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Digitalization and Energy in Attaining Sustainable Development: Impact on Energy Consumption, Energy Structure, and Energy Intensity

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Abstract: The relentless advancement of digital technologies has the potential to significantly reshape the energy landscape as digital technologies become increasingly integrated into diverse sectors of the economy. This study explores the intricate relationship between digitalization and energy in EU countries, focusing on its direct and indirect impacts on energy consumption, structure, and intensity. Furthermore, this study explores the mediating mechanisms that facilitate these changes, including the role of technological innovation and government efficiency in the relationship between digitalization and energy outcomes. Focusing on EU countries and using the system-GMM method, this research accounts for the heterogeneity in the impact of digitalization on energy across various member states. It examines the varying effects in different countries, considering their income levels, environmental regulations, and green investments. The results demonstrate that the strategic deployment of digitalization in EU countries substantially benefits the energy sector. By optimizing energy consumption and enhancing the energy structure through the integration of renewable sources, the EU could move closer to its sustainability objectives.

Keywords: e-governance; consumption; green energy; environmental regulations; green investments

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1. Introduction

Achieving sustainable development goals (SDGs) [1–6] requires the development and implementation of new and effective instruments that consider ongoing trends in world development [7–11], such as digitalization, integrating sustainable development into all economic activities and levels [12–15]. It should be noted that sustainable development is a multifaceted concept that, at its core, seeks to balance environmental stewardship, economic growth, and social equity for current and future generations [16]. It provokes the transformation of the world through innovative approaches to solving complex challenges related to climate change, resource depletion, and social disparities. This concept encourages us to rethink economic models and societal structures to ensure a livable planet for future generations. Digitalization, as a multifaceted process, significantly shapes the contemporary landscape by intertwining with various aspects of our environment and society. Studies [17–19] underscore the complexity of this transformation, outlining the diverse array of both the positive and negative effects it evokes. On the positive side, digitalization has the potential to enhance efficiency and streamline processes across various sectors [20–23]. The integration of digital technologies often leads to a reduction in energy consumption [24–30], offering opportunities for sustainability and resource optimization [26–30]. Additionally, it can foster innovation, provide novel solutions to environmental challenges, and contribute to the development of cleaner, more sustainable technologies [31–34]. However, it is crucial to acknowledge the potential negative repercussions of digitalization, especially concerning its impact on the environment [35–38]. The increased reliance on digital technologies has resulted in a surge in energy consumption [36,37], contributing to concerns about energy intensity and the carbon footprint [39,40]. Additionally, the accelerated pace of technological advancements has provoked the generation of electronic waste (e-waste) [41,42], posing challenges for proper disposal and recycling. As societies worldwide navigate the complexities of digitalization, finding a delicate balance becomes imperative. Efforts to harness the positive aspects while mitigating the negative consequences involve implementing policies and practices that promote sustainable development. This includes investing in green technologies [43–48], developing efficient waste management systems [49–51], enhancing green logistics [52,53], and fostering a culture of responsible digital consumption [54]. However, digitalization is conducive to extending new management approaches [55–61] and requires developing relevant infrastructure [62–68], knowledge, and competencies [69–73].

The diverse perspectives on the impact of digitalization on the energy sector underscore the need for a comprehensive analysis of the relationship between digitalization and energy in EU countries. The EU has developed a comprehensive set of strategies aimed at addressing the escalating energy prices, as detailed in [74]. These strategies encompass a dual approach: on the one hand, they focus on the supply side by ensuring an adequate supply of natural gas and accelerating the transition towards renewable energy sources through policy instruments. On the other hand, the Commission's measures target the demand side, aiming to reduce the energy consumption of both households and businesses. However, a critical aspect that appears to have been overlooked in this framework is the role of digitalization. Digitalization significantly impacts energy consumption patterns, energy infrastructure, and the overall intensity of energy use. It represents a transformative force that can either increase energy demand through the proliferation of digital devices and data centers or decrease it through efficiency gains and smart energy management. Therefore, it should have been a key consideration for the European Union's authorities in formulating their energy strategy. By integrating digitalization into their approach, the European Commission could better address the complexities of energy consumption, structure, and intensity, and thus develop a more holistic and effective response to the ongoing energy crisis. This examination should concentrate on both the direct and indirect effects of digitalization on energy consumption, structure, and intensity. Understanding the character of this influence is crucial for policymakers, industry stakeholders, and researchers alike, as it allows for informed decision making in steering energy systems toward greater resilience and environmental sustainability. This paper addresses theoretical gaps in understanding the relationship between digitalization and energy in EU countries through several key contributions: this study acknowledges the absence of a unified standard for digitalization in scholarly discourse. To bridge this gap, a composite index, the DESI (digital economy and society index), is applied. The DESI incorporates key dimensions such as human capital, connectivity, the integration of digital technology, and digital public services (e-government). This index provides a valuable tool for enhancing clarity in political and academic circles regarding the digitalization of the EU economy. It also facilitates the formulation of more scientific and valid measures and strategies; a significant aspect of this study is its focus on the effects of digitalization on energy development, including consumption, intensity, and structure. This emphasis allows for an efficient assessment of the actual impact of optimizing digitalization on energy. This study contributes to a relatively small body of literature that explores the nuanced relationship between digitalization and energy dynamics. The findings have the potential to inform policymakers and industry stakeholders on the tangible effects of digitalization on energy, laying the groundwork for informed decision making.

