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How Does the Interplay Between Banking Performance, Digitalization, and Renewable Energy Consumption Shape Sustainable Development in European Union Countries?

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Abstract: In the context of current global challenges, the integration of digitalization, financial performance, and renewable energy is pivotal in fostering sustainable and resilient economic development. The aim of this paper is to explore the interplay between banking performance, digitalization, and renewable energy consumption in the context of the European Union (EU), with a focus on sustainable economic development. This study examines the extent to which the digitalization and efficiency of the banking sector influence the uptake of renewable energy considering the EU's environmental and economic priorities. The methodology used involves an econometric analysis based on statistical data from EU countries, using Fully Modified Ordinary Least Squares (FMOLS) to assess causal relationships between variables, complemented by Vector Autoregression (VAR) models and Granger causality tests to further investigate the dynamic interactions among the variables. The data were analyzed to examine the correlation between banking performance, digitalization, and renewable energy consumption levels. The results reveal a positive correlation between greater digitalization in the banking sector, stronger financial performance, and higher investments in renewable energy sources. These factors also support the transition to a green economy, but the effect varies between EU countries depending on national policies and existing digital infrastructure. Recommendations for policymakers include stimulating digitalization in the financial sector, creating a regulatory framework to encourage green energy investments, and strengthening collaboration between financial institutions and the energy sector to facilitate the transition to renewables. This paper also suggests a fiscal policy conducive to technological innovation and digitalization to accelerate the uptake of renewable energy.

Keywords: banking performance; digitalization; renewable energy

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1. Introduction

In recent years, there has been a global consensus on the need to reduce carbon emissions, largely due to major initiatives such as the new 2030 Agenda for Sustainable Development [1] and the Paris Agreement [2]. Among the key measures adopted in this regard, increasing renewable energy consumption is a fundamental strategy to decrease CO_2 emissions and ensure long-term sustainability [3–6]. However, global renewable energy consumption remains below the Paris Agreement, indicating the need to increase the use of renewable energy sources [7].

Increasing environmental pollution is one of the most significant and urgent challenges facing the planet [8,9], and the banking sector is instrumental in mobilizing the financial resources needed to support sustainable development and green innovation initiatives [10,11].

According to Wu and Broadstock [12], first, the expansion of the financial sector facilitates the adoption of renewable energy sources by spurring technological innovation and increasing capital accumulation. Second, the allocation of financial resources to profitable projects contributes to the increased use of renewable energy, leading an increasing number of actors to adopt renewable energy sources. These findings suggest that a well-structured banking sector has the ability to mitigate liquidity risks and efficiently mobilize the financial resources needed for sustainable investments in renewable energy sources [8,10,13,14].

The financial sector has undergone significant transformations due to rapid technological innovations [15–17]. Thus, digital financial technologies such as blockchain, supported by the European Union and other international organizations, have increased the accessibility of financial services [16,18–21]. Information technology has also facilitated the transformation of financial markets, streamlining banking operations [22–25]. In addition, studies indicate that access to digital finance has the potential to substantially enhance household consumption and contribute to financial inclusion [26–28].

These advances in financial technologies are taking place in a context where the banking sector is under increasing pressure to modernize and reduce its CO_2 emissions, as its performance influences renewable energy consumption in various ways [13,29,30]. To enhance energy efficiency, it is essential to optimize bank size, improve asset quality, and implement efficient management in high-income economies [31–33]. In the context of this global push for sustainability, addressing climate change and improving gender equality have become the most important objectives for banks that are signatories to the Principles for Responsible Banking (PRB), followed by financial inclusion, which has been integrated into the sustainability strategies of 76.4% of PRB signatories [34]. On the other hand, the Net-Zero Banking Alliance, launched in April 2021, brought together 144 banks globally by September 2024, committing to achieve net-zero emissions by 2050 and set interim targets for 2030, with annual reporting and transparency targets [35]. By integrating these sustainable practices into their strategies, banks can not only reduce their financial risks but also contribute to the transition to carbon neutrality.

In addition, under the regulations of financial institutions, banks can redistribute funds from less efficient energy sources to clean and renewable ones [36]. For example, many banks in developed countries, such as Sweden and Germany, have implemented green mortgage and green vehicle loan programs [37,38]. These financial products offer customers interest rate discounts, thus facilitating access to cleaner energy solutions. Finally, a large-scale infrastructure is essential to support sustainable renewable energy research and technology development, which can be realized through adequate financial support [12]. As banks improve their performance by showing positive financial results, they are likely to support such investments, which could contribute significantly to the growth of renewable energy consumption [13,39].

The interaction channel between digitalization, banking performance, and renewable energy can be explained from an economic perspective through several mechanisms. First, the digitalization of the banking sector facilitates fast and efficient access to financial information, allowing financial institutions to optimize their processes and reduce operational costs [20]. This can lead to better financial performance, and banks with robust financial performance have more resources to invest in green technologies and projects, including in the renewable energy sector [36–38]. Second, digitization can support the development of innovative financial instruments, such as participatory finance or green bonds, which facilitate investments in renewable energy infrastructure [16,17].

Moreover, digitization improves access to financial markets for renewable energy projects, reducing risks and transaction costs, and the financial performance of banks becomes an important factor in the allocation of capital to green projects [12–14]. Thus, strong financial performance of the banking sector can lead to increased investment in renewable energy sources, supporting the transition to a green and sustainable economy [13,40]. In principle, digitization helps to integrate renewables more efficiently into the energy mix by using advanced technological solutions to manage resources and distribution networks more efficiently, thus contributing to increased renewable energy consumption [39].

As a result, we aim to explore the interaction between banking performance, digitalization, and renewable energy consumption in the context of the European Union, with a focus on sustainable economic development. This study will examine the extent to which digitalization and efficiency of the banking sector influence renewable energy consumption in light of the EU's economic and environmental priorities. This research aligns with the strategic objectives of the European Union, which aims to become a global leader in the energy transition. It will also make an important contribution to the literature by highlighting the relationship between these variables. The methodology used will involve a quantitative analysis based on statistical data from EU countries, using econometric models to assess the causal relationships between variables.

This study fills some important gaps in the literature. First, the integrated approach to digitalization, bank performance, and renewable energy consumption fills a significant gap, as previous research has examined these variables in a fragmented manner. On the one hand, most studies have focused either on the impact of digitalization on the economy or on the financial sustainability of the banking sector. On the other hand, the current study shows how all these dimensions can work together to stimulate green investment. However, questions remain about regional specificities and how these variables interact in different economic and political contexts.

Moreover, this study makes significant contributions to our understanding of how banking performance, digitalization, and renewable energy consumption interact to support sustainable development in the European Union. First, this study provides an integrated analysis of these three factors, which allows a clearer view of the synergistic role of digitalization and the financial sector in facilitating the green transition. While many previous studies have treated these dimensions separately, this study combines them in a holistic approach. On the other hand, it also highlights the diversity of impacts according to the national specificities of the EU countries, thus underlining the need for a differentiated policy approach to support the energy transition. The analysis also highlights the importance of cooperation between the banking and energy sectors, as financially strong banks can make a decisive contribution to financing green projects.

The paper is delimited into six parts: Section 2 outlines the context framework and reviews the relevant literature; Section 3 explains the econometric methodology, and data; Section 4 focuses on interpreting the results; Section 5 discusses the findings in depth; and Section 6 concludes with this study's conclusions, policy implications, future research directions, and limitations.

2. Literature Review

2.1. Digitalization of the Banking Sector Shapes Investment Patterns in Renewable Energy

The study of the interaction between banking performance, digitalization, and renewable energy consumption has gained particular attention in economic and financial research, especially in the context of sustainable development goals. The literature has emphasized the important role of bank digitalization in improving operational efficiency and reducing transaction costs, thereby contributing to improved financial performance [40–44]. Several studies have highlighted that digitalization promotes innovation in the banking sector, reducing the carbon footprint by optimizing workflows and automating processes [45–47].

Digitalization in the financial sector is widely recognized as a key factor in improving efficiency and transparency. Gao [48] highlights that the digitalization of finance has a significant positive effect on accounting transparency in the long run, facilitates better allocation of resources, and increases trust in financial markets. In the same vein, the study by Wu et al. [49] emphasizes that banking digitalization promotes energy efficiency by facilitating access to green loans, which can contribute to increased consumption of renewable energy.

Moreover, digitalization also contributes to reducing urban carbon emissions by optimizing resource use. The study by Zhao et al. [50] shows that digital finance plays an important role in reducing the carbon intensity of cities, especially in regions with developed digital infrastructure. Similar results are found by Lin and Xu [51], who show that digitalization can improve the environmental performance of small and medium-sized enterprises by facilitating access to finance and reducing financial constraints.

In the context of emerging economies, Hung [52] shows that financial digitalization has a significant positive impact on economic and environmental sustainability by facilitating investment in green resources and innovative technologies. He suggests that the widespread adoption of digital solutions in the banking sector can accelerate the green transition in the EU, especially in economies with developing digital infrastructures.

This observation is supported by the argument that digital activities, such as e-commerce, e-banking, online shopping, virtual meetings, and e-books, contribute to reducing resource and energy consumption, thereby reducing environmental pollution. In this context, digitalization is also associated with waste management systems, which have shown significant growth in OECD countries since 2000, offering great opportunities to positively influence the environment. This negative correlation between digitalization and the environment is consistent with previous findings by Caglar et al. [53], Chen [54], Ha et al. [55], and Ma et al. [56].

Another study by Manta et al. [57] makes a significant contribution to understanding the relationship between the use of e-commerce and e-banking in the context of climate change mitigation and reducing resource and energy consumption. In the literature, this study emphasizes the positive effects of digital activities on the environment, providing empirical evidence that the intensive use of e-commerce and e-banking services contributes to a reduction in the carbon footprint in European Union countries. At the same time, the study warns about the complexity of various electronic sales channels, showing that not all of them are effective in reducing climate impacts, which calls for a nuanced analysis of the potential benefits of digitalization in sustainable development efforts [57].

Digitalization is also an important driver for renewable energy. The study by Sheraz et al. [58] emphasizes that digitalization can enhance the energy transition and support green finance initiatives in OECD countries, thereby advancing the realization of the sustainable development goals. In addition, Wu et al. [49] show that financial digitalization can reduce distortions in input markets by optimizing energy efficiency and promoting the use of renewable energy sources. Ngo Thai Hung [52] shows that green investment, digitalization, and financial development have a positive impact on economic sustainability and support the transition to a low-carbon economy. The results of the study are also confirmed by research by Ullah et al. [59], who emphasize that digitalization and technological innovation play a significant role in improving environmental quality and reducing carbon emissions. A similar conclusion is reached by Wu et al. [49], who examine the interactions between FinTech and the renewable energy market in the EU and show that digital solutions can facilitate the green transition and promote long-term sustainable development. Moreover, digitalization not only optimizes the allocation of resources but also reduces market volatility and increases market stability.

In addition to these studies, the nexus between financial development and energy consumption has been extensively examined in the literature [60–63], providing valuable insights for the analysis of the interaction between banking performance, digitalization and renewable energy consumption in our paper. Some researchers [64–66] have highlighted a positive correlation between financial development and energy consumption, while others [67–69] suggest that financial development can lead to a reduction in energy consumption. This complexity of the relationship is also emphasized by empirical studies; for instance, Yue et al. [70], analyzing data from 21 transitional economies, found that while the direct impact of financial development on energy consumption was negligible, advancements in financial intermediation, capital markets, and financial openness significantly influenced energy consumption. These findings provide valuable context for understanding how banking digitalization may affect energy sustainability within the European Union.

On the other hand, some researchers [71,72] have found that the impact of financial development on energy consumption is insignificant. Even though the research on this effect has not produced a uniform conclusion, many feasible policy proposals have been made to address the potential problems related to energy supply.

