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Nuclear energy generation's impact on the CO2 emissions and ecological footprint among European Union countries

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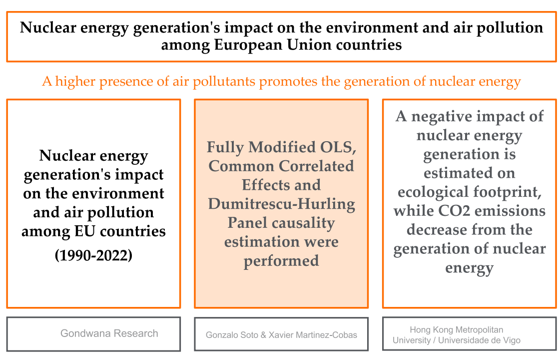
HIGHLIGHTS

- It is performed a comparative analysis of nuclear energy generation impacts on environment.
- European Union members were examined between the period 1990 and 2022.
- Fully Modified OLS, Common Correlated Effects and Dumitrescu-Hurling Panel causality estimation were performed.
- A negative impact of nuclear energy generation is estimated on ecological footprint, while CO2 emissions decrease.
- A higher presence of air pollutants promotes the generation of nuclear energy as an alternative to fossil fuel energy.

GRAPHICAL ABSTRACT



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ABSTRACT

This study employs Fully Modified Ordinary Least Squares, Common Correlated Effects and Dumitrescu-Hurlin panel causality techniques to investigate the environmental impacts of nuclear energy generation in European Union countries from 1990 to 2022. The ongoing debate within the European Union and the empirical contradictions in the literature, coupled with the overall singular-dimensionality surrounding the impacts of nuclear energy on the environment, necessitate a broader and comprehensive examination of its effects across various environmental dimensions. These dimensions include the presence of CO2 emissions and the ecological footprint generated. The findings reveal that nuclear energy adoption by countries tends to affect CO2 emissions but this relationship goes from CO2 to nuclear energy consumption as per the causality test, while the ecological footprint variable does not exhibit a causal relationship with nuclear energy consumption. We estimated that a higher presence of air pollutants promotes the generation of nuclear energy as an alternative to fossil fuel energy sources. The study highlights that while nuclear energy generation produces no air pollution, it does impose significant land use requirements, potentially leading to ecosystem degradation. Factors such as uranium extraction, nuclear waste management, disposal, and accidents contribute to this impact. Further research is needed to understand the specific mechanisms and factors contributing to the observed environmental degradation associated with nuclear energy generation.

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1. Introduction

As the world becomes more interconnected in terms of economy, society, and politics, the expansion of urbanization and industrialization has become a prominent feature. These processes reflect the modern economic landscape and drive the growing need for energy in our overall energy mix. Additionally, our actions and lifestyle choices contribute to the increasing demand for energy, which has long-term implications for environmental sustainability as demonstrated in previous works (Dasgupta, 1996; Villanthenkodath and Mahalik, 2022). It is projected that the amount of energy available will need to double between 2016 and 2030 to meet the demand for productivity derived from industrial activities (Sarkodie and Adams, 2020).

The escalating demand for energy poses a significant environmental challenge, as economies, both developing and developed, heavily rely on fossil fuels (Sharma et al., 2021). Fossil fuel usage leads to the emission of carbon dioxide, resulting in air pollution. This pollution, in turn, contributes to environmental degradation by reducing the natural environment's carrying capacity. As pollution levels rise, the environment struggles to absorb and assimilate the increasing waste, ultimately leading to environmental degradation.

In an effort to reduce reliance on fossil fuels, nuclear energy has emerged as a proposed alternative energy source. In Europe, nuclear energy accounts for 13 % of the total energy consumption. Notably, France stands as the second-largest nuclear reactor country globally, with nuclear energy representing 70 % of its electricity production. Similarly, Spain exhibits a significant dependence on nuclear energy, which makes up over 20 % of the country's total electricity generation. Recently, the Nuclear Alliance, spearheaded by France, has advocated for the European Commission to intensify the promotion of the nuclear sector within Europe and beyond.

The economic and energy benefits derived from wind power production are counterbalanced by significant health and management risks, which have led to the reluctance of several European countries, such as Germany, in implementing these alternative energy sources. In this regard, the economic benefits stemming from greater energy independence from traditional resources are derived from a pull of alternative energies that aid in energy supply and price standardization by ensuring increased competition (Hassan et al., 2020b).

However, the production of nuclear energy carries significant externalities that limit the returns of these benefits, primarily related to the management of radioactive resources. This pertains to the management of waste resulting from the nuclear energy production process or, in the worst-case scenarios, externalities arising from facility malfunctions experienced in the past.

Nevertheless, while some countries consider nuclear energy as unsafe due to these aspects, as previously mentioned, the reorientation of these markets toward enhanced facility safety and increased state regulation for energy supply has resulted in higher safety and resource management standards (EU., 2023). Therefore, countries such as France and Green parties in Scandinavian countries have changed their stance on energy diversification and have begun utilizing nuclear energy (Reuters, 2024). Consequently, the safety and management processes associated with upgrading nuclear facilities to meet these elevated production standards tend to benefit the overall economy while preserving public health.

As a result, new nuclear energy technologies have the potential to lessen nuclear energy's environmental impact. These are applied as part of the EU nuclear energy regulation, particularly regarding air pollution, and include advanced reactor designs such as Small Modular Reactors (SMRs) and Generation IV reactors, which offer improved safety, fuel efficiency, and waste management capabilities. Thorium-based reactors present an alternative with potentially less long-lived radioactive waste and enhanced safety features. Molten Salt Reactors (MSRs) utilize liquid fuel for improved safety and waste management, and fusion energy, although still experimental, holds promise as a clean and virtually limitless power source. All of these technologies, while relatively newly developed, aim to mitigate air pollution and address environmental concerns associated with traditional nuclear energy, ensuring safety in the managerial process of radioactive disposals (EU., 2024).

