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Governing the Green Transition: The Role of Artificial Intelligence, Green Finance, and Institutional Governance in Achieving the SDGs Through Renewable Energy

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Abstract: This study examines the effects of artificial intelligence investments, green financing, government stability, and institutional quality on renewable energy consumption from a multidimensional perspective. Using panel data for the period 2014–2023, 15 leading countries in the field of green financing were included in the analysis. The Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) method was preferred in the empirical analysis; robustness tests were conducted with Fully Modified OLS (FMOLS) and Dynamic OLS (DOLS) estimators to assess the reliability of the findings. According to the findings, artificial intelligence investments have a significant and positive impact on renewable energy consumption in both the short and long term. Similarly, green financing contributes strongly and statistically significantly by enhancing the feasibility of clean energy projects. Furthermore, stable governments and the effective functioning of institutional structures support this process; both factors are observed to have a positive effect on renewable energy consumption. This study offers concrete policy recommendations in line with the United Nations sustainable development goals (SDGs) 7, 9, 13, and 16.

Keywords: artificial intelligence investments; green finance; renewable energy; government stability; sustainable development goals

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1. Introduction

The increasing importance of renewable energy systems shows that not only environmental concerns but also technological innovations have begun to play a transformative role in this area. In this transformation, artificial intelligence (AI) technologies in particular have become a strategic tool to overcome technical, economic, and managerial challenges encountered in the processes from energy production to consumption [1,2]. AI-supported solutions are becoming widespread in applications such as increasing the accuracy of production estimates of variable resources such as solar and wind, providing smart grid

management, optimizing microgrids, and increasing energy efficiency; this accelerates the digitalization of energy systems [3–5]. AI investments are considered not only as technological progress but also as a multidimensional mechanism that accelerates the low-carbon energy transition. With technologies such as data analytics and machine learning, AI both optimizes short-term supply–demand balancing and contributes to the shaping of long-term energy policies [6,7].

The tangible reflection of this technological transformation on sustainable energy investments is largely achieved through green finance instruments. In this process, where artificial intelligence investments are also guiding, access to affordable and long-term financing sources for projects that minimize environmental impact has become critical. Various sustainable finance instruments, especially green bonds, increase the capital flow towards clean energy projects and encourage private sector investments [8,9]. In addition, AI enables a more accurate estimation of investment risks with financial decision support systems, facilitating the emergence of green finance mechanisms in the eyes of investors [10,11]. With the development of green finance, it is observed that governments have developed tax incentives, subsidies, and sustainability standards that support environmentally friendly investments; thus, the energy transformation has gained momentum at the macro level [12–14]. In this context, there is a mutually nurturing relationship between green finance and AI investments.

On the other hand, political stability represents a governance dimension that directly affects the feasibility and continuity of this transformation. In particular, a long-term, predictable, and stable political environment is necessary for the success of advanced technology investments such as artificial intelligence and green finance [15]. Frequent changes in governments or uncertainties in decision-making processes delay the implementation of energy projects and reduce private sector investment appetite [16]. On the other hand, stable political structures can finance large-scale projects faster with public–private partnership models and create a more effective regulatory framework [17,18]. In addition, a stable and coordinated governance structure is needed to ensure the integration of these systems between institutions for the spread of AI-based energy management systems [19].

Finally, institutional quality is a factor that not only supports political stability but also structurally determines the success of renewable energy investments. Institutional quality includes many elements such as the rule of law, fight against corruption, effectiveness of public administration, and regulatory transparency, and when these structures are strong, the energy transition can be achieved more quickly and effectively [20,21]. Especially in developing countries, high institutional capacity plays a critical role in directing public investments and provides support for clean energy projects by increasing the level of social acceptance [22,23]. The integration of digital transformation tools such as artificial intelligence into the energy sector depends on the transparency of institutional processes and digital literacy. Ref. [24] shows that institutional quality increases renewable energy investments not only through its direct effect, but also synergistically by interacting with green finance and technological innovation. Ref. [25] emphasizes that publicly funded projects in countries with high institutional quality create more efficient and long-term outcomes. In this context, the need for an integrated energy transformation model in which artificial intelligence, financial systems, and institutional structures work together emerges.