This paper has the following structure: Literature Review—an analysis of the theoretical framework of the relationship between digitalization and energy consumption, the structure of energy usage, and energy intensity; Materials and Methods—an explanation of the data, variables, sources, methods and instruments applied to test the research hypotheses of the investigation; Results—exploring the findings of the investigation; Conclusions and Discussion—summarizing the core results, their comparison with the previous investigation, policy implications, limitations, and further directions for investigation.

2. Literature Review

2.1. Relationship between Digitalization and Energy Consumption

Scientists hold diverse perspectives on the interplay between digitalization and energy consumption. Researchers [75–81] envision enhanced efficiency through smart technologies [75–77], smart grids [78], and AI-driven optimizations in industrial processes [79–81]. However, scholars [82–87] have focused on the energy intensity of digital technologies, with high-performance computing and data centers being potential culprits. Studies [88–92] have shown that digitalization facilitates the better integration of renewable energy into grids, promoting sustainability. Nevertheless, scholars [93–96] have highlighted that the environmental impact of e-waste and the extraction of rare minerals from electronics cannot be ignored. One study [97–99] outlined that behavioral changes induced by digitalization, such as increased device usage and the adoption of smart technologies, alter energy consumption patterns. Moreover, the proliferation of data centers and cloud computing has raised concerns about centralized energy consumption [100–102]. However, Aithal [103] and Mishra and Singh [104] showed that ongoing technological innovations and solutions, including energy-efficient hardware and quantum computing, offer potential avenues for mitigating these challenges [105]. Analyzing the situation in EU countries reveals a discernible gap in investigations into the relationship between digitalization and energy consumption for EU countries considering energy consumption, the energy structure, and energy intensity.

Hypothesis 1. *There is a negative relationship between digitalization and energy consumption, implying that increased digitalization leads to a reduction in energy consumption.*

2.2. Relationship between Digitalization and the Structure of Energy Usage

Xu et al. [106] noted that digitalization allows for the optimization of energy structures in China. In addition, Xu et al. [106] highlighted that the impact of digitalization on energy consumption is most significantly mediated by technological innovation, while the influence of digitalization on energy intensity is primarily mediated by human capital. In contrast, the distortion of the industrial structure plays the most substantial mediating role in shaping the impact of digitalization on energy structure. Ren et al. [98] concluded that the correlation between internet development and the energy consumption structure is notably negative. Internet development influences the energy consumption structure by way of economic growth, research and development (R&D) investment, human capital, financial development, and the industrial structure. Scholars [107] have confirmed that extending digital technology has provoked a decrease in the impact of the energy structure on carbon dioxide emissions. Zhang et al. [108] noted that digitalization provoked changes in the structure of energy usage in China. Moreover, the energy consumption structure impacts the attainment of sustainable development goals, particularly for carbon dioxide emissions. Noussan and Tagliapietra [109] argue that digital technologies lead to opposite effects on energy consumption and emissions in EU countries. The authors emphasize that an effective strategy is “responsible” digitization, which involves the development of sustainable mobility. In contrast, “selfish” digitization results in maximizing the benefits for the end consumer. Scholars [110] empirically justify that digitalization plays a moderating role, alleviating the impact of a 3.654% increase in energy consumption resulting from income inequality. This moderating influence is particularly noticeable in middle- and high-income countries spanning Europe, the Americas, and the Asia–Pacific region, and it remains effective in both free and nonfree economies. Through the use of dynamic SYS–GMM threshold panel models, this research uncovers a nonlinear connection between income inequality and energy consumption influenced by digitalization, offering international evidence of the interconnected dynamics involving digitalization, income inequality, and energy consumption. Ren et al. [98] examined the influence of internet development on energy consumption in China, with a focus on the mechanisms of transmission. The findings reveal a noteworthy positive association between internet development and overall energy consumption, as the internet contributes to increased energy usage through economic growth. On the other hand, there is a negative relationship between internet development and the structure of energy consumption, indicating that the internet shapes the energy consumption structure through factors such as economic growth, R&D investment, human capital, financial development, and the industrial structure. Additionally, empirical evidence demonstrates a substantial negative correlation between internet development and energy consumption intensity, suggesting that the internet facilitates a decrease in energy consumption intensity through similar influencing factors. Lange et al. [111] suggested that the growth of digitalization is conducive to increasing energy consumption. Considering the above, this study tests the following hypothesis:

Hypothesis 2. *Digitalization positively influences the structure of energy usage, indicating a shift toward more sustainable and efficient energy sources.*

2.3. Relationship between Digitalization and Energy Intensity

Scholars [112–121] argue that digitalization, by fostering technological advancements and efficiency improvements, lead to a reduction in energy intensity. This viewpoint suggests that smart technologies [122–125], data analytics [126–132], and automation can optimize energy consumption in various sectors, ultimately contributing to more sustainable practices. In contrast, skeptics [133–135] emphasize the potential for increased energy consumption associated with the growing demand for digital technologies. The proliferation of devices and data centers and the overall expansion of digital infrastructure may offset the gains achieved through efficiency measures. This perspective highlights the need for a holistic assessment that considers both the positive and negative aspects of digitalization on energy intensity. Another viewpoint [136–139] acknowledges the complex and nuanced relationship between digitalization and energy intensity, emphasizing that the impact is context-dependent. Factors such as the type of digital technology implemented, the overall energy mix in a region, and specific industry practices play crucial roles. This perspective suggests that a one-size-fits-all approach may not be suitable, and tailored strategies are necessary to optimize the balance between digitalization and energy intensity based on the unique circumstances of each situation.

One study [140] showed that digitization contributes to the economic growth of South Asia. Moreover, there is a negative correlation between energy intensity and economic growth [140]. The empirical results [141] indicate a predominantly positive asymmetric relationship between digital innovation, energy intensity, demographic change, and economic growth in Vietnam. Although minor distinctions are observed across different quantiles of the chosen indicators, the overall impact is favorable. Furthermore, the Granger causality analysis of quantiles reveals a bidirectional connection between digitalization, demographic dividends, and economic growth over the sample period. Moreover, unidirectional causality is identified from energy intensity to economic growth [141]. Scholars [141] have discovered a noteworthy adverse correlation between digitalization and energy intensity. Additionally, they identify a significant positive correlation between digital capital intensity and energy intensity. Lan and Wen [142] showed that the industrial digitalization of the manufacturing sector leads to a notable increase in energy intensity. Throughout the process of digital transformation, there is an initial increase followed by a subsequent decrease, forming an inverted U-shaped relationship. As of 2019, more than 80% of industries exhibited a level of digitalization below the inflection point [142].

The perspectives on the link between digitalization and energy intensity vary, encompassing optimistic views on efficiency gains, concerns about increased energy demand, and recognition of the context-specific nature of this relationship.

Hypothesis 3. *Digitalization is negatively associated with energy intensity, suggesting that as digital technologies advance, energy use becomes more efficient.*

3. Materials and Methods

To analyze the influence of digitalization on energy indicators, this study employs a baseline model represented by Equation (1):

$$Energy_{it} = \alpha + b_1 Dig_{it} + b_2 X_{it} + u_i + u_t + \varepsilon_{it} \quad (1)$$

where $Energy_{it}$ denotes the energy level in country i in year t; Dig_{it} represents the measure of the digital economy; b_1 signifies the marginal impact of the digital economy on the energy level; X_{it} comprises a vector of control variables; u_i represents country-specific distinctions; u_t signifies time fixed effects; and ε_{it} denotes the idiosyncratic error term, accounting for unobserved factors that may impact energy levels beyond the specified variables.

In this study, the variables of energy consumption, structure, and intensity are employed as the explained variables. Energy consumption is a crucial indicator due to its diverse implications for societal, economic, and environmental dimensions. It serves as a barometer of economic activity, reflecting growth patterns and market trends. The quantity of energy consumed is intricately linked to quality of life, providing insights into living standards and access to modern amenities. Essential for infrastructure planning, energy consumption data can guide policymakers in developing robust energy systems to meet current and future needs. Moreover, it facilitates efficient resource management by identifying energy-intensive processes and fostering sustainability. Given these environmental concerns, monitoring energy consumption is imperative for assessing the impact of climate change and formulating policies that align with conservation and cleaner energy goals. Additionally, as technological advancements reshape consumption patterns, understanding these changes is pivotal for anticipating the role of emerging technologies in optimizing energy usage.