However, the use of nuclear energy remains a contentious topic, with varying opinions expressing support or opposition. Advocates of nuclear energy argue that it is a clean and efficient energy source devoid of greenhouse gas emissions. Proponents highlight the relatively low greenhouse gas emissions associated with nuclear energy and its comparably modest ecological footprint when compared to other energy sources. Conversely, opponents emphasize the generation of radioactive waste by nuclear energy, which poses long-term hazards and may require thousands of years for proper disposal. Furthermore, critics argue that nuclear energy is a non-renewable resource and can potentially contribute to the proliferation of nuclear weapons.

In this regard, the existing literature has attempted to study the key aspects or causal mechanisms through which nuclear energy tends to contribute to or worsen the environment. However, most cases have yielded contradictory conclusions, highlighting the need for further investigation into the effects and causalities associated with the exploitation and, ultimately, consumption of nuclear energy. Moreover, this debate aligns with the current European discourse on the implementation of nuclear power plants to meet energy demands in the transition to green societies, in hopes of achieving less environmental degradation as well as more diversified energy supply, which might be jeopardized by reliance on one single energy source, and raising energy prices (Zhang et al., 2023c). Countries such as Germany and Spain have committed to closing such facilities, while France strengthens its position as a nuclear power in Europe. This context motivates our research, which aims to go beyond the limitations of existing studies by analyzing the impact of nuclear energy on two components of environmental quality: CO2 emissions and ecological footprint.

This research offers novel contributions by departing from the traditional approach of solely using one variable to assess the environmental impact of nuclear energy consumption. Instead, it adopts a comprehensive measure known as the ecological footprint, which considers multiple components of environmental degradation. Furthermore, we introduce a novel conclusion that can contribute to enriching both academic and political debates. Our findings suggest that based on the indicators employed in this study, the quality of air or overall environmental degradation may prompt governments to consider a higher proportion of nuclear energy in their national energy mix. By incorporating these diverse factors, the study provides a more nuanced understanding of the ecological pressure resulting from human activities in relation to nuclear energy consumption. Additionally, this research introduces the use of causality panels to analyze the direction of the relationship between nuclear energy and environmental variables.

In our study, we present the literature review in Section 2; in Section 3 we gather the data sources and the methodology; in Section 4 we present the empirical findings, while in Section 5 we end the paper with some conclusions and policy recommendations.

2. Brief literature review

The relationship between nuclear energy and the environment has been a subject of debate for decades, both politically and scholarly. Previous studies, conducted within time series and panel frameworks, have explored the relationship between numerous variables in this sense, mainly related to environmental degradation and nuclear energy use (Tauseef Hassan et al., 2023a; Ulucak et al., 2020). However, there is a limited body of research examining the extent of environmental degradation and economic growth associated with nuclear energy production, considering the growing demand for cleaner energy sources as a replacement for polluting ones (Bandyopadhyay et al., 2022; Danish et al., 2022). Notably, some studies have highlighted the broader significance of nuclear energy compared to alternative energy sources

(AlFarra and Abu-Hijleh, 2012; Dong et al., 2018). This is due to the limitations of renewable energy sources, which can hinder economic activities, creating challenges for countries of all income levels in transitioning quickly from fossil fuels economies to the so called “green” economies (Guo et al., 2023; Hassan et al., 2019, 2022). As a result, a clean energy policy may encompass a swift transition from coal and oil to nuclear energy. However, it should be acknowledged that nuclear energy itself may have limitations in effectively managing environmental degradation (Hassan et al., 2020a).

Furthermore, the literature on the relationship between nuclear energy consumption and environmental degradation can be categorized into two strands. The first group of studies supports the notion that nuclear energy usage contributes to improved environmental quality (Bandyopadhyay and Rej, 2021; Mahmood et al., 2020; Nathaniel et al., 2021), while the second group of studies focuses on the detrimental effects of nuclear energy consumption on the environment (Bandyopadhyay and Rej, 2021; Nathaniel et al., 2021).

Previous works have explored the role of nuclear energy in all kind of pollutants, such as in the case of Mahmood et al., which concluded that there is a significant relationship between nuclear energy consumption and the presence of air pollutants in Pakistan from 1973 to 2017 (Mahmood et al., 2020). Similarly, Sarkodie and Adams examined the impact of nuclear energy consumption on the natural environment in South Africa and found positive effects (Sarkodie and Adams, 2018). The work of Azam et al., on the other hand, denoted a positive impact of nuclear energy consumption by preserving the environment based on their analysis of the top ten CO2 emitting countries (Azam et al., 2021b). Other works lead to different conclusions where CO2 is not affected by nuclear energy consumption (Al-mulali, 2014). Additionally, Saidi and Ben Mbarek found no relationship between nuclear energy consumption and CO2 emissions in their panel study of nine countries (Saidi and Ben Mbarek, 2016), and Jin and Kim also did not observe a relationship between nuclear energy consumption and CO2 emissions in their study of 30 countries (Jin and Kim, 2018). A more extensive literature review stating the negative effects of nuclear energy on the environment can be found in Bandyopadhyay and Rej (2021) Table 1.

The literature lacks a comprehensive and comparative analysis of environmental degradation across multiple variables, to which our work offers novel contributions by departing from the traditional approach of solely examining one variable to assess the environmental impact of nuclear energy consumption. Instead, we adopt a holistic measure known as the ecological footprint, which takes into account multiple dimensions of environmental degradation, one narrower, CO2, and another broader, the ecological footprint (Danish et al., 2019; Tauseef Hassan et al., 2023b). The former has been extensively employed in literature to date, but the latter has been used in a very limited fashion, and offers a much richer concept of the environmental condition.

