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The Impact of Energy Innovations and Environmental Performance on the Sustainable Development of the EU Countries in a Globalized Digital Economy

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The research conducted in this paper aims to examine the role of energy innovations, digital technological transformation, and environmental performance in enhancing the sustainable economic development of the European Union (EU) countries, widely shaped by the globalization process. An advanced empirical analysis is configured on a cross-sectional dataset of EU-27 Member States compiled at the level of 2018 based on several modern econometric procedures, namely robust regression, structural equation modelling (SEM) and network analysis through Gaussian graphical models (GGM). We apply the econometric procedures to firstly identify and assess the direct, indirect, and total interlinkages between all considered variables, as well as their further cumulated spillover impact on sustainable economic development. EU countries are afterward clustered according to the Ward method inset on hierarchical clustering for an in-depth assessment and tailored policy design by accounting for the level of financial and trade globalization (captured through the KOF Index of Globalization), environmental performance and sustainability (captured through the Environmental Performance Index—EPI), and the degree of integration of digital technologies (proxied through the Digital Economy and Society Index—DESI). Main results highlight that there are significant beneficial effects induced by energy innovations, increased environmental performance and digital transformation on the sustainable development of EU countries, with notable differentiation among them. Policy guidelines and strategic directions are also enhanced and largely presented within the paper.

Keywords: energy innovations, digital transformation, environmental performance, sustainable economic development, European Union countries, econometric procedures

INTRODUCTION

Twin transition is the main concern of the European authorities and the new watchword that reshapes the activity of companies, but also of other categories of stakeholders considering both the need to protect the environment and promote the low carbon economy, and to take advantage of the opportunities offered by digitalization. The European Union (EU) countries have set well-marked targets for the energy transition, driven by the need to manage the challenges posed by climate change. Through its efforts to regulate the energy transition process, the EU is an international leader in a world where the connections generated by globalization are increasingly intense and the need for energy security is pressing in the new geopolitical context (Radulescu and Popescu, 2015; Andrei et al., 2017; Popescu et al., 2018; Voica and Panait, 2019; Manea et al., 2020; Simionescu et al., 2020; Bucur et al., 2021). The intensification of the economic activity as a result of the liberalization of goods, services and capital movements is strongly interrelated with the globalization of the world economy, the positive effects, but especially the negative ones being in the attention of different categories of stakeholders. Globalization has also led to an intensification of the economic activity, which is why more and more specialists are attributing to this phenomenon increasingly negative effects, such as environmental pollution, accelerated consumption of natural resources and especially of energy, destruction of ecosystems, loss of biodiversity, an increase of energy prices and, therefore, an alleviation of energy accessibility for the poorest people (Zhao et al., 2022). Dealing with the negative effects of globalization has led to an increase in concerns for technical innovation, especially in the field of energy, but also for the promotion of the principles of sustainable development of different categories of stakeholders, at micro and macroeconomic levels (Vasile and Balan, 2008; Cristea and Dobrota, 2017; Shahbaz et al., 2018; Hysa et al., 2020; Rehman et al., 2021; Sichigea et al., 2021; Awan et al., 2022). The need to promote sustainable development at the microeconomic level has generated a paradigm shift at the level of companies that have nuanced their primary objective, which is no longer maximizing profit for shareholders, but maximizing value for stakeholders. The increase in the financial performance is no longer the only target of the management teams, which tend to rather focus on the improvement of the social and environmental performance in the long run, while Corporate Social Responsibility (CSR) is being integrated with the business strategy (Vollero et al., 2011; Andrei et al., 2014; Paun, 2017; Brezoi, 2018; Siminica et al., 2019; Voica et al., 2019; Morina et al., 2021; Noja et al., 2021; Puime et al., 2022).

Technological innovation is increasingly promoted in the production, preservation, and consumption of energy, which is why smart energy is a new reality, through which the process of the energy transition is brought to the fore. Moreover, the concerns about smart energy production have positive consequences, not only on the environment but also on consumers. The phenomenon of energy poverty is substantially diminished, thus bringing beneficial reverberation to the quality of life (Zhao et al., 2022). Technological innovations like the Internet of Things (IoT) have a dramatic impact on the energy sector in different segments like energy supply, power generation, or renewable energy integration, considering the challenges that this type of energy generates, namely the seasonality of production in the conditions of a continuous consumption (Ahmad and Zhang, 2021; Wang et al., 2021; Nassani et al., 2022).

The technological innovation that accompanies the energy transition is accomplished on two levels that imply, on the one hand, the development of technologies for the production and consumption of renewable energy, and, on the other hand, the emergence of equipment with high energy efficiency. Both situations generate a certain resistance from consumers and local communities, the acceptance and use of new technologies being complex processes with psychological, social, and economic determinations (Jabeen et al., 2021; Rafiq et al., 2022).

The fourth industrial revolution is also making its presence felt in the energy sector. Industry 4.0 technologies (like cloud computing, Internet of Things—IoT, big data) are now used also on the generation, production, distribution, and retail of energy, and it induces structural changes in the energy market as well, specialists even talking about energy 4.0. (Alimkhan et al., 2019). The digital revolution also included the energy sector. New digital technologies are essential for the energy sector given the challenges they face, namely increasing energy demand (as a result of urbanization, economic growth, increasing life expectancy and quality of life in developed countries), liberalization of the energy market, and the existence of numerous producers, distributors, and even prosumers, also the integration into the energy system of new renewable energy sources (Satuyeva et al., 2019; Ramzan et al., 2022). The technological challenges that companies in the energy sector must face, will generate new business models in the energy field, massive investments in Information and communication technology (ICT), and the reconfiguration of the legal framework considering the concerns for regulating some aspects related to data ownership, protection of intellectual property, outsourcing (Lang, 2016).

In this complex nowadays framework, the general objective of our research is to examine the synergy among energy innovations, digital technological transformation, and environmental performance in enhancing the sustainable economic development of the EU countries, widely shaped by the globalization process. We perform an advanced empirical analysis, configured on a cross-sectional dataset of EU-27 Member States (MS), compiled at the level of 2018, based on several modern econometric procedures, namely robust regression model (RREG), structural equation modeling (SEM), network analysis through graphical Gaussian models (GGM), and cluster analysis. These econometric procedures aim to firstly identify and assess the direct, indirect, and total interlinkages between all considered variables, as well as their further cumulated spillover impact on sustainable economic development (measured by the real Gross Domestic Product—GDP, per capita). The EU countries are afterward clustered according to the level of economic globalization (captured through the KOF indexes of financial and trade globalization), environmental performance (captured through the Environmental Performance Index—EPI), the degree of integration of digital technologies (proxied through the Digital Economy and Society Index—DESI), and sustainable economic development (GDP per capita) for an in-depth assessment and tailored policy design. Therefore, the main research questions are: *i)* what is the configuration of the synergy among energy innovations, environmental performance, digital transformations, economic globalization, and the sustainable development of the EU countries?; *ii)* what are the differences among the EU countries in terms of these coordinates?