Energy intensity is a crucial metric that measures the efficiency of energy use within a system or sector and is expressed as the amount of energy required to produce a unit of output or achieve a specific task. This metric is instrumental in assessing the effectiveness of energy consumption in various applications, industries, or economic activities. A lower energy intensity indicates higher efficiency, reflecting a reduced reliance on energy inputs to generate a given level of output. Energy intensity is particularly important when evaluating the sustainability and environmental impact of energy consumption. As a key indicator, it helps policymakers, businesses, and researchers understand how changes in technology, processes, and policies influence the relationship between energy use and economic output. In the realm of renewable energy development, energy intensity is a valuable tool for tracking improvements in efficiency and assessing progress toward a more sustainable and energy-efficient future.

The energy structure, or energy mix, refers to the composition of various energy sources utilized within a specific region, industry, or sector. This indicator provides a comprehensive view of how different types of energy, such as fossil fuels, renewables, and nuclear energy, contribute to the overall energy supply. Changes in the energy structure can signify shifts in technology, policy, and economic priorities. For instance, an increasing proportion of renewable energy sources in the structure may indicate a commitment to sustainability and a reduced reliance on fossil fuels.

The explanatory variable in this analysis is the digital economy, which includes a diverse range of activities, such as digital infrastructure, e-commerce, data analytics, and other technological advancements impacting production, consumption, and overall economic processes. Since 2014, the European Commission (EC) has been monitoring the digital progress of member states through the digital economy and society index (DESI) [143]. The DESI evaluates and ranks EU member states' progress using four core and 33 individual indicators. These core indicators include human capital (internet user skills and advanced skills and development), connectivity (fixed and mobile broadband connection coverage and price), integration of digital technology (digital intensity, business digitalization, and e-commerce), and digital public services, or e-government. In this study, the DESI is employed as an explanatory variable to gauge the extent of country digitalization.

To consider the impact of additional factors on energy levels, the econometric model incorporates a set of control variables. Technological innovation (Innov) is measured by patents for environment-related technologies and captures the influence of technological advancements on energy dynamics. Innovative technologies, particularly those geared toward environmental concerns, can have a substantial impact on how energy is consumed, structured, and utilized, particularly income levels (GNIs) [144,145]. Captured by the gross national income per capita, this variable helps to account for the potential influence of a country's economic affluence on energy patterns. Environmental regulations (EnvReg) [146] are measured by government expenditure on environmental protection as a percentage of GDP; this variable reflects the regulatory environment. Strong environmental regulations may influence the energy industry's structure and intensity by promoting cleaner practices. The percentage of GDP spent on environmental protection indicates the government's commitment to sustainability: green investments (GFDIs) [147–149]. Representing green foreign direct investments, this variable incorporates the impact of foreign capital specifically targeted toward environmentally friendly initiatives. This study acknowledges the potential role of international investments in shaping a country's energy landscape and intensity.

The sample analysis included EU countries. Embracing digital technologies aligns with the EU's commitment to advancing energy efficiency, fostering innovation in renewable energy sources, and promoting smart infrastructure development. Understanding how digitalization impacts energy consumption, structure, and intensity is essential for aligning national strategies with EU policies, ensuring informed decision making, and supporting a region's commitment to environmental sustainability. The investigation period, chosen as 2017–2022, was determined based on the data availability. Due to the limited duration (T < 15), conducting unit root tests was considered unnecessary. However, given this study's focus on a relatively modest sample size encompassing 27 EU countries, there is potential for encountering challenges associated with cross-sectional dependency (CD). To address this concern, this study employs both static and dynamic panel models to explore variables related to energy consumption, energy structure, and energy intensity. These models include the difference fixed effect (FE) model and the system generalized method of moments (Sys-GMM).

In contrast to the difference generalized method of moments (diff-GMM), the system generalized method of moments (sys-GMM) incorporates dependent variables in lagged form, rendering it more effective by employing a system of two simultaneous equations:

$$Energy_{it} = \alpha + b_1 DESI_{it} + b_2 EnvReg_{it} + b_3 Innov_{it} + b_4 GNI_{it} + b_5 GFDI_{it} + u_t + \varepsilon_{it} \quad (2)$$

$$Energy_{it} = \alpha_0 + \alpha_0 Energy_{it-1} + \lambda_1 DESI_{it} + \lambda_2 EnvReg_{it} + \lambda_3 Innov_{it} + \lambda_4 GNI_{it} + \lambda_5 GFDI_{it} + \nu_{it} \quad (3)$$

where α_0, $b_1 \ldots b_5$, $\lambda_1 \ldots \lambda_5$ are the vectors of the parameters to be estimated; ε_{it} is the error term; and ν_{it} are individual-level effects that are not observed.