Other strands in the literature have emphasized the link between financial development and the growth of renewable energy consumption, highlighting the role of the banking sector and foreign direct investment in this process. In one study, Paramati et al. [73] analyzed the impact of foreign direct investment and stock market growth on clean energy, concluding that both are key factors influencing renewable energy generation and utilization. Similarly, Dogan and Seker [74] demonstrated that commercial and financial development can promote the adoption of clean technologies, thereby increasing renewable energy consumption. Using data from 22 emerging economies and employing the generalized method of moments (GMM), Wu and Broadstock [12] found that financial development and institutional quality positively affect renewable energy consumption. In the same vein, Kutan et al. [75] investigated four emerging economies and determined that stock markets and foreign direct investment significantly contribute to renewable energy consumption growth. Anto and Afloarei Nucu Nucu [76] corroborated this relationship in a study of 28 EU countries, showing that financial development positively influences the share of renewable energy consumption, as evidenced by their fixed-effects model analysis.

Digitalization plays a key role in improving banking efficiency and performance, has a significant impact on the optimization of financial processes [77,78], and, in the context of sustainable development, also contributes to promoting the use of renewable energy. According to the study by other authors [79], a digitalization index for the banking sector in Central and Eastern European countries was proposed, highlighting the importance of investments in digitalization and financial education to enhance access to banking services and support sustainable economic growth in regions with already saturated markets.

Thus, the following research hypothesis can be postulated:

Hypothesis 1. *Digitalization of the banking sector increases investment in renewable energy.*

2.2. Banks' Financial Performance Influences the Transition to a Green Economy

In a study by Amuakwa-Mensah and Näsström [80], the association between bank performance and renewable energy consumption was analyzed using financial indicators such as return on assets and asset quality on a global panel of 124 countries. The results showed that an improvement in bank performance is positively correlated with an increase in renewable energy consumption, highlighting significant differences across countries' income groups; in particular, high-income countries benefited from bank size and low non-performing loans. In contrast, in low- and middle-income countries, although asset returns and financial stability had a positive impact on renewable energy consumption, low levels of non-performing loans seemed to reduce its share in total energy consumption.

Although studies on the impact of banks' financial performance indicators on renewable energy consumption are limited, research indicates that the banking sector plays an important role in increasing renewable energy consumption. Omri and Nyugen [81] suggested that a low cost of credit can incentivize renewable energy use, supporting the idea that a well-performing banking sector can contribute to increased renewable energy consumption. Studies from sub-Saharan Africa have also shown that good banking sector performance improves energy efficiency, suggesting a similar effect on renewable energy [13].

Moreover, bank performance plays a key role in supporting green investment by helping to mobilize capital for renewable energy projects. The study by Haoyue Wu et al. [82] shows that banks with strong financial performance are more likely to support green energy investments, especially in regions with intense banking competition and limited natural resources. This is essential for EU countries, where financing green projects is becoming a priority in the sustainable development strategy.

Furthermore, Kayani et al. [83] examine the interactions between digital assets, traditional assets and renewable energy prices and show that digital assets have the potential to convey meaningful information to financial markets and reduce their volatility. These findings are supported by Ha [84], who examines the volatility of the renewable energy market in times of crisis and highlights the role of FinTech in stabilizing these markets by facilitating long-term sustainable investments.

Additionally, Quttainah and Ayadi [85] explore the impact of digital integration on corporate sustainability, showing that digitalization can improve resource efficiency and stimulate green innovation, thereby contributing to emissions reduction and sustainable development. These findings are relevant for EU banks, which play a central role in mobilizing capital for renewable energy projects.

Complementing these findings, the study by Selin et al. [86] highlights the role of digitalization, green innovation, renewable energy, and financial development in promoting environmental sustainability. The interaction between these elements amplifies the positive effect of digitalization on reducing the ecological footprint. Digital activities, such as e-commerce and e-banking, contribute to lower resource consumption and reduce pollution, and the development of waste management systems in OECD countries offers significant opportunities for positive environmental impacts.

The financial performance of banks has a significant impact on the transition to a green economy, as banks with financial stability can direct investments towards ecological projects and sustainable technologies, according to recent studies [87,88]. Research highlights [89] that financially strong banks are more capable of adopting financing strategies that support the development of green projects, integrating sustainability criteria into risk assessment and lending practices. Thus, according to studies [90,91], by promoting innovative and favorable financial solutions, banks can actively contribute to reducing environmental impact and developing an economic model based on ecological principles.

Thus, the following research hypothesis can be formulated:

Hypothesis 2. *Banks' financial performance positively influences investment in renewable energy sources.*

Thus, the literature review highlights the importance of digitalization and banking performance in supporting green investment and sustainable development in the European Union. Digitalization of the financial sector can facilitate access to finance for renewable energy projects and stimulate green innovation, thus contributing to the transition to a green economy. Based on these conclusions, public policies should support the further digitalization of the banking sector and foster cooperation between financial institutions and the energy sector to accelerate the green energy transition.

2.3. Exploring the Interconnections of Banking Performance, Digitalization, and Renewable Energy Through a Bibliometric Lens

To support the substantiation of the literature on our topic [92], we conducted a bibliometric analysis using papers published in two recognized databases, the Web of Science Core Collection and Scopus. By searching for the keywords *banking performance*, *digitalization*, and *renewable energy*, we identified 438 relevant documents in the Web of Science database and 1402 documents in Scopus. This dual approach allowed us to capture a more comprehensive picture of existing research by analyzing the co-occurrence of all the keywords used in the relevant studies, thus providing a solid basis for the interpretation of our results (Figures 1 and 2).

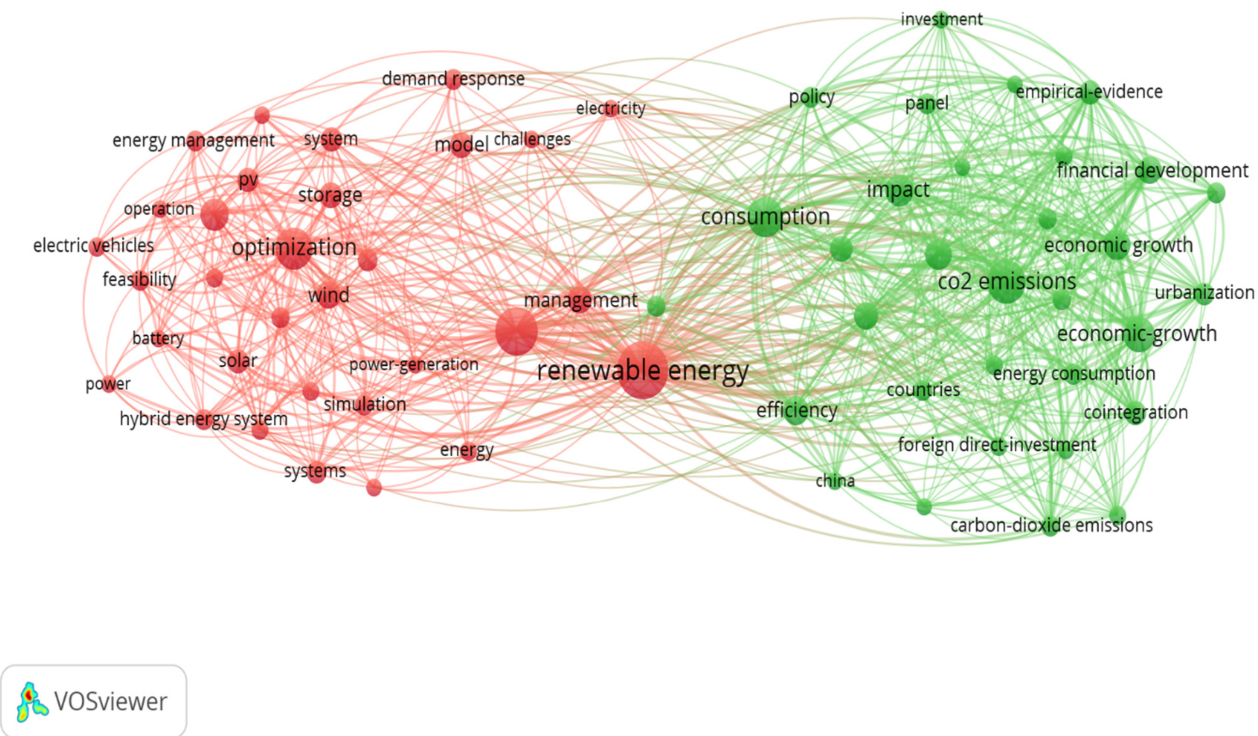

Figure 1. Co-occurrence and keyword connections in the literature on banking performance, digitalization, and renewable energy. Source: created by authors using VOSviewer 1.6.20 with Web of Science indexed articles.

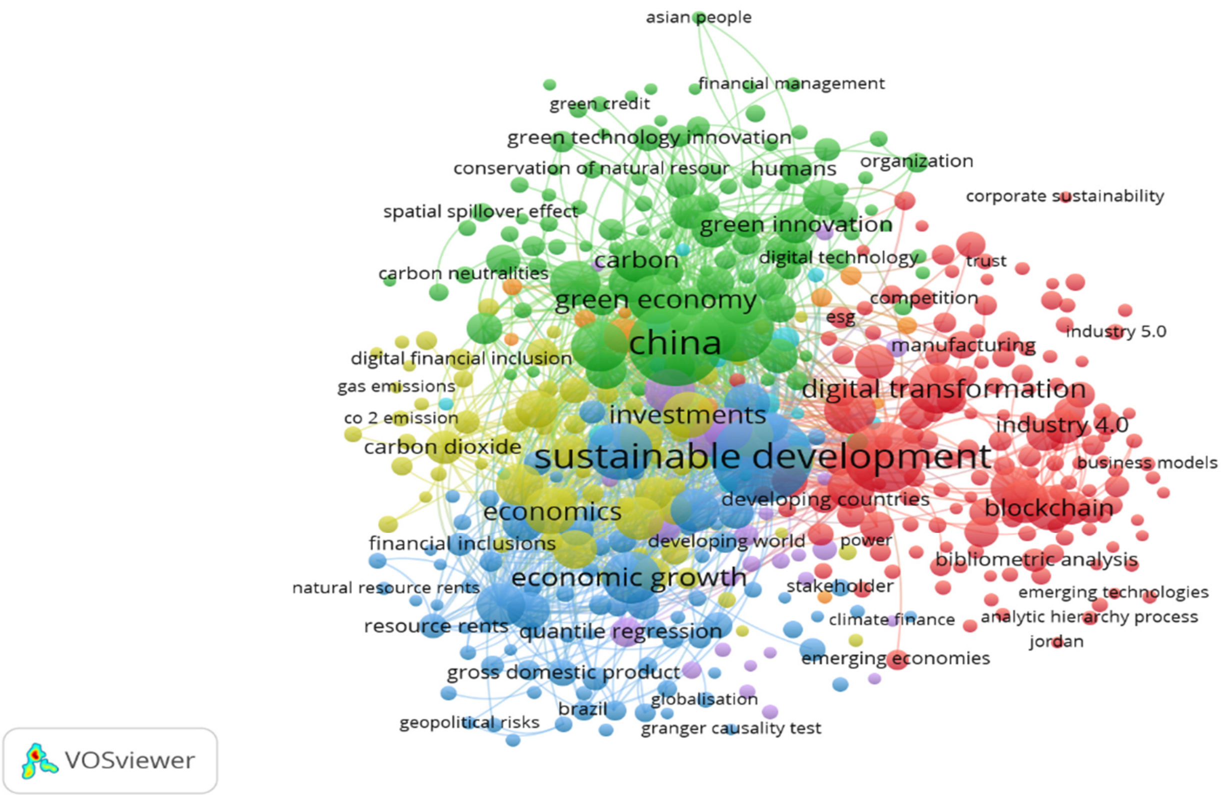

Figure 2. Co-occurrence and keyword connections in the literature on banking performance, digitalization, and renewable energy. Source: created by authors using VOSviewer 1.6.20 with Scopus indexed articles.

Figure 1, revealing the co-occurrence of keyword documents in the Web of Science database, shows two well-delineated clusters. The red cluster focuses on technical and technological aspects related to “renewable energy”, such as “optimization”, “solar”, “wind”, “storage”, and “systems”. These keywords reflect researchers’ interest in improving the efficiency and management of renewable energy, including the integration of technologies such as electric vehicles and hybrid energy systems. The green cluster focuses on economic and impact dimensions, with large nodes such as “consumption”, “economic growth”, “CO_2 emissions”, and “financial development”. This cluster reflects studies on the impact of renewable energy on economic growth and carbon reduction, with a focus on factors such as “foreign direct investment” and “energy consumption”. The central term “renewable energy” connects the two clusters, suggesting the interdependence between technological optimization and economic and environmental impact.