The acceleration of the transition to renewable energy is possible not only with technological developments but also with the existence of financial, political, and institutional structures that support this process [19,26–29]. This perspective is grounded in the Ecological Modernization Theory (EMT), which suggests that environmental sustainability can be achieved through technological innovation, institutional reform, and market-based tools. However, most of these enabling factors have generally been addressed independently in the literature, and the role of emerging technologies such as artificial intelligence invest-

ments in energy transformation has been examined within a limited framework. While the impact of green finance on investment has mostly been evaluated at the macroeconomic level, governance-related factors such as political stability and institutional quality have either been overlooked or restricted to single-country analyses. Moreover, analyses that fail to consider the interaction among these variables hinder the development of holistic strategies in energy policymaking. Adopting a Stakeholder Theory lens, this study emphasizes that the success of the energy transition relies not only on state-led efforts but also on the coordinated contributions of diverse actors, including financial institutions, private sector technology developers, and civil society. This study aims to fill an important gap in the literature by examining the effects of artificial intelligence investments, green finance, government stability, and institutional quality on renewable energy consumption from a multidimensional and comparative perspective. The existing literature contains limited comprehensive studies that jointly consider these factors and their interactions, especially regarding the contribution of artificial intelligence investments to renewable energy consumption alongside financial and governance quality factors, offering a novel and original approach. Within the scope of this research, data from the period 2014–2023 were used to focus on 15 prominent countries leading in green bond issuance, sustainable investment volume, and environmental policy practices. This selected group of countries, characterized by high financial and institutional capacity, allows for a more accurate and comprehensive assessment of the impact of artificial intelligence investments on renewable energy consumption. Thus, this study provides a holistic analysis of the interactions between technological, financial, and governance elements shaping the energy transition, achieving high representativeness in the policy context.

The findings of this study will serve as a direct guide for policymakers, development agencies, ministries of environment and energy, regulatory bodies, and international financial institutions, especially those involved in the design and implementation of energy policies. A holistic analysis of the effects of artificial intelligence investments, green financing opportunities, and governance quality on renewable energy consumption will enable these institutions to make more accurate decisions regarding resource allocation, technology transfer, and regulatory reforms. Moreover, providing concrete recommendations on how countries' financial support mechanisms and digital infrastructure investments should be integrated with energy policies will strengthen strategy development processes aimed at sustainable development goals. This study's findings are also of strategic importance for private sector investors, international development organizations, technology firms, and companies operating in the energy sector. Revealing the extent and conditions under which artificial intelligence investments support renewable energy consumption offers valuable insights to guide the technology-focused investment decisions of the private sector. In this regard, this study not only fills an empirical gap in the literature but also aims to provide a comprehensive roadmap that considers the integration, governance, and technological interactions for all stakeholders involved in the transition to sustainable energy. This roadmap clarifies the roles of various actors, fosters effective collaboration between policymakers and the private sector, and significantly contributes to accelerating the sustainable energy transition.

This study consists of five main sections. The second section reviews the literature on the effects of AI investments, green finance, institutional quality, and political stability on renewable energy consumption. The following sections present the data, methodology, and empirical findings and conclude with policy recommendations and future research directions.

2. Literature Review

2.1. Artificial Intelligence Investments and Renewable Energy Consumption

In recent years, the integration of artificial intelligence (AI) technologies into the energy sector has initiated a remarkable transformation, especially in terms of renewable energy production and consumption. In the literature, the impact of AI on renewable energy systems is addressed in multidimensional aspects such as increasing forecast accuracy, providing operational efficiency, reducing costs, and contributing to sustainable development goals [1,2,4].