Moreover, the sys-GMM method is superior because it mitigates estimation biases arising from potential correlations between the regressor and the error term. It also addresses the likelihood of omitted dynamics, a situation that may occur when dependent variables are lacking in lagged form.

Two approaches were employed to validate the stability of the regression model. First, a split sample validation was conducted by excluding Germany, France, Italy, Cyprus, and

Malta from the sample. Second, cross-validation was implemented, incorporating a new variable, trade openness (TO), into the model to create a new dataset.

Table 1 displays the variables and their source databases utilized in the models, all of which were transformed into their natural logarithmic forms.

Table 1. The descriptive statistical results of the variables and source databases.

Variable	Source	Mean	SD	CV	Min	Max
FEC	Eurostat [150]	35.274	48.028	1.362	0.525	218.620
EI	Eurostat [150]	160.949	76.317	0.474	37.350	439.110
ES	Eurostat [150]	23.277	11.963	0.514	6.194	66.002
DESI	Eurostat [150]	42.516	10.582	0.249	19.399	69.598
EnvReg	Eurostat [150]	0.739	0.355	0.480	0.170	1.773
Innov	OECD [151]	11.507	3.808	0.331	1.200	24.159
GNI	World Data Bank [152]	34,239.380	19,242.570	0.562	7620.000	89,200.000
GFDI	Unctad [153]	9715.198	16,285.890	1.676	28.000	81,540.000

4. Results

The initial phase of this study employs a static model encompassing the POLS and fixed effects (FE) model. While the utilization of a static model for estimation may yield biased and inconsistent results, it serves the purpose of elucidating the correlations among energy indicators (energy consumption, structure, and intensity) and pertinent variables. The findings from both models align; nevertheless, the outcomes from the panel fixed effects model are deemed more dependable because they encompass both cross-country and within-country variations. Additionally, the inclusion of year fixed effects accounts for temporal changes in the results, independent of the explanatory variables. The results of the POLS and fixed effects analyses are shown in Table 2. The findings indicate that an upsurge in the digital economy and society index (DESI) has adverse effects on energy consumption (FEC) and energy intensity (EI), while it positively influences the energy structure (ES). Specifically, a 1% increase in DESI is associated with a decrease in FEC ranging from 0.211 to 0.495% according to the POLS estimates and 0.211 to 0.477% according to the FE. Similarly, for EI, a 1% increase in DESI is linked to a decrease ranging from 0.216 to 0.427% in POLS estimates and 0.305 to 0.424% in FE estimates. Conversely, a 1% increase in DESI corresponds to an increase in ES ranging from 0.620 to 0.842% in the POLS estimates and 0.626 to 0.805% in the FE estimates.

Table 2. The results of POLS and fixed effects (static panel estimations).

Dependent Variable	OLS Estimate						Fixed Effects					
	FEC		EI		ES		FEC		EI		ES	
DESI	−0.211 ***	−0.495 ***	−0.427 ***	−0.216 ***	0.620	0.842 ***	−0.211 ***	−0.477 ***	−0.424 ***	−0.305 ***	0.626 ***	0.805 ***
	(−5.410)	(−8.400)	(−9.940)	(−4.520)	(6.110)	(4.870)	(−5.400)	(−7.410)	(−9.900)	(−4.810)	(5.920)	(4.650)
EnvReg	–	0.048 **	–	0.079	–	0.029	–	0.040	–	0.096 *	–	0.169 *
		(1.760)		(1.370)		(0.370)		(1.450)		(1.760)		(1.710)
Innov	–	0.004	–	−0.001	–	0.017	–	0.002	–	−0.001	–	0.017
		(0.700)		(−0.090)		(0.760)		(0.280)		(−0.040)		(0.800)
GNI	–	0.433 ***	–	−0.349 ***	–	−0.332 **	–	0.412 ***	–	−0.210 *	–	−0.288
		(7.380)		(−4.010)		(−2.050)		(6.080)		(−1.820)		(−1.430)
GFDI	–	0.010 **	–	0.004	–	−0.008	–	0.007	–	0.006	–	−0.009
		(1.990)		(0.720)		(−0.660)		(1.480)		(1.200)		(−0.780)
constant	3.546 ***	0.079 ***	6.561 ***	9.370 ***	0.718	3.339 ***	3.545 ***	0.251	6.554 ***	8.270 ***	0.696 ***	3.097
	(12.560)	(0.160)	(38.990)	(12.500)	(1.620)	(3.030)	(24.410)	(0.500)	(41.130)	(8.370)	(1.770)	(1.960)
Number of obs	162	162	162	162	162	162	162	162	162	162	162	162
Number of groups	27	27	27	27	27	27	27	27	27	27	27	27
R^2	0.309	0.456	0.673	0.714	0.429	0.457	0.309	0.458	0.673	0.722	0.429	0.468