In Figure 2, the co-occurrence map of keywords in the Scopus database, the largest nodes are “sustainable development”, “china”, “economic growth”, and “digital transformation”. These terms are highlighted as central, indicating predominant themes in the analyzed literature. Large and connected nodes indicate that these terms are frequently used together in research and are central to the areas discussed. Strong connections exist between terms in the field of digitalization (such as blockchain or Industry 4.0) and those related to sustainable development and the green economy, such as green economy and carbon [92].

The findings of the bibliometric analysis in the two databases suggest a close interconnection between the technological and economic dimensions of renewable energy, highlighting the central role of technological optimization and economic impact in the existing literature. The red cluster in Figure 1 highlights researchers’ interest in improving the efficiency and management of renewable energy through advanced technologies, while the green cluster emphasizes their economic impacts, such as economic growth and CO_2 emission reductions. Similarly, the analysis in Scopus (Figure 2) indicates a strong link between digitalization and sustainable development, emphasizing the impact of digital transformations on the green economy and carbon reduction, highlighting the prevailing trends in recent research.

The review of the literature on the interaction between banking performance, digitalization, and renewable energy consumption in sustainable development highlights some important limitations. While there is a substantial body of research that examines these areas separately, studies that integrate all three into a unified framework remain rare. First, most previous papers focus either on the impact of digitalization on banking performance and operational efficiency or on the relationship between financial development and energy consumption, without directly exploring the combined influences on renewable energy consumption.

Another limiting aspect is the lack of econometric models that integrate factors such as technological development, eco-innovation, and institutional quality in the analysis of the nexus between digitalization and banking performance, although these elements are recognized as essential for sustainable development. Also, most studies are based on macroeconomic data at the global or regional level (e.g., emerging economies or OECD countries), and the specific EU context is not always well reflected.

Moreover, the current literature does not sufficiently explore the complex interplay between bank performance, digitalization, and renewable energy consumption, with most studies focusing on bilateral relationships between these variables. Indicators such as return on equity have not been sufficiently analyzed in relation to the transition to renewable energy sources, especially in the EU context. Also, digital inclusive measures such as internet access and use are rarely integrated into models investigating their impact on sustainable development.

These gaps provide research opportunities to investigate in more detail how the interaction between banking performance, digitalization, and renewable energy consumption can influence sustainable development goals in EU countries, contributing to improved economic and financial policy strategies. By utilizing advanced econometric models to assess the causal relationships between these variables, our study will contribute to a deeper understanding of the dynamics underlying the interplay between financial performance and sustainability, thus highlighting the importance of an integrated approach in analyzing this complex area.

Thus, the following research hypothesis can be postulated:

Hypothesis 3. *The nexus between banking performance, digitalization, and renewable energy consumption can influence sustainable development goals in EU countries.*

3. Materials and Methods

This study investigates how renewable energy consumption is influenced by digitalization and banking performance in the EU, analyzing these dynamics within the broader context of sustainable economic development. The selected time period of 10 years (2013–2022) was chosen to capture significant trends in the evolution of digitalization in the banking sector, as well as its impact on renewable energy consumption, considering the major economic and technological transformations that took place during this time. Additionally, the 10-year period ensures a relevant analysis of economic and financial data, allowing for the identification of meaningful relationships between the studied variables. To achieve this study's objective, we utilized the variables outlined in Table 1, with financial data sourced from the International Monetary Fund, "Financial Soundness Indicators" [93], and from the Eurostat database [94,95].

Table 1. Description of variables and data sources.

Acronym	Description	Variable Type	Unit of Measure	Time	Source
REN	Share of energy from renewable sources	Dependent variable	Percentage	2013–2022	Eurostat
ROE	Return on equity	Independent variable	Percentage	2013–2022	Financial Soundness Indicators from International Monetary Fund
EBANK	Individuals using the internet for internet banking: e-banking	Independent variable	Percentage	2013–2022	Eurostat
DIGINCL	Digital inclusion—frequency of internet access: once a week (including every day)	Control variable	Percentage	2013–2022	Eurostat

Source: Authors' own calculation. Note: The data were collected from official sources, such as Eurostat and the IMF, for the period 2013–2022. The dependent variable (REN) reflects the percentage of energy from renewable sources out of total energy production, while ROE represents financial profitability (return on equity). The analysis controls for variables EBANK and DIGINCL, which measure digital inclusion and internet banking usage among the population.

The choice of these variables is justified by the multidimensional exploration of the effect that renewable energy consumption has on banking performance and digitalization in EU countries.

First and foremost, the share of energy from renewable sources (REN) is a key indicator for sustainability and the green transition and is a central priority for the European Union in its quest to reduce carbon emissions and meet climate targets. Analyzing this indicator as a dependent variable allows us to examine how economic and digital factors contribute to the uptake of renewable energy sources and whether there is a correlation between the development of the financial sector and the use of green energy.

Second, return on equity (ROE) is a measure of financial performance and efficiency in the banking sector that highlights how well banks use invested capital to generate profits. By analyzing ROE, this study explores whether investments and innovations in renewable energy have a positive impact on bank profitability. Given that green energy can influence investor preferences and confidence and that banks are increasingly attracted to sustainable investments, ROE is a key indicator to understand the potential benefits of green energy on bank performance.

The variable individuals using the internet for internet banking (EBANK) is included to capture the degree of digitalization in the banking sector, as this is a useful proxy for the adoption of digital technologies in financial activity. The extent of internet banking reflects not only consumer accessibility and trust, but also the potential for effective integration of green energy into banking strategies through more efficient and sustainable digital services. This variable thus makes it possible to assess whether the uptake of renewable energy is influencing the evolution of digital banking services in EU countries.

Finally, digital inclusion (DIGINCL) measures the level of Internet access and usage, indicating the degree of digital inclusion of the population. This variable is included to investigate whether having a digitally included population has positive effects on energy transition and financial performance. Renewable energy use is largely associated with advanced technologies and smart solutions, and a well-connected population can stimulate the adoption and acceptance of these innovations. Digital inclusion thus becomes a supporting factor in the analysis of the transition to renewable energy, showing the extent to which frequent internet access can facilitate the adoption of green energy and enhance the efficiency of the digital banking sector.

Among the independent variables mentioned, the variable digital inclusion can be considered an appropriate control variable, as it represents an essential contextual condition for the adoption and use of digital banking services but does not have a direct impact on the financial performance of the banking sector, such as return on equity (ROE). In general, a control variable is introduced to capture contextual influences on the dependent variable, in this case share of energy from renewable sources, without constituting a direct causality to the main objective of this study—the relationship between renewable energy use and the financial and digital performance of the banking sector. Digital inclusion can indirectly control the effects of widespread digital access to the internet on the variables of interest (ROE and e-banking), thus providing a baseline for estimates of the true digital effects.

Therefore, these variables are chosen to create an integrated approach to how the transition to green energy is supported by financial performance, banking digitalization, and digital inclusion, providing a holistic picture of the interplay of these areas in the EU context.

To investigate the causal relationship between banking performance, digitalization, and renewable energy consumption, the following methodological steps will be employed: initially, the stationarity of the data series will be examined through the application of unit root tests. Subsequently, the Fully Modified Ordinary Least Squares (FMOLS) method will be utilized to assess the statistical significance of the variables included in the model and to determine the existence of a long-term cointegration relationship among these variables. Finally, the Granger causality test [96] will be conducted to establish the causal nexus between the variables under consideration.

Therefore, this study employs an advanced econometric framework designed to explore the complexity of the relationships under investigation. This study relies on cointegrated panel data analysis, which is particularly suited to examining the long-run equilibrium dynamics between variables. Fully Modified Ordinary Least Squares (FMOLS) was chosen because of its ability to account for endogeneity and serial correlation, which are common problems in panel data, while also allowing for cross-sectional heterogeneity. This approach ensures that the estimations are both unbiased and robust, allowing for a nuanced understanding of how renewable energy adoption interacts with banking performance and digitalization in different EU contexts. Additionally, FMOLS is well suited for cointegration analyses, allowing for the identification of long-term relationships between the studied variables, making it a robust and efficient method for assessing the link between digitalization, banking performance, and renewable energy consumption.

The use of a co-integration framework reflects the need to identify stable long-term relationships despite the non-stationarity of individual variables. Panel unit root and cointegration tests were conducted to confirm the appropriateness of this methodology. These preliminary steps are essential to avoid spurious results and to ensure that the relationships studied are meaningful over long periods of time. By capturing the equilibrium relationships between variables, this methodological choice considers the dynamic and policy-driven nature of the phenomena under study.

In addition to FMOLS, Granger causality tests were used to examine the directionality of the relationships, providing insights into whether changes in one variable precede or predict changes in another. These results add depth to the analysis by revealing short-term causal mechanisms that complement the long-term dynamics captured by the cointegration model. The inclusion of impulse response functions derived from vector autoregressive models further enriches the analysis by illustrating how shocks to one variable propagate through the system over time, shedding light on temporal interactions and policy implications.

The relationships tested in this study are not limited to simple linear dependencies but are embedded in a comprehensive econometric framework that captures both short-run and long-run interactions. This distinction underlines the rigor of the methodological approach and its alignment with the objectives of this study. This study highlights how these methodological choices provide a robust foundation for understanding the interplay between bank performance, digitalization and renewable energy adoption, ensuring that the findings are both credible and relevant to the academic and policy communities.

Consequently, we develop the following econometric model, building on the framework elaborated by He and Richard [97], as outlined in Equation (1):

$$LNREN_{it} = \beta_1 + \beta_2 LNROE_{it} + \beta_3 LNEBANK_{it} + \beta_4 LNDIGINCL_{it} + \mu\beta_{it} \quad (1)$$

where LNREN—logarithm of share of energy from renewable sources; LNROE—logarithm of return on equity; LNEBANK—logarithm of e-banking; LNDIGINCL—logarithm of digital inclusion; β(1, 4)—coefficients associated with the variables; $\mu\beta_{it}$—residual term; i—country; t—time.

The methodological framework of this study builds on the strengths of the Fully Modified Ordinary Least Squares (FMOLS) method, Granger causality tests and impulse response analysis [96–103] to investigate the relationships between renewable energy consumption, banking performance, and digitalization in the context of the European Union. Each method plays a distinct but inter-related role in addressing the research objectives, particularly in examining long-run relationships, establishing causality, and quantifying dynamic interactions over time.

FMOLS [98–103] is particularly well suited for analyzing long-term relationships in panel data with cointegration, as it effectively addresses endogeneity and serial correlation, both of which are common challenges in such analyses. In the context of this study, the presence of cointegration between variables—renewable energy consumption, banking performance, and digitalization—implies that these variables evolve together over time, despite short-term fluctuations. FMOLS adjusts for trends that may arise due to endogeneity by incorporating a non-parametric standard error correction, ensuring that the estimated coefficients are not only consistent but also asymptotically unbiased. This makes FMOLS a robust choice for identifying stable, long-run relationships that are essential for understanding how structural factors such as digitalization and financial performance influence renewable energy adoption in EU countries.

Granger causality tests [96] complement FMOLS by addressing the directionality of influence between variables. While FMOLS establishes the existence of long-run relationships, it does not infer causality. Granger causality tests fill this gap by determining whether past values of one variable can predict current values of another. In this study, Granger causality tests reveal bidirectional influences between digitalization and renewable energy consumption, as well as significant paths from bank performance to renewable energy investment. These insights are essential for policymakers and researchers, as they indicate not only associations but also the temporal precedence and predictive power of relationships. Such findings help identify action points to encourage digital and financial initiatives that promote sustainability.

Furthermore, the inclusion of the Vector Autoregression (VAR) and Vector Error Correction Model (VECM) methodologies [104,105] is essential in capturing the dynamic and long-term relationships between the variables under investigation—renewable energy consumption, banking performance and digitalization—in the context of the European Union. VAR allows the examination of interdependencies between several time series, treating all variables symmetrically, without an a priori distinction between dependent and independent variables. This is particularly useful in exploring how shocks to a variable propagate through the system.