The novelty of the research conducted in this paper is entailed by the innovative approach centered on the importance of digitalization, which is increasingly present in the energy industry, within the environmental performance and globalization process. The production and consumption of clean and smart energy is a new international trend that is embraced by both consumers and companies in the field, which have adapted their business strategies to keep up with the new industrial revolution that has included the energy sector. Energy 4.0 is the new watchword at the international level, the interest of the stakeholders being more and more encompassed considering the smart management of the energy sector, economic, social, and technical challenges and the environments that the new energy transition raises (Rodrigues et al., 2022).

The paper is divided into distinct sections. After the introduction and brief literature review, the authors present the data, econometric methods applied, and the results obtained. In the last section, the authors draw the conclusions of the study and mention the limits of the research, along with future research directions. The study concludes with economic policy recommendations considering the results obtained.

LITERATURE REVIEW

The energy transition is accompanied by many economic, social, technical, and environmental challenges. Researchers are looking to find technical solutions that are efficient and economically viable to reduce the impact that economic development has on the environment through the production and consumption of energy (Khan et al., 2016; Armeanu et al., 2018; Panait et al., 2019; Anser et al., 2020; Sharif et al., 2020; Adebayo et al., 2021; Balsalobre-Lorente et al., 2022). Companies from the energy sector have specificities considering that they perform public tasks through market-based strategies (Dobrowolski and Sułkowski, 2021) and energy production must be under the sign of energy security (Dobrowolski, 2021).

As regards environmental protection, Carrión-Flores and Innes (2010) found positive results in the long run through the intensification of the environmental innovation process as an outcome of research and development (R&D) support provided by authorities for the reduction of environmental pollution. Carrión-Flores and Innes (2010) measured the environmental innovation by environmental patents (including patents for wind and geothermal energy), using 127 manufacturing industries over the period 1989–2004. The authors entail that the concerns of authorities to reduce the pollution generate the intensification of the environmental innovation process.

Linking the environment with the energy implications, Álvarez-Herránz et al. (2017a) demonstrate the importance of energy innovation in the decrease of energy intensity and environmental pollution for 28 countries from the Organisation for Economic Co-operation and Development (OECD), from 1990 to 2014. These underpinnings stand out by highlighting the role that energy innovations play in environmental quality processes. By analyzing the environmental Kuznets curve (EKC) relationship between economic growth and environmental quality, Álvarez-Herránz et al. (2017a) (p. 99) proved the necessity "to promote regulation in energy RD&D to reduce greenhouse gas emissions and energy intensity", because technological innovations generate the reduction of carbon emissions.

A similar study demonstrated the positive relationship between energy research, development and demonstration (ERD&D), procedures, and energy efficiency for the 17 developed countries of the OECD, during 1990–2012 (Álvarez-Herránz et al., 2017b). Improving sustainability in the energy sector is achieved, on the one hand, by using renewable resources, but also by implementing technical innovations. The study pointed out the existence of EKC patterns for selected OECD developed countries and the importance of energy innovations and regulations on the environmental performance of specific economies. However, the effects of innovation are felt in the long run, which also demonstrates the importance of economic policy measures that must aim, on the one hand, to reduce the negative effects of global warming and, on the other hand, to promote sustainable development.

The environmental innovation, trade, renewable energy consumption, and CO2 emissions were analyzed by Ali et al. (2021) for the top 10 carbon emitter countries (namely, Brazil, China, Germany, India, Indonesia, Japan, South Korea, Mexico, Russian Federation, and the United States), using cross-sectionally augment autoregressive distributed lags (CS-ARDL) method and data from 1990 to 2017. Ali et al. (2021) state that changes in GDP, renewable energy consumption, exports, imports, and eco-innovation may cause CO2 emissions.

Ghisetti and Rennings (2014) have analyzed the relationship between competitiveness and environmental performance of German companies, based on the Mannheim Innovation Panel survey in 2009 and 2011. The authors noticed that innovations impact the companies' performances and competitiveness. These findings bring forward that the energy innovation generates a potential "win-win" situation because the improvement of environmental impact leads to an increase in economic performance.

Solarin and Bello (2020) proved that energy innovations improved environmental quality (measured by three indicators—CO_2 emissions, ecological footprint, and carbon footprint) in the United States (US) economy, using STIRPAT ("Stochastic Impacts by Regression on Population, Affluence and Technology") approach, based on data for the period 1974 to 2016. However, Solarin and Bello (2020) draw attention to the risk that energy innovation may generate because energy waste can be registered by lowering costs. Therefore, the rebound effect is a reality that accompanies energy innovation and must be properly managed by stakeholders (Zaman et al., 2020; Gradinaru et al., 2021).

Levänen et al. (2015) highlighted the role of frugal energy innovations as a promoter of sustainable development in India. This type of innovation, based on alternative energy sources, is beneficial not only in terms of the environmental impact, but also due to the positive effects it generates on the quality of life, especially for low-income people, but also on employment and new business development. The researchers point to the asymmetric impact that economic policy measures apply to facilitating the energy transition. The main factors that can explain the asymmetric impact of energy innovation are the economic complexity specific to each country, the firmness of the application of the economic policy measures adopted, and the attitude of consumers towards new technologies (Altıntaş and Kassouri, 2020; Bashir et al., 2022; Sun et al., 2022).

The use of renewable energy and the promotion of technological innovations have a positive impact on the quality of life by reducing the energy poverty that affects the economies of the EU, in different proportions, regardless of the specific weather conditions of each country. The innovations improved considerably the energy affordability and accessibility not only in terms of renewable energy production and consumption but also by intensifying concerns for increasing energy efficiency (Sinha et al., 2022; Zhao et al., 2022).

As regards financial credentials and energy innovations, the study conducted by Shahbaz et al. (2018) for the French economy analyzed the relationship between foreign direct investment (FDI), financial development, economic growth, energy consumption, and energy research innovations, as independent variables, and CO_2 emissions, as a dependent variable, for the period 1955–2016. Their findings revealed that the increase in FDI flows has a negative impact on the environmental quality by increasing carbon emissions, so the Pollution-Heaven hypothesis is validated. The synergy between energy innovation and carbon emissions was negative, which demonstrated the importance of public expenditure on energy research and development in improving environmental quality by lowering carbon emissions. The Pollution-Heaven hypothesis was tested also by Nathaniel et al. (2020) for ten coastal Mediterranean countries, by applying STIRPAT framework, to analyze the relationship between environmental degradation, energy consumption, urbanization and FDI, for the 1980—2016 period. Their results substantiate that FDI positively impacted environmental quality in selected countries, and "energy consumption significantly increases environmental degradation while economic growth and urbanization lead to mixed results for the different representation of environmental degradation" (Nathaniel et al., 2020, p. 35,484).

