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Evaluation of the effectiveness of energy sustainability measures through the dynamic energy consumption model

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The current context of economic development requires paying close attention to the energy industry. Since 2022, European countries has been facing specific problems due to energy crises against the background of the geopolitical conflict and the measures provided by European forums in order to reduce dependence on energy imports from Russia. In this context, we aim to define a new model of energy consumption and the function of energy sustainability at the European level, aspects that will lead to highlighting the position of the 27 European member states in the period 2005–2022 in terms of their energy sustainability. The methodology used is based on the study of literature, the consolidation of databases, econometric modelling, and procedures for testing the validity of modelling results. The results of the study are useful to European energy policy decision-makers in view of the necessary adjustments to achieve the objectives of the 2030 and 2050 Agenda.

KEYWORDS

energy policy, final energy consumption, energy sustainability, econometric model, economic development

1 Introduction

The European energy crisis has been a pressing issue in recent years, with a significant impact on the region's economy and daily life. This crisis has been primarily driven by a combination of factors such as the increasing demand for energy, supply disruptions, and the transition towards renewable sources (Eurostat, 2023h). Additionally, geopolitical tensions and changing weather patterns have further exacerbated the situation, making it important for European countries to implement sustainable and diversified energy strategies to mitigate the effects of this crisis. The EU has set targets to reduce greenhouse gas emissions and increase the share of renewable energy in the overall energy mix, ensuring a more sustainable and secure energy future for Europe (M. Yu et al., 2021). European measures to reduce the energy crisis include promoting renewable energy sources, such as wind and solar power, and increasing energy efficiency through stricter regulations on energy consumption (IEA, 2022). The European Union has implemented policies to encourage energy conservation and the development of innovative technologies to address the energy crisis. Some of the specific regulations implemented include setting energy efficiency standards for appliances and buildings, promoting the use of renewable energy sources, and implementing carbon pricing mechanisms to incentivize the reduction of greenhouse gas emissions. These measures not only help combat climate change, but also stimulate economic growth and job creation in the clean energy sector (IRENA, 2023). The EU's commitment to renewable energy sources has already resulted in the creation of thousands of jobs in the green energy sector. As solar panels and wind turbines become more affordable and efficient, the demand for skilled workers in these industries continues to rise (IEA, 2022). Moreover, the development of energy interconnections between countries opens up new avenues for collaboration and trade, fostering a sense of shared responsibility and mutual benefit.

In this context, we aim to define a new model of energy consumption and the function of energy sustainability at the European level, aspects that will lead to highlighting the position of the 27 European member states in the period 2005–2022 in terms of their energy sustainability.

Given the above context, we consider it important to assess the effectiveness of energy sustainability measures by means of a dynamic energy consumption model and propose to achieve this goal through the following specific objectives:

O1: Identifying a typology of sustainable energy measures found in the literature.

O2: Enhancing the accuracy and reducing the duplication of data by applying dedicated statistical methods to the panel databases.

O3: Developing a new dynamic energy consumption model using panels data regression with fixed effects.

O4: Defining the energy sustainability function based on the new dynamic energy consumption model.

The novelty of the study lies, on the one hand, in the critical analysis of the dynamics of energy consumption, but also in the design of the energy sustainability function that can be used by European decision-makers to develop future energy development strategies in the European Union, thus underlining its importance in ensuring an efficient and sustainable energy transition capable of meeting the current challenges of climate change, energy security and sustainable economic growth. This study provides a robust framework for energy policies that not only optimise resource use, but also promote innovation and resilience in the face of global energy market fluctuations. This being absolutely new at the level of literature. The study continues with the presentation of the extensive study of the literature, the presentation of the methodological approaches, the results and the discussions regarding the level of energy sustainability in Europe, and its conclusions will be presented at the end of the research.

2 Literature review and research hypotheses

Research interest in the sustainable development of the energy sector has increased significantly in recent times especially in areas such as political, economic and social energy security (Luty et al., 2023); green energy transition strategies (Wang et al., 2023); increasing renewable energy sources (Cristea et al., 2022; Kemec and Altinay, 2023; Raza et al., 2023); reducing carbon emissions (Wang et al., 2023; Streimikiene, 2023); the impact of social responsibility on energy poverty reduction (Batool et al., 2023; Shkura and Fedulova, 2023); combating climate change and developing renewable energy sources (Tang and Solangi, 2023; Trojanowski and Kozak, 2023; Tweneboah-Koduah et al., 2023).

According to the Web of Science database, in 2023, 7,343 Open Access articles were published by the phrase "sustainable energy" used in the titles, abstracts or keywords of the articles included in this database (Figure 1). Analysing the 7,343 published articles we find that the Hirsch index was 15 points while the citation rate was 3.97 on an article with no author citations.

We used Vosviewer software to perform a bibliometric analysis grouping the 7,343 articles into areas of research interest such as sustainable development, renewable energy, carbon emissions, performance, optimization, economic growth, green innovations, energy transition, green energy, energy policy, climate change (Figure 1).

2.1 Political, economic and social energy security

In a study, Madurai Elavarasan R. et al. (Madurai Elavarasan et al., 2022) develop a new composite energy sustainability index to assess energy sustainability performance in 40 European countries. The composite index is compared to the current SDG 7 index, which includes indicators defined by the UN. Sensitivity analysis shows that clean energy is the most influential indicator.

Russia's war against Ukraine is a global challenge, causing inflation, disruptions to GDP growth, food and energy crises, and supply chain pressures. The volatility of energy prices adds uncertainty to socioeconomic relations, turning energy into a weapon against stability, authors Shkura and Fedulova (Shkura and Fedulova, 2023) state. The study confirms the close relationship between sustainable investment and the sustainable competitiveness of countries, indicating that increasing volumes of sustainable investment and clean energy projects are the primary conditions for sustainable competitiveness. In the current context of energy crises and the transition to renewables, the relationship between final energy consumption and import dependency is becoming increasingly relevant for European energy policy. The author Hille (Hille, 2023) provides empirical evidence in recent research on the effect of geopolitical risks in fossil fuel supplying countries on the diffusion of renewable energy in fossil fuel importing countries and the mediating role of rising electricity prices and high import dependence. The results of the study showed that rising electricity prices and high import dependence, especially for coal, partially amplified the effects on renewable energy diffusion, and despite high import dependence, natural gas seems to have partially played the role of a transition technology for energy transition.

Interesting research has been carried out by the authors Rokicki et al. (Rokicki et al., 2023) assessing the impact of the crises resulting from the COVID-19 pandemic and the war in Ukraine on changes in the European Union's dependence on imports of energy commodities, particularly from Russia. The results showed changes in the energy balance of the whole EU in the period before and during the COVID-19 pandemic and the war in Ukraine, showed changes in the concentration of energy imports

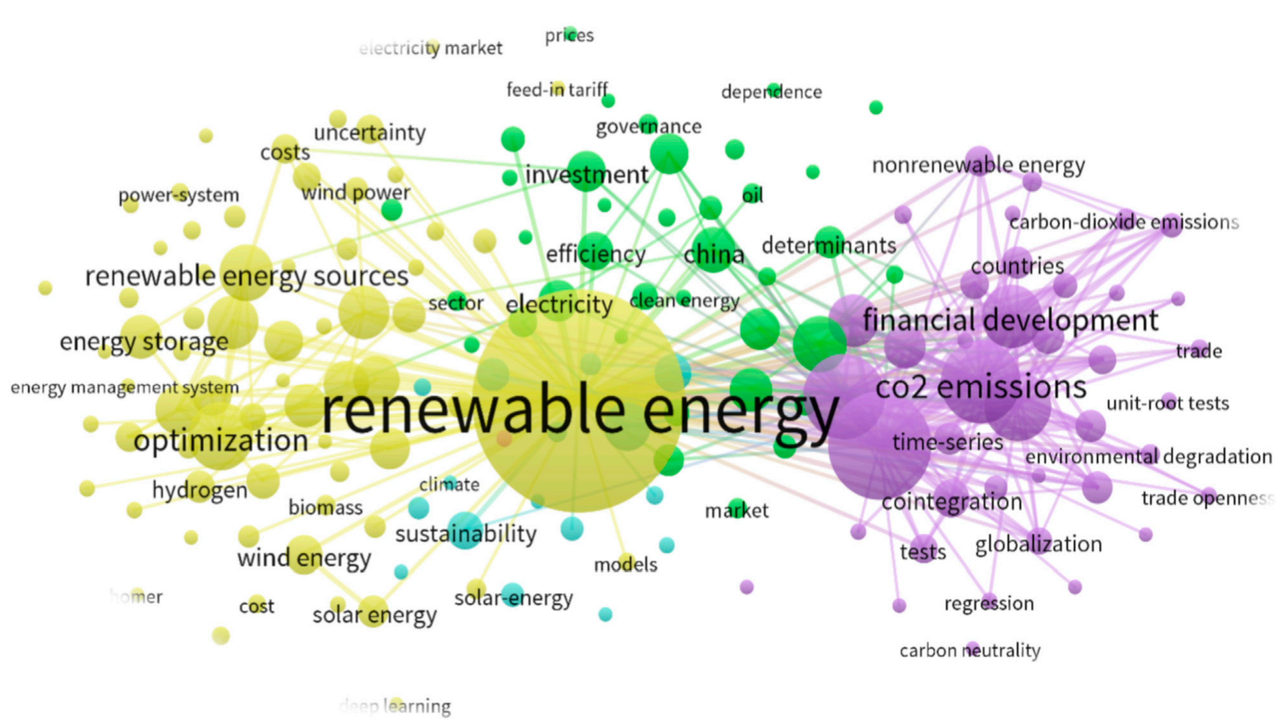

FIGURE 1
The bibliometric analysis of sustainable energy in the reference literature. Source: Elaborated by the authors using Vosviewer software.