The VECM framework is particularly relevant when there is cointegration between variables. By combining short-run dynamics with long-run equilibrium relations, the VECM provides a robust mechanism for analyzing equilibrium adjustments following a perturbation. This is essential to capture the nuances of how renewable energy consumption interacts with banking performance and digitalization over different time horizons. The error-correction term in the VECM quantifies the speed at which deviations from long-run equilibrium are corrected, providing information on system stability and responsiveness.

These methodologies complement the FMOLS method by addressing different dimensions of the research problem. While FMOLS focuses on estimating the long-run coefficients in the presence of cointegration and correcting for potential endogeneity and serial correlation, VAR and VECM deepen the directionality and temporal dynamics of the relationships. Furthermore, Granger causality tests, as part of the VAR and VECM frameworks, establish the causal influence between variables, clarifying whether banking performance drives the adoption of renewable energy or whether digitalization facilitates this transition.

Moreover, the impulse response analysis [106,107] performed in VAR quantifies the magnitude and duration of dynamic responses to shocks. This is particularly valuable for policymakers as it sheds light on the temporal effects of changes in digitalization or financial performance on renewable energy adoption. Collectively, these methodologies provide a comprehensive set of tools to explore both immediate and sustained interactions between variables, aligning with the research objective of understanding the interplay between economic, environmental, and digital factors in EU policy contexts.

Thus, impulse response analysis adds a dynamic dimension to the analysis by quantifying how a shock to one variable affects the others over time. While FMOLS and Granger causality provide information on long-run equilibrium and causality, impulse response functions (IRFs) trace the trajectory of these effects following an exogenous shock. For example, this study uses impulse response analysis to demonstrate how a sudden increase in digital inclusion influences renewable energy consumption in subsequent periods. This method provides a nuanced understanding of temporal adjustment mechanisms, highlighting the speed and persistence of the effects. Such dynamic insights are essential for policymakers designing phased interventions as they shed light on both the immediate and delayed impacts of policy measures.

The sequential application of FMOLS, Granger causality tests, and impulse response analysis provides a comprehensive investigation of relationships. FMOLS establishes structural relationships, Granger causality tests validate directional influences, and impulse response analysis contextualizes these relationships in a dynamic temporal framework. Together, these methods provide a robust and multifaceted understanding of how banking performance and digitalization contribute to renewable energy adoption, closely aligning with the research objectives and providing useful insights for policy and strategy development.

4. Results

4.1. Trends of Key Indicators in EU Countries Through Exploratory Data Analysis

Figure 3 illustrates the trends of the selected indicators for the period 2013–2022 for the 27 Member States of the European Union [93–95].

Return on equity: ROE, an indicator of financial performance, has varied considerably across EU countries and over time. Countries such as Romania, Lithuania, and Sweden showed a more stable financial performance in the second half of the period under review, while countries such as Italy and Cyprus experienced large fluctuations, including negative values in previous years. In Romania, ROE has increased steadily since 2014, after a low in that year (−15.2%), to reach 15.7% in 2022. This reflects a significant improvement in banks' performance. Cyprus and Slovenia both have negative ROE values at the beginning of the period, but Cyprus recovers to 5.1% in 2022, while Slovenia shows a more consistent recovery to 13.3%.

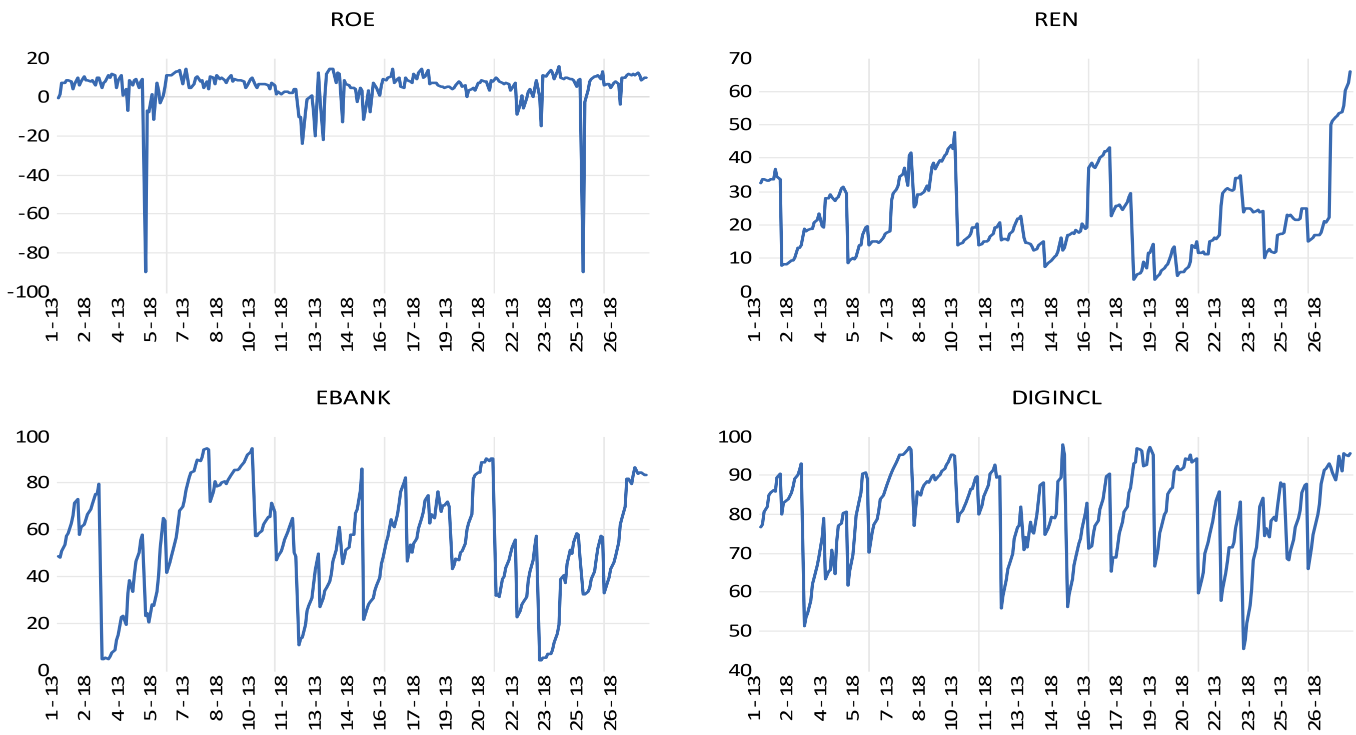

Figure 3. Key variables for 27 EU countries. Source: Own processing. Note: 1—Austria; 2—Belgium; 3—Bulgaria; 4—Croatia; 5—Cyprus; 6—Czech Republic; 7—Denmark; 8—Estonia; 9—Finland; 10—France; 11—Germany; 12—Greece; 13—Hungary; 14—Ireland; 15—Italy; 16—Latvia; 17—Lithuania; 18—Luxembourg; 19—Malta; 20—Netherlands; 21—Poland; 22—Portugal; 23—Romania; 24—Slovakia; 25—Slovenia; 26—Spain; 27—Sweden; 13, 14, . . . , 22 represent years included in the analyzed period.

Internet usage for internet banking (e-banking): Internet usage for e-banking has increased in all EU countries, with significant differences between countries. Countries such as Sweden, Denmark, and the Netherlands have reached high percentages since the beginning of the period (over 80%) and will exceed 90% by 2022. In Romania, the evolution is significant, from only 4.3% in 2013 to 19.19% in 2022, but still lags behind the EU average. This indicates a slow uptake of digital banking compared to other Member States. Countries with high usage like Denmark, Sweden, and the Netherlands are leading in this area, with percentages consistently above 90%.

Share of renewable energy (REN): Sweden is a clear leader in the use of renewable energy, starting from an already high level of 50% in 2013 and reaching 66% in 2022. This reflects Sweden's commitment to a rapid green transition. In Romania, the indicator is steady at 24–25%, showing stability in the use of renewables, but no significant increase over the period. Leading countries like Sweden, Finland, and Latvia also have high values with percentages above 40%.

Digital inclusion: Internet usage has increased significantly in all Member States. Countries such as Denmark, the Netherlands, and Sweden are already close to peaks of over 95%, while countries such as Romania and Bulgaria have seen significant increases but are lagging behind others. In Romania, the percentage of people utilizing the internet at least once a week has increased from 45.38% in 2013 to 84.05% in 2022, indicating a significant improvement in digital inclusion.

The analyzed sample shows significant progress for all EU countries in digital banking usage and digital inclusion, but with significant differences between countries. Nordic states like Sweden and Denmark, alongside the Netherlands, are leaders in both digitalization and digital inclusion. Romania and Bulgaria have made considerable progress but are lagging behind in terms of e-banking and digital inclusion. This suggests the need for more effective policies to accelerate these processes in Eastern European countries.

This comparative analysis of the 27 EU Member States for the period 2013–2022 provides a clear picture of the evolution of financial performance and digitalization indicators. In terms of ROE, the countries analyzed show significant fluctuations, reflecting both domestic economic challenges and the impact of global economic crises. Romania, for example, goes from a negative value in 2014 (−15.2%) to a steady increase, reaching 15.7% in 2022. This reflects a stabilization and improvement in the banking sector's performance in the context of an emerging economy. On the other hand, countries such as Cyprus and Slovenia show large fluctuations, with negative values at the beginning of the period, followed by a significant recovery towards the end, indicating a gradual recovery of the financial system.

At the same time, the use of e-banking showed an upward trend in all EU countries, with considerable differences between the countries analyzed. Nordic countries, such as Sweden and Denmark, had consistently high levels of internet usage for e-banking, exceeding 90% in 2022, in contrast to Romania, where the take-up of these services was slower, reaching only 19.19% in the same year. This highlights the differences in technology adoption between western and eastern EU countries.

In terms of the transition to renewable energy, Sweden stands out with a very high share, steadily increasing from 50% in 2013 to 66% in 2022, demonstrating its commitment to sustainability goals. Romania has maintained a relatively stable share around 24–25%, indicating slower progress in the transition to green energy. This study thus suggests differences in the implementation of energy transition policies between Member States, with Sweden and Finland leading the way.

Finally, data on digital inclusion show a significant increase in internet access and use in all EU countries. Although Romania has made remarkable progress in this area, increasing from 45.38% in 2013 to 84.05% in 2022, it lags behind other Member States in terms of digital inclusion. The Nordic countries, on the other hand, have already reached a level close to the peak, confirming their position as leaders in digitalization in Europe.

The analysis therefore highlights the significant progress made in digitalization and energy transition, but also the regional disparities in the uptake of these transformations. On the one hand, Western and Northern European countries have demonstrated a high capacity to adapt to technological change and implement sustainability policies, while Eastern European states have improved but still face challenges related to digitalization and the uptake of renewable energy sources.

4.2. Assessment of Digitalization's and Banking Performance's Impact and Causality on Renewable Energy Consumption Through the Obtained Econometric Results

Before proceeding with the panel regression analysis, it is essential to conduct a covariance analysis. Thus, Table 2 provides information on the linear relationships between the variables analyzed, namely share of renewable energy (LNREN), return on equity (LNROE), use of online banking (LNEBANK), and digital inclusion (LNDIGINCL). Covariance quantifies the extent to which two variables change in tandem, and the values in the table indicate the strength and direction of these relationships.

Table 2. Correlation matrix.

Correlation/Probability				
	LNREN	LNROE	LNEBANK	LNDIGINCL
LNREN	1.000000			

LNROE	0.162229	1.000000		
	0.0122	-----		
LNEBANK	0.069451	−0.007052	1.000000	
	0.2859	0.9138	-----	
LNDIGINCL	0.062357	0.020212	0.829855	1.000000
	0.3381	0.7564	0.0000	-----

Source: Authors' own calculation. Note: The table presents the correlation coefficients (upper values) and the corresponding *p*-values (lower values) between the logarithmic transformations of the variables: renewable energy use (LNREN), return on equity (LNROE), e-banking usage (LNEBANK), and digital inclusion (LNDIGINCL). The correlations range from weak to moderate, with statistical significance indicated by *p*-values below 0.05.

