directly addresses pollution concerns. It is imperative for Europe's biggest economies that in order to combat the climate change crisis in the long run, and it is crucial to implement and enhance energy efficiency programs, particularly targeting major industries. The goal can be achieved by lowering dependence on gas and oil in the industrial sector by investing in technological advancements and energy-efficient practices; industries and economies can contribute to reducing harmful emissions. By enhancing energy efficiency programs, Europe's major economies can not only mitigate the immediate environmental impact but also position themselves for long-term resilience and sustainability [27,30]. Moreover, these efforts would directly contribute to Europe's climate neutrality goal for 2050, ensuring that industries can meet stringent emission reduction targets without sacrificing economic growth [27].

Secondly, to effectively combat the climate change crisis in the long run, it is essential to strengthen mechanisms for utilizing ET. Despite a positive association, the observed negative relationship in certain scenarios underlines the need for streamlined processes. It is crucial to streamline the deployment of ET to target specific pollution reduction activities more effectively. Transparent, accountable, and well-targeted tax policies can provide the necessary financial resources for substantial environmental management investments [30]. Additionally, it is important to integrate ET with broader energy efficiency initiatives, as the two strategies must work in tandem to address the complex challenges of climate change [26]. By ensuring that ET is channeled efficiently into pollution abatement initiatives, European power countries can maximize the impact of these financial resources. Also, implementing transparent and accountable mechanisms will address environmental challenges and contribute to long-term sustainability by supporting impactful environmental management activities. However, alone, ET would not combat the environmental challenges; managing and increasing energy efficiency go side by side with the intervention of policy instruments like ET.

Lastly, it is imperative to introduce and reinforce environmental regulations, ensuring that FDI aligns with sustainable practices. The observed negative relationship between FDI and environmental management underscores the need to prevent potential environmental

degradation resulting from relaxed regulations to attract investments. By implementing stringent and environmentally conscious regulations, European nations can attract foreign investments and safeguard against detrimental impacts on the environment. There is also a need to strengthen international collaboration further to ensure that trade relations align with environmental goals, creating a harmonized approach to combat climate change. By engaging in coordinated efforts, countries can collectively promote environmentally friendly practices in global trade, contributing to long-term environmental conservation.

### 5.1. Limitation and future direction

The current research, akin to other scholarly investigations, is not without its limitations. We have explored the biggest European economies. Consequently, it is recommended that subsequent investigators initially explore the interrelation among EI, ET, and environmental management within developing nations, specifically focusing on major emitters such as China and the United States. There is also scope for

potential expansions of ET on distinct energy sectors and by incorporating technological variables like research and development and renewable energy capacity, along with political considerations such as institutional quality. Lastly, applying advanced econometrics techniques based on the nature of data is highly suggested.

### CRedit authorship contribution statement

**Fayyaz Ahmad:** Conceptualization, Writing – original draft, Writing – review & editing, Validation. **Nabila Abid:** Conceptualization, manuscript revision, Writing – review & editing, Supervision. **Junaid Aftab:** Data curation, Methodology, Validation. **Aamir Javed:** Data curation, Methodology, Visualization, Software and analysis.

### Declaration of competing interest

Authors declare no conflict of interest.

## Appendix A

Panel A
Germany
United Kingdom
France
Italy
Spain
Panel B
Netherlands
Poland
Sweden
Belgium
Ireland
Austria)

### Data availability

Data will be made available on request.

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