TABLE 1 Indicators of analysis at European member state level, for the period 2005–2022.

Symbol	Explanation	Unit of measure	Source
FEC	Final energy consumption - Dependent Variable	Million tonnes of oil equivalent *per capita*	Eurostat (Eurostat, 2023d)
EIMPD	Energy import dependency	%	Eurostat (Eurostat, 2023b)
SRNWEN	Share of renewable energy in gross final energy consumption	%	Eurostat (Eurostat, 2023i)
PEC	Primary energy consumption	Million tonnes of oil equivalent *per capita*	Eurostat (Eurostat, 2023f)
NGRNHE	Net greenhouse gas emissions	%, (1990 = 100)	Eurostat (Eurostat, 2023e)
GDPCAP	Real GDP *per capita*	Euro *per capita*	Eurostat (Eurostat, 2023g)
ENPROD	Energy productivity	Euro per kilogram of oil equivalent	Eurostat (Eurostat, 2023c)

Source: Elaborated by the authors.

into EU countries during crises, identified the dependence on imports of individual energy resources for the whole EU, identified the dependence of the whole EU on imports of individual groups of energy resources from Russia, and showed changes in the concentration of energy imports from Russia into EU countries during crises.

With the Russian invasion of Ukraine in 2022 and the subsequent disruption of Russian natural gas imports, Europe's energy dependence on Russia has become more apparent, necessitating a detailed investigation of the short and long-term effects on the development of the European energy system. The authors Moskalenko et al. (Moskalenko et al., 2024) quantitatively analysed the impact of reduced availability of Russian natural gas on the European energy system. The results showed that the effects are more pronounced in the short and medium term, but in the long term a faster phase-out of fossil fuels can be achieved. The reduction in gas imports is offset by increased LNG imports and domestic gas production to cover the supply shortfall. Limiting imports of fossil fuels from Russia is also not a long-term threat to the European energy system or to the transition away from fossil fuels, but can accelerate the process of decarbonisation and reduce energy demand.

According to the authors F. Liu et al. (Liu et al., 2023) increasingly complex global geopolitical situations have a serious impact on energy markets and make renewable energy (RE) the best energy option. By applying the moving window Granger causality test, the authors find that political risk has a positive and negative impact on renewable energy. However, renewable energy expansion is vulnerable to national policy changes and critical resource competition, which induces new geopolitical conflicts.

TABLE 2 Hausman test.

Variable	(b) fixed	(B) random	(b-B) Difference	Std. err.
SRNWEN	0.0955	0.1923	−0.0968	0.0000
EIMPD	0.0700	0.0786	−0.0086	0.0000
PEC	0.4577	0.6562	−0.1985	0.0050
NGRNHE	0.0249	−0.0011	0.0260	0.0000
GDPCAP	0.0002	−0.00001	0.0002	0.0000
ENPROD	−0.4829	0.3602	−0.8431	0.0000
b = Consistent under H0 and Ha; obtained from xtreg.				
B = Inconsistent under Ha, efficient under H0; obtained from xtreg.				
Test of H0: Difference in coefficients not systematic				
chi2 (6) = 1523.70				
Prob > chi2 = 0.0000				

TABLE 3 Model summary.

Fixed-effects (within) regression			Number of obs = 504			
Group variable: DMU			Number of groups = 28			
R-squared			Obs per group			
Within = 0.8972			Min = 18			
Between = 0.9983			Avg = 18.0			
Overall = 0.9976			Max = 18			
corr (u_i, Xb) = 0.9912			F (6, 470) = 683.84			
			Prob > F = 0.0000			
FEC	Coefficient	Std. err.	t	P>|t|	[95% conf. interval]	
SRNWEN	0.0955	0.0390	2.45	0.015	0.0187	0.172
EIMPD	0.0700	0.0179	3.91	0.000	0.0348	0.105
PEC	0.4577	0.0076	59.54	0.000	0.4426	0.472
NGRNHE	0.0249	0.0125	1.98	0.048	0.0002	0.049
GDPCAP	0.0002	0.00008	3.22	0.001	0.0001	0.0004
ENPROD	−0.4829	0.2258	−2.14	0.033	−0.9267	−0.0390
_cons	13.4196	2.1235	6.32	0.000	9.2468	17.592
sigma_u 66.412032						
sigma_e 2.5422525						
Rho 0.99853679 (fraction of variance due to u_i)						
F test that all u_i = 0: F (27, 470) = 103.78 Prob > F = 0.0000						

The latest global financial and real turmoil has highlighted the importance of stable and effective economic policies according to the authors Dima et al. (Dima et al., 2017). Using a recently developed measure of economic policy uncertainty, the authors found that inflation volatility exerts the largest overall impact, followed by personal consumption expenditure volatility, while trade and industrial credit have a small (albeit significant) effect, thus stable and predictable economic policy is essential for economic growth.

TABLE 4 Hadri LM test.

Hadri LM test		
H0: All panels are stationary	Number of panels =	28
Ha: Some panels contain unit roots	Number of periods =	18
Time trend: Not included	Asymptotics: T, N ->	Infinity
Heteroskedasticity: LR variance: Not robust (not used)		
	Statistic	*p*-value
FEC	31.5850	0.0000
SRNWEN	49.8685	0.0000
EIMPD	28.5739	0.0000
PEC	43.2944	0.0000
NGRNHE	31.5655	0.0000
GDPCAP	41.8524	0.0000
ENPROD	48.0593	0.0000

The results of the Hadri LM, test (large statistics and *p*-value of 0.0000) indicate that the null hypothesis can be rejected for all variables. This means that there is strong evidence that some panels are non-stationary and contain unit roots.

This approach provides evidence to support working hypothesis number one.

H1. At the European level, the level of final energy consumption is directly dependent on the increasing dependence on import.

A group of authors Rokicki T. and others (Rokicki et al., 2022) find that the COVID-19 pandemic has had a significant impact on energy consumption and intensity in different in the countries of the European Union (Stankowska, 2022). The authors show that the structure of energy consumption has remained unchanged, dominated by industry, transport and households, and the pandemic has reduced energy consumption in all sectors, with transport and services being the largest and industry being the smallest. The pandemic has also increased energy intensity across all sectors, with Western European countries being less energy intensive than Central and Eastern European countries. In a relevant paper (Tsemekidi Tzeiranaki et al., 2019) analyzes trends in residential energy consumption in the EU, focusing on energy and climate strategies for 2020 and 2030. The analysis highlights the complex dynamics behind energy demand in the residential sector. A group of authors Reuter M. and others (Reuter et al., 2019) analyzes the effects of autonomous policies and developments on final energy consumption in the European Union (EU28). The results show that energy efficiency in industry leads to final energy consumption, followed by households, with space heating being the main energy savings. Energy efficiency is recognised as one of the surest ways to tackle some of the most pressing global challenges, including ensuring energy independence and combating the negative effects of climate change. Focusing on the EU28 since 2000, the authors Román-Collado and Economidou (Román-Collado and Economidou, 2021) in one study sought to identify the main drivers behind changes in energy consumption at global and sectoral levels. The results provide some energy policy recommendations related to the effectiveness of past energy efficiency measures. Higher energy productivity means that more economic activity is carried out with less energy, which reduces final energy consumption. Given the increasing consumption and use of resources linked to the growth of human activity that threatens both energy security and sustainability, in order to ensure and integrate environmental wellbeing through channels such as energy efficiency, the authors Quito et al. (Quito et al., 2023) examined the relationship between energy efficiency, renewable energy and financial development. The data analysed showed that the use of renewable energy is conducive to energy efficiency improvements and that moving closer to countries that replace traditional energy use with alternative sources has a positive effect on national energy efficiency.

The energy crisis caused by Russia's invasion of Ukraine has highlighted Europe's vulnerability to external fluctuations in energy supply. Reduced Russian gas imports have forced the EU to reconfigure its energy sources, highlighting the importance of energy productivity in managing final energy consumption. Studies show that economies with high energy productivity are more resilient to energy crises because they can maintain economic activity with low energy consumption (Farghali et al., 2023; Halkos and Aslanidis, 2023). Energy efficiency measures, such as upgrading infrastructure, promoting green technologies and adopting stricter efficiency standards, contribute to increasing energy productivity. These measures have a direct impact on reducing final energy consumption. Investments in energy efficiency are key to achieving the EU's climate goals and ensuring long-term energy security. The REPowerEU plan underlines the importance of these measures in the context of the energy transition (Demertzis and Ruer, 2024).