The covariance analysis reveals a modest positive correlation between renewable energy use (LNREN) and return on equity (LNROE) (0.162, $p = 0.0122$), suggesting that increased renewable energy adoption may have a slight positive influence on banking performance. However, e-banking (LNEBANK) shows very weak, non-significant correlations with both LNREN (0.069) and LNROE (−0.007), indicating minimal direct impact on sustainable energy investments or financial returns. Digital inclusion (LNDIGINCL) correlates strongly with e-banking (0.830, $p = 0.0000$), yet its weak, non-significant correlations with LNREN and LNROE suggest that while digital inclusion supports e-banking adoption, it does not directly drive renewable energy investment or improve financial performance. These findings imply that policy measures beyond digital inclusion may be necessary to link banking performance more effectively with sustainable energy goals.

Table 3 provides a comprehensive summary of the statistical properties of the variables across EU countries. The normality of the data is evaluated using Skewness and Kurtosis metrics, complemented by probabilities from the Jarque–Bera normality test. Skewness values near zero suggest a symmetrical distribution, aligning with the characteristics of the examined variables. Kurtosis values below three for most data series indicate relatively flat distributions, though certain variables exhibit deviations characterized by more pronounced peaks. These observations are further supported by the Jarque–Bera test, which evaluates the null hypothesis of normality.

Table 3. Summary statistics.

	LNREN	**LNROE**	**LNEBANK**	**LNDIGINCL**
Mean	2.942665	1.905499	3.920252	4.402422
Median	2.938659	2.054124	4.054477	4.427179
Maximum	4.189685	2.753661	4.550503	4.584661
Minimum	1.251047	−1.203973	1.481605	3.936716
Std. Dev.	0.587429	0.633829	0.619635	0.129407
Skewness	−0.373652	−2.170399	−2.239741	−1.072572
Kurtosis	2.892529	9.328512	8.326163	4.157963
Jarque–Bera	5.652638	584.0183	480.3016	58.92999
Probability	0.059230	0.000000	0.000000	0.000000
Sum	700.3542	453.5088	933.0200	1047.776
Sum Sq. Dev.	81.78223	95.21231	90.99569	3.968829
Observations	238	238	238	238

Source: Authors' own calculation.

Analysis of the descriptive statistics for the logarithmic variables of renewable energy sources (LNREN), shareholder profitability (LNROE), internet usage for banking (LNEBANK), and digital inclusion (LNDIGINCL) highlights some interesting aspects related to the distribution and variability of the data.

Mean and median values are fairly close for all four variables, indicating a relatively symmetric distribution of the data overall. The mean for LNREN (2.94) and the median (2.94) show that, on average, the share of renewable energy is fairly constant over the period analyzed. Similarly, for LNROE (mean 1.91, median 2.05), the financial variables have an overall positive trend, but larger variations are observed than for the other variables. LNEBANK and LNDIDIGINCL also have relatively similar values between the mean and the median, indicating a steady increase in internet use for banking and digital inclusion.

The maximum and minimum values highlight the range of variation for each indicator. For LNREN, the range is wide, with a minimum of 1.25 and a maximum of 4.19, suggesting that European countries differ significantly in the share of renewable energy used. LNROE has a very low minimum (−1.20), suggesting significant financial losses in some cases, and a maximum of 2.75 indicates large profits for other countries. LNEBANK ranges between 1.48 and 4.55, reflecting the large differences in the adoption rate of internet banking within European countries, with some countries at much more advanced stages than others. In the case of LNDIGINCL, the values are narrower, ranging from 3.94 to 4.58, suggesting a relatively uniform degree of digital inclusion across EU countries.

The standard deviation for LNREN (0.587) shows a moderate variability in the share of renewable energy, suggesting that some countries are more advanced in the transition to green energy. In contrast, LNROE (0.633) has significant variability, indicating large fluctuations in banking profitability within the EU. LNEBANK (0.619) has similar variability, confirming the differences between countries that have adopted online banking intensively and those where this process is still in its infancy. LNDIGINCL (0.129) has the smallest standard deviation, suggesting that differences in internet access and usage are smaller in the EU compared to the other indicators.

Skewness indicators show that most of the distributions are skewed to the left, suggesting that lower values of the analyzed variables are more common. LNROE (−2.17) and LNEBANK (−2.23) have a pronounced skewness, indicating that most countries have lower values of these indicators, with a few extreme exceptions at high values. Similarly, the negative skewness for LNDIGINCL (−1.07) suggests that a small number of countries have very high digital inclusion, while the majority have more uniform access. The high kurtosis for LNROE (9.33) and LNEBANK (8.33) suggests a leptokurtic distribution, implying that there are a few extreme observations that influence these distributions. LNDIGINCL has a moderate kurtosis value (4.16), suggesting a tendency towards a more concentrated distribution around the mean.

The Jarque–Bera test, which measures the normality of the distribution, has significant values for all variables ($p < 0.05$), suggesting that none of the analyzed distributions are normal. This is important for the interpretation of the results, as it indicates the presence of extreme values or skewed distributions that could affect the analytical conclusions if not treated appropriately.

Thus, the descriptive analysis indicates significant variability across EU countries in renewable energy uptake, financial performance, internet use for banking, and digital inclusion. Also, the distributions of these indicators are not normal, with skewness and concentrations around extreme values, which could suggest that structural, economic, and political factors play a key role in determining these performances.

As outlined in the methodology section, the stationarity of the data series was tested prior to the application of the Fully Modified Ordinary Least Squares (FMOLS) method. Following the assertion of Hamit-Haggar [98], FMOLS is recognized as an optimal approach for panels characterized by heterogeneous cointegration. The stationarity tests employed included the Levin-Lin-Chu [99] panel root test, the ADF and PP–Fisher Chi-square tests, all tailored for panel data analysis. The results, evidenced in Table 4, indicate that data achieve stationarity at their first differences.

Table 4. LLC, ADF, and PP tests.

Methods Level/First Difference (D)	Statistic (p) in LLC	Statistic (p) in ADF	Statistic (p) in PP
LNREN	2.58609 (0.9951)	13.4373 (1.0000)	23.6538 (0.9999)
D(LNREN)	−5.53267 (0.0000)	92.8274 (0.0008)	228.944 (0.0000)
LNROE	−5.76030 (0.0000)	79.7227 (0.0008)	153.682 (0.0000)
D(LNROE)	−7.69780 (0.0000)	83.5955 (0.0001)	197.776 (0.0000)
LNEBANK	2.86333 (0.9979)	18.3327 (1.0000)	34.9930 (0.9791)
D(LNEBANK)	−11.6431 (0.0000)	124.551 (0.0000)	227.526 (0.0000)
LNDIGINCL	−3.78926 (0.0001)	39.5776 (0.9291)	91.3054 (0.0011)
D(LNDIGINCL)	−10.0992 (0.0000)	105.233 (0.0000)	202.512 (0.0000)

Source: Authors' own calculation.

Since all variables are stationary at their first differences, a Kao [100] co-integration test was conducted. The results, outlined in Table 5, confirm the long-term relationship among the variables.

Table 5. Kao co-integration test.

	t-Statistic	Prob.
ADF	2.792536	0.0026
Residual variance	0.008652	
HAC variance	0.009346	

Source: Authors' own calculation. Note: The table presents the Kao co-integration test, with the Augmented Dickey–Fuller (ADF) t-statistic significant at the 1% level ($p = 0.0026$). This confirms the presence of a long-term co-integration relationship among the variables. The residual variance and HAC (heteroskedasticity and autocorrelation consistent) variance provide additional measures of model estimation consistency.

The findings confirm at least one cointegration relationship among the model variables. To validate this further, the Johansen Fisher Panel Cointegration Test was applied, as shown in Table 6, identifying two cointegrating equations at 0.05 significance level.

Table 6. Johansen Fisher Panel Cointegration Test.

Unrestricted Cointegration Rank Test				
Hypothesized No. of CE(s)	Fisher Stat. (from trace test)	Prob.	Fisher Stat. (from max-eigen test)	Prob.
None *	146.5611	0.0000	80.87478	0.0000
At most 1 *	65.68637	0.0000	36.30704	0.0002
At most 2 *	29.37932	0.0002	18.38850	0.0105
At most 3 *	10.99082	0.0009	10.99082	0.0009

Trace test indicates 4 cointegrating eqn(s) at the 0.05 level; Max-eigenvalue test indicates 4 cointegrating eqn(s) at the 0.05 level; * denotes rejection of the hypothesis at the 0.05 level. Source: Authors' own calculation.

To ensure the reliability of FMOLS results, multicollinearity among the independent variables was assessed using the Variance Inflation Factor (VIF) in EViews. With VIF values below 10, as shown in Table 7, the results confirm minimal correlation between the independent variables. Thus, the analysis of VIF indicates the absence of multicollinearity among the variables included in the model, namely LNROE, LNEBANK, and LNDIGINCL. The VIF values are very close to 1, with all variables showing values below 1.01, suggesting negligible collinearity among them.

Table 7. VIF values.

Variable	Coefficient Variance	Uncentered VIF
LNROE	0.007820	1.001642
LNEBANK	0.000267	1.005137
LNDIGINCL	0.000320	1.006466

Source: Authors' own calculation.

This result is important as a high VIF would indicate a strong linear relationship between the independent variables, which could bias the coefficient estimates and interpretations of the relationships between the variables. The absence of multicollinearity allows for a better interpretation of the obtained coefficients, thus strengthening the robustness of the model in estimating the relationships between financial digitalization, digital inclusion, and return on equity in support of renewable energy. This clarity in the interpretation of the coefficients is essential to validate the proposed theoretical correlations, allowing for an independent interpretation of the impact of each variable in relation to sustainability and financial performance objectives.

Thus, the model can be considered suitable for interpretation, allowing for clear and robust conclusions on the economic and digital influences on the transition to renewable energy without the risk of significant biases due to multicollinearity.

Following the assessment of model stability [101–103], the results derived from the application of the Fully Modified Ordinary Least Squares (FMOLS) are presented, aimed at identifying the long-term cointegration coefficients. The first-difference transformation within the heterogeneous FMOLS framework ensures robustness by addressing non-stationarity issues detected in level data (Table 4). This transformation mitigates spurious correlations, allowing FMOLS to precisely assess the long-term nexus while effectively addressing panel data heterogeneity. This approach enhances the analysis's reliability [108], particularly for policy-focused studies across EU countries.

As shown in Table 8, all variables in the model are statistically significant (p = 0.0000), with LNROE, LNEBANK, and LNDIGINCL positively influencing banking performance, suggesting that increases in these variables enhance banking performance in the analyzed countries.

Table 8. FMOLS estimation.

	Dependent Variable: LNREN			
Variable	**Coef.**	**Std. Error**	**t-Stat.**	**Prob.**
LNROE	0.461446	0.088432	5.218089	0.0000
LNEBANK	0.384860	0.016354	23.53330	0.0000
LNDIGINCL	0.804325	0.017888	44.96342	0.0000

Source: Authors' own calculation.

The FMOLS results provide insight into the long-run relationships between the dependent variable LNREN and the independent variables LNROE, LNEBANK, and LNDIGINCL.

The coefficients of the independent variables are positive and statistically significant, indicating that, in the long run, each of these factors has a positive influence on the share of renewable energy in the economies of the countries analyzed. The coefficient for LNDIGINCL is the largest (0.804), suggesting that digital inclusion has the strongest impact on renewable energy use. This can be interpreted as a confirmation that digital access and inclusion facilitates the adoption of green technologies and initiatives, enabling a faster transition to sustainable energy sources. The result is supported by recent research, which emphasizes the role of digitalization in promoting sustainability and energy efficiency [49,85].

The coefficient for LNROE, although lower (0.461), is still significant, indicating that financial returns contribute to the growth of renewable energy investments. This suggests that firms' positive financial performance can facilitate long-term investments in green technologies and infrastructure, in line with Gao's [48] findings, which emphasize the link between financial stability and transparency needed to support sustainable initiatives.