This research aims to address this gap by conducting a systematic examination using a sample of countries that have not been previously studied with panel data approaches, to the best of our knowledge. Furthermore, we explore the dynamics in nuclear energy generation and not its consumption as per the literature. By incorporating these diverse factors, our study aims to provide a deeper understanding of the macroeconomic dynamics in the ecological pressures resulting from human activities related to nuclear energy consumption. Additionally, we employ causality panel analysis as a methodological approach to examine the direction of the relationship between nuclear energy and environmental variables. This approach surpasses mere correlation analysis, enabling the identification of driving forces, examination of dynamic interactions, and exploration of causal pathways. By employing this methodology, our research aims to fill the gap in the literature by providing a more comprehensive understanding of the intricate relationship between nuclear energy and the environment from a holistic perspective, enhancing the overall rigor and depth of our findings.

Table 1
Descriptive statistics.

	EF	Nuc	GDPpc	ren	Co2
Obs	782,00	792,00	766,00	732,00	744,00
Min	0,06	0,00	7,00	-2,41	1,98
Max	2,28	5,84	11,80	4,07	2,62
Mean	1,58	1,62	9,86	2,36	2,37
St. Dev.	0,39	1,98	0,92	1,08	0,13

Notes: Countries included in the sample (24): Austria, Belgium, Bulgaria, Croatia, Cyprus, Denmark, Estonia, Finland, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovenia, Spain, and Sweden.

3. Data, model and methodology

3.1. Methodology

To examine the significance of nuclear energy generation and its ramifications on various indicators of environmental degradation, this study aims to assess the impact of nuclear energy on the ecological footprint and CO2 emissions. To achieve this, we adopt the methodology employed by Pata and Kartal in their recent work on the environmental implications of nuclear energy generation in Korea (Pata and Kartal, 2023). The chosen model incorporates three key variables: nuclear energy generation, gross domestic product (GDP), and renewable energy utilization, which collectively serve to elucidate the environmental impacts of nuclear energy production.

In line with the model, this study incorporates GDP per capita to evaluate the applicability of the EKC hypothesis. Additionally, similar to the referenced model, the quadratic term of income level will be introduced. Consequently, the proposed model can be expressed as Eq. (4) after rearrangement:

$$ln(X_{it}) = \beta_0 + \beta_1 ln(Nuc_{it}) + \beta_2 ln(GDPpc_{it}) + \beta_3 ln\left(GDPpc_{it}^2\right) + \beta_6 ln(Ren_{it}) + \mu_{it} \tag{4}$$

Eq. (4) presents an overview of the interrelations between the variables under investigation. In this equation, X denotes a vector encompassing environmental-related variables, Nuc signifies nuclear energy generation, GDPpc represents gross domestic product per capita, Ren signifies renewable energy consumption, and μ denotes the random error term. With reference to Eq. (4), and to explore the potential asymmetric effects of nuclear generation on diverse environmental variables, X will be replaced by two primary pollution variables: the ecological footprint and CO2 emissions. The ecological footprint captures a broader scope of environmental degradation, encompassing multiple indices. Conversely, CO2 emissions reflect a narrower facet of environmental degradation, focusing solely on air pollution and the presence of such pollutants in the environment.

As such, Eq. (4) will be explored in terms of Eqs. (5) and (6):

$$ln(EF_{it}) = \beta_0 + \beta_1 ln(Nuc_{it}) + \beta_2 ln(GDPpc_{it}) + \beta_3 ln\left(GDPpc_{it}^2\right) + \beta_6 ln(Ren_{it}) + \mu_{it} \tag{5}$$

$$\begin{aligned} ln(Co2_{it}) = {} & \beta_0 + \beta_1 ln(Nuc_{it}) + \beta_2 ln(GDPpc_{it}) \\ & + \beta_3 ln\left(GDPpc_{it}^2\right) + \beta_6 ln(Ren_{it}) + \mu_{it} \end{aligned} \tag{6}$$

where EF represents the environmental footprint as mentioned above, and Co2 represents the emissions of carbon dioxide present in the environment.

To evaluate the interrelationships among variables based on the specified models, we employ two techniques that ensure enhanced robustness, taking into account the established principles in the existing literature, such as stationarity and cointegration. These two techniques are FMOLS (Fully Modified Ordinary Least Squares) and CCR (Canonical Cointegration Regression) estimation, which offer distinct advantages for estimating cointegrated relationships compared to other approaches.

FMOLS addresses issues of heteroscedasticity and autocorrelation in the data, thereby improving the efficiency of estimators and yielding more precise inferences. By considering the properties of errors, FMOLS provides consistent and efficient estimations in the presence of general form errors (Pedroni, 2001; Yahyaoui and Bouchoucha, 2021). In turn, CCR is a technique employed in time series analysis to model cointegration relationships among variables. It enables the capture of long-term relationships between economically linked variables. By incorporating cointegration, CCR yields more accurate estimations and robust economic relationships, facilitating the interpretation and comprehension of results in economic analysis (Park, 1992). Considering these benefits and the inherent properties of our data, we deem these techniques useful for estimating our findings.