Along the same line, the relationship between financial development, globalization, and energy consumption in Pakistan was analyzed by Ulucak (2021) for the period 1980—2017. Using a newly developed method—bootstrap auto-regressive distributive lag (BARDL)—Ulucak (2021) evidenced that globalization and financial development have a major impact on energy consumption in Pakistan. Including advanced technologies, the study conducted by Ramzan et al. (2022) focused on the impact of financial development, ICT, trade openness, and fossil fuel energy on ecological footprints in Pakistan, from the period 1960—2019. Their findings uphold that financial and economic growth causes the rise of ecological footprint, while the use of ICT "reinforces the causal association of ecological footprint and financial development" (Ramzan et al., 2022, p.13) and, in addition, generates the intensification of trade activities.

Using a panel quantile regression, Chen and Lei (2018) analyzed the effects of renewable energy consumption and technological innovation on the environment-energy-growth nexus for 30 countries over the period 1980–2014. Chen and Lei (2018) (p. 10) found that technological innovation has a greater impact on countries with relatively higher CO2 emissions because it generates lower costs and bigger energy efficiency, so "technological progress is the main factor for reducing carbon emissions". Technological innovation also generates a higher rate of acceptance and use of renewable energy, given the reluctance shown by certain stakeholders, such as local communities or citizens (Spandagos et al., 2022).

Simionescu et al. (2021) tested the renewable Kuznets curve for ten countries from Central and Eastern Europe (CEE) using the index of economic freedom, FDI, domestic credit to the private sector and labour productivity, as control variables, and indicators reflecting the quality of governance, for the period 2006–2019. The study demonstrated the importance of involving state authorities in the process of reducing pollution, which through various tools can shape both the behavior of local companies and consumers and foreign capital businesses.

Synthesizing the relevant literature underpinnings, we point out the following: energy innovations and environmental pollution were intensively debated by researchers, most of them proving their beneficial impact on economic development; energy innovations (such as renewable energies) and environmental protection are vital for economic development on the long run, both at macro- and microeconomic level; financial determinants in conjunction with energy innovation and environmental degradation may induce diverse implications; considering technological innovation and globalization, the synergy energy innovation-environment-economic development can be better assessed, with positive effects.

DATA AND METHODOLOGY

Relying on the main findings from the literature and the research objective of our study, the data is disposed on five groups of indicators that target energy, environmental, digitalization, globalization, and sustainable economic development credentials. The dataset comprises indicators for the EU-27 MS compiled at the level of 2018, and includes the following groups of variables:

- *energy dimensions*: final energy consumption (eng_cons); energy productivity (eng_prod); energy efficiency (eng_eff); share of renewable energy in gross final energy consumption;
- *environmental dimensions*: environmental performance index (epi); national expenditure on environmental protection (env_exp); exposure to air pollution by particulate matter (air_poll); greenhouse gas emissions intensity of energy consumption (gge_ec);
- *digital transformations*: DESI - Human Capital (desi_hc); DESI—Connectivity (desi_con); DESI - Integration of Digital Technology (desi_tech); DESI - Digital Public Services (desi_dpserv); high-speed internet coverage (hs_internet);
- *economic globalization dimensions (the KOF Economic Globalization Index):* trade globalization (kof_tr); financial globalization (kof_fin);
- *sustainable economic development indicators*: the real GDP per capita (gdp_cap); gross domestic expenditure on research and development (R&D) (gerd).

We employed a homogenous dataset for 2018 due to the limited availability of time series data for the indicators selected in our analysis, namely the KOF Index of Economic Globalization, EPI, or DESI. For instance, environmental performance and sustainability, captured through EPI, were determined starting with 2006 every 2 years, 2020 being the last year, while the globalization index (KOF Economic Globalization Index) was available until 2018 (at the time of our data collection).

Environmental dimensions are focused, mainly, on the composite indicator "Environmental Performance Index (EPI)", which was determined starting in 2006, being measured every 2 years. At the level of 2018, EPI captures 24 indicators that target "environmental health and ecosystem vitality", covering 10 groups of fields: "air quality, water and sanitation, heavy metals, biodiversity and habitat, forests, fisheries, climate and energy, air pollution, water resources, and agriculture" for 180 countries (YCELP et al., 2018).

Digital transformation dimensions in Europe are measured by the "Digital Economy and Society Index (DESI)" that comprises, for the year 2018, four main categories: "Connectivity, Human Capital, Integration of Digital Technology, and Digital Public Services" (European Commission, 2018a). For the year 2020, DESI includes another one more dimension, namely "Use of Internet".

The globalization dimension is measured by the KOF Globalization Index, which comprises three coordinates of globalization, namely economic, social and political (Gygli et al., 2019; ETH Zurich and KOF Swiss Economic Institute, 2021). The economic pillar comprises two coordinates: trade and financial. Social pillar encloses three coordinates: interpersonal, informational and cultural, while the political component includes "the diffusion of government policies" (Gygli et al., 2019, p. 555). KOF Globalization Index was built based on data starting with 1970. In our research, given the economic relevance, we focus only on economic globalization dimensions.

The full description of the indicators is presented in **Supplementary Table S1**.

With reference to economic globalization dimensions, the summary statistics (**Table 1**) evidenced that financial globalization (kof_fin) registered higher values (mean, minimum and maximum indexes) than trade globalization (kof_tr), with the highest index for Luxembourg (99) and the minimum for Romania (56), as regards financial globalization, respectively maximum value for the Netherlands (87), and minimum one for Italy (49), as regards trade globalization (ETH Zurich and KOF Swiss Economic Institute, 2021). Environmental performance and sustainability (epi) registered the maximum value in France (83.95), and the minimum one, in Poland (64.11) (YCELP et al., 2018). As for DESI components, digital public services (desi_dpserv) registered the highest mean value (over 13) among other 3 dimensions - human capital, connectivity and integration of digital technology—also with the highest maximum value (over 19, in Estonia), and the lowest minimum value (over 3, in Romania) (European Commission, 2018a). Good values among the four DESI components were obtained also for human capital, with a mean value over 11, and good values of the minimum and maximum range. Huge discrepancies among the EU-27 countries were obtained in the case of energy efficiency (eng_eff), with the minimum value (0.82) in Malta and the maximum one (292.15) in Germany, but also for the high-speed internet coverage (hs_internet), with the minimum value (0.4) in Greece and the maximum one (87.8) in Latvia, and GDP per capita (gdp_cap), with the minimum value (6,330) in Bulgaria, and the maximum one (84,040) in Luxembourg (European Commission, 2018b).

The methodology applied, configured on the cross-sectional dataset of EU-27 MS at the level of 2018, is based on the following econometric procedures:

- robust regression (RREG)—to evidence direct impacts of the considered variables on sustainable economic development;
- structural equation modelling (SEM) and Gaussian graphical model (GGM) with partial correlations—to evaluate overall interlinkages between all variables and the sustainable economic development;
- and cluster analysis, for an in-depth assessment of homogeneous groups of EU countries in order to set tailored strategies.