AI has the potential to reduce system imbalance by increasing the accuracy of forecast models, especially in energy production based on variable resources such as solar and wind. Refs. [5,30] emphasize that AI algorithms enable a more effective grid integration of renewable energy sources by improving production forecasts based on meteorological data. Ref. [3] shows that AI-supported demand management applications in smart grid systems optimize energy consumption behaviors. Especially in developing countries, AI applications play a role in accelerating energy transformation despite infrastructure deficiencies. Ref. [31] shows that AI facilitates access to energy by increasing the success of renewable energy investments in low-income economies. Similarly, Refs. [32,33] argue that AI technologies provide energy efficiency and sustainability in microgrids and smart buildings.

Refs. [10,34] state that AI also plays a decisive role in the economic optimization of energy systems. These studies reveal that AI supports investment decisions, increases cost-effectiveness and strengthens financial sustainability. In this context, AI is considered not only a technological innovation, but also a strategic tool in the development of a clean energy economy. The impact of AI on sustainable development is evaluated not only in terms of environmental but also social dimensions. Ref. [2] state that AI makes significant contributions to achieving SDG 7 (accessible and clean energy) and SDG 13 (climate action). In studies conducted specifically for Europe, Ref. [35] has shown that AI-based energy solutions play a central role in achieving the clean energy targets within the scope of the European Green Deal.

As energy systems become more flexible and intelligent, AI also creates significant impacts on the restructuring of energy markets. Ref. [36] state that AI transforms the relationship between traditional and clean energy markets; it affects market predictability and investment behaviors. Ref. [6] emphasize that the impact of AI on energy systems is not linear and that environmental impacts become more pronounced after certain threshold values. Finally, some studies predict that, in the future, AI can combine with quantum computing to provide solutions to more complex problems in energy systems. Refs. [11,37] argue that AI will accelerate the development of clean energy technologies in many areas, from material discovery to performance prediction. This approach reveals that AI technologies will be decisive not only in the construction of current energy structures but also in the construction of a climate-neutral future.

Ref. [38] examined the impact of artificial intelligence on renewable energy investment using data from China. Their findings suggest that, while AI technologies may initially introduce uncertainty, they ultimately play a stimulating role in renewable energy investment over the long term. This study particularly highlights how AI-powered energy forecasting systems facilitate investment decision making. Similarly, Ref. [39] investigated how artificial intelligence contributes to the development of renewable energy and found that this relationship is reinforced through climate finance. The authors argue that AI enhances the effectiveness of climate finance by improving efficiency, reducing costs, and minimizing risks, thereby encouraging greater investment in renewable energy. Both studies under-

score the importance of AI in the energy transition and emphasize the strategic value of integrating emerging technologies with financial mechanisms.

2.2. Green Finance and Renewable Energy Consumption

In recent years, increasing environmental concerns and efforts to combat the climate crisis have brought the restructuring of the financial system to support sustainable investments to the agenda [40]. In this context, green finance, especially through instruments such as green bonds, plays an important role in financing renewable energy investments. In the literature, the supportive effect of green finance on renewable energy investments and production has been empirically demonstrated for various countries and periods.

Numerous studies conducted on the example of China show that there is a strong and positive relationship between green finance and renewable energy. Refs. [8,41] show that green financial instruments reduce capital costs, especially in wind and solar energy projects, and increase investor confidence, encouraging renewable energy production. Similarly, Ref. [42] emphasizes that green finance increases China's clean energy capacity in line with sustainable development goals. Studies conducted specifically on developing countries also support the contribution of green finance to energy transformation. Ref. [43] indicates that the increase in the level of green finance in developing countries is directly reflected in the growth of renewable energy investments. Similarly, Ref. [44] reports that green finance targets and policy priorities are strongly associated with the structural transformation in renewable energy production.