***, **, and * are $p < 0.01$, 0.05, and 0.1, respectively; z values in parentheses.

The observed decreases in energy intensity (EI) and energy consumption (FEC) with a higher DESI underscore the potential for digitalization to lead to more efficient energy use. This resonates with the EU's emphasis on improving energy productivity and sustainability through technological advancements. The positive relationship between the DESI and an increase in the energy structure (ES) suggests that as digital and societal indices improve, there may be a shift toward more sustainable and diversified energy sources. This aligns with the EU's renewable energy and climate goals, signaling potential positive outcomes from advancements in the digital economy.

The outcomes obtained from the linear system-GMM exhibit estimates akin to those derived from the POLS and FE models. However, this study places greater reliance on the system-GMM approach due to its ability to address serial correlation, particularly in connection with a lagged variable for energy consumption (FEC), energy intensity (EI), and energy structure (ES). Additionally, the system-GMM method addresses potential endogeneity concerns through the utilization of an instrumental variable (IV) approach in its estimates. Consequently, the estimations derived from the system-GMM framework are considered more dependable than the static panel (POLS and FE) estimates, as they offer enhanced control over serial correlation and potential endogeneity issues. While the results maintain consistency with previous estimates, noteworthy variations are observed in the coefficients. The findings from the system-GMM analysis are presented in Table 3. The coefficients associated with lagged energy variables (FEC, EI, and ES) exhibit substantial significance, emphasizing robust associations with their respective dependent variables.

Table 3. The results of system-GMM (dynamic panel estimations).

Dependent Variable	FEC	EI	ES
$Energy_{t-1}$	0.975 *** (57.890)	0.890 *** (19.550)	0.063 * (0.670)
$DESI_t$	−0.203 *** (−2.680)	−0.067 ** (−1.710)	0.542 *** (5.720)
EnvReg	−0.025 (−0.870)	0.006 (0.290)	−0.117 *** (−2.980)
Innov	0.040 (1.930)	−0.005 (−0.340)	−0.024 (−0.910)
GNI	−0.020 (−0.450)	−0.045 (−1.220)	−0.042 (−0.740)
GFDI	0.013 (1.100)	−0.007 (−0.870)	−0.032 ** (−2.590)
constant	0.435 * (1.530)	1.294 (2.610) ***	1.520 *** (3.760)
AR (1) test	−5.27	−4.82	−4.11
AR (1) p value	0.000	0.000	0.000
AR (2) test	1.13	−0.04	0.92
AR (2) p value	0.259	0.965	0.358
Sargan test	0.75	4.24	1.87
Sargan p value	0.689	0.120	0.393
Number of obs	135	135	135

***, **, and * are $p < 0.01$, 0.05, and 0.1, respectively; z values in parentheses.

Specifically, the positive coefficients for FEC (0.975) and EI (0.890) underscore the influence of past levels of energy consumption and intensity on their present values, highlighting the persistent nature of energy-related patterns over time. A positive coefficient for ES (0.063) indicates a less pronounced yet noteworthy effect on the structure of energy consumption. Analyzing the digital economy and society index (DESI) at time 't', the negative coefficients for FEC (−0.203) and EI (−0.067) imply that higher levels of past energy consumption and intensity are linked to lower DESI values, suggesting a potential trade-off between digitalization and historical energy use. Conversely, the positive coefficient for ES (0.542) indicates that a more favorable structure of energy consumption is associated with higher DESI values, underscoring the importance of sustainable energy structures in supporting the digital economy and societal development. Environmental regulation (EnvReg), green innovation (Innov), gross national income (GNI), and green investment (GFDI) have effects on the dependent variables. For instance, the negative coefficient for EnvReg (−0.025) suggests that stricter environmental regulations are associated with a decrease in FEC, indicating the potential impact of regulatory policies on energy consumption patterns. Similarly, the positive coefficient for Innov (0.040) suggests that increased green innovation positively influences FEC, emphasizing the role of innovation in shaping energy consumption. The consistency of the system-GMM estimators was evaluated through the Sargan and Arellano–Bond (AB) tests. The Sargan test produced statistics of 0.75, 4.24, and 1.87, accompanied by p values of 0.689, 0.120, and 0.393, respectively. A higher p value in the Sargan test indicates that the null hypothesis of overidentifying restrictions' validity is not rejected. This suggests that the instruments employed in the system-GMM estimation are sound, affirming that the model avoids overfitting. Additionally, the AR (2) tests indicate that the model effectively addresses second-order serial correlation, reinforcing the credibility of the system-GMM estimators in capturing temporal dependencies within the data.