Robust regression (RREG) model is employed in this research to cope with possible outliers within our sample considering the heterogeneity of the EU countries, and to provide robust estimates. RREG model is configured as in **Eq. 1**, being processed based on two types of iterations, Huber and biweight.

$$\begin{aligned} gdp_{cap} = \alpha_0 + \alpha_1 kof_{tr} + \alpha_2 kof_{fin} + \alpha_3 epi + \alpha_4 desi_{tech} + \alpha_5 eng_{cons} \\ +\alpha_6 eng_{prod} + +\alpha_7 eng_{eff} + \alpha_8 env_{\exp} + \alpha_9 gge_{ec} + \alpha_{10} renew_{eng} \\ + \alpha_{11} air_{poll} + \alpha_{12} hs_{\text{internet}} + \alpha_{13} desi_{hc} + +\alpha_{14} desi_{con} \\ + \alpha_{15} desi_{dpserv} + \alpha_{16} gerd + \theta_i + \varepsilon \end{aligned} \quad (1)$$

TABLE 1 | Summary statistics of the data used in the analysis.

Variables	N	Mean	Standard Deviation (sd)	Minimum	Maximum
kof_tr	27	72.8888	10.2369	49	87
kof_fin	27	83.1481	10.8191	56	99
eng_cons	27	2.43740	1.1907	1.21	7.16
gge_ec	27	84.7963	9.5722	57.6	102.1
renew_eng	27	21.4760	11.8340	7.34	54.651
eng_prod	27	8.6100	2.7761	4.788	18.54
eng_eff	27	50.9466	72.3420	0.82	292.15
air_poll	26	22.5269	6.2702	11.5	33.8
hs_internet	27	39.4518	25.1592	0.4	87.8
gerd	27	1.5525	0.8662	0.5	3.32
gdp_cap	27	27,228.15	17,509.41	6,330	84,040
env_exp	27	1.8111	0.6417	0.6	3.2
epi	27	73.3311	6.3314	64.11	83.95
desi_hc	27	11.5868	2.3362	7.5032	16.7782
desi_con	27	8.8657	1.6618	5.1030	11.6231
desi_tech	27	7.6293	2.0653	4.2246	11.7674
desi_dpserv	27	13.842	3.7492	3.1757	19.1353

Authors' contribution.

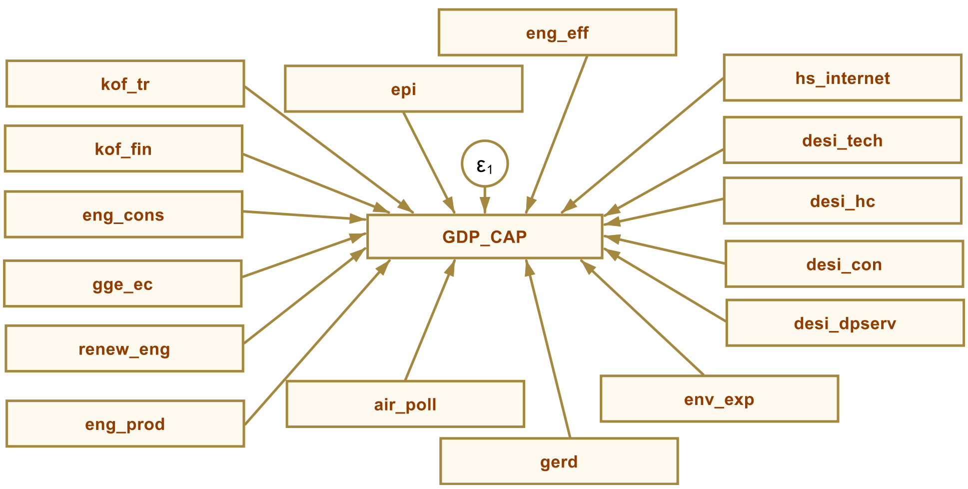

FIGURE 1 | | General configuration of the SEM model. Source: Authors' contribution.

where: θ_i—variable that captures the country effects; ε—error term (residual variable).

Furthermore, to better capture the indirect and total effects of all considered credentials on sustainable economic development, we configured a *structural equation model (SEM)*, processed through the maximum likelihood estimator (MLE). SEM complements robust regression models and, through a different estimation method and a measurement component, allows us to enhance a comprehensive view of all interlinkages between considered variables. The general configuration of the SEM model is presented below in **Figure 1**.

Moreover, a Gaussian graphical model (GGM) is employed following the same objective of an in-depth assessment of the interlinkages between environmental performance, digital transformation and sustainable economic development framed by the globalization process. GGM aims at providing additional groundings to enhance all paths graphically represented through edges (blue edges entail positive partial correlations and red edges outline negative partial correlations) between specific variables (captured as circles/nodes of the GGM). GGM complements the SEM model considering the possible limitations induced by various measurement units of the indicators and a relatively small cross-sectional sample.

In the final stages of our empirical endeavor, and in line with the main objective of current research, we applied cluster analysis through the Ward method and based on the Euclidean distance, inset for hierarchical clusters. The Ward method was selected based on the specialized literature in this field showing that it provides the highest accuracy in most situations, being the most widely used form of clustering in practice (Kettenring, 2006). EU

TABLE 2 | Results of robust regression models (RREG) and structural equations models (SEM)—dependent variable GDP per capita.

Variables	Model 1 (RREG)	Model 2 (SEM)
Main		
kof_tr	−409.3*** (6.903)	−154.2 (119.1)
kof_fin	−176.4*** (4.364)	62.23 (110.5)
epi	478.6*** (9.975)	551.4** (194.4)
desi_tech	246.2** (51.86)	−302.8 (575.0)
eng_cons	10,207.8*** (108.3)	6,956.8*** (860.4)
eng_prod	1,093.4*** (15.67)	1,560.8*** (258.0)
eng_eff	−55.92*** (1.291)	−33.40* (16.33)
env_exp	−8,518.4*** (93.53)	−6,587.7*** (1713.2)
gge_ec	25.00* (7.156)	−73.43 (98.72)
renew_eng	−172.3*** (3.510)	−265.7*** (79.81)
air_poll	301.0*** (5.562)	346.8* (152.7)
hs_internet	−320.2*** (3.123)	−139.3 (79.36)
desi_hc	1874.2*** (36.85)	1,139.3 (738.4)
desi_con	3,447.6*** (40.32)	2073.6 (1,058.6)
desi_dpserv	1,194.1*** (11.96)	860.6* (380.9)
gerd	2,922.9*** (56.62)	5,643.4*** (1,274.9)
_cons	−45112.9*** (858.0)	−63981.5*** (18,395.8)
—/ var (e.gdp_cap)	—	4,843,625.6*** (1,343,380.0)

Authors' contribution in Stata.

clustering allowed us to better capture specific groups of EU MS according to several fundamental credentials followed in this research in order to design tailored policies and strategies.