The relationship between green finance and energy efficiency is also quite remarkable. Ref. [45] argues that green finance provides a holistic contribution to the sustainable energy structure by supporting not only production but also energy efficiency projects. Ref. [46] states that, if green bonds are supported by a legislative infrastructure in Southeast Asia, both energy efficiency and renewable investments can increase. The structure of the financial system is also one of the determining factors in the green finance–renewable energy relationship. Ref. [47] states that green finance carried out through bank loans not only increases the efficiency of renewable energy investments but also provides a more efficient use of resources in investment projects. Ref. [12] shows that the impact of green finance has become more evident with energy governance, environmental regulations, and market reforms.

Global studies reveal that green finance contributes not only to environmental goals but also to economic growth. Ref. [48] states that green finance positively affects clean energy investments worldwide and that this effect is valid in both developed and developing countries. Similarly, Ref. [49] reports that green finance accelerates energy transition processes and reduces fossil fuel dependency in E-7 countries. The power of green finance to guide energy investments has continued in the post-COVID-19 pandemic period. Ref. [50] shows that investors have become more sensitive to environmental risks and are increasingly inclined to green financial products after the pandemic, which has a direct incentive effect on renewable energy investments. Ref. [13] states in its assessment of China that green finance and clean energy development are complementary structures and provide higher environmental and economic returns when coordinated together. Ref. [51] emphasizes that green bonds play a critical role in achieving zero-emission targets. In its studies, it has been empirically demonstrated that increasing green bond issuances both improves environmental quality and accelerates renewable energy investments. Ref. [9] states that green financing structures offer a long-term, low-cost, and secure financing source for sustainable energy projects, and that this area should be developed further.

Recent studies have increasingly emphasized the critical role of green finance and credit policies in promoting renewable energy development and addressing environmental

challenges. For instance, Ref. [52], focusing on EU countries, found that green finance and green technology innovation significantly boost renewable energy use, while fiscal decentralization enhances this effect. However, this study also highlights that political risk may moderate these relationships, potentially weakening policy effectiveness. Similarly, Ref. [39] examined the Chinese economy during the COVID-19 pandemic and confirmed that green finance and renewable energy development jointly contribute to increased renewable energy investment and reduced carbon emissions. These findings suggest that green financial mechanisms serve as a bridge between environmental goals and energy transition.

In a more detailed framework, Ref. [53] explores the dynamic impact of green finance from three perspectives: scale, structure, and efficiency. Their results indicate that not only the amount but also the composition and effectiveness of green finance play a key role in supporting renewable energy development. Furthermore, Ref. [54], analyzing China's green finance pilot zones, shows that green finance reforms substantially contribute to the low-carbon energy transition by facilitating project financing in clean energy sectors. Complementary to these findings, Ref. [55] demonstrates that sustainable credit policies reduce energy consumption intensity, reinforcing the link between financial tools and environmental efficiency. Lastly, Ref. [56] provides evidence that green finance, alongside economic growth and renewable resources, contributes significantly to pollution mitigation and sustainability. Collectively, these studies provide strong empirical support for the argument that well-designed green financial instruments and credit frameworks are indispensable in accelerating renewable energy adoption and achieving broader sustainability goals.

2.3. Government Stability and Renewable Energy Consumption

The renewable energy transition is closely related not only to technological and economic factors, but also to political and governance stability. The literature has shown that government stability plays a critical role in the feasibility of energy policies, the sustainability of private sector investments, and the continuity of energy transition processes [57]. The predictability of the political system, together with investor confidence, directly affects the energy transition.

Ref. [58], in its study of E-7 countries, emphasizes the positive effect of government stability on the spread of green energy technologies. Its authors state that the strategic orientation and support capacity of governments for green technology works more effectively under stable political structures. Similarly, Ref. [59] shows that the combination of government support and political stability is an important element in explaining the differences in renewable energy production between countries. Ref. [19], in its study on Tunisia, revealed that negative shocks in government stability negatively affect renewable energy consumption in both the short and long term. This finding shows that political fluctuations, especially in countries undergoing democratic transition processes, weaken the applicability and continuity of energy policies. In this context, it is possible to talk about not only the positive effects of government stability, but also the risks created by imbalances.