The long-term panel estimator, while effective in estimating long-term coefficients, lacks the ability to determine the causal direction between the selected variables. To provide a comprehensive analysis and offer informed policy recommendations, it is essential to employ panel causality analysis. In this study, we adopt the panel causality approach proposed by Dumitrescu and Hurlin, building upon recent advancements in the field (Dumitrescu and Hurlin, 2012; Usman and Radulescu, 2022). This approach is known for its ability to generate robust estimates based upon datasets with a model's sample size. This test is estimated as Eq. (7) shown below:

$$X_{it} = \alpha_i \vdash \Sigma_{j-1}^{J} \beta_i^j X_{i(t-j)} + \Sigma_{j-1}^{J} \Upsilon_i^j Z_{i(t-j)} + \mu_{it} \tag{7}$$

In Eq. (7), X and Z denote both the dependent and independent variables, respectively, while β_i^j and Υ_i^j denote the long-run dynamics and autoregression (AR) parameters, respectively. The null (H0) and the alternative (H1) hypotheses are represented in Eqs. (8) and (9):

$$H_0 : \mu_i = 0 \, for \forall i \tag{8}$$

$$H_1 \begin{cases} \mu_i = 0 \, for \, all \, i = 1, 2, 3 \ldots N_1 \\ \mu_i \neq 0 \, for \, all \, i = N_1 + 1, 2, 3 \ldots N \end{cases} \tag{9}$$

3.2. Data and model

To conduct this study, we utilized data between 1990 and 2022 from 24 European Union countries. Our research focuses on the environmental implications of nuclear energy, for which we have obtained data from the Eurostat database (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Nuclear_energy_statistics). Specifically, we collected information on nuclear energy generation measured in gigawatt hours. This variable serves as the basis for our examination of two key environmental indicators: CO2 emissions, which quantifies the amount of carbon dioxide in tons and is sourced from the World Bank database, and ecological footprint (EF) in gha per capita, which provides a broader measure of environmental degradation, primarily encompassing land degradation. The EF variable encompasses various dimensions of the ecological footprint, including built-up land, carbon, cropland, fishing grounds, forest products, and grazing land (Arshad Ansari et al., 2020). A higher value of the EF variable indicates greater environmental degradation, while an elevated level of the CO2 variable signifies a greater presence of pollutants in the atmosphere.

Figs. 1, 2, and 3 depict the time series of the primary variables of interest employed in our research. Across all three figures, a discernible downward trend is observed in the Nuclear, EF, and CO2 variables, particularly evident since 2010. This suggests that European Union member states have made concerted efforts to enhance their environmental performance by reducing their ecological footprint and mitigating air pollution. Notably, there has been a significant decline in the reliance on nuclear energy, with electricity generation from nuclear plants in the EU decreasing by approximately 20 % between 2006 and 2021. However, recent developments within Europe have spurred the proactive promotion of nuclear energy generation among member countries. As a result, several nations, previously moving away from nuclear energy, have undertaken initiatives to refurbish and reactivate previously decommissioned nuclear plants, as exemplified by Spain and France.

The remaining data utilized in this research pertains to the GDP per capita, as stipulated by the environmental Kuznets Curve (EKC) hypothesis, and the utilization of renewable energy, which has been extensively examined in the existing scholarly literature (Hao et al., 2022; Majeed et al., 2022; Sadiq et al., 2022; Shahbaz and Sinha, 2019). These datasets have been sourced from the World Bank dataset, ensuring their reliability and comprehensiveness. A comprehensive depiction of the key attributes of the data employed in this study is presented in Table 1. All variables were transformed into logs to account for heteroskedasticity and to allow for the estimation of long-run elasticities. It is important to note that this table shows a list of the countries that have been selected for analysis in this study.

Table 2 presents the correlation matrix for the variables under investigation, indicating the absence of significant concerns regarding multicollinearity. This finding suggests that the selected variables are appropriate for conducting a panel regression analysis.

To assess robustness of our estimates based on the most appropriate estimation technique, we rely on the examination of unit root and cointegration tests. We utilized second-generation unit root tests, namely, the CIPS (Meo et al., 2020) and CADF (Hansen, 1995; Lupi, 2009) unit root tests, where rejecting the null hypothesis denotes stationarity.

The outcomes of both tests are presented in Table 3. The majority of variables exhibit non-stationarity at the level. However, by employing the first difference I (1), the data sequence achieves stationarity.

To ensure accurate estimation of long-term relationships, cointegration tests are deemed necessary. In this study, we have opted to employ the second-generation cointegration test proposed by Westerlund, which offers robust estimates of long-term cointegration dynamics when cross-sectional dependency is present (Westerlund, 2005). Additionally, using the Westerlund cointegration test allow us to estimate where there is cointegration among some or all panels.

The findings of the panel data cointegration test conducted using the

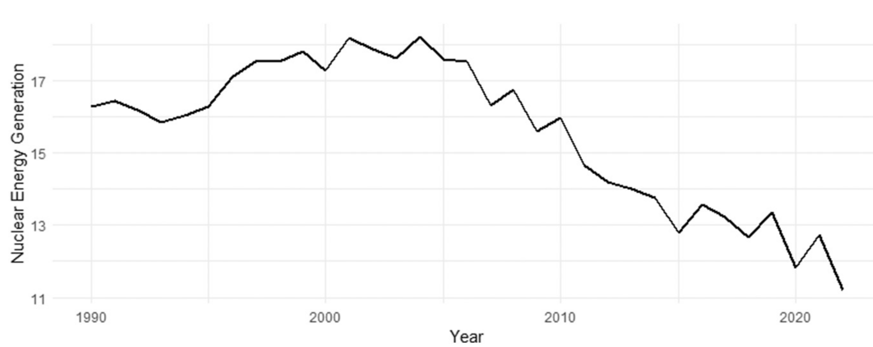

Fig. 1. Nuclear energy generation per year, 1990–2022 (logged).

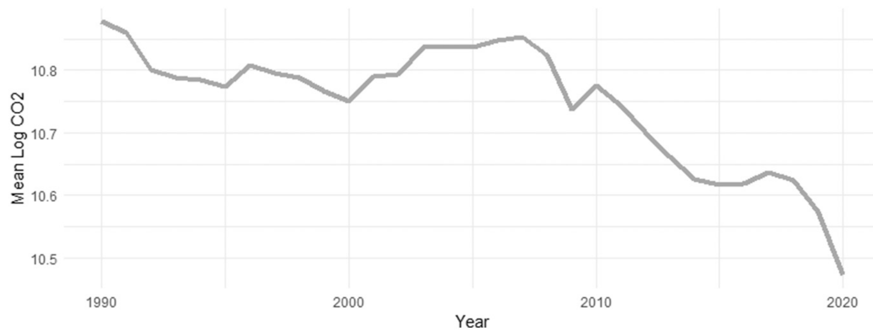

Fig. 2. CO2 emissions, 1990–2020 (logged).