Also, the coefficient for LNEBANK (0.385) suggests that the adoption of online banking is positively associated with the use of renewable energy, although the effect is smaller compared to that of digital inclusion. This result may reflect the impact of the digital transformation in the financial sector, which indirectly contributes to reducing the carbon footprint by promoting more sustainable financial solutions, similar to the findings of Ha et al. [55], which discusses the influences of FinTech innovation on the volatility of renewable energy markets.

The R-squared (0.8137) and its fit (0.7829) indicate a high level of model fit, suggesting that the independent variables explain a large part of the variation in renewable energy use. However, the standard error of the regression (0.271) and the sum of squared residuals (12.427) indicate that there are other variables not included in the model that could explain the rest of the variation.

This study highlights the importance of digital inclusion and digital transformation in promoting renewable energy. However, the results also suggest the need for sustained policies that support both financial stability and the adoption of digital technologies to facilitate the green transition in the long term.

Furthermore, the Vector Error Correction Model (VECM) [104,105] estimation (Table 9) explores the short-run relationships and error correction mechanisms between selected variables, focusing on the influences between the renewable energy rate (LNREN), return on equity (LNROE), online banking usage (LNEBANK), and digital inclusion (LNDIGINCL).

Table 9. Vector Error Correction (VEC) estimates.

Cointegrating Eq:	CointEq1
LNREN(−1)	1.000000
LNROE(−1)	0.290250
	(0.71822)
	[0.40412]
LNEBANK(−1)	−0.599860
	(0.95770)
	[−0.62635]
LNDIGINCL(−1)	−31.24338
	(5.08810)
	[−6.14048]
C	136.9917

Source: Authors' own calculation.

In the cointegration equation, the coefficients of the independent variables indicate their long-term impact on renewable energy. The negative coefficient for LNDIGINCL(−1) is significant (t = −6.14048), suggesting a strong inverse influence on renewable energy, which may reflect specific challenges for integrating digitalization with the transition to renewable energy sources. The result is in line with recent papers [84], which mention that digitalization may contribute to volatility, having a complex impact on the energy transition. On the other hand, the positive coefficients on the LNROE(−1) and LNEBANK(−1) variables suggest that both financial profitability and bank digitalization support a long-run renewable energy growth.

Thus, the findings validate the short- and long-run interdependencies between digitalization, financial sustainability and energy transition. Similarly to previous research, such as studies by Gao [48] and Sheraz et al. [58], these results emphasize the importance of digitalization and financial stability in supporting renewable energy goals but also point to the complexities and dynamic interactions that can amplify sustainability challenges.

Moreover, least squares analysis of the estimated system (Table 10) shows significant interactions between the main variables of interest: share of renewable energy (LNREN), return on equity (LNROE), use of online banking (LNEBANK), and digital inclusion (LNDIGINCL). In the long run, these variables show a positive interdependent relationship, suggesting that the development of digital technologies, increased economic profitability and the expansion of online banking are all factors contributing to the increased use of renewable energy sources.

Table 10. Least squares analysis of the estimated system.

	Coefficient	Std. Error	t-Statistic	Prob.
C(1)	−0.008388	0.002652	−3.162654	0.0016
C(2)	−0.198833	0.089595	−2.219250	0.0269
C(3)	−0.011845	0.018447	−0.642073	0.5211
C(4)	−0.083972	0.121787	−0.689499	0.4908
C(5)	0.644707	0.373444	1.726385	0.0848
C(6)	0.147206	0.092095	1.598415	0.1105
C(7)	0.003614	0.017650	0.204764	0.8378
C(8)	−0.074838	0.121544	−0.615727	0.5383
C(9)	0.119233	0.346475	0.344132	0.7309
C(10)	0.042347	0.015649	2.706121	0.0070
C(11)	0.003022	0.013080	0.231063	0.8174
C(12)	−0.104304	0.433696	−0.240501	0.8100
C(13)	−0.469589	0.089238	−5.262178	0.0000
C(14)	0.444028	0.589125	0.753707	0.4513
C(15)	−2.621918	1.892098	−1.385720	0.1664
C(16)	0.210327	0.446112	0.471466	0.6375
C(17)	−0.227580	0.085479	−2.662396	0.0080
C(18)	−0.160560	0.589141	−0.272533	0.7853
C(19)	1.698863	1.677535	1.012714	0.3116
C(20)	0.008765	0.076187	0.115047	0.9084
C(21)	0.008765	0.001973	4.442575	0.0000
C(22)	−0.012123	0.066651	−0.181888	0.8557
C(23)	−0.012150	0.013723	−0.885354	0.3764
C(24)	0.082205	0.090600	0.907341	0.3646
C(25)	0.358142	0.277812	1.289149	0.1979
C(26)	0.059406	0.068511	0.867096	0.3863
C(27)	0.003606	0.013130	0.274613	0.7837
C(28)	0.379194	0.090419	4.193733	0.0000
C(29)	−0.449351	0.257750	−1.743361	0.0818
C(30)	0.030556	0.011641	2.624736	0.0089
C(31)	0.004918	0.000512	9.600730	0.0000
C(32)	0.005319	0.017307	0.307356	0.7587
C(33)	−0.003539	0.003563	−0.993037	0.3211
C(34)	0.023884	0.023525	1.015257	0.3104
C(35)	−0.085144	0.072136	−1.180322	0.2384
C(36)	0.005326	0.017789	0.299388	0.7648
C(37)	−0.007223	0.003409	−2.118568	0.0346
C(38)	0.008103	0.023478	0.345135	0.7301
C(39)	−0.148076	0.066927	−2.212498	0.0273
C(40)	0.025775	0.003023	8.526970	0.0000

Source: Authors' own calculation.

The positive coefficients associated with C(5) and C(10) indicate that digital inclusion plays a key role in promoting the adoption of renewable energy in the long run and that this relationship is statistically supported (probability of 0.007 indicating significance). This can be explained by the fact that increased access to technology and digitalization facilitates innovation and optimization processes, which in turn allow renewable energy to be adopted in a more efficient way. At the same time, the positive coefficient associated with the use of online banking services, C(28), indicates that these services contribute to increasing the share of renewable energy, possibly by attracting finance and investment in clean technologies.

In the short term, the identified impacts are more complex. For example, C(13) reflects a significant negative influence of the lagged variable return on equity on its evolution (probability 0.0000). This suggests that, in the short run, an increase in ROE may have a negative influence on the subsequent increase in profitability, reflecting adjustment costs or short-term market volatility.

There is also a significant interaction between ROE and digital penetration, with the coefficient C(37) indicating a negative impact of the ROE lag variable on digital penetration. This result suggests that, in the short run, increased profitability of firms may reduce the availability or accessibility of digital technologies, possibly due to a reallocation of resources towards investments with immediate financial returns at the expense of investments in digital infrastructure. However, positive long-term influences, such as those captured by coefficients C(1), C(28) and C(10), suggest that the development of these sectors is mutually reinforcing over time, leading to integrated growth in renewable energy, digital inclusion and online banking.

In conclusion, the results suggest that although in the short run there may be tensions between short-term profitability and increased investment in digital inclusion or renewable energy, in the long run, the digitalization and integration of online financial services contribute significantly to the sustainable development of the European energy economy.

To determine the direction of causality among the variables, the Granger causality test [96] was employed. This approach allows for the coefficients to vary across cross-sections, enhancing the robustness of the analysis. The results depicted in Figure 4 highlight the complex interconnections among the variables, illustrated through directional arrows indicating the flow and influence between them.

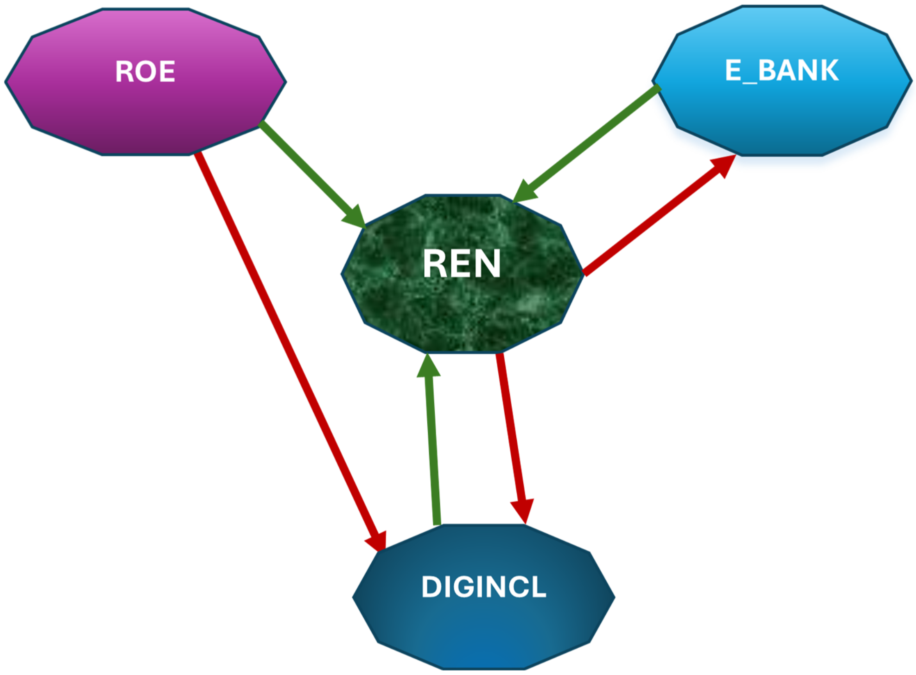

Figure 4. Granger causality test. Source: Authors' calculation.

Figure 4 illustrates the complex interactions between the variables analyzed in the context of the nexus between the share of renewable energy (REN), return on equity (ROE), use of online banking (EBANK), and digital inclusion (DIGINCL), distinguishing between short-term effects (indicated by red arrows) and long-term effects (indicated by green arrows).

In the long run, the indicated positive relationships between ROE, EBANK, DIGINCL, and REN suggest that an increase in economic profitability (ROE), digital banking usage (EBANK), and digital inclusion (DIGINCL) favors the adoption of renewable energy sources. This can be explained by the fact that a more profitable and technologized economy is better able to sustain green energy investments, while an extensive digital infrastructure enables the optimization of these resources. At the same time, digitalization contributes to a more efficient energy transition by facilitating access to modern technologies.

On the other hand, the red arrows indicating short-term effects reflect certain diverging tensions and influences. In particular, ROE has a negative impact on digital inclusion in the short term, which may suggest that in periods of rapid growth in profitability, attention and resources are focused on immediate investments, temporarily reducing the availability for digital infrastructure expansion. In the longer term, however, this effect becomes positive, suggesting a convergence in the development of the two dimensions.

REN has a positive impact on both digital inclusion and the use of online banking services, demonstrating that the adoption of renewable energy sources can support a more digitalized and networked economy, which is important for sustainable development. In this sense, green energy is not only a benefit for the environment, but also a stimulus for technological innovation and access to modern services. Figure 4 thus summarizes the dynamic interdependencies between the variables analyzed, suggesting that although there may be some negative influences between profitability and digitalization in the short term, in the long term, they converge towards a mutually beneficial development pattern, where economic profitability, digitalization, and the transition to renewable energy are mutually reinforcing.

Furthermore, Figure 5 shows the dynamics and interdependence between the variables LNREN, LNROE, LNEBANK, and LNDIGINCL in response to innovations or Cholesky shocks.