In summary, the role of energy imports, energy productivity, renewable energy, and the reduction of greenhouse gas emissions are interconnected through the lenses of political, economic, and social energy security. The political landscape, influenced by geopolitical tensions and energy dependencies, drives the urgent need for energy independence and the adoption of renewable energy. Economically,

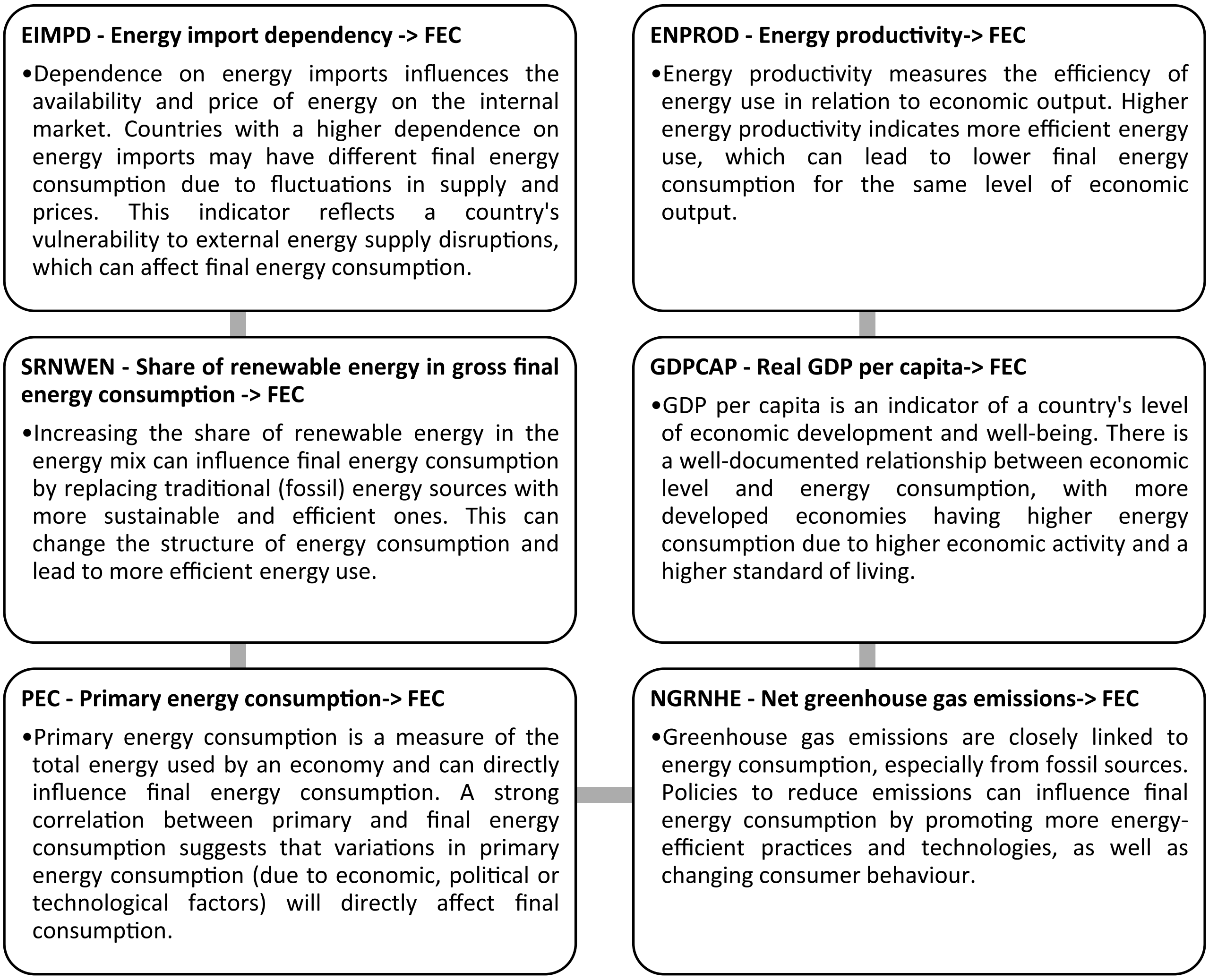

FIGURE 2
Argumentation for the selection of indicators. Source: Elaborated by the authors.

enhancing energy productivity and investing in renewable energy projects are crucial for stabilizing markets and ensuring sustainable growth. Socially, these efforts contribute to improved living standards, energy reliability, and the overall resilience of communities in the face of climate change and economic uncertainties. The transition to a sustainable energy system is not just an environmental imperative but a multifaceted strategy for comprehensive energy security.

This approach provides evidence to support working hypothesis number two.

H2. Energy productivity has a direct, proportional, and significant influence on final energy consumption, which is sensitive to the effects of the energy crisis.

2.2 Green energy transition strategies

The main objective of the European Union is to increase the use of renewable energy sources, increase energy efficiency and reduce dependence on imported fossil fuels, according to research by the authors Senegacnik et al. (Senegacnik et al., 2023).

In a study carried out by the authors Tutak M. and Brodny (Tutak and Brodny, 2022a) the impact of renewable energy consumption on the economy, the environment and conventional energy sources in the European Union is analyzed. The results of the study show us a significant increase in the consumption of renewable energy, with significant differences between countries and sectors. Another paper (Tu et al., 2022) analyzes the determinants of renewable energy development in 27 EU member states in the period 2011–2020. The results of the study show us that economic development and high employment in advanced technology production boost the deployment of renewable energy, while unemployment negatively affects deployment. Geographical location is a determining factor, and policy implications include economic deregulation, open market development, and educational transformations.

The COVID-19 pandemic, the climate crisis and the war in Ukraine have highlighted the need for sustainable energy transition and locally sourced renewable energies. However,

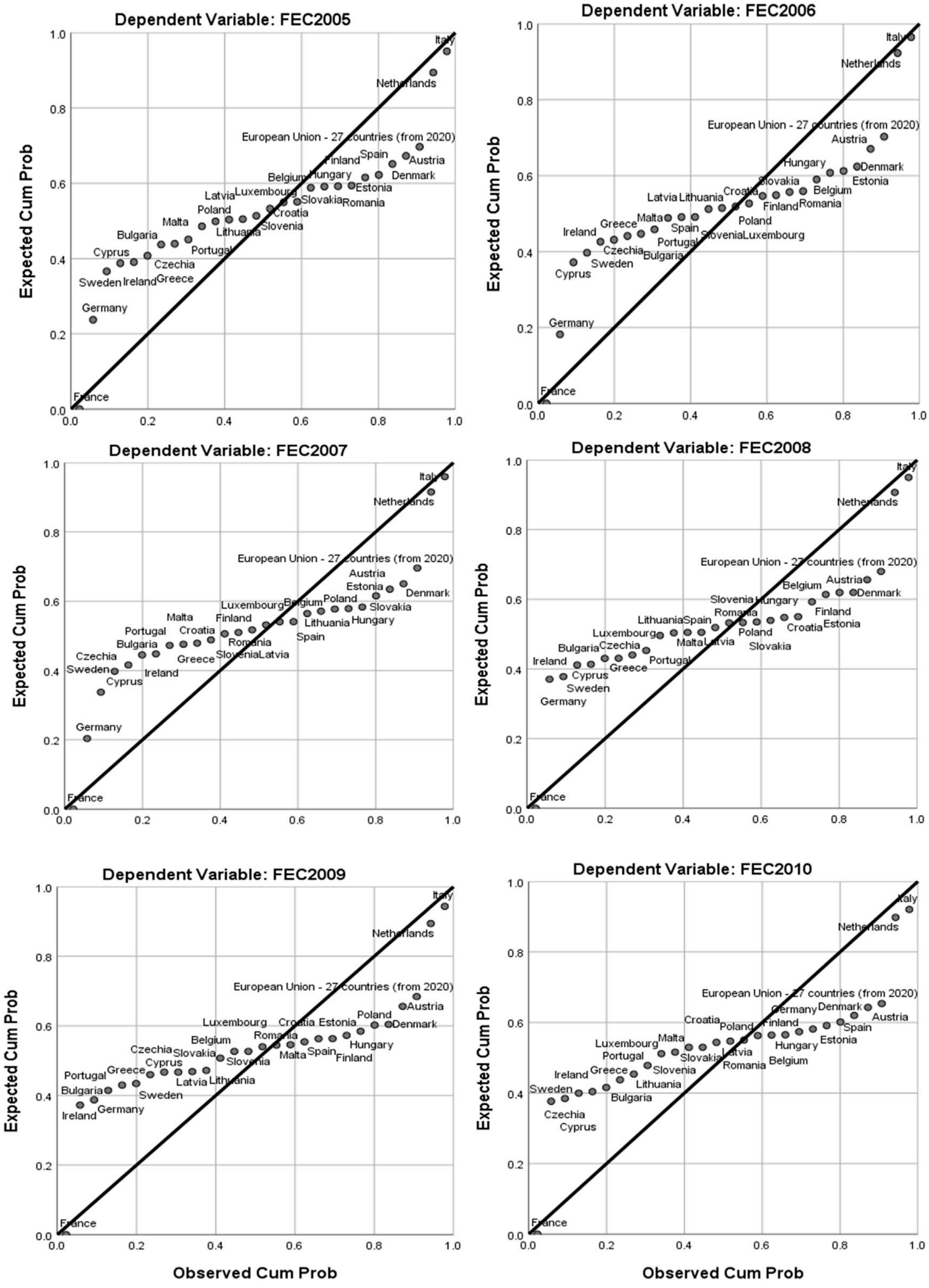

FIGURE 3
P-P Plot of the standardized regression for the dependent variable FEC over the period 2005–2010. Source: Elaborated by the authors using SPSS software v.26.

local communities face various models, preconditions and implications that affect their implementation stated the collective of authors formed by Kazak et al. (Kazak et al., 2023). The study explores the spatial distribution and discrepancies in the implementation of renewable energy, insufficient support for the expansion of local renewable energy systems is an obstacle to adapting to the climate crisis and balancing local energy supply and demand.