The hypotheses followed in this research endeavor, based on the general objective and the main research questions addressed at the beginning of the paper, are the following:

- *H_1. Energy innovations directly and notably shaped the sustainable development of the EU countries within the economic globalization framework;*
- *H_2. Environmental performance directly and significantly influenced the sustainable development of the EU countries within the economic globalization framework;*
- *H_3. Digital transformations directly and significantly influenced the sustainable development of the EU countries within the economic globalization framework;*
- *H_4. Energy innovations, within global interlinkages with environmental performance, digital transformations and economic globalization, notably influenced the sustainable development of the EU countries;*
- *H_5. There are significant differences among the EU countries in terms of sustainable development, financial and trade globalization, environmental performance, and the degree of integration of digital technologies.*

RESULTS AND DISCUSSIONS

Results of Robust Regression Model

To assess the extent to which there are direct favorable influences of energy innovations (H_1), environmental performance (H_2), and digital transformations (H_3) on the sustainable development of the EU countries within the economic globalization framework, we first built the robust regression models (RREG) (**Table 2**, Model 1). The results reveal a very good association among variables and a notable impact on sustainable development (GDP per capita).

Within the unfavorable direct implications of trade (*kof_tr*) and financial globalization (*kof_fin*) on GDP per capita (negative and statistically significant coefficients), we follow the results obtained in the case of each advanced hypothesis (**Table 2**, Model 1). Moreover, the literature underpinnings also revealed that economic globalization induced an increase of energy prices, as well as accessibility alleviation to energy for the poorest people (Zhao et al., 2022).

As regards direct impacts of energy innovations on the GDP per capita of the EU countries (significant from the statistical point of view), the results foreground favorable influences in the case of consumption (*eng_cons*) and productivity of energy (*eng_prod*), while in the case of energy efficiency (*eng_eff*) and the renewable energy consumption (*renew_eng*), the results were unfavorable (**Table 2**, model 1). These results are reversed to those obtained by Ghisetti and Rennings (2014) and Levänen et al. (2015) which highlighted that the energy innovation leads to an increase in economic performance. Therefore, hypothesis *H_1, Energy innovations directly and notably shaped the sustainable development of the EU countries within the economic globalization framework,* is partially fulfilled.

Environmental dimensions have registered favorable direct impacts on the GDP per capita only following the environmental performance index (*epi*) (positive and statistically significant coefficient), while for national expenditure allocation for environmental protection (*env_exp*) (negative and statistically significant coefficient), air pollution by particulate matter (*air_poll*) and the intensity of greenhouse gas emissions of energy consumption (*gge_ec*) (positive and statistically significant coefficients), the influences upon the GDP per capita were unfavorable. Therefore, policymakers must consider the improvement of environmental impacts, which would lead to an increase in economic performance, as Ghisetti and Rennings (2014) and Ali et al. (2021) also highlighted. Consequently, hypothesis *H_2, Environmental performance directly and significantly influenced the sustainable development of the EU countries within the economic globalization framework,* is also partially fulfilled.

Digital transformations of the economy and society positively and directly influenced the GDP per capita for all dimensions of DESI, namely human capital (*desi_hc*), connectivity (*desi_con*), integration of digital technology (*desi_tech*), and public services (*desi_dpserv*) (positive and statistically significant coefficients). However, the distinctive speed of internet coverage (*hs_internet*) negatively influenced the GDP per capita. Moreover, technological innovations and renewable energy may induce a positive impact on the quality of life by reducing the energy deficiency that affects the economies of the EU, but also the energy affordability and accessibility as Sinha et al. (2022) and Zhao et al. (2022) also proved.

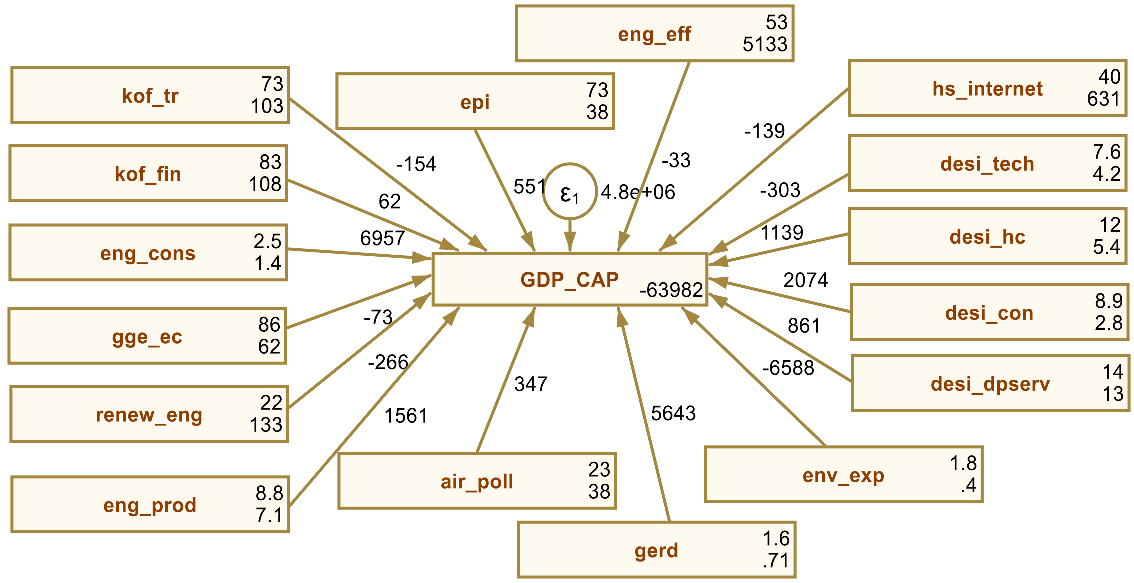

FIGURE 2 | | Results of SEM for the EU-27 MS. Source: Authors' research.

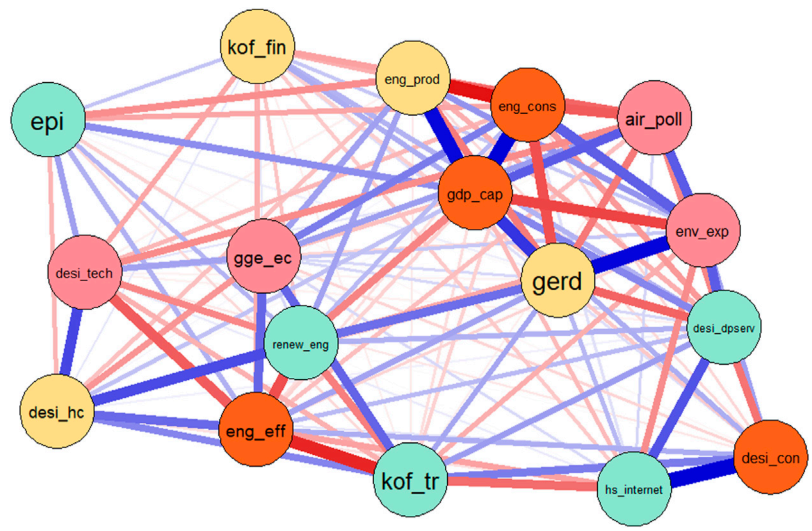

FIGURE 3 | | Gaussian graphical model, partial correlations, EU-27 MS, 2018. Source: Authors' research.