Ref. [18] states that political instability has a suppressive effect on renewable energy innovation and that this effect is particularly concentrated on R&D investments and technological innovations. The authors emphasize that energy investments are postponed in an environment of policy uncertainty and that the private sector avoids long-term projects. This situation reveals that not only technical capacity but also administrative continuity is vital for the development of sustainable energy technologies. Similarly, Ref. [16] shows that government stability encourages innovation in renewable energy technologies by reducing

the level of economic risk. Based on empirical analyses conducted at the international level, this study argues that political stability is a determinant not only on local but also on global energy transformation policies. In addition, Ref. [15] states that clean energy investments are increasing rapidly, and investors' decision-making processes are more rational in countries with policy continuity. Ref. [17], in its study on the Gulf countries, has shown that governance durability and political stability can enable the transition to renewable energy even in countries dependent on fossil fuels. In this context, government stability not only affects the investment environment but also determines the capacity of countries to implement their energy visions.

2.4. Institutional Quality and Renewable Energy Consumption

Institutional quality is considered one of the main determinants in terms of the development, implementation, and sustainability of energy policies. Ref. [20] empirically confirms the effect of governance quality on energy transformation processes by revealing that renewable energy consumption is higher in countries with high institutional quality. Similarly, Ref. [60] emphasizes that strong institutional structures play an important role in the transition from fossil fuels to renewable resources even in countries rich in energy resources. Studies on OECD countries further clarify the positive relationship between institutional quality and renewable energy consumption. Ref. [21] states that institutional quality in OECD countries both supports clean energy investments and increases energy supply security. Ref. [49] shows that institutional quality positively affects renewable energy consumption by reducing this risk in cases where political risk is high. Ref. [61] argues that financial development can only have an effect on renewable energy consumption when combined with high institutional quality. Studies conducted in the context of developing countries show that the level of institutional quality highlights vulnerabilities in the energy transition as a determining factor. Refs. [23,62] report that weak institutional structures slow down the renewable energy transition by threatening policy continuity and investment security. Ref. [63] emphasizes that the interaction of institutional quality, economic growth, and financial development creates multidimensional effects on the energy transition through the example of Tunisia. Ref. [64] reveals that institutional vulnerabilities limit the applicability of energy policies in the context of South Africa.

Institutional quality also determines the nature and direction of renewable energy investments. Ref. [25] states that institutional quality plays a critical role in the efficient direction of public investments, while Ref. [22] shows that countries with high institutional capacity in African countries are able to attract more renewable energy capital. Ref. [65] presents empirical findings confirming the impact of institutional arrangements on the renewable energy transition in Poland. Institutional quality also creates stronger effects on the energy transition when it works together with financial and technological factors. Ref. [24] shows that institutional quality, green finance, and technological innovation interact to increase renewable energy development. Ref. [66] states that the level of institutional quality constitutes a threshold value in the impact of financial development on renewable energy; in other words, if the institutional structure is not sufficiently developed, financial development cannot contribute to the energy transition. This result indicates that institutional reforms should be carried out in coordination with financial strategies. Finally, Ref. [67], which explored the subject with a different methodological approach, shows that the scientific literature on the subject is largely shaped around the themes of "institutional regulatory capacity", "governance reforms", and "fighting corruption", and that this gradually deepens at the level of theory and practice of renewable energy transformation on the axis of institutional quality. This situation reveals that not only technical capacity

but also a strong and effective institutional framework are necessary for the success of energy policies.