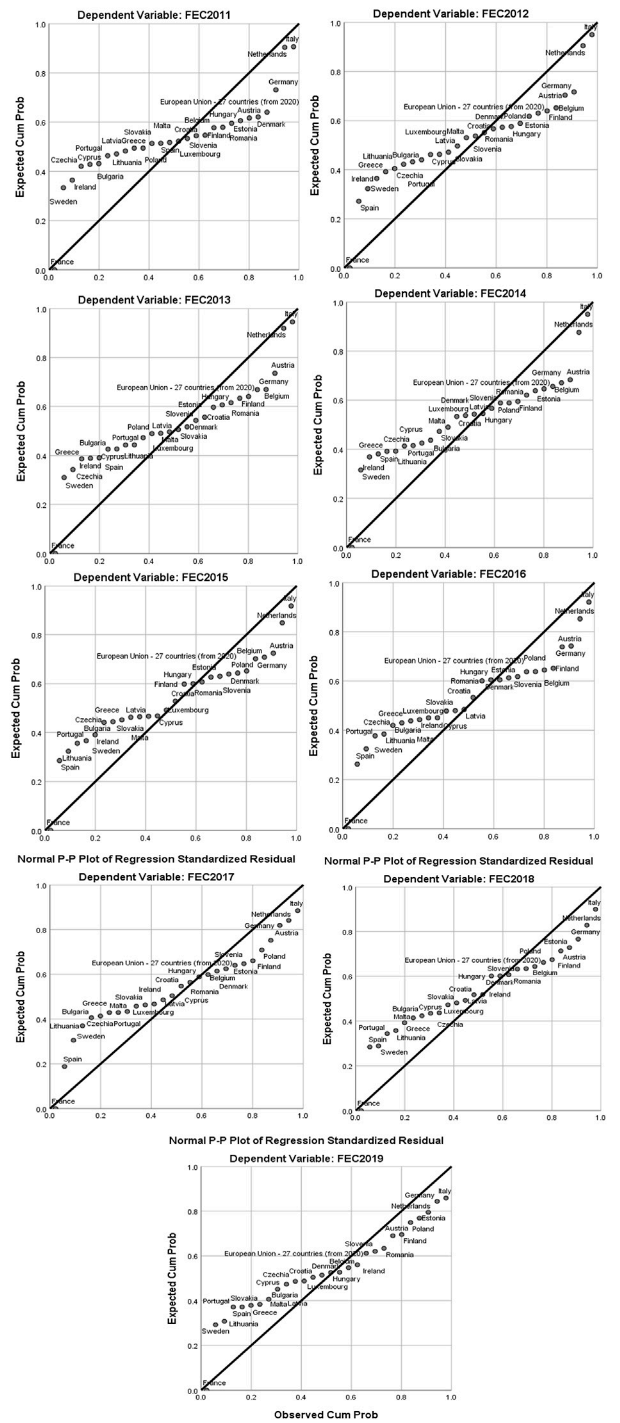

FIGURE 4
P-P Plot of the standardized regression for the dependent variable FEC over the period 2011–2019. Source: Elaborated by the authors using SPSS software v.26.

A survey conducted in a small village in Galicia by Haq et al. (Haq et al., 2023) reveals the heterogeneity of investors' attitudes and concerns, affecting their willingness to invest in renewable energy projects. Rural areas are essential for the sustainable energy transition and the mitigation of climate change through renewable energy technologies according to the collective of authors Miramontes-Vina et al. (Miramontes-Vina et al., 2023). However, renewable energy planning and decision-making in rural areas have not been developed at the local level, focusing on alternative sources. In the study the authors suggest the development of a rural index of renewable energy potential to identify suitable locations for hybrid renewable energy systems.

Energy sustainability in the EU is directly influenced by increasing the share of renewable energy in gross final energy consumption. As this share increases, there is a reduction in dependence on fossil fuels and an improvement in energy efficiency. According to the authors Rodríguez et al. (Rodríguez et al., 2023), energy efficiency is a critical issue in public policy, as it is the key to decoupling economic growth and energy consumption to cope with the energy crisis and the new geopolitical scenarios offered by the war in Ukraine. The authors defined six scenarios for energy savings in primary and final energy consumption for both fossil fuel products and all energy products, using Portugal as a case study. The results of the simulated scenarios provided relevant information for policymakers on: heterogeneous effects on efficiency and GDP, the impact of taxation, energy policy efficiency and energy intensity indicators. The results showed that the size of the trade-off between economic and environmental concerns depends on the location and type of energy savings targeted.

Other authors Halilbegović et al. (Halilbegović et al., 2023) set out to investigate the relationship between economic growth and renewable and non-renewable energy consumption in nine countries in South-Eastern Europe using panel estimation and causal inference techniques. Empirical results indicated that both renewable and non-renewable energy consumption positively affect economic growth. Green transition is at the heart of the European political agenda to achieve the ambitious goal of climate neutrality, following the launch of the European Green Deal. The authors Chatzistamoulou and Koundouri (Chatzistamoulou and Koundouri, 2024) developed a conceptual framework to study the green transition as a system of resource efficiency measures affected by feedback loops, path dependency, green technologies and green policy instruments by designing a single balanced panel covering the EU-28 states from 2010 to 2019, including policy efforts that pave the way for the green transition. Econometric results based on a system of fractional probit models indicated that resource efficiency measures are interconnected through feedback loops, particularly in the case of eco-efficiency. Green technologies affect the green transition, but in the case of energy efficiency there are feedback effects. Evidence suggests that green taxation favours energy efficiency while hindering eco-efficiency. The asymmetric functioning of feedback loops and green taxation on energy and environmental efficiency highlights that horizontal policies hinder rather than foster the green transition.

The United Nations' adaptation of the 2030 Sustainable Development Goals (SDGs) agenda has shifted attention to sustainability. In a recent study the authors Azam et al. (Azam et al., 2023a) investigated the link between agricultural productivity, renewable energy, ICT, human capital, CO_2 emissions and natural resources in a panel of ten European Union (EU) countries from 1996 to 2019. Empirical results showed that a 1% increase in the renewable energy, ICT and human capital coefficients increases agricultural productivity by 0.174%, 0.030% and 2.158% in the long run, while CO_2 emissions and natural resources decrease agricultural productivity.

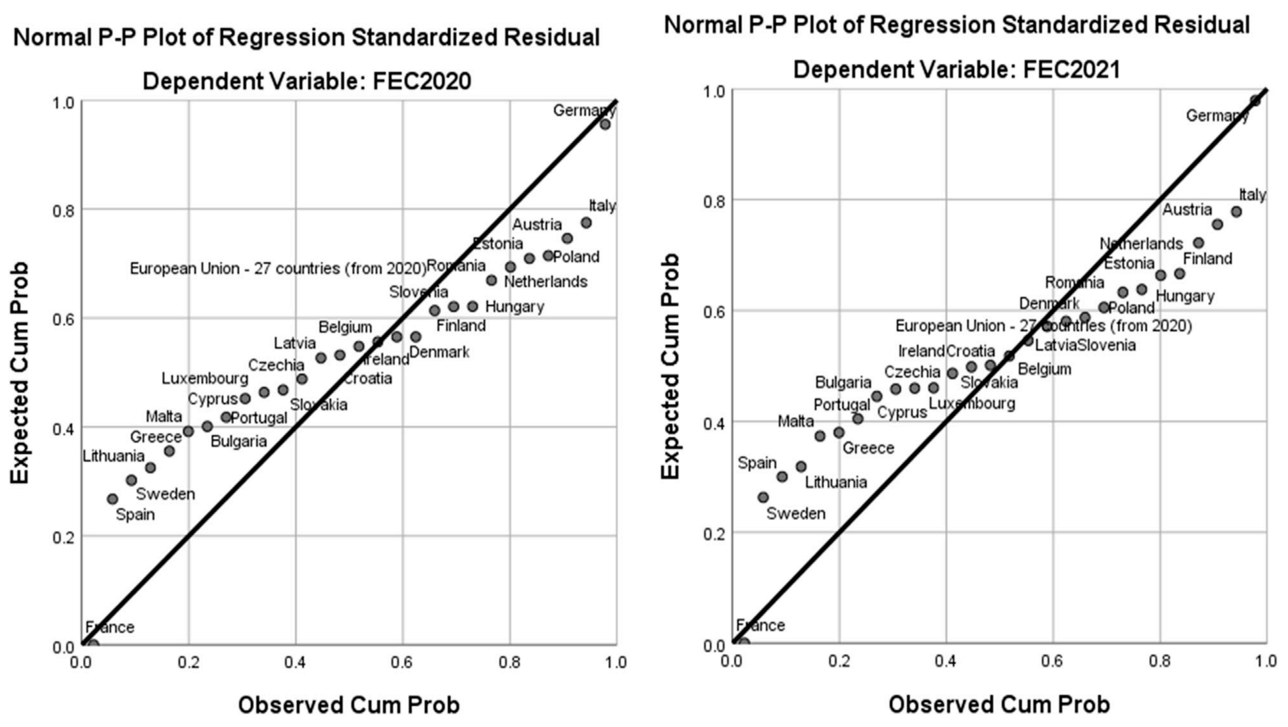

FIGURE 5
P-P Plot of the standardized regression for the dependent variable FEC over the period 2020–2021. Source: Elaborated by the authors using SPSS software v.26.