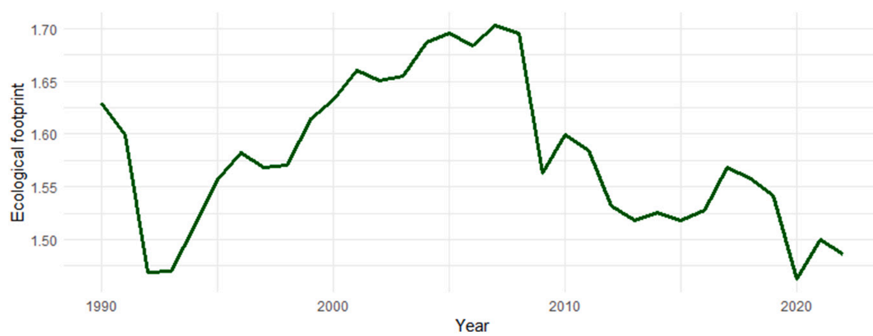

Fig. 3. Ecological footprint, averaged 1990–2022 (logged).

Table 2
Correlation matrix.

	EF	Nuc	GDPpc	ren	CO2
EF	1,00	0,12	0,18	0,00	0,22
Nuc	0,12	1,00	0,03	0,02	0,41
GDPpc	0,18	0,03	1,00	0,02	0,05
ren	0,00	0,02	0,02	1,00	−0,03
CO2	0,22	0,41	0,05	−0,03	1,00

Westerlund methodology are presented in Table 4. Two main tests are presented, one for the individual panels (Dh_g) and for the panel as a whole (Dh_p), with the null hypothesis being the absence of cointegration. Both results indicate that there is evidence at 1 % level that there is cointegration, since we rejected the null. These robust findings strongly support the presence of a long-term equilibrium relationship among the variables under investigation.

4. Empirical results

4.1. FMOLS estimation

Table 5 contains the results from the fully modified ordinary least squares estimation for both Eqs. (5) and (6).

The EF regression analysis reveals a contradictory relationship between nuclear energy and the ecological footprint. While nuclear energy demonstrates a negative impact on the ecological footprint, this contrasts with its positive effects on reducing CO2 emissions. The disparity in these findings can be attributed to the comprehensive nature of the EF variable, which encompasses a broader spectrum of environmental indicators compared to the singular focus of CO2 emissions. The ecological footprint takes into account various aspects of the environment, and it is plausible that other components within the EF variable are influenced by nuclear energy generation. This negative relationship was already stated in the recent work of Bandyopadhyay et al. for 2 out of the 3

Table 3
2nd generation unit root test.

		CIPS				CADF			
		Levels		Diffs		Levels		Diffs	
		Stat	P-val	Stat	P-val	Stat	P-val	Stat	P-val
EF	I	−1.22	0.1	−3.09*	0.01	−0.59	0.46	−23.07*	0.01
	I&T	−2.41	0.1	−3.41*	0.01	−4.47*	0.00	−23.03*	0.01
CO2	I	−1.62	0.04	−2.20*	0.01	−4.18*	0.00	−16.42*	0.01
	I&T	−1.70	0.1	−2.52*	0.01	−0.05	0.10	−16.96*	0.01
NUC	I	−0.67	0.1	2.87*	0.01	−1.98	0.05	−19.17*	0.01
	I&T	−0.88	0.1	2.94*	0.01	−2.93	0.15	−19.16*	0.01
GDP	I	−0.83	0.1	−3.02*	0.01	0.96	0.91	−16.51*	0.01
	I&T	−1.52	0.1	−3.64*	0.01	−5.43*	0.00	−19.63*	0.01
REN	I	−1.613	0.047	−2.90*	0.01	3.58	0.10	−13.73*	0.01
	I&T	−2.99	0.01	−3.18*	0.01	−7.43*	0.00	−15.69*	0.01

Notes
1. "*" Signifies 1 % significance level.
2. I denotes the presence of intercept and I&T represents Intercept and Trend.

Table 4
Westerlund Cointegration test

	EF		CO2	
	Stat	p-val	Stat	p-val
Dh_g	−2.00*	0.02	−2.07*	0.01
Dh_p	−2.11*	0.01	−1.65***	0.04

Notes:
1. "*" Signifies 1 % significance level.

Table 5
FMOLS estimation.

	EF		CO2	
	Coef.	Std. Err.	Coef.	Std. Err.
Nuc	0.269*	0.056	−0.017*	0.003
GDPpc	1.673**	0.686	0.640*	0.103
GDPpc2	−0.073**	0.036	−0.030*	0.004
ren	−0.211*	0.056	−0.097*	0.003
_cons	−8.180	8.945	2.475*	0.551
R	0.84		0.92	
R^2	0.83		0.91	

Notes:
1. "*"and "**" Signifies 1 % and 5 % significance level, respectively.

European countries they studied, where nuclear power dependence in Germany and France causes environmental degradation (Bandyopadhyay et al., 2022).

On the other hand, the positive effects of nuclear energy in reducing the presence of CO2 in the environment can be attributed to its low carbon emissions. Nuclear power plants generate electricity through nuclear fission, which does not release carbon dioxide or other greenhouse gases. As a result, nuclear energy can contribute to lowering CO2 emissions, as it serves as a cleaner alternative to fossil fuel-based energy sources (Hassan et al., 2024; Kartal et al., 2023; Ozgur et al., 2022; Saidi and Omri, 2020).