2.5. Research Gap

Existing studies on renewable energy consumption have largely focused on macroeconomic determinants such as economic growth, energy prices, openness to the outside world, environmental regulations, and energy infrastructure. However, in recent years, the impact of rapidly developing digital technologies, artificial intelligence applications, and green financing mechanisms on this transformation has been addressed holistically in relatively limited studies. In particular, the impact of artificial intelligence investments directly on renewable energy consumption has only recently begun to be discussed in the literature, and most studies have addressed this relationship only from a technology-based or energy efficiency perspective.

Governance-focused factors such as institutional quality and government stability have mostly been evaluated through indirect effects, and how these variables shape the applicability of energy policies has been included in case study-based studies. The existing literature has mostly examined the impact of these variables by focusing on a single country (e.g., China, Poland, or Tunisia) or regionally. However, comprehensive and multivariate panel data analyses in which green finance leader countries are comparatively examined and the four factors, i.e., artificial intelligence, green finance, government stability, and institutional quality, are tested together have not been given sufficient space in the literature. Empirical studies that reveal how digitalization, governance, and financial system integration affect renewable energy consumption in a multidimensional manner, especially in a sample of countries with high green bond issuance capacity, are quite limited. In addition, most of the existing studies focus on the individual effects of these variables, ignoring their interactions and the effects they exert together. This makes it difficult for policymakers to develop holistic and targeted energy.

3. Data and Estimation Strategy

3.1. Data Description

Increasing renewable energy consumption today plays a key role in achieving sustainable development goals. In this context, how many factors, from digital technologies to artificial intelligence investments, from financial instruments to corporate governance structures, affect the energy transition has become an important research area. The main purpose of this study is to analyze the effects of factors such as artificial intelligence investments, green financing, government stability, and institutional quality on renewable energy consumption. In this study, 15 leading countries in the field of green financing (the United States, the United Kingdom, Sweden, Spain, South Africa, Poland, the Philippines, Norway, New Zealand, the Netherlands, Mexico, Malaysia, Japan, Italy, and India) were examined econometrically using data from the period 2014–2023. These countries were selected based on criteria such as green bond issuance, sustainable finance practices, and environmental policy leadership. This research aims to reveal the role of digitalization and governance quality in reshaping energy policies with a sustainability perspective.

In this study, in line with the literature [68–71], the total renewable energy consumption of countries was determined as the dependent variable. This variable is an important indicator reflecting the success of sustainable energy policies and the level of environmental transformation. The first independent variable examined in this study was defined as the "number of AI investments", which represents the digitalization process and technology investments. This variable allows the potential impact of the investment intensity in artificial intelligence technologies on the energy transformation of countries to be evaluated.

The second independent variable in this study is green finance, measured through the issuance of green bonds. This variable reflects the environmentally focused investment capacity of countries and the level of use of sustainable finance instruments. It is frequently emphasized in the literature that green finance supports the energy transition by increasing financial resources directed to renewable energy infrastructure [46,72]. In particular, green bonds provide long-term capital flows to environmentally friendly energy investments such as solar, wind, and geothermal. The third independent variable in this study is government stability. Government stability is an important institutional indicator that can directly and indirectly affect the renewable energy transition. It is stated in the literature that stable government structures facilitate the implementation of long-term environmental policies, increase confidence in the investment environment, and encourage the private sector to participate in renewable energy projects [19,73–75]. In this study, the direction and significance of this relationship were tested empirically using data based on the government stability index. The last independent variable considered in this study is institutional quality. This concept includes dimensions such as the rule of law, the control of corruption, bureaucratic effectiveness, administrative accountability, and the general effectiveness of public institutions. Institutional quality is the basic governance element that ensures the stable, transparent, and efficient implementation of energy policies in a country. In the literature, it is stated that countries with strong institutional structures can more effectively sustain their energy policies with long-term perspective, direct investments in renewable energy and ensure the efficient use of financial resources [76–78]. In addition, high institutional quality encourages direct investments by increasing the trust of the private sector in the field of renewable energy. Whether this variable plays a role in facilitating the transition to sustainable energy has been tested in the context of sample countries. In this study, government stability (GS) and institutional quality (IQ) are employed as distinct indicators to capture the different dimensions of governance. *Government stability* refers to a short-term political risk and reflects the degree of cohesion within the government, legislative strength, and public support. It is measured on a scale from 0 to 4 and obtained from political risk assessments. In contrast, *institutional quality* is a broader, structural measure that reflects the long-term institutional capacity and rule-based governance framework. It is constructed using principal component analysis (PCA) based on multiple governance-related components, including law and order, corruption control, democratic accountability, bureaucratic quality, and government stability. While both variables relate to governance, GS captures immediate political conditions, whereas IQ reflects deeper, systemic institutional characteristics.