The dynamic link between green energy, employment, fossil fuel energy and the human development index, including additional variables such as education, life expectancy and poverty, based on panel data from 30 developing countries over the period 1990–2017 was conducted by the authors Azam, Rafiq, et al. (Azam et al., 2023b). The results showed that all variables are co-integrated and the regression analysis results indicated that green energy, education, life expectancy and employment increase the human development index, but fossil fuel energy and poverty decrease the human development index by −0.016% and 0.023%. The vector error correction model showed that there is a bidirectional causality between green energy consumption and the human development index, for developing countries the development and use of green energy sources (wind, solar, geothermal, etc.) is needed.

In the context of globalisation, global warming is emerging as a consequence of climate change, drawing researchers' attention to the need to achieve sustainability by ensuring sufficient access to energy and reducing negative environmental impacts. Given the circumstances outlined above, the authors Azam et al. (Azam et al., 2022) conducted a study examining the heterogeneous impact of nuclear power, renewable energy and information and communication technologies (ICTs) on reducing pollution emissions for the top five countries with the highest emissions, covering data from 1995–2017. The results showed that nuclear energy consumption is insignificant in terms of its contribution to reducing environmental pollution.

Renewable energy consumption and information and communication technologies (ICT) significantly reduce carbon emissions in large greenhouse gas emitting economies, with a more pronounced negative influence at the (0.30–0.80) and (0.10–0.20) quantiles. Both factors contribute to reducing environmental pollution in the five countries analysed. Finally, the findings of the study provide key policy recommendations for policymakers.

In summary, the text highlights the EU's strategic focus on reducing energy imports, improving energy productivity, increasing the share of renewable energy, and reducing greenhouse gas emissions. These goals are interconnected, with renewable energy playing a central role in enhancing energy security, improving energy efficiency, and mitigating climate change. The studies cited provide a comprehensive view of the challenges and opportunities in achieving these objectives, emphasizing the importance of policy support, technological innovation, and community involvement in driving the sustainable energy transition.

This approach provides evidence to support working hypothesis number three.

H3. Energy sustainability is expressed by the dynamic increase of the FEC dependence on the indicator Share of renewable energy in gross final energy consumption.

2.3 Combating climate change and developing renewable energy sources

Authors Zaharia A. and others (Zaharia et al., 2019) analyze the influence of the SDG 7 factors on primary and final energy

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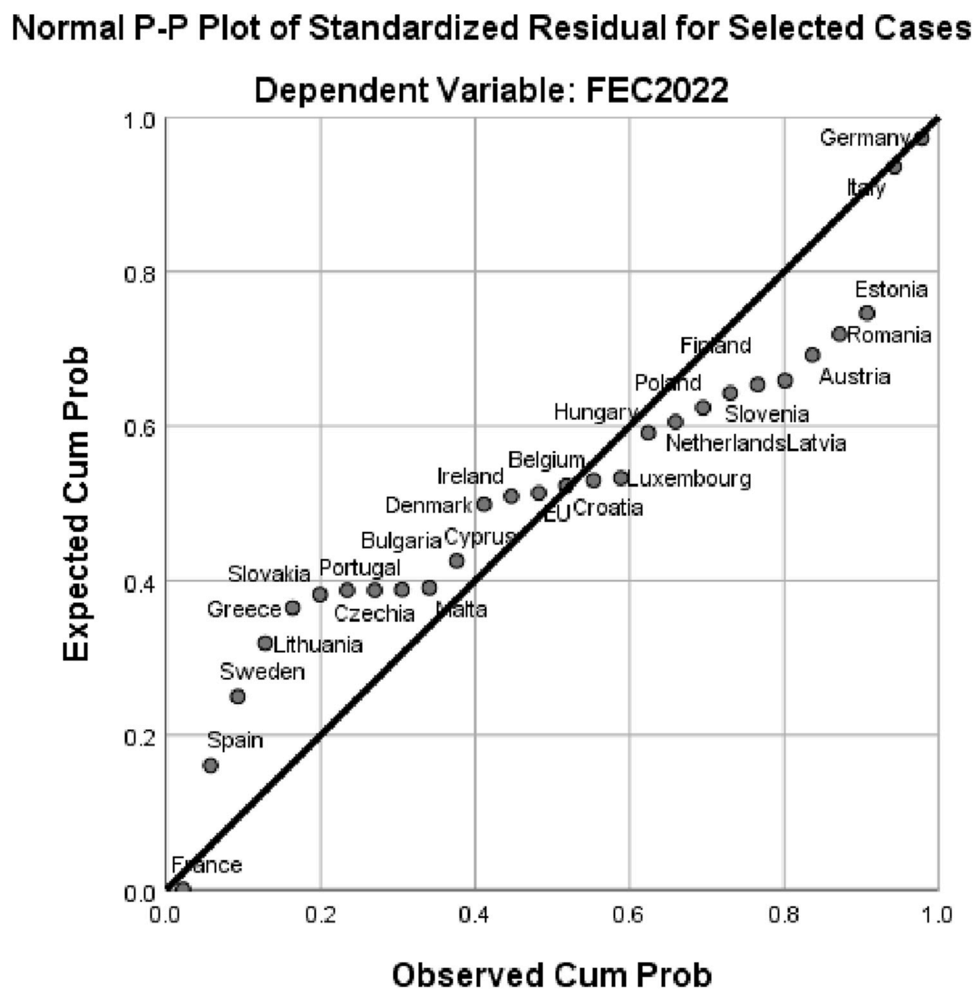

FIGURE 6
P-P Plot of the standardized regression for the dependent variable FEC in 2022. Source: Elaborated by the authors using SPSS software v.26.

consumption through a panel analysis. The results of the study show us that greenhouse gas emissions, GDP, population, and labor force growth positively influence energy consumption, while female population growth, healthcare spending and energy taxes have a negative impact on consumption. An interesting work by the authors Golombek et al. (Golombek et al., 2022) looks at the development of the European electricity sector in line with the EU's climate and energy targets for 2030 and 2050. It examines energy storage and transport under different scenarios, including the costs of electric batteries, restrictions on the expansion of transmission network and the future variability of electricity demand. Two models, LIBEMOD and TIMES-Europe, are used to analyze decarbonization, considering weather-dependent renewable energy generation and electricity demand uncertainty. The study shows that the European energy sector can decarbonize with 65%–70% wind and solar power by 2050.

In an interesting paper, a collective of authors Liu et al. (Liu et al., 2023) using the Granger causality test examined the link between renewable energy and sustainable development. The results of the study showed that energy from renewable sources can alleviate environmental burdens and contribute to the progress of sustainable development. However, as the authors state, economic and government policy changes can affect sustainable investment in the renewable energy sector, with negative impacts on renewable energy development. The relationship between sustainable development, renewable energy consumption, non-renewable energy use and GDP was examined by author Guney (Guney, 2023) using OECD nation statistics from 1990–2015 and adjusted net savings as an indicator of sustainable development. Research results showed that a 1% increase in renewable energy use increases sustainable development by 0.06%.

Sustainable energy consumption in households involves energy savings and renewable energy sources, which contribute to the reduction of greenhouse gas emissions, states the author Streimikiene (Streimikiene, 2023). In this study, the author analyzes the behavioral barriers and offers policy recommendations to overcome these barriers. Climate change mitigation policies primarily target the energy supply sector but struggle to overcome behavioral barriers. Chien et al. (Chien et al., 2023) examine the role of carbon finance, taxes, sustainable energy technologies, industrialization and population growth in ASEAN countries. To achieve the goal of zero carbon emissions, the adoption of green technologies and sustainable investments in green technologies are necessary. Recent research (Adebayo and Ullah,

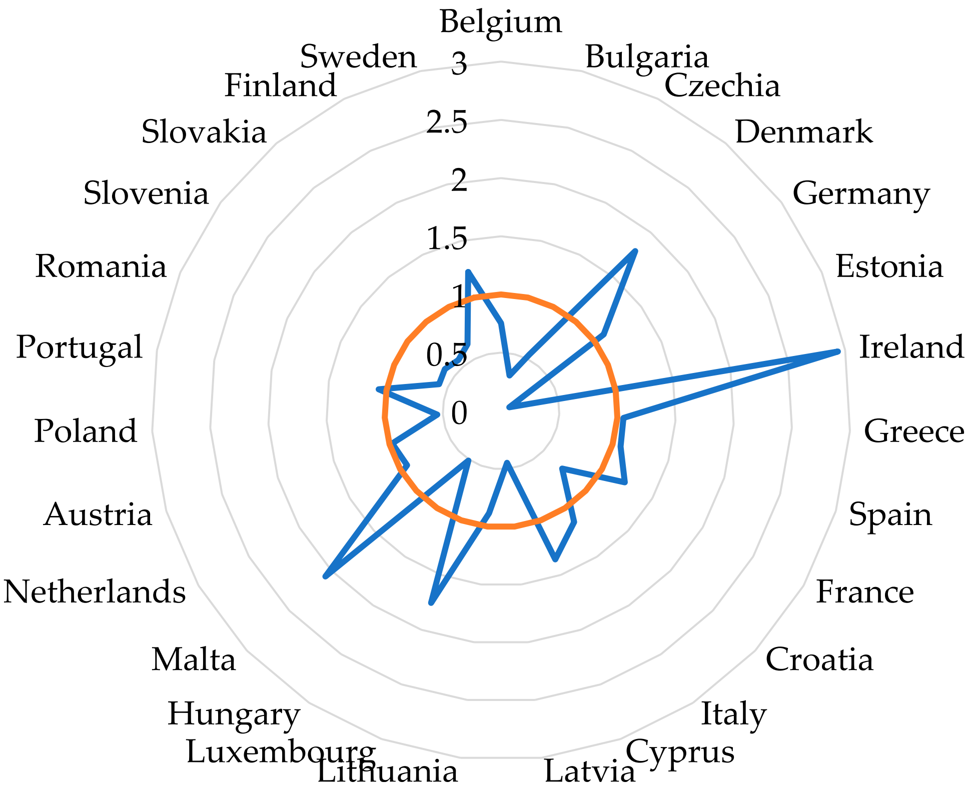

FIGURE 7
Energy sustainability chart for Member States in 2022. Source: Elaborated by the authors.