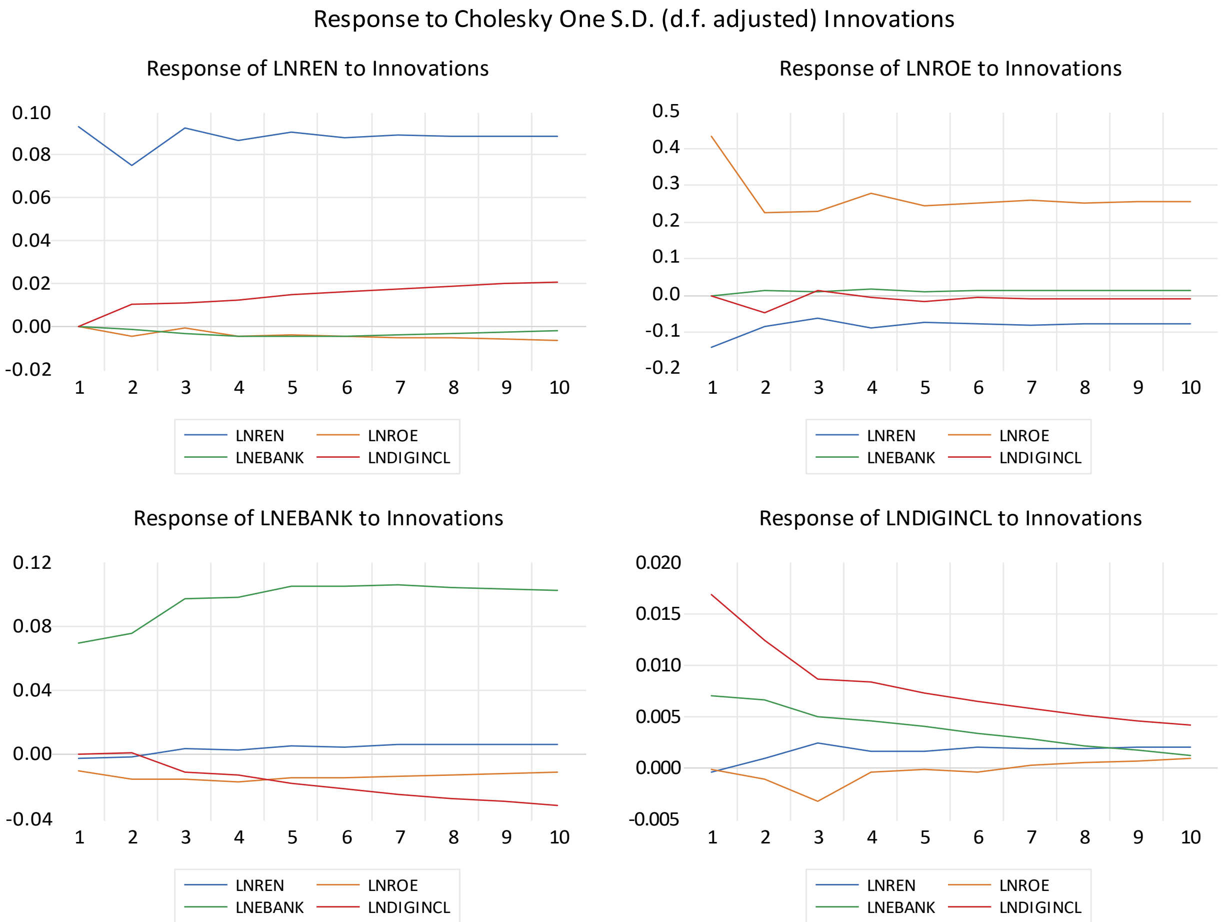

Figure 5. Response to innovations or Cholesky shocks. Source: Own calculation.

Figure 5 illustrates the dynamic responses of renewable energy consumption (LNREN) to changes in key explanatory variables—return on equity (LNROE), e-banking (LNEBANK), and digital inclusion (LNDIGINCL)—as derived from the impulse response function analysis. The y-axis in this figure represents the magnitude of the variable's response (percentage change) to a unit shock in the independent variables over time. The y-axis quantifies the extent to which renewable energy consumption responds to shocks in explanatory variables, providing insights into the strength and direction of these relationships. In Figure 5, the Cholesky one standard deviation (S.D.) impulse response analysis is employed to examine the dynamic relationships between the variables over a 10-period horizon. Each panel in the figure corresponds to the response of a particular variable (LNREN, LNROE, LNEBANK, or LNDIGINCL) to shocks originating from the variables in the system. This analysis provides valuable insights into the magnitude, direction, and duration of these responses, which are important for understanding how innovations in one variable influence the others in the long run.

The upper-left panel shows the response of LNREN (log-transformed share of renewable energy consumption) to shocks from LNREN, LNROE, LNEBANK, and LNDIGINCL. The positive response to its own shocks stabilizes over time, indicating resilience and persistence in renewable energy adoption trends. Additionally, minor but consistent positive responses to LNDIGINCL and LNEBANK suggest that increased digitalization and internet banking usage support the development of renewable energy adoption, aligning with the hypothesis that digital infrastructure and financial accessibility drive energy transitions.

The upper-right panel illustrates the response of LNROE (log-transformed return on equity) to shocks. The initial strong negative response to shocks from LNDIGINCL reflects a potentially short-term inverse relationship between digital inclusion and equity returns. However, LNROE demonstrates a gradual stabilization after the initial shock, indicating limited long-term effects from LNDIGINCL. This suggests that short-term costs associated with digital infrastructure investments may influence returns before yielding long-term benefits.

In the lower-left panel, the response of LNEBANK (log-transformed e-banking usage) is predominantly positive to shocks from LNREN and LNDIGINCL. The positive and sustained response to LNDIGINCL indicates that digital inclusion directly stimulates e-banking adoption. This is a significant finding, as it reflects the synergies between digitalization and financial sector modernization. Moreover, the mild positive response to LNREN suggests that renewable energy adoption may be partially facilitated by advancements in financial services, reinforcing the interplay between green energy investments and banking digitalization.

The lower-right panel illustrates the response of LNDIGINCL (log-transformed digital inclusion) to shocks from other variables. LNDIGINCL exhibits a positive response to shocks in LNREN, underscoring how renewable energy consumption aligns with broader digitalization trends, possibly through policy and market incentives that integrate green and digital priorities. Interestingly, the response to LNROE is initially negative but stabilizes over time, mirroring the transitional adjustments in financial performance associated with digital transformations.

Overall, Figure 5 provides empirical evidence of the dynamic interplay between renewable energy consumption, banking performance, e-banking adoption, and digital inclusion. These findings highlight the importance of policy interventions to harmonize green energy investments with digital and financial sector developments. They underscore the necessity for tailored national strategies to optimize the mutual benefits of sustainability, digitalization, and economic performance. These insights are also consistent with previous literature emphasizing the impact of financial innovation and digital transformation in addressing sustainable energy transitions.

Therefore, the figure reflects the complexity of the relationships between these economic and social variables, suggesting that while the share of renewable energy and shareholder returns have a self-regulating dynamic, digital inclusion and the use of online banking play a significant role in inclusion and affordability.

5. Discussion

A comparative analysis of EU countries, based on the results obtained from the dataset, reveals differences and similarities between EU Member States in terms of share of renewable energy in total consumption (REN), return on equity (ROE), internet usage for banking (e-banking), and digital inclusion (DIGINCL). These results have significant implications in the context of the economic and digital development of EU countries, but also for the adoption of sustainability policies.

The REN indicator shows clear differences between EU countries in the use of renewable energy. Sweden, Finland, and Latvia have the highest shares of renewable energy, reflecting significant investment in green technologies. In contrast, countries such as Luxembourg, Malta, and Cyprus have much lower shares, indicating a greater reliance on fossil fuels. Thus, countries with a high share of renewable energy are well positioned to meet EU sustainability targets and reduce carbon emissions. Countries with low shares should accelerate their energy transition through policies that favor investment in green technologies.

ROE provides an insight into the financial health of the banking system in EU countries. Countries such as Lithuania, Estonia, and Romania have reported steady growth in ROE, suggesting a solid performance within the banking sector. In contrast, countries such as Italy and Greece have experienced periods of financial volatility and negative ROE, especially in the years following the 2008 economic crisis, reflecting structural problems in the banking sector. Therefore, countries with low or negative ROE may have a banking system that is vulnerable and less resilient to economic shocks. These countries could benefit from structural reforms to improve the governance and financial soundness of banking institutions.

The differences between EU countries in the use of online banking services are significant. Nordic countries such as Denmark, Sweden, and Finland are at the top of the league table, with over 90% of the population using e-banking. This is in line with their high level of digitalization and technological infrastructure. On the other hand, countries in the south and east, such as Romania, Bulgaria, and Greece, have seen slower growth, with e-banking usage rates well below the EU average, which may reflect both digital infrastructure barriers and the level of trust in online banking systems. Therefore, countries with high e-banking usage rates tend to be those that have adopted digital transformation and technological innovation in banking more quickly. Countries with lower usage may need policies that both incentivize digital literacy and lower barriers to access secure and efficient e-banking services.

Digital inclusion (access to technology and frequent use of the internet) is an important factor in a country's digital competitiveness. Nordic countries such as Denmark and Sweden have the highest levels of digital inclusion, with more than 95% of the population using the internet frequently. In contrast, countries such as Romania and Bulgaria have lower scores, with less than 80% of the population digitally engaged. Thus, high levels of digital inclusion are closely linked to innovation and economic growth in the global digital economy. Countries with lower levels of digital inclusion are at risk of falling behind in the digital transition, affecting competitiveness and economic innovation.

The findings of this study are closely linked to the methodological framework employed, in particular the use of Fully Modified Ordinary Least Squares (FMOLS) and Granger causality tests. Each key finding is framed by these methods, ensuring a robust understanding of the relationships between renewable energy consumption, banking performance and digitalization in the context of the EU.

The FMOLS method was instrumental in evaluating the long-run coefficients of the relationships under investigation. This approach addresses potential endogeneity by controlling simultaneity bias and serial correlation, which are common problems in panel data analysis. The results show that renewable energy consumption is significantly influenced by digitalization and banking performance, with FMOLS providing unbiased estimates of these relationships. For example, the positive long-run influence of digitalization on renewable energy consumption reflects the ability of digital technologies to rationalize investments in sustainable energy. The robustness of these results is underscored by the ability of FMOLS to incorporate heterogeneity across countries, accounting for differences in digital infrastructure and financial system maturity.

The Granger causality tests further validate the directional influences between variables. By identifying causal pathways, these tests show that banking performance and digitalization are not only correlated with the adoption of renewable energy, but they also have predictive power over its dynamics. The results indicate a bidirectional causality between digital inclusion and renewable energy consumption, suggesting that advances in digital access facilitate investment in renewable energy, while increased renewable energy adoption encourages further digital innovation. This interplay is consistent with the theoretical expectation that digital and financial integration support the transition to a green economy.

The short-term dynamics captured by Granger causality complement the long-term equilibrium relationships identified by FMOLS. For example, the immediate impact of digital banking on renewable energy consumption, while less pronounced than the long-term effects, highlights the importance of fostering digital adoption to achieve faster gains in renewable energy investment. In addition, the methodological rigor ensures that these findings are not artifacts of omitted variable bias or reverse causation, thereby strengthening their validity.

By explicitly linking the results to the methodological framework, this discussion provides a coherent narrative that bridges theoretical expectations with empirical evidence. The integration of FMOLS and Granger causality tests not only accounts for the complexity of the relationships but also ensures that the findings are actionable and relevant for policymakers seeking to leverage digitalization and banking efficiency to promote sustainable energy transitions. This alignment between methodology and results strengthens the credibility and applicability of this study's contributions.

Additionally, the results of our FMOLS estimation are largely consistent with other research in the literature, although there are some notable differences. As for the similarities, our research confirms the positive relationship between digitalization and energy efficiency, in line with the work of Wu et al. [49] and Hung [52], which emphasize the role of digitalization in promoting sustainability and energy efficiency. Similarly, the work of Quttainah and Ayadi [85] shows that digital inclusion promotes green innovation and resource efficiency, similar to our findings on the impact of digital inclusion on renewable energy use (REN). These studies, like this one, support the idea that digitalization is a catalyst for the transition to a more sustainable economy.

However, they differ in their assessment of the short-term impact of digitalization on financial performance. For example, Gao [48] emphasizes that digital transformation in the financial sector improves transparency and thus financial performance in the short run. In contrast, our study suggests that return on equity (ROE) has a negative impact on digital inclusion (DIGINCL) in the EU context in the short run, suggesting that short-term financial priorities may reduce investment in digitalization. This difference may be explained by the fact that previous studies, such as Gao's, were conducted in different economic contexts, such as emerging markets, where the digital transformation can bring immediate benefits in terms of financial transparency and efficiency.

On the other hand, Ha et al. [55] and Zhao et al. [50] place particular emphasis on the negative impact of economic volatility on digital innovation and the influence of the macroeconomic environment on digitalization. Our study confirms this observation to some extent, showing that the short-term effects of financial volatility on digital inclusion can vary, with results suggesting that investment in digitalization tends to be postponed or reduced during periods of economic instability.