The relationship between nuclear energy generation and its impact on environmental degradation is controlled by the introduction of the *ren* variable, which exhibits the expected signs in both regressions and is statistically significant at the 1 % level. Extensive prior literature has elucidated this relationship (Shabbir Alam et al., 2023; Z. Wang et al., 2022), demonstrating that a greater reliance on renewable energy sources is associated with a reduction in environmental degradation. By including both the CO2 and EF variables in the analysis, it is evident that this effect applies to both a narrower focus on carbon dioxide emissions and a broader conception of environmental impact represented by the ecological footprint (EF) variable.

The EKC hypothesis, as applied in our analysis, is substantiated as a control variable in both regressions, revealing an inverted U-shaped relationship between income levels and environmental degradation variables (EF and CO2). This finding aligns with the existing scholarly literature (Arshad Ansari et al., 2020; Wang et al., 2023), indicating that per capita income plays a significant role in determining levels of environmental degradation. Specifically, countries with lower income tend to experience higher pollution levels until a turning point is reached, after which degradation rates improve as income per capita increases.

4.2. CCR estimation

To provide a higher robustness in our estimations, we present in Table 6 the results of the common correlated effects estimation for panel data.

The findings from the CCR estimation yield outcomes consistent with our earlier FMOLS estimation, both in terms of the direction and magnitude of the results. The relationship between nuclear energy generation and the variables of interest, as discussed in the previous section, remains consistent in the second estimation. Similarly, the control variables, including GDP per capita and its quadratic term, continue to demonstrate statistical significance, reaffirming the validity of the EKC hypothesis. Moreover, the ren variable remains significant at a 1 % level, with its impact aligning with the previous estimation, thus contributing to the overall promotion of environmental sustainability.

Table 6
CCR estimation.

	EF		CO2	
	Coef.	Std. Err.	Coef.	Std. Err.
Nuc	0.266*	0.081	−0.016*	0.005
GDPpc	1.699**	0.234	0.630*	0.138
GDPpc2	−0.075**	0.035	−0.020*	0.006
ren	−0.210*	0.064	−0.097*	0.003
_cons	−8.305	11.761	2.484*	0.725
R	0.89		0.91	
R^2	0.86		0.90	

Notes:
1. "*"and "**" Signifies 1 % and 5 % significance level, respectively.

4.3. Dumitrescu-Hurlin panel causality test

Finally, Table 7 shows the results of the estimation of the Granger causality test for the environmental-related variables, as it is the main purpose of this paper to explore environmental impacts. To keep it comprehensive, other causality relationships among control variables are not deemed within the scope of this work.

The analysis reveals three bidirectional causality relationships: between CO2 and GDP, CO2 and renewable energy (REN), and ecological footprint (EF) and REN. Additionally, two unidirectional causality relationships exist: from CO2 to nuclear energy (NUC) and from EF to GDP.

The causality relationship where CO2 acts as a Granger cause of nuclear energy can be justified by the European countries' efforts to promote low-carbon energy sources in response to high carbon emissions. Consequently, a higher presence of carbon pollutants can trigger European policies aimed at bolstering and advocating for the use of nuclear energy as a means to reduce dependence on fossil fuels within the region. While a bidirectional causality was encountered in previous works, we determine a uni-directional causality relationship for the case of European Union countries (Apergis et al., 2010).

The bidirectional Granger causality relationship between CO2 emissions and GDP, as documented in previous literature (Ben Jebli et al., 2015), stems from the interplay between economic growth and carbon-intensive activities (Zhang et al., 2023b). Economic expansion, as reflected by GDP, is frequently linked to heightened industrialization and energy consumption, particularly in fossil fuel-dependent sectors,

Table 7
Panel granger causality test.

Effect	Cause	Z Tilde	*P* value	Relationship	
CO2	NUC	1.37	0.16		CO2 –→ NUC
NUC	CO2	4.35*	0.00	Causality	
CO2	GDP pc	14.79*	0.00	Bi causality	CO2 ↔ GDP
GDP pc	CO2	4.56*	0.00	Bi causality	
CO2	REN	12.00*	0.00	Bi causality	CO2 ↔ REN
REN	CO2	4.35*	0.00	Bi causality	
EF	NUC	1.94	0.05		
NUC	EF	1.31	0.18		
EF	GDP pc	8.70*	0.00	Causality	EF →GDP
GDP pc	EF	1.72	0.08		
EF	REN	9.75*	0.00	Bi causality	EF ↔ REN
REN	EF	3.92*	0.00	Bi causality	

Notes:
1. "*" Signifies 1 % significance level.

resulting in elevated CO2 emissions. Conversely, CO2 emissions can impact economic growth through the implementation of environmental regulations targeting carbon-intensive industries, which may curtail productivity. Furthermore, endeavors to reduce CO2 emissions commonly entail transitioning to cleaner and sustainable technologies and fostering investment prospects and innovation, thereby positively shaping economic development (Lerede et al., 2023; Ming-Zhi Gao et al., 2022).

The bidirectional causality between CO2 emissions and renewable energy consumption (REN) is evident, as both variables act as causes and effects of each other. This relationship extends to the EF variable as well. Higher levels of environmental degradation can motivate a greater utilization of renewable energy sources, supported by national institutions aiming to reduce environmental harm and carbon emissions (Azam et al., 2021a). Conversely, increased adoption of renewable energy can lead to reduced environmental degradation, indicating a reciprocal causality among these variables.