TABLE 5 The impact of energy policies at European level based on the fixed effects model.

Determined effect	Proposed policy	Policy implementation by constituent elements
H1 Dependence on energy imports (as countries become more dependent on imported energy, their total energy consumption tends to increase) FEC ~ EIMPD (β >0)	Reducing dependence on energy imports by promoting local renewable energy sources and diversifying import sources	Encourage exploration and exploitation of local oil and gas resources where possible. Develop biofuel production capacity to reduce dependence on fossil fuel imports.
H2 Energy productivity (improving energy use efficiency can reduce total energy consumption) FEC ~ ENPROD (β <0)	Promote energy efficiency measures in all sectors of the economy, including through efficient technologies, strict regulations and financial incentives.	Imposing minimum energy efficiency standards. Retrofitting energy-efficient industrial equipment. Promoting energy efficient technologies.
H3 Share of renewable energy in gross final energy consumption (use of renewable energy can boost total energy consumption due to possible cost savings and efficiencies) FEC ~ SRNWEN (β >0)	European governments should continue and increase support for renewable energy, ensuring that infrastructure and regulations are adapted to facilitate its efficient integration.	Providing grants for the installation of solar panels, wind turbines and other renewable energy technologies for households and businesses. Implementing a system of guaranteed tariffs for electricity from renewable sources, providing a fixed price per kWh for green energy producers. Simplify permitting procedures and reduce bureaucratic barriers for renewable energy projects.
H4 Net greenhouse gas emissions (high energy consumption contributes to increased greenhouse gas emissions) FEC ~ NGRNHE (β >0)	Implement policies to reduce greenhouse gas emissions by promoting energy efficiency and low-emission energy sources.	Introduction of carbon taxes and emissions trading schemes. Investment in carbon capture and storage technologies to reduce emissions from the industrial and energy sectors.

2023) showed a significant negative correlation between CO2 emissions and energy efficiency measures such as coal and gas, as well as renewable energy use and urbanization. The authors Sharif et al. (Sharif et al., 2023) investigated the impact of green energy, environmental innovations on US economic growth and CO2 emissions. The authors' approach shows that green energy consumption mitigates CO2 emissions, while eco-innovations contribute to economic growth by reducing emissions, with a bidirectional causality between green energy consumption, economic growth, and CO2 emissions. Authors Kemec and

Altinay (Kemec and Altinay, 2023), based on bibliometric research, have shown that sustainable energy is an emerging topic in research in the field of sustainability and energy, with a significant number of published publications, a field that, by exploring current developments, highlighting the gaps in the specialized literature, is also recommended for future research on lasting development.

The European Union has set ambitious targets for reducing greenhouse gas emissions under the Paris Agreement. These targets include reducing emissions by 55% by 2030 and achieving climate neutrality by 2050 (European Commission, 2023). The EU's decarbonisation strategies involve transitioning to renewable energy sources, improving energy efficiency and reducing reliance on fossil fuels. These measures are key to achieving emission reduction targets (European Environment Agency, 2024). The authors Nagaj et al. (Nagaj et al., 2024) sought to assess the effectiveness of three main decarbonisation strategies adopted by EU economies, namely improving energy efficiency, promoting renewable energy consumption and reducing fossil fuel consumption. The research results highlight that, within decarbonisation policies, improving energy efficiency and increasing the share of renewable energy sources in total consumption have a statistically significant impact on reducing carbon dioxide emissions in almost all EU countries. On the other hand, the strategy with the least impact, adopted by only a minority of Member States, focuses on reducing the share of fossil fuels in primary energy consumption. Reducing greenhouse gas emissions automatically implies a decrease in final energy consumption from non-renewable sources. This is achieved by adopting energy efficient technologies and increasing the share of renewable energy in the energy mix. As the global population grows, the demand for energy is continually increasing due to technological advances and globalisation, and the finite nature of traditional energy sources has spurred the transition to renewable energy, especially in developing countries where environmental degradation and declining quality of life are major concerns. The authors Dilanchiev et al. (Dilanchiev et al., 2023) have analysed the interaction between urbanisation, carbon dioxide emissions, economic growth and renewable energy production in the member states of the Organisation of the Black Sea Economic Cooperation, offering new insights into the energy market. Using annual data from 1995 to 2020 and advanced panel cointegration tests, the authors have produced a comprehensive analysis of the determinants of renewable energy for developing countries. The results showed a substantial and long-term relationship between urbanisation, emissions, growth and renewable energy production and have important implications for policymakers and highlight the critical role of renewable energy in mitigating climate change in developing countries.

In summary, combating climate change and developing renewable energy sources are intertwined goals that require a multifaceted approach. Reducing dependence on energy imports, particularly from politically unstable regions, enhances energy security and supports the transition to renewable energy. Improving energy productivity through policies that promote energy efficiency and reduce consumption is crucial for sustainable development. The expansion of renewable energy is central to mitigating climate change, with significant potential for reducing greenhouse gas emissions. The studies analyzed emphasize the importance of supportive policies, technological innovation, and behavioral changes to achieve these objectives. The findings collectively highlight the need for comprehensive strategies that integrate political, economic, and social dimensions to effectively combat climate change and promote renewable energy development.

This approach provides evidence to support working hypothesis number four.

H4. Reducing greenhouse gas emissions is a European attribute of energy sustainability and has an inverse proportional influence on final energy consumption.

3 Methodology

This study aims to identify and analyse the determinants of final energy consumption (FEC) in European Union (EU) Member States over the period 2005–2022 using information from the Eurostat platform (Eurostat, 2023a) to design a panel data model with fixed effects. The theoretical framework aims to investigate the determinants of final energy consumption (FEC) in the European Union, focusing in particular on the role of energy import dependence, the share of renewable energy, primary energy consumption, greenhouse gas emissions, GDP *per capita* and energy productivity. The study provides new insights and fills gaps in the existing literature, contributing to the development of more efficient and sustainable energy policies. Unlike many studies in the literature that focus on a single factor, this research integrates multiple variables, including the share of renewable energy and energy productivity, to provide a holistic understanding of FEC. From a renewable energy share perspective this research investigates the direct impact of renewable energy share on the FEC, providing empirical evidence on how increasing renewable energy use influences overall energy consumption patterns. With respect to energy import dependency the study examines how energy import dependency directly affects the FEC, contributing to the energy security and sustainability discussions by showing the quantitative impact of import dependency. By linking PEC to FEC, the study provides a nuanced view of how total energy demand translates into end-user consumption, highlighting the importance of reducing primary energy consumption to lower FEC. Through empirical analysis of the impact of energy productivity on FEC, the research highlights its role in decoupling economic growth from energy consumption. The methodology used takes into account the estimation of the power of the model with fixed or random effects using the Hausman test, the independence of the residuals using the Breusch-Pagan test, the application of the Pesaran's test for cross-sectional independence and the modified Wald test for heteroscedasticity. The Hadri LM test was also applied to test for deviations from stationarity. The proposed model is based on the use of the multiple linear regression method with fixed effects (according to the Hausman test results) whose validity was tested by calculating the statistical representativeness of the model and testing the error distributions at the chosen representativeness threshold of 5%.

In order to quantify the dynamics of final energy consumption as a dependent variable, in the fixed-effects panel regression model we designed the model equation with reference to sustainability indicators expressed by the dynamics of energy import dependency, the dynamics of the transition to green energy, primary energy consumption, greenhouse gas emission limitation, sustainable development and energy productivity dynamics at the level of each European Member State. Based on the consolidated data, we designed the model Equation 1 as shown below:

$$FEC_{it} = \beta 0 + \beta 1 * \mathrm{SRNWEN}_{it} + \beta 2 * \mathrm{EIMPD}_{it} + \beta 3 * \mathrm{PEC}_{it} + \beta 4 * \mathrm{NGRNHE}_{it} + \beta 5 * \mathrm{GDPCAP}_{it} + \beta 6 * \mathrm{ENPROD}_{it} + u_i + \varepsilon_{it} \quad (1)$$

Where:

FEC_{it}, dependent variable final energy consumption for unit i at time t; $\beta 0$, is the intercept; $\beta 1, \beta 2, \beta 3, \beta 4, \beta 5, \beta 6$, are the coefficients of the independent variables; SRNWEN_{it}, is the share of renewable energy in gross final energy consumption; EIMPD_{it}, is dependence on imported energy; PEC_{it}, is primary energy consumption; NGRNHE_{it}, are net greenhouse gas emissions; GDPCAP_{it}, is real GDP *per capita*; ENPROD_{it}, is the energy productivity

u_i, represents the fixed effects specific to each DMU

ε_{it}, is the error term

The indicators selected for the econometric model are presented in Table 1.