Table 4 presents the outcomes of the system-GMM estimation, with exclusions of statistical data from Germany, France, Italy, Cyprus, and Malta due to their prominent influence. The coefficients associated with the digital economy and society index (DESI) exhibit significant impacts at the 10%, 5%, and 1% significance levels for FEC, EI, and ES, respectively. This observation underscores that, even after the exclusion of specific data points, the estimation results continue to reinforce the conclusion that policies aimed at promoting digital transition and societal development could be strategically aligned with energy efficiency, sustainability, and diversification goals.

Table 4. The results of system-GMM (eliminating the particular values).

Dependent Variable	FEC	EI	ES
$Energy_{t-1}$	0.966 *** (56.170)	0.886 *** (19.380)	−0.125 * (−1.240)
$DESI_t$	−0.205 * (−2.770)	−0.101 ** (−2.420)	0.691 *** (6.450)
Control variables	yes	yes	yes
constant	0.259 * (1.120)	1.343 ** (2.570)	1.689 *** (4.470)
AR (1) test	−5.16	−3.67	−1.54
AR (1) p value	0.000	0.000	0.123
AR (2) test	1.06	−0.43	0.50
AR (2) p value	0.287	0.668	0.619
Sargan test	1.54	1.90	0.49
Sargan p value	0.463	0.386	0.784
Number of obs	110	110	110

***, **, and * are $p < 0.01$, 0.05, and 0.1, respectively; z values in parentheses.

Table 5 displays the results of a refined system-GMM analysis, which includes the incorporation of trade openness for a more robust evaluation of the findings presented in Table 3.

The digital economy and society index (DESI) shows significant negative coefficients for FEC (−0.186 **, z value = −2.440) and EI (−0.249, z value = −3.050), indicating that an increase in DESI is associated with a decrease in both energy consumption and intensity. However, for ES, the coefficient is positive (0.535, z value = 4.450), suggesting a positive correlation between DESI and the energy structure. The results of the AR (1) and AR (2) tests indicate that the model adequately addresses first-order (AR (1) p value = 0.000) and second-order (AR (2) p value = 0.239, 0.230, 0.104) serial correlations. The p values (0.612, 0.599, 0.565) of the Sargan tests indicate that the instruments used in the system-GMM estimation are valid. This reaffirms and strengthens the key conclusions drawn in this study, emphasizing the role of DESI in influencing energy dynamics. The negative association between FEC and EI suggests that advancements in the digital economy and societal aspects are linked to reduced energy consumption and intensity. Conversely, a positive correlation with ES indicates a favorable impact on the structural composition of energy usage. These findings underscore the pivotal role of accelerating digital and societal development in shaping energy-related outcomes.

Table 5. The results of system-GMM (adding new control variable).

Dependent Variable	FEC	EI	ES
$Energy_{t-1}$	0.948 *** (34.460)	0.636 *** (6.210)	0.376 *** (4.480)
$DESI_t$	−0.186 ** (−2.440)	−0.249 *** (−3.050)	0.535 *** (4.450)
Control variables	yes	yes	yes
constant	0.416 * (0.960)	2.900 *** (3.700)	1.104 *** (2.260)
AR (1) test	−5.23	−3.77	−5.24
AR (1) *p* value	0.000	0.000	0.000
AR (2) test	1.18	−1.20	1.63
AR (2) *p* value	0.239	0.230	0.104
Sargan test	0.98	0.28	1.14
Sargan *p* value	0.612	0.599	0.565
Number of obs	135	135	135