Therefore, hypothesis *H3, Digital transformations directly and significantly influenced the sustainable development of the EU countries within the economic globalization framework,* is fulfilled only in the case of DESI dimensions.

Results of Structural Equation Modeling and Gaussian Graphical Model

For ***global interlinkages*** between energy innovations, environmental performance, digital transformations, economic globalization, and the sustainable economic development of the EU countries (H_4), we run structural equations models (**Table 2**, Model 2, **Figure 2**) and a Gaussian graphical model (**Figure 3**).

Several robustness checks were performed before placing an economic interpretation on the results. Hence, goodness-of-fit tests were applied, along with Cronbach's alpha calculations for scale reliability. Detailed test results are presented in **Tables 3**, **4**, entailing that the model provides accurate estimates, despite being processed on a relatively small sample.

As for global interlinkages of the variables on sustainable development, revealed by SEM results (model 2 from **Table 2** to **Figure 2**), we draw attention to the following dimensions

TABLE 3 | Cronbach's alpha for the SEM model.

Item	Sign	Item-test correlation	Average interitem correlation	Alpha
kof_tr	–	0.2152	0.2530	0.8356
kof_fin	+	0.6576	0.2174	0.8065
eng_cons	+	0.5454	0.2265	0.8146
gge_ec	–	0.5007	0.2295	0.8172
renew_eng	+	0.4199	0.2366	0.8229
air_poll	–	0.8157	0.2041	0.7937
epi	+	0.7500	0.2101	0.7996
hs_internet	+	0.2684	0.2488	0.8324
desi_tech	+	0.7613	0.2093	0.7988
desi_hc	+	0.8414	0.2029	0.7924
desi_con	+	0.5455	0.2266	0.8146
desi_dpserv	+	0.7670	0.2087	0.7983
eng_prod	+	0.1503	0.2582	0.8392
env_exp	+	0.2794	0.2479	0.8317
eng_eff	+	0.2494	0.2503	0.8335
gerd	+	0.6346	0.2193	0.8082
Total scale	—	—	—	0.8254

Authors' contribution in Stata.

TABLE 4 | Goodness-of-fit tests for the SEM model.

Description	SEM
Likelihood ratio	
"Baseline vs saturated" chi^2_bs (16)	107.761
$p > chi^2$	0.000
Information criteria	
"AIC (Akaike's information criterion)"	2,533.576
"BIC (Bayesian information criterion)"	2,556.222
Baseline comparison	
"CFI (Comparative fit index)"	1.000
"TLI (Tucker–Lewis index)"	1.000
Size of residuals	
"SRMR (Standardized root mean squared residual)"	0.000
"CD (Coefficient of determination)"	0.984

Authors' contribution in Stata.

(statistically significant): *energy innovations*, with the same favorable influences of consumption (*eng_cons*) and productivity of energy (*eng_prod*), and unfavorable in case of energy efficiency (*eng_eff*) and renewable energy consumption (*renew_eng*) (**Table 2**, model 2)—being opposite to those obtained by Ghisetti and Rennings (2014) that highlighted that the energy innovation leads to an increase in economic performance; *environmental performance and sustainability,* with favorable direct impacts only for the environmental performance index (*epi*), and unfavorable implications induced by expenditure allocation for environmental protection (*env_exp*) (negative and statistically significant coefficient) and air pollution by particulate matter (*air_poll*) (positive and statistically significant coefficient)—being almost similar with the results proved by Ali et al. (2021), which stated that changes in GDP, renewable energy consumption, and eco-innovation may cause CO_2 emissions; *digital transformations,* with favorable impact only in case of digital public services (*desi_dpserv*) component of DESI. Opposite to our findings, Álvarez-Herránz et al. (2017b), for certain developed countries of the OECD, proved that sustainability in the energy sector may be attained by favorable impacts induced by using renewable resources and implementing technical innovations. Therefore, for these risks, specific policies and strategies are needed. Economic globalization, measured by trade (*kof_tr*) and financial globalization (*kof_fin*), have not induced any statistically significant influences on GDP per capita, being reversed to those obtained by Ulucak (2021) that evidenced a major impact of globalization and financial development on energy consumption in Pakistan, with final impact on economic development.

Both in the case of direct and overall impacts of expenditures allotted for R&D (*gerd*), the implications on GDP per capita were favorable (**Table 2**, Model 1 and Model 2). Our findings are similar to those obtained by Álvarez-Herránz et al. (2017a) (p. 99) that highlighted the role that energy innovations play in environmental quality processes and economic development, with the paramount support of regulation as regards energy research, development and demonstration (ERD&D).

The Gaussian graphical model entails very strong interlinkages between all variables/credentials considered in this research, as reflected through the width/thickness of the paths (**Figure 3**). Environmental performance (*epi*) tends to stand out in the network, being strongly connected with digital transformation and integration of technologies (*desi_tech*), as well as with financial globalization (*kof_fin*). At the same time, sustainable economic development (*gdp_cap*) is positively partially correlated with energy production (*eng_prod*), energy consumption (*eng_cons*), and research and development activities (*gerd*), but also with environmental performance (*epi*). Research and development activities is also positively correlated with renewable energy consumption (*renew_eng*) and energy efficiency (*eng_eff*). These results are similar to those obtained by Carrión-Flores and Innes (2010) and Álvarez-Herránz et al. (2017a) that found the importance of energy innovation in the decrease of energy intensity and