From the literature review, we have observed an increased interest in energy efficiency. In this respect, some authors (Yumashev et al., 2020; Qasim Alabed et al., 2021; Zhen et al., 2022; Hafez et al., 2023; Anser et al., 2024) have observed the link between sustainable development and efficient management of energy consumption. Using various regression models, the authors find that (Shafique et al., 2020; Aboul-Atta and Rashed, 2021; Maaouane et al., 2021; Tahmasebinia et al., 2022; Bouznit et al., 2023; Guamán et al., 2023; Soava and Mehedintu, 2023) there is a direct link between final energy consumption and sustainable development. The current study aims to identify and analyse the determinants of final energy consumption (FEC) in European Union (EU) Member States over the period 2005–2022. Although, this is an area that has been researched in the last period, we have noticed that no study investigates comprehensively the link between final energy consumption and sustainable development and the current European geopolitical context makes this topic even more important as global interests converge towards the EU area during this period. The proposed model uses in a new and innovative way the linear regression of panel data to determine the variations of energy import dependency, share of renewable energy in gross final energy consumption, primary energy consumption, net greenhouse gas emissions, real GDP *per capita* and energy productivity on final energy consumption from a sustainable perspective.

The choice of these indicators is based on their theoretical and empirical relevance in explaining final energy consumption (Figure 2). By using a fixed effects model, we can control for unobservable characteristics specific to each entity, thus obtaining more robust and informative results.

To achieve the proposed goal the working hypotheses H1- H4 will be tested during the modelling.

The proposed dynamic energy consumption model is based on the application of the least squares method and multiple linear regression to the panel data using STATA program vs. 18. The Hausman test is used to compare fixed and random effects models. The null hypothesis (H0) of the Hausman test states that the differences between the coefficients are not systematic, which means that the random effects model is appropriate. If the null hypothesis is rejected, it suggests that the fixed effects model is more appropriate (see Table 2).

Analyzing the data and the Hausman test results, we can conclude that the fixed effects model is preferred over the random effects model for this data set. The variables show systematic differences between the coefficients obtained from the two models, suggesting that the fixed effects better capture the variation in the data.

4 Results and discussions

The regression model was run on a dataset consisting of 504 observations, grouped into 28 decision units (DMUs), and revealed an impressive R-squared coefficient of determination of 0.8972 within groups, 0.9983 between groups and 0.9976 overall, with an F-test for the whole model (6, 470) resulting in a value of 683.84 and an associated probability (Prob > F) of 0.0000, indicating the extremely high statistical significance of the model, all complemented by a very strong correlation between individual effects and prediction values (u_i, Xb) of 0.9912 (see Table 3).

The coefficient for EIMPD (Energy Import Dependence) indicates a positive relationship between energy import dependence and final energy consumption. The level of significance ($p < 0.001$) indicates that the coefficient is statistically significant, allowing us to state with a high degree of confidence that energy import dependence influences final energy consumption. This validates Hypothesis 1 that dependence on energy imports exerts a significant positive effect on final energy consumption is well supported by the data from the fixed effects regression model. Comparing these results with those in the literature, we observe significant consistency. For example, studies by Wu and Chen (Wu and Chen, 2017), Dey et al. (Dey et al., 2022), Shahbaz et al. (Shahbaz et al., 2024) and Dogan et al. (Doğan et al., 2022) also found a positive relationship between energy import dependence and final energy consumption. This research suggests that countries with a high dependence on energy imports tend to have higher final energy consumption, which is attributed to the need to supplement the lack of domestic production with imports. Thus, we can conclude that countries with a higher dependence on energy imports tend to have higher levels of final energy consumption, which can be attributed to the need to supplement insufficient domestic demand with external purchases.

The coefficient for the SRNWEN indicator (Share of renewable energy in final energy consumption) indicates a positive relationship between the share of renewable energy and final energy consumption. The level of significance ($p < 0.015$) indicates that the coefficient is statistically significant, which allows us to state with a high degree of confidence that the percentage of renewable energy influences final energy consumption. These confirmed factors indicate that hypothesis 3 that the share of renewable energy in final energy consumption has a significant positive impact on final energy consumption is well supported by the data from the fixed effects regression model. The positive relationship between the share of renewable energy and final energy consumption is well documented and supported by previous studies, a higher share of renewable energy in the national energy mix is associated with higher final energy consumption (Shahbaz et al., 2020; Tutak and Brodny, 2022b; Nibedita and Irfan, 2024). Other studies (Arbolino et al., 2024; Liu and Feng, 2023; Zhao et al., 2022) suggest that policies that promote renewable energy sources boost overall energy use. Thus, it can be concluded that an increase in the share of renewable energy in the national energy mix is associated with increased end-use energy use. This phenomenon can be attributed, in part, to government policies promoting renewable energy sources and the infrastructure needed to integrate these sources into the national energy system.

The value of the coefficient of primary energy consumption indicates a positive relationship between primary energy consumption and final energy consumption. The *p*-value associated with the PEC coefficient is less than 0.001 ($p < 0.001$), having a statistically significant level which allows us to state with a high degree of confidence that primary energy consumption influences final energy consumption. An increase in primary energy consumption is associated with a proportional increase in final energy consumption, reflecting the interdependence between these two variables and highlighting the importance of monitoring and managing primary energy resources efficiently to ensure energy sustainability. These results are also supported by the literature which stresses the importance of implementing efficient energy policies and careful management of primary energy resources to ensure energy sustainability and economic growth (Economidou et al., 2022; Su et al., 2023; Yu et al., 2023).

For the NGRNHE indicator (Net Greenhouse Gas Emissions) the coefficient value was 0.0249, which indicated a positive relationship between net greenhouse gas emissions and final energy consumption. The *p*-value associated with the NGRNHE coefficient is less than 0.048, signifying a statistically significant level which allows us to state with reasonable confidence that net greenhouse gas emissions influence final energy consumption. This validates hypothesis 4 of the study. Thus, we can conclude that countries with higher greenhouse gas emissions also tend to have higher final energy consumption, reflecting both the reliance on fossil energy sources and the energy efficiency of the economy. This underlines the importance of policies to reduce emissions and increase energy efficiency in order to control final energy consumption and reduce environmental impacts. Ensuring comparability with the literature, the results highlight the need to implement effective policies to reduce emissions and increase energy efficiency in order to ensure energy sustainability and reduce environmental impacts, which is supported by previous studies (Khan et al., 2022; Paramati et al., 2022; Xu and Xu, 2022; Xue et al., 2022).

In the case of the GDPCAP indicator, the coefficient value showed a positive relationship between real GDP *per capita* and final energy consumption. The *p*-value associated with the GDPCAP coefficient ($p < 0.001$) is highly statistically significant, allowing us to state with a very high degree of confidence that real GDP *per capita* influences final energy consumption. Thus, we can conclude that an increase in real GDP *per capita* is associated with an increase in final energy consumption, reflecting the economic capacity and living standards of the population. It underlines the importance of considering economic growth and sustainable development in energy policy making to ensure a balance between economic progress and efficient use of energy resources. Previous studies in the literature have shown a positive relationship between *per capita* GDP growth and final energy consumption. This research (Su et al., 2022; Tran et al., 2022; Wang et al., 2024) suggests that as economies grow and *per capita* incomes rise, so does the demand for energy to support economic activities and the standard of living of the population.

The coefficient value for the ENPROD indicator is showing a negative relationship between energy productivity and final energy consumption. The *p*-value associated with the ENPROD coefficient ($p < 0.033$), allows us to state with a reasonable degree of confidence that energy productivity influences final energy consumption. Energy productivity, defined as the ratio of GDP to energy consumption, is an indicator of the efficiency of the use of energy resources in the production of economic value. A negative and significant relationship between ENPROD and FEC reflects the fact that economies that use energy more efficiently have lower final energy consumption, which is essential for sustainability and reducing environmental impacts. This validates hypothesis 2 of the study. Thus, we can conclude that an increase in energy productivity is associated with a reduction in final energy consumption, reflecting a more efficient and sustainable use of energy resources. This underlines the importance of policies and technologies that improve energy efficiency to control energy consumption and promote sustainable development. Energy productivity has a significant negative impact on final energy consumption, a point well supported by the literature (Ding et al., 2021; Sun et al., 2024; Wang et al., 2024; Zhen et al., 2022) results highlight the need to implement policies and technologies to improve energy efficiency in order to control energy consumption and promote sustainable development (Chen et al., 2021; Zakari et al., 2022; Anser et al., 2024; Song et al., 2024).

The Breusch-Pagan LM test for independence is used to test for the presence of serial dependence between the residuals of the regression model. In the context of a panel regression model, the test checks for correlation between the residuals of different time units. The value of 1211.799 is calculated for 378 degrees of freedom. The probability of 0.0000 indicates that the observed chi-square value is extremely unlikely under the null hypothesis.

Pesaran's test for cross-sectional independence is used to assess the presence of correlation between time units in a panel regression model. The results of the test are: Pesaran's test of cross sectional independence = 4.643, Pr = 0.0000, Average absolute value of the off-diagonal elements = 0.352. This is a significant test statistic indicating the degree of cross-sectional independence between residuals from different units. A Pr value of 0.0000 suggests that the observed test value is highly unlikely under the null hypothesis. The mean absolute value of the off-diagonal items indicates that there is a moderate correlation between residuals in different units.

The results of the modified Wald test for heteroscedasticity (chi2 (28) = 1.6×10^5, Prob > chi2 = 0.0000) indicate that the null hypothesis can be rejected.