At the same time, research by Kayani et al. [83] suggests that digital assets can provide a safe haven in times of economic downturn, which contrasts with our results, which highlight that in the EU context, digitalization does not appear to benefit immediately from increased ROE but requires a longer time horizon to generate an important influence. Thus, our research contributes to the debate on digitalization and energy efficiency, confirming some of the existing literature, but also providing a different perspective on the short-term effects of ROE on digital transformation and energy transition.

The results of this research provide important insights into the interplay between renewable energy consumption, banking performance, and digitalization in the context of the EU. To deepen the implications of these findings, it is important to contextualize them within the broader framework of EU environmental and digitalization policies, while comparing them with findings from studies conducted in other regions. This comparative approach enriches the understanding of how these dynamics manifest themselves in different contexts and contributes to the global discourse on sustainability, digitalization and financial development.

From the perspective of the alignment with EU environmental and digitalization policies, it can be outlined that the European Union has long championed initiatives such as the European Green Deal [109], Digital Compass 2030 [110], and Fit for 55 [111], all of which emphasize the integration of sustainability and digitalization in promoting economic growth. Our results show that increased digital inclusion and robust banking performance positively influence renewable energy consumption, supporting the EU's vision of transitioning to a green and digital economy. In particular, the observed long-run relationships between these variables highlight the systemic impact of digital infrastructure and financial sector efficiency in fostering investment in renewable energy. These findings underscore the importance of policies that promote digital access and banking innovation, in line with the EU's strategic goals of achieving carbon neutrality and promoting digital resilience.

When compared with studies from other regions, key similarities and differences emerge. Thus, Gao [48] and Wu et al. [49] highlight the role of digital finance in promoting environmental sustainability in China and other Asian economies. Similarly to our findings, these studies highlight the importance of digital tools in mobilizing financial resources for green investments. However, unlike the EU, where a robust policy framework explicitly integrates digitalization and sustainability goals, these regions often face a fragmented policy landscape. As a result, while digital finance has significant impacts, the lack of coordinated policies may limit the scalability and consistency of these impacts.

In contrast, studies in emerging economies, such as those by Hung [52], highlight the role of green investment as a mediating factor between financial performance and renewable energy deployment. While the EU context shows a direct influence of banking performance and digitalization on renewable energy consumption, emerging economies often require additional mechanisms, such as government subsidies or international financial support, to bridge the gaps in green investment capabilities. This distinction highlights the advanced state of financial and digital infrastructure in the EU, which directly facilitates sustainability goals without relying heavily on external interventions.

A notable divergence between this study and those from other regions lies in the strength of the relationships. For example, Zhao et al. [50] find a weaker correlation between digital inclusion and renewable energy adoption in Chinese cities, attributing this to uneven digital access and socioeconomic disparities. In contrast, relatively high levels of digital literacy and standardized regulatory frameworks in the EU are likely to explain the stronger linkages observed in our analysis. This finding underscores the significant role of equitable digital access and harmonized policies in maximizing the synergies between digitalization and sustainability.

Moreover, our study differs from research in developing countries, where financial sector inefficiencies often dilute the potential benefits of bank performance on green investment. For example, studies by Ullah et al. [59] and Ha et al. [55] point to institutional weaknesses and financial instability as barriers to leveraging banking systems for environmental goals. In the EU, however, strong financial institutions provide a stable platform for directing capital flows to renewable energy projects, reinforcing the findings of this study.

By placing our findings in the context of EU policies and comparing them with studies from other regions, this discussion highlights the unique strengths of the European model while acknowledging global challenges. The EU's integrated approach to digitalization and environmental sustainability serves as a benchmark for other regions seeking to achieve similar goals. Moreover, the strong empirical evidence on the interplay between banking performance, digitalization, and renewable energy consumption contributes to the broader literature by validating the effectiveness of coordinated policy frameworks.

Therefore, this comparative analysis shows that while the EU offers a coherent model for integrating digitalization and sustainability, regional differences in digital access, financial stability, and policy coherence need to be addressed in order to replicate these successes elsewhere. These findings provide valuable guidance for policymakers seeking to align financial, digital and environmental strategies in different socioeconomic contexts.

From an energy policy perspective, this study highlights the necessity of fostering financial instruments tailored to green investments. Policymakers are encouraged to create supportive regulatory frameworks that incentivize digital banking adoption while integrating sustainability metrics into banking operations. The role of digital infrastructure becomes essential, as improved access to digital platforms can enhance financial inclusivity and streamline investments in renewable energy technologies. These insights offer a roadmap for countries to align their financial systems with renewable energy objectives, thereby contributing to both energy security and environmental sustainability.

6. Conclusions

This study aims to explore the interplay between renewable energy consumption, banking performance and digitalization in the European Union (EU), focusing on their role in sustainable economic development. It examines how digital inclusion and efficiency in the banking sector influence investment in renewable energy, in line with the EU's environmental and digital priorities. A quantitative methodology is applied, using Fully Modified Ordinary Least Squares (FMOLS), Vector Error Correction Models (VECM), Granger causality tests, and impulse response analyses. These approaches ensure a robust examination of long-run relationships, directional effects, and dynamic interactions between variables.

Key findings indicate that increased digital inclusion and banking performance significantly increase allocation of resources toward renewable energy development. Digitalization, represented by the adoption of internet banking, shows a strong positive influence on renewable energy adoption, while banking performance, measured by return on equity, also contributes positively, but its effects vary across countries. The results highlight that these relationships are contextual, reflecting differences in national policies, digital infrastructure and financial sector maturity.

This study contributes to the existing literature by providing empirical evidence on the dynamic interactions between sustainability, digitalization, and financial performance in the EU. It builds on previous research by offering a detailed insight into these connections through advanced econometric methods and highlights actionable strategies to accelerate the green transition. These insights are valuable for policymakers, financial institutions, and energy sector stakeholders seeking to align economic, digital, and environmental goals.

In terms of the hypotheses tested, this study validates the claim that the digitalization of the banking sector plays a key role in increasing investment in renewable energy. It thus confirms that the adoption of digital technologies not only increases banking efficiency but also facilitates access to finance for green projects. This study also confirms the hypothesis that strong financial performance of banks has a positive impact on the transition to a green economy. However, the effects vary across Member States, highlighting the importance of national digital infrastructures and policies, as confirmed by the differences found in the data analysis. These differences confirm the hypothesis that the impact of digitalization is not uniform and depends on the specific country; thus, the nexus between banking performance, digitalization, and renewable energy consumption can influence sustainable development goals in EU countries.

This study brings several innovative elements to the field of economic and energy research. First, by integrating the three dimensions—banking performance, digitalization, and renewable energy consumption—this study provides a comprehensive and coherent approach to sustainable development. On the one hand, this integration has rarely been explored in the literature, making this study a benchmark for understanding how the financial and energy sectors can work together to support the green transition. On the other hand, the use of the FMOLS econometric methodology is a notable methodological contribution, providing a robust framework for assessing the long-run relationships between variables. However, the main novelty lies in the differentiated analysis across EU Member States, which underlines the importance of national approaches in supporting digitalization and green investments.

The results from econometric model indicate complex interactions between these indicators. In the long run, the share of renewable energy (REN) is positively influenced by digital inclusion (DIGINCL), but also by banking sector performance (EBANK) and return on equity (ROE). However, in the short run, digital inclusion is negatively influenced by ROE, while REN has a positive impact on both DIGINCL and EBANK. These relationships suggest that digital development and investment in green technologies are synergistic. Countries that invest in digital technologies and renewable energy not only improve their sustainability but also increase their economic competitiveness. In the short term, financial stability can affect digital inclusion, suggesting that a healthy banking sector is essential for a successful digital transition.

The implications of this study are manifold and relevant in several areas. On the one hand, for policymakers, the results point to the need for policies that support the further digitalization of the banking sector, which has a positive impact on green investments. On the other hand, banks can benefit from the adoption of digital technologies not only by improving their financial performance, but also by contributing to sustainable development. At the same time, engaging the energy sector in collaborations with the banking sector can facilitate access to finance for renewable energy projects, thereby accelerating the transition to a low-carbon economy. However, this study also suggests that these benefits may vary depending on the national context, which calls for adaptation of public policies at the local level.

Moreover, benchmarking EU countries against the four indicators shows significant differences between Member States in terms of digital adoption, energy sustainability and financial health. Northern European countries are leaders in both digital inclusion and renewable energy use and are well positioned to benefit from the green and digital transition. In contrast, countries in Southern and Eastern Europe face challenges in adopting digital technologies and sustainable solutions, requiring more aggressive policies to stimulate investment and bridge the economic and digital divide. Thus, public policies should focus on stimulating innovation in the energy and digital sectors, strengthening the banking sector and improving access to modern digital and financial infrastructure to ensure greater convergence between EU Member States in these essential areas.

Nevertheless, this study has relevant implications for policymakers but also for other actors involved in the transition to a sustainable economy, providing valuable insights into how digitalization, digital inclusion, and return on capital influence the uptake and growth of renewable energy sources. For policymakers, the results of this study emphasize the importance of developing a robust digital infrastructure and promoting digital inclusion. These initiatives not only support the uptake of e-banking but also stimulate interest and investment in green technologies, which can accelerate the energy transition. Investing in digital accessibility, for example, through policies to expand internet access and digital literacy, can have a multiplier effect, fostering access to financial instruments and information relevant for sustainable development.

For financial institutions, the implications of this study highlight the need to integrate sustainability criteria into their digitalization and funding strategies. The results suggest that by facilitating access to electronic banking and other digital financial services, financial institutions can significantly contribute to advancing renewable energy initiatives. Encouraging investment in green projects through digitally accessible financial instruments could boost both the development of renewables and the profitability of financial institutions, bringing long-term benefits and increasing transparency and accountability in capital allocation.

For investors and other private sector stakeholders, the results of this study can serve as a call to step up investments in digitalization and sustainability-oriented technological innovations. As digital inclusion proves to have a positive impact on the development of renewable energy sources, investors should recognize the added value of digitalization not only as a driver of operational efficiency, but also as an opportunity to align with global sustainability trends. This is essential as governments and other international organizations intensify sustainability regulations, and adapting quickly to these requirements can create a competitive advantage.

For international and regulatory organizations, this study provides additional evidence that can justify initiatives to promote cross-border cooperation for sustainable digitalization. This could include the creation of common standards for integrating digitalization into sustainability objectives, facilitating the exchange of best practices, and supporting countries in their transition toward a sustainable economy. The results also highlight the relevance of creating regulatory frameworks that support both digitalization and renewable energy investments, demonstrating their potential to stimulate innovation and efficiency in different economic sectors.

Therefore, this study draws attention to the need for an integrated approach between digitalization and sustainable development policies, suggesting that the synergy between them can significantly contribute to emission reduction targets and increase access to renewable energy sources. By offering empirical evidence of the dynamic relationships between these variables, this study contributes to the broader discourse on energy policy and sustainability. Its findings are particularly relevant for policymakers seeking to harmonize digitalization and financial development with renewable energy targets, offering actionable strategies to foster long-term environmental and economic resilience. These contributions provide a foundation for future research on the synergies between energy, finance, and digitalization in diverse regional and global contexts.

Future research can extend the analysis in several directions. First, the impact of digitalization on other economic sectors, such as agriculture or transport, can be explored to understand how digital technologies can facilitate the green transition at the system level. Second, research can explore the role of emerging technologies, such as blockchain and artificial intelligence, in optimizing green finance and the energy transition. Future studies could also compare how digitalization supports the green transition in different regions of the world, providing a global comparative perspective. However, an analysis of the risks associated with digitalization, such as cybersecurity, which may affect green investments, would also be needed.

This study is not without limitations. Firstly, the analysis of differences between EU Member States is limited by data availability and specific economic contexts, which may affect the generalizability of the conclusions. In addition, the focus on the EU context may limit the applicability of this study to other regions of the world where digital infrastructure and sustainability policies are different. On the other hand, the lack of a qualitative component limits the understanding of subjective aspects related to the perceptions of financial and energy stakeholders, which may be a valuable direction for future research.

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