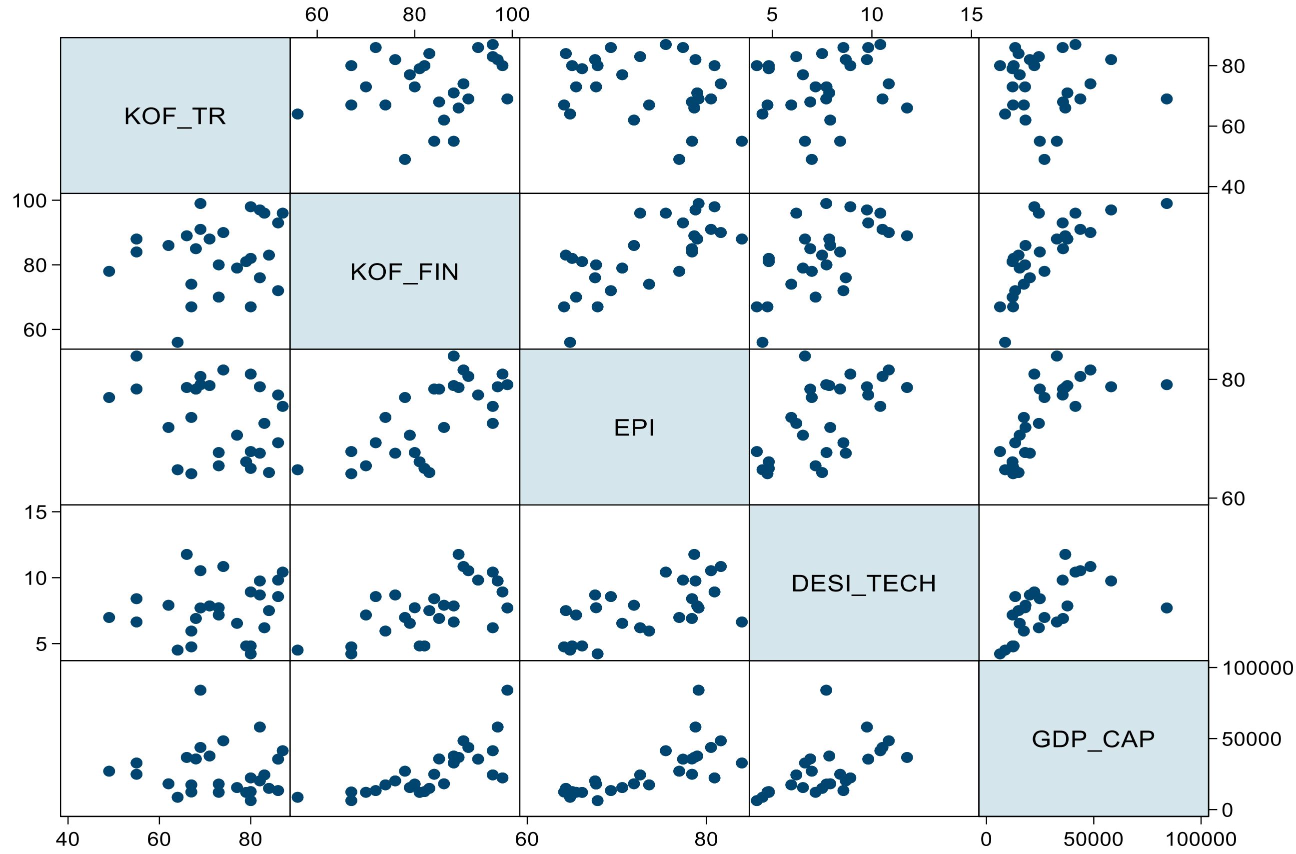

FIGURE 4 | | Correlation matrix for the main indicators used in clustering, EU-27, 2018. Source: Authors' contribution.

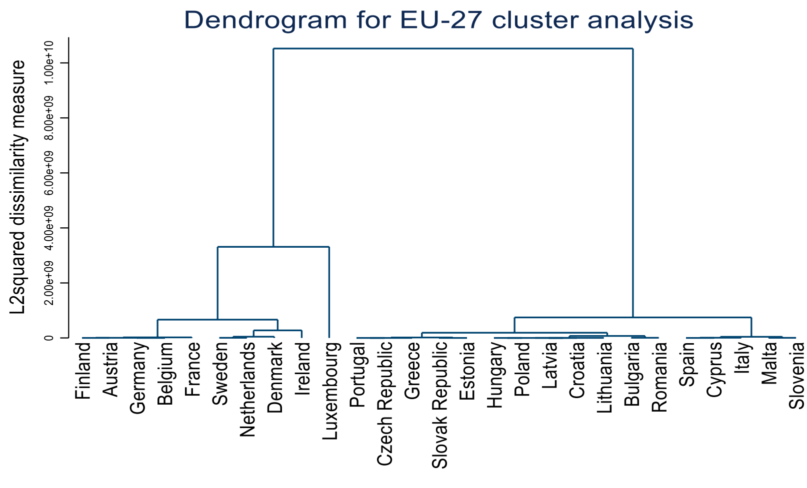

FIGURE 5 | | Dendrogram of cluster analysis, EU-27, 2018. Source: Authors' contribution.

environmental pollution, as a result of research and development support provided by authorities. Therefore, energy innovations, environmental performance, and digitalization drive represent enablers of sustainable economic development.

Consequently, hypothesis *H4. Energy innovations, within global interlinkages with environmental performance, digital transformations and economic globalization, notably influenced the sustainable development of the EU countries,* is partially fulfilled.

TABLE 5 | Clusters associated results with the interlinkages between trade and financial globalization, environmental performance, digital transformation and sustainable economic development, EU-27, 2018.

Clusters (C)	EU-27 member states	Cluster modelling—Ward method
		Performance
C1	France, Belgium, Sweden, Finland, the Netherlands, Denmark, Germany, Austria, Ireland, Luxembourg	*High* (through largest levels of *kof_fin, kof_tr, epi, desi_tech, gdp_cap*)
C2	Italy, Malta, Spain, Cyprus, Slovenia	*Medium* (through all variables, with notable differences between *kof*_tr and *kof_fin*)
C3	Hungary, Lithuania, Bulgaria, Estonia, Greece, Poland, the Slovak Republic, Croatia, Portugal, Romania, Latvia, the Czech Republic	*Low* (particularly through low levels of *gdp_cap, epi, desi_tech and kof_fin*, but with good levels of *kof_tr*)

Authors' contribution in Stata.

TABLE 6 | Cluster analysis results (Ward method).

Indicators	*Cluster 1 (C1)*			*Cluster 2 (C2*			*Cluster 3 (C3*			*R-sq*	*F*
	N	*mean*	*Sd*	*N*	*mean*	*sd*	*N*	*mean*	*sd*		
kof_tr	10	73.11	10.39	5	69.80	16.42	12	74.33	7.93	0.2324	2.2568
kof_fin	10	90.77	3.92	5	86.40	10.13	12	74.75	8.70	0.5502	9.3769**
epi	10	79.29	2.46	5	75.28	5.26	12	67.56	3.17	0.7407	21.8951***
desi_tech	10	9.39	1.82	5	7.84	1.18	12	6.20	1.54	0.4731	6.8851**
gdp_cap	10	41,138.89	7,981.25	5	23,780	2,591.24	12	13,497.5	3,613.39	0.9147	82.1919***

Authors' contribution in Stata.
N, number; Sd, Standard Deviation; R-sq, R-squared; F, Fisher-tests.

Results of Cluster Analysis

Considering the notable differences among the EU MS, the research endeavor is continued with an in-depth assessment of specific groups of EU countries and, implicitly, of the differences among them—as regards the sustainable development (GDP per capita), economic (financial and trade) globalization, environmental performance, and the integration of digital technologies. In this regard, we have applied *cluster analysis,* through the Ward method inset on hierarchical clustering.