The absence of an identifiable causal relationship between nuclear energy generation and the ecological footprint, despite the observed negative impact revealed by the FMOLS estimation, necessitates further exploration in the upcoming literature. This discrepancy may be attributed to the presence of confounding factors that intricately influence both nuclear energy generation and the ecological footprint, thereby obfuscating the establishment of a direct causal link (Hakkak et al., 2023; Usman and Radulescu, 2022). Moreover, the multifaceted nature of the relationship between these variables, characterized by intricate interactions within the broader ecological system, further complicates the elucidation of a clear and unambiguous causal pathway (Guo et al., 2023; Sadiq et al., 2022). Following that line of reasoning, it is of utmost importance to underscore that the absence of a discernible causal relationship must not undermine the substantive significance of the observed negative impact of nuclear energy generation on the ecological footprint. Instead, it underscores the imperative for sustained scholarly inquiry aimed at exploring the underlying mechanisms and potential indirect effects that contribute to this relationship.

Furthermore, the ecological footprint (EF) Granger causes changes in GDP per capita, as heightened environmental degradation can impose limitations on economic activities to mitigate externalities associated with higher productivity. Conversely, a greater level of environmental degradation, particularly in terms of land use, may facilitate higher productivity in terms of resource utilization and the use of space, thereby boosting GDP (Apergis et al., 2010).

5. Discussion and conclusions

In the preceding sections, we employed FMOLS and CCR estimation techniques to assess the environmental impacts of nuclear energy generation in European Union countries from 1990 to 2022. While previous studies have predominantly focused on the role of nuclear energy consumption in reducing carbon dependency and greenhouse gas emissions (Ozturk, 2017; Saidi and Ben Mbarek, 2016; Shahbaz et al., 2015), our analysis focuses on nuclear energy generation, in contrast to that of previous literature (Bandyopadhyay et al., 2022; Pata and Kartal, 2023), and covers a broader set of environmental variables, specifically the ecological footprint, thus adding further depth to the existing body of knowledge, in contrast to the main body of former literature (Arshad Ansari et al., 2020).

Our findings indicate that the consumption of nuclear energy in European Union member societies tends to increase the ecological footprint. However, this environmental degradation is not caused by CO2 emissions. Instead, the impact of nuclear energy consumption is manifested in other aspects of environmental quality, such as deforestation and air quality. Our study considers the ecological footprint as a holistic measure that goes beyond carbon dioxide emissions, encompassing a comprehensive dimension of environmental quality that includes the impact on local biodiversity.

One significant aspect of these relationships is the causality between nuclear energy generation and the reduction of CO2 emissions. We have observed that the causality operates from the latter variable (CO2 emissions) to the former (nuclear energy generation). This suggests that European countries turn to nuclear energy as a less carbon-intensive alternative to mitigate carbon dependency and reduce air pollution, particularly in the form of CO2 emissions. This trend aligns with the transition to green economies and the goal of reducing carbon dependency, which is part of the European Green Deal (Crowley-Vigneau et al., 2023; Dunlap and Laratte, 2022; European Commission, 2023). More concerningly, this situation could be aggravated by political tensions and the role of Russia as an energy supplier to the European Union since the beginning of the war in Ukraine (Zhang et al., 2023a). Consequently, future research should elucidate on these relationships. Previous studies have also highlighted the substitution or reorientation of the energy system toward alternative sources, including renewables and nuclear power, and our conclusions show similar findings.

However, it is important to note that not all European countries support reliance on nuclear energy sources, such as Germany, while others, like France, heavily utilize nuclear energy in their ecological transition process. These trends have further solidified since the early 2020s (EU., 2024). Therefore, considering both the generation and consumption of nuclear energy, as we have done in this study, provides a more comprehensive understanding of its ecological impact compared to previous research.

Thus, it is possible that while the generation of nuclear energy may or may not directly cause environmental deterioration, its consumption does not contribute to carbon emissions. However, in line with Jevons' paradox (Freire-González, 2021; X. Wang et al., 2022), the consumption of nuclear energy may incentivize resource-intensive activities and dynamics, thus framing nuclear energy consumption as a stimulus for resource exploitation and intensifying the ecological footprint. Moreover, this reasoning can help contextualize the non-causality previously observed in the causal analysis, where the effects of electricity consumption indirectly affect the ecological footprint through third-party activities, potentially diluting the direct effects.

Nuclear energy generation is recognized for its absence of CO2 emissions due to the inherent characteristics of nuclear power plants (Pata and Kartal, 2023). Unlike fossil fuel-based power plants, nuclear reactors produce electricity through nuclear fission, a process that does not release carbon dioxide or other greenhouse gases into the atmosphere. The absence of combustion in nuclear reactions eliminates direct CO2 emissions, positioning nuclear energy as a carbon-free source of electricity (Danish et al., 2021; Hassan et al., 2020a; Iwata et al., 2010). This attribute has led to the recognition of nuclear power as a low-carbon or even carbon-neutral energy option, as it does not contribute to the accumulation of greenhouse gases and aids in the mitigation of climate change. Furthermore, the high energy density of nuclear power plants allows the production of substantial amounts of electricity without relying heavily on large quantities of fossil fuels, further reducing the carbon footprint associated with energy generation.

Regarding the other variables, specifically income level based on GDP per capita and its quadratic term, our findings confirm the hypotheses of the environmental Kuznets curve (Grossman and Krueger, 1995; Hao et al., 2022) for both the ecological footprint (EF) and CO2 variables. Higher income levels contribute to environmental degradation up to a certain point, after which this relationship reverses, leading to improved environmental standards. Furthermore, in line with the majority of literature on the subject (Hakkak et al., 2023; Shabbir Alam et al., 2023), our study finds that renewable energy consumption contributes to reducing both metrics of environmental impact estimated in this research.

To capitalize on the environmental benefits of nuclear energy generation, countries often turn to nuclear power as a means to mitigate CO2 emissions and address environmental concerns. As the urgency surrounding climate change and greenhouse gas emissions grows, nuclear power has emerged as a low-carbon alternative to fossil fuel-based energy sources. Thus, the causality relationship observed suggests that countries adopt nuclear energy as a strategy to reduce their carbon emissions and tackle environmental challenges.