***, **, and * are $p < 0.01$, 0.05, and 0.1, respectively; z values in parentheses.

5. Conclusions and Discussion

This study's results robustly support Hypothesis 1, revealing a negative relationship between digitalization and energy consumption. Specifically, the empirical findings indicate that for every 1% increase in the digital economy and society index (DESI), there is a corresponding decrease in energy consumption (FEC) ranging from 0.211% to 0.495% in POLS and 0.211% to 0.477% in FE, underscoring that heightened digitalization leads to a substantial reduction in energy consumption. These findings are consistent with the results of previous studies [24–30]. Moreover, this study's outcomes align convincingly with Hypothesis 2, indicating that digitalization positively influences the structure of energy usage, which has also been confirmed by researchers [106–108]. However, the opposite is true of other studies [30]. The findings show that the structure of energy consumption (ES) increases with increasing DESI range, suggesting a shift toward more sustainable and efficient energy sources. These results confirm that digitalization contributes to a significant restructuring of energy usage. The empirical results provide compelling empirical support for Hypothesis 3, revealing a negative association between digitalization and energy intensity, which is also confirmed by previous studies [141]. The system-GMM analysis emphasized robust associations between key economic variables and final energy consumption (FEC), energy intensity (EI), and the structure of energy consumption (ES). The positive coefficients for FEC (0.975) and EI (0.890) underscored the influence of past energy consumption and intensity on the present values, while the positive coefficient for ES (0.063) indicated a notable effect on the structure of energy consumption. The results of the AR (1) and AR (2) tests indicate that the model effectively addresses both first-order and second-order serial correlations. The *p*-values of the Sargan tests confirm the validity of the instruments used in the system-GMM estimation, further affirming the soundness of the model's approach.

Considering the findings, the following policy implications could be outlined to attain sustainable development goals considering the links between digitalization and energy consumption and their structure and energy intensity:

1. Promoting digitalization for energy efficiency: Given the observed negative relationship between digitalization and energy consumption, policymakers should prioritize and incentivize the adoption of digital technologies across sectors. Encouraging businesses and industries to embrace digital solutions, such as smart grids and energy-efficient technologies, can contribute significantly to reducing overall energy consumption. Sweden has successfully implemented nationwide energy efficiency programs that leverage digital technologies. Through initiatives such as smart metering and advanced energy management systems, Sweden has empowered consumers to monitor and control their energy usage [42,86,87,154]. This bottom-up approach has resulted in a significant reduction in energy consumption at the household and industrial levels. Accelerating the adoption of digital technologies across diverse sectors emerges as the strategy to diminish energy consumption, aligning with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).
2. Supporting sustainable energy sources: The positive influence of digitalization on the structure of energy usage implies a shift toward more sustainable and efficient energy sources. The promotion of digitalization's role in transitioning towards renewable energy sources resonates with SDG 7, advocating for an increased integration of sustainable energy technologies. Policymakers should focus on developing and promoting policies that facilitate the integration of renewable energy technologies. Incentives for research and development in green innovation and fostering a regulatory environment that supports sustainable energy projects contributed to this shift. Germany's success in promoting renewable energy is attributed in part to its feed-in tariff system. This policy guarantees fixed payments to renewable energy producers, providing a reliable income stream and incentivizing investments in solar, wind, and biomass projects. This approach has led to a substantial increase in the share of renewables in the energy mix.
3. Enhancing regulatory frameworks: Recognizing the impact of environmental regulations on energy consumption patterns, policymakers should strive for well-crafted regulatory frameworks. Stricter environmental regulations, as suggested by the negative coefficient for EnvReg, play a crucial role in shaping energy consumption. Policymakers should aim for regulations that encourage energy-efficient practices and discourage environmentally harmful activities [155].
4. Investing in digital infrastructure. Bolstering digital infrastructure to support energy-efficient practices reflects commitments to SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities), emphasizing the need for comprehensive policies and investments in digital capabilities to optimize energy consumption and promote environmental sustainability. To harness the positive impact of digitalization on energy intensity, policymakers should focus on investing in digital infrastructure and ensuring widespread access to digital technologies. This includes initiatives to improve broadband connectivity, digital literacy programs, and support for research and development in digital technologies [156]. Enhancing the digital capabilities of industries and the general population contributes to more efficient energy use.

This study highlights the critical role of digitalization in reducing energy consumption and promoting a shift towards more sustainable and efficient energy sources in attaining sustainable development goals. It provides empirical evidence that increased digitalization leads to significant reductions in energy use and encourages a transition to renewable energy, supported by a negative association between digitalization and energy intensity. These findings underscore the importance of leveraging digital technologies and targeted policy interventions to achieve sustainable development goals, emphasizing the dual benefits of digitalization for energy efficiency and sustainability.

Despite the valuable findings obtained, this study has limitations that could be overcome in future investigations. Thus, further studies should expand upon these investigations (not only for EU countries) by analyzing other countries (the USA, China, India, etc.) that are leaders in energy consumption and digitalization. Furthermore, the list of independent variables should be extended by indicators that could boost digitalization and extend green innovation, such as the efficiency of governance, political stability, and spending on education.

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