The correlation matrix of the indicators used to configure the clusters is given in **Figure 4**.

Both through the dendrogram and the Calinski-Harabasz stopping rule (evaluation criterion), the clustering procedure indicated the formation of an optimal number of 3 clusters (**Figure 5**; **Tables 5**, **6**).

In the first cluster (C1) there are ten EU MS, namely France, Belgium, Sweden, Finland, the Netherlands, Denmark, Germany, Austria, Ireland, and Luxembourg. These countries are placed by the Ward method together in C1 considering the high performance achieved as regards the financial globalization, environmental performance, digital integration of technologies, and increased economic outcomes (very high levels of GDP per capita). The second cluster (C2) comprises five EU MS, namely Italy, Malta, Spain, Cyprus, Slovenia, with medium performances as regards the degree of digital integration of technologies, and trade globalization, despite a good environmental performance (*epi*), and medium levels of GDP per capita. In the third cluster (C3), there are 12 EU MS (Hungary, Lithuania, Bulgaria, Estonia, Greece, Poland, the Slovak Republic, Croatia, Portugal, Romania, Latvia, the Czech Republic) with low levels of environmental performance, and integration of technologies, as well as a relatively low level of GDP per capita and financial globalization, compared to the other clusters, even though the countries placed in C3 have the largest average level of trade globalization. Related to these findings, we propose targeted strategies and measures for each group of countries. Moreover, the economic complexity specific to each country will require the steadiness of the economic policy measures adopted, as many authors recommended (Altıntaş and Kassouri, 2020; Bashir et al., 2022; Sun et al., 2022).

Therefore, hypothesis H_5, *There are significant differences among the EU countries in terms of sustainable development, financial and trade globalization, environmental performance, and the degree of integration of digital technologies,* is fulfilled.

CONCLUSION

Given the fact that the EU member states are in a complex process of transition, divided into two levels—digitalization and green economy, and between the two phenomena, there are strong interdependencies, in this paper, we examined the role of energy innovations, digital technological transformation, and environmental performance in enhancing the sustainable economic development of the EU countries, widely shaped by the globalization process. We have developed a top-down approach to research methodology, by assessing, firstly, the nexus (direct and overall) for all EU countries, and secondly, EU countries were clustered to ensure in-depth assessment and tailored policy design by accounting for the level of financial and trade globalization, environmental performance, and sustainability, and the degree of integration of digital technologies.

Following the research hypotheses drawn, we brought robust empirical evidence to attest that energy innovations, environmental performance and digital transformations have directly and globally shaped the sustainable development of the EU countries within the economic globalization framework (H_1-H_4), with focus on awareness for the following directions: higher and better allocation of national expenditure on environmental protection, reconsideration of energy efficiency by better involving the state authorities in the process of pollution reduction, which through various tools can shape both the behavior of local companies and consumers and foreign capital businesses, as Simionescu et al. (2021) also mentioned; energy innovations deployed by using the renewable energy, including advanced technologies and ICT, since economic growth may induce the rise of ecological footprint, as Ramzan et al. (2022) also stated.

As regards the differences among the EU countries in terms of sustainable development, financial and trade globalization, environmental performance, and the degree of integration of digital technologies, revealed by the cluster analysis (H_5), the following tailored policies and strategies could be considered by the EU MS to diminish the deterring factors of environmental and digitalization performance and enhance sustainable economic development: *i)* for the countries comprised in C1 (France, Belgium, Sweden, Finland, the Netherlands, Denmark, Germany, Austria, Ireland, and Luxembourg), with very good performance of financial globalization, environmental performance, digital integration of technologies on the background of high economic development, policies to enforce these dimensions are needed, within a comprehensive trade globalization process, as Álvarez-Herránz et al. (2017a) and Shahbaz et al. (2018) also stated for the developed countries of the OECD; *ii)* in the case of EU MS comprised in C2 (Italy, Malta, Spain, Cyprus, Slovenia), better integration of financial and trade globalization, involving state authorities in the process of reducing pollution to enhance environmental performance, as well as technological innovation may improve sustainable economic development, as Simionescu et al. (2021) also mentioned; *iii)* as regards the countries included in C3 (Hungary, Lithuania, Bulgaria, Estonia, Greece, Poland, the Slovak Republic, Croatia, Portugal, Romania, Latvia, the Czech Republic), consistent policies are needed in order to improve the environment-energy-growth nexus with the economic globalization and technological innovation.

Overall, we can state that transition to digitalization and green economy will ensure the development of a low carbon economy in the context of efficiency considering the facilities generated by digitalization, both for consumers and for companies in different fields of activity. The energy transition must ensure not only the protection of the environment, but also the increase of energy affordability and accessibility. The use of renewable energy can be a solution to reduce energy poverty, technological innovation being essential to change the energy mix in EU countries (Sinha et al., 2022; Zhao et al., 2022). The concern of energy companies to intensify the process of technological innovation must be accompanied by a change of attitude and behavior among consumers who should embrace new technologies and become aware of the importance of saving energy by using new equipment that is more efficient (Altıntaş and Kassouri, 2020; Ahmad and Zhang, 2021; Bashir et al., 2022; Sun et al., 2022).

The Covid-19 crisis has demonstrated the importance of the digitalization process of the economic activity, companies being increasingly concerned with supporting the investment in the Information Technology (IT) field. The European authorities' investment concerns and efforts are key to both digitalization and the energy transition. Ensuring the legal and institutional framework and developing public-private partnerships are the main directions in which the European authorities can act. The process of technological innovation is more and more intense, the companies making efforts to find viable solutions from a technical point of view for carrying out productive activities in conditions of social responsibility. Protecting the environment is a growing concern in the business strategy of companies, given the pressures exerted by consumers and public authorities. Involvement in local communities and supporting their development is at the heart of the concerns of companies that have realized the importance of this category of stakeholders. Sustainable development is a goal that can be achieved at the level of the EU, the results being remarkable.

Unfortunately, economic activity is subject to multiple risks, with political risk having a significant impact on the world economy. For this reason, the energy transition process is one of reconfiguration given the need to increase energy security in the context of the dependence of EU countries on Russian oil and gas.

For this reason, being aware of the limitations of the research conducted in this paper, regarding mainly the reduced availability of relevant data on longer time series, and the economic and geopolitical risk induced by the Russian invasion into Ukraine, the authors consider the follow-up of current research with trends in the twin transition process for the EU countries, from the perspective of the impacts induced by the political risk and the quality of governance.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Conceptualization, GN, MC, MP, ST, and CP; methodology, GN and MC; software, GN; data collection, GN and MC; validation, GN, MC, and MP; formal analysis, GN, MC, and MP; investigation, MC, MP, ST, and CP; writing—original draft preparation, GN, MC, MP, ST, and CP; writing—review and editing, GN, MC, MP, ST, and CP.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.934404/full#supplementary-material

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