The Hadri LM test (Table 4) is used to check whether data panels are stationary or contain unit roots. The null hypothesis (H0) of the Hadri test is that all panels are stationary, while the alternative hypothesis (Ha) is that some panels contain unit roots, i.e. are not stationary.

From the point of view of the distribution of errors it can be observed that they tend to flatten out towards the end of the period with the largest magnitudes of errors being observed graphically in the period 2005–2010 (Figures 3–5).

Energy consumption in the European Union experienced a slight increase between 2005 and 2010. This can be attributed to the growing population and economic development in some member states. Additionally, advancements in technology and industrial processes also contributed to the rise in energy consumption. However, efforts were made during this period to promote energy efficiency and renewable energy sources, which helped mitigate the overall impact on the environment. These efforts included the implementation of energy-saving policies and regulations, such as the Energy Efficiency Directive and the Renewable Energy Directive. Many member states also invested in renewable energy infrastructure, such as wind farms and solar power plants, to reduce their dependence on fossil fuels. Furthermore, public awareness campaigns and incentives were introduced to encourage individuals and businesses to adopt energy-saving practices and technologies. As a result of these combined efforts, the European Union was able to achieve a more sustainable energy future despite the increase in consumption.

Energy consumption in the European Union has seen a gradual decline from 2011 to 2019. This can be attributed to the region's increased focus on renewable energy sources and energy efficiency measures. The implementation of stricter regulations and policies has resulted in significant improvements in energy conservation, leading to a more sustainable and environmentally-friendly energy landscape in the European Union. Furthermore, advancements in technology have played a crucial role in reducing energy consumption. The adoption of smart grids and energy-efficient appliances has allowed for better energy management and reduced wastage. Additionally, the shift towards cleaner and greener modes of transportation, such as electric vehicles, has also contributed to the overall decrease in energy consumption. These efforts have not only helped the European Union achieve its climate goals but have also created new opportunities for the development of a green economy.

Energy consumption in the European Union experienced a significant decline in 2020–2021 due to the impact of the COVID-19 pandemic. Lockdown measures and travel restrictions led to a decrease in industrial activity, transportation, and overall energy demand. Additionally, the shift towards remote working and online activities further contributed to the reduction in energy consumption. As a result, the European Union made significant progress towards achieving its clean energy goals and reducing carbon emissions during this period. Furthermore, the decrease in energy consumption also led to a decrease in the use of fossil fuels, such as coal and oil, which are major sources of carbon emissions. This reduction in carbon emissions not only helped the European Union meet its climate targets but also contributed to improved air quality and reduced pollution levels. The pandemic served as a catalyst for the adoption of renewable energy sources and the implementation of energy-efficient practices, setting the stage for a more sustainable and resilient energy sector in the future. Despite the challenges faced during this time, the decline in energy consumption brought about positive environmental outcomes, demonstrating the potential for a greener and more sustainable future.

In the year 2022 it can be seen from the Normal P-P Plot of the standardised residuals (Figure 6) for final energy consumption that countries with energy sustainability such as Italy and Malta have improved their position towards the new model due to energy reforms by reducing the value of the standardised residuals compared to the right of the trend while for countries with lower energy sustainability such as Romania and Slovakia the position compared to the right of the trend indicates a move away from the proposed sustainability model.

In Italy, for example, progress has been made on the back of major investments in wind farms and the continued optimisation of the use of hydropower resources, with the country managing to maximise energy production from these sources. At the same time, Italy has adopted measures to reduce its dependence on fossil fuel imports through the use of biofuels and diversification of energy sources, in which case it has increased its gas storage infrastructure as part of its energy security measures. Malta, for its part, has made progress in developing infrastructure for renewable energy sources, with the government implementing subsidy programmes for the installation of photovoltaic panels in 2022. Malta has also offered subsidies for the purchase of energy efficient household appliances and has been pushing for the diversification of energy sources by encouraging the adoption of new technologies and innovations to support the energy transition such as smart grid technologies and investments in energy storage technologies. At the other end of the spectrum, Romania and Slovakia's energy sustainability model has experienced difficulties and challenges that have led to a worsening energy situation in both countries. Romania has shown a high dependence on fossil fuels and delays in the adoption of renewable energy based on insufficient investment and lack of adequate government incentives. Romania's outdated energy infrastructure and rising energy prices amid the geopolitical conflict in Ukraine have contributed to Romania's energy sustainability. As in the case of Romania, Slovakia is a country that relies significantly on the use of fossil fuels and is lagging behind in the adoption of renewable energy due to legislative instability and the lack of a clear and coherent strategy to support the transition to more sustainable energy.

We define the energy sustainability function based on the dynamic energy consumption model Equation 2 as follows:

$$SEN\,year_i = \frac{\begin{pmatrix} 0.101 * EIMPD\,year_i + 0.129 * SRNWEN\,year_i \\ +0.739 * PEC\,year_i - 0.033 * NGRNHE\,year_i - \\ 0.00002 * GDPCAP\,year_i + 0.171 * ENPROD\,year_i - 6.987 \end{pmatrix} * ENPROD\,year_i}{ENPROD\,year_{EU27}} \tag{2}$$

$$\begin{cases} SEN\,year_i > 1 \rightarrow economy\ with\ a\ good\ enegergetic\ sustainability \\ SEN\,year_i = 1 \rightarrow economy\ with\ a\ minimum\ enegergetic\ sustainability \\ SEN\,year_i < 1 \rightarrow economy\ with\ a\ poor\ enegergetic\ sustainability \end{cases}$$

Where, SENyeari-energy sustainability of state i based on changes in dynamic model regression indicators and member state energy productivity index compared to the European average.

For the year 2022 the equation becomes Equation 3:

$$SEN2022_i = \frac{\begin{pmatrix} 0.101 * EIMPD2022_i + 0.129 * SRNWEN2022_i \\ +0.739 * PEC2022_i - 0.033 * NGRNHE2022_i - \\ 0.00002 * GDPCAP2022_i + 0.171 * ENPROD2022_i - 6.987 \end{pmatrix} * ENPROD2022_i}{ENPROD2022_{EU27}} \quad (3)$$

The graphical representation of energy sustainability in 2022 is shown in Figures 5, 7.

It can be seen from the graph that countries such as Belgium, Germany, Ireland, France, Italy, Luxembourg and Malta have a high level of energy sustainability while at the opposite pole Romania, Slovakia, Bulgaria, Czech Republic are in the position of energy unsustainability.

Based on the research results, we propose the following implementable public policies to improve energy sustainability in European states (Table 5).

We appreciated that well formulated and implemented energy policies can make a significant contribution to creating a sustainable and efficient energy system in Europe.

5 Conclusions

We set out to study the sustainability of the energy sector by means of the newly designed dynamic econometric model, whose importance as a methodological tool for the correlative statistical investigation of sustainability from the perspective of SDG 7, exceeds the European reference space of the analysis, and can be used with favorable results at the global level. The study achieved all the research objectives by conducting an extensive literature search that substantiated the working hypotheses, the authors showing that at the European level, the degree of final energy consumption is directly influenced by the growing reliance on imports. The sustainability of energy is indicated by the increasing dependence of final energy consumption on the proportion of renewable energy in the overall energy consumption across different sectors. The reduction of greenhouse gas emissions is a key aspect of energy sustainability in Europe and has an inverse relationship with final energy consumption. Additionally, energy productivity plays a significant role in determining final energy consumption, as it is sensitive to the impacts of energy crises.

The new dynamic model showed the link between consumption and the sustainable dimension, the results were statistically significant, and the model was homogeneous and well determined. The energy sustainability function has been defined and the energy sustainability ranking of the Member States in 2022 has been prepared. The results of the study are useful for energy policymakers to adjust their energy strategies for the coming years in order to achieve the targets proposed by Agenda 2030 and 2050. As we showed in the paper, economic policies should encourage sustainable growth by integrating energy efficiency measures and promoting technologies and economic practices that reduce energy consumption. The fixed effects regression model clearly shows that different economic and policy factors influence final energy consumption in Europe. To ensure a more sustainable and efficient energy system, energy policies should focus on reducing import dependency, promoting renewable energy, improving energy efficiency and reducing greenhouse gas emissions.

The dynamics of the energy sector in the context of the transition to climate neutrality is a very important aspect that makes it necessary to complete the database and other indicators on the transition to the green economy, this is a limitation of this study, the authors propose to carry out new research in which to quantitatively expand the research area by completing the database and to refine the conclusions of the present research based on new relevant observations.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: Eurostat https://ec.europa.eu/eurostat/data/database?gclid=Cj0KCQiAzoeuBhDqARIsAMdH14GrVGsRctLAe76Wv5Kt8p81Wy_lzG6YogF_WNaNOemRmxp_Jl9oel0aAgiWEALw_wcB.

Author contributions

CF: Conceptualization, Data curation, Formal Analysis, Methodology, Writing–original draft, Writing–review and editing. DC: Conceptualization, Investigation, Software, Supervision, Writing–original draft, Writing–review and editing. MZ: Conceptualization, Investigation, Methodology, Project administration, Validation, Writing–original draft, Writing–review and editing. VA: Conceptualization, Data curation, Formal Analysis, Methodology, Writing–original draft, Writing–review and editing. MN: Formal Analysis, Project administration, Resources, Validation, Visualization, Writing–original draft, Writing–review and editing. NC: Data curation, Formal Analysis, Methodology, Project administration, Supervision, Writing–original draft, Writing–review and editing. IL: Data curation, Formal Analysis, Resources, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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