Therefore, the integration of nuclear energy into the EU's comprehensive sustainable energy framework can play a crucial role in reducing air pollution effects and helping the EU meet its climate targets. Nuclear power's low carbon emissions make it a valuable addition to the energy mix, enabling a significant reduction in reliance on fossil fuels and their associated air pollution and climate change impacts (EU., 2023, 2024). Additionally, nuclear power plants provide reliable and stable baseload power, complementing intermittent renewable energy sources and reducing the need for fossil fuel-based backup plants that contribute to air pollution (Michaelides and Michaelides, 2020). By diversifying the energy mix with nuclear energy, the EU can enhance energy independence, decrease reliance on imported fossil fuels, and reduce pollution associated with their extraction and combustion. Moreover, nuclear power's long lifespan supports long-term emission reductions, aligning with the EU's commitment to decarbonizing the energy sector and achieving climate goals.

Several European countries have successfully leveraged nuclear energy as a pivotal component of their strategies to decrease CO2 emissions. France, for instance, stands out as a prominent example, with nuclear power contributing to approximately 70 % of its electricity generation. This significant reliance on nuclear energy has enabled France to maintain a low-carbon electricity system and minimize its CO2 emissions (Bandyopadhyay et al., 2022; Iwata et al., 2010). Similarly, Sweden has effectively harnessed nuclear power to reduce its carbon footprint, with nuclear energy accounting for a substantial portion of its electricity production. By capitalizing on the advantages of nuclear energy, these countries have made significant strides in reducing their dependence on fossil fuel-based power generation and have propelled themselves toward achieving their emissions reduction goals and fostering a cleaner energy future.

Expanding on the implications for the scalability and generalizability of the findings in the EU, it is important to consider the diverse factors that may influence nuclear energy adoption within the region. While the study indicates a causal relationship from CO2 emissions to nuclear energy consumption, suggesting that countries with higher emissions are more likely to adopt nuclear power, it is crucial to recognize the unique characteristics of each EU member state. Since EU member states present varying energy profiles, policy priorities, and available resources, factors such as energy infrastructure, political considerations, public acceptance, and economic viability play a significant role in shaping the adoption of nuclear energy within individual countries. Therefore, while the findings provide valuable insights into the overall relationship between CO2 emissions and nuclear energy consumption, applying these findings uniformly across all EU countries may oversimplify the complex dynamics at play.

Governments can adopt specific policies and strategies to promote nuclear energy as part of their broader environmental and energy agendas. This may involve implementing robust energy transition policies that prioritize nuclear power as a low-carbon alternative to fossil fuel-based energy sources. International cooperation and agreements play a crucial role in facilitating the exchange of knowledge, expertise, and resources related to nuclear energy while also ensuring safety standards, proper waste management, and non-proliferation efforts. However, public perception and acceptance are pivotal factors in the political landscape surrounding nuclear energy. Governments must engage in transparent communication, address safety concerns, and involve the public in decision-making processes to foster trust and acceptance of nuclear power as a viable solution for mitigating environmental degradation and reducing CO2 emissions. Additionally, continuous research and development efforts, coupled with stringent regulatory frameworks, are necessary to ensure the safe and sustainable utilization of nuclear energy in the pursuit of environmental and climate goals.

This process must be undertaken Fthe sustainable growth of local economies, as denoted in the European Green Deal. As a consequence, constructing policy frameworks that successfully combine environmental conservation with economic growth goals requires a comprehensive and integrated approach. By way of example, this means that, firstly, policies should incentivize sustainable practices and technologies, promoting resource efficiency, renewable energy, and circular economy principles. This can be achieved through targeted subsidies, tax incentives, and regulatory frameworks that encourage environmentally friendly practices. Additionally, policies should foster innovation and research in green industries, creating new economic opportunities while addressing environmental challenges. Furthermore, integrating environmental considerations into economic decision-making processes, such as cost-benefit analyses and environmental impact assessments, ensures that environmental conservation is given due consideration in development projects. Lastly, effective stakeholder engagement, including collaboration with businesses, NGOs, and local communities, allows for shared ownership and implementation of conservation and growth policies, promoting a balanced and inclusive approach.

Policy interventions play a crucial role in addressing ecological footprint deficiencies within the EU. These interventions can include a range of measures such as regulations, incentives, and awareness campaigns. Policies aimed at promoting sustainable consumption and production patterns, encouraging resource efficiency, and reducing waste generation, can help mitigate ecological footprint deficiencies. Additionally, setting targets and implementing regulations to reduce emissions and promote renewable energy sources can contribute to lowering the EU's ecological footprint. Furthermore, policies that support the conservation and restoration of ecosystems, as well as sustainable land and water management practices, can help protect biodiversity and natural resources, thus reducing ecological footprints.

Further research, encompassing detailed case studies and comprehensive analysis, is indispensable to fully comprehend the specific mechanisms and factors contributing to the observed higher environmental degradation associated with nuclear energy generation, as measured by the EF variable. This research should delve into not only the direct impacts of nuclear energy production but also the indirect effects, such as the environmental effects of the nuclear energy-related activities, which might result into a more intensive demand for natural resources, leading to a higher ecological footprint. By examining the entire lifecycle of nuclear energy, including the nuclear energy supplied activities, a more nuanced understanding of its environmental implications can be achieved. Exploring the interactions between nuclear energy and other environmental indicators, such as land use, resource consumption, and biodiversity, can contribute to a more holistic understanding of the overall environmental footprint associated with nuclear energy generation, in consensus with the exploration of the dynamics and trade-offs between nuclear energy generation and consumption.

Statements

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The authors declare that they have no competing financial interests.

Data availability

Data will be made available on request.

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