As a result, the summary of the variables used in this study is shown in Table 1. In order to estimate the relationships in question, the logarithmic regression model is used as follows:

$$RE_{i,t} = \beta_0 + \beta_1 AI_{i,t} + \beta_2 GF_{i,t} + \beta_3 GS_{i,t} + \beta_4 IQ_{i,t} + \varepsilon_{i,t} \quad (1)$$

Table 1. Data description.

Variables	Symbols	Definition	Source
Renewable Energy	RE	Total renewable energy consumption in kiloton equivalents (Ktoe)	International energy Agency (IEA)
AI Investments	AI	Number of AI investments	OECD
Green Finance	GF	Green bonds, Billion USD	Climate Bonds Initiative
Government Stability	GS	A risk score ranging from 0 to 4, combining government cohesion, legislative robustness, and public support	ICRG

Table 1. *Cont.*

Variables	Symbols	Definition	Source
Institutional Quality	IQ	An index encompassing law and order, corruption, democratic accountability, bureaucratic quality, and government stability is constructed using the principal component analysis (PCA) method	International Country Risk Guide (ICRG)

3.2. Estimation Strategy

In the first stage of this study, cross-sectional dependency was analyzed. For this purpose, the LM test developed by [79] and the scaled LM (CD_{LM}) and CD tests proposed by [80] were applied. The Pesaran CD test can be used in cases where both the time dimension and the cross-sectional dimension are dominant. The LM test statistic was calculated as described in the literature, as in Equation (2):

$$LM = T \sum_{\text{İ}=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij}{}^2 \tag{2}$$

In this equation, $\hat{\rho}$ represents the sample-based measurement of the pairwise correlation of the residuals, while the second cross-sectional dependence test used in this study is the CD test developed by Ref. [80] and shown in Equation (3):

$$CD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=1+1}^{N} \hat{\rho}_{ij} \right) \tag{3}$$

Based on the cross-sectional dependency test results, the CADF (Equations (4) and (5)) and CIPS (Equation (6)) panel unit root tests developed by Ref. [81] and including lagged cross-sectional averages were applied in this study.

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t-1} + u_{it} \tag{4}$$

$$u_{it} = \gamma f_t + \tag{5}$$

$$\Delta y_{it} = \alpha_i + \rho_i y_{i,t-1} + d_0 \overline{y}_{t-1} + d_1 \Delta \overline{y}_t + \varepsilon_{it} \tag{6}$$

If there is autocorrelation in the error term or in the variable, the model can be extended by including the first differences of the variables y_{it} and $\overline{y}_{it}$,it (Equation (7)). In the case of autocorrelation in the error term or variable, the model can be expanded by adding the first differences of the variables y_{it} and $\overline{y}_{it}$ (Equation (7)).

$$\Delta y_{i,t} = \alpha_i + \rho_i y_{i,t-1} + c_i \overline{y}_{t-1} + \sum_{j=0}^{p} d_{i,j} \Delta \overline{y}_{t-j} + \sum_{j=0}^{p} \beta_{i,j} \Delta y_{i,t-j} + \mu_{i,t} \tag{7}$$

Ref. [82] describes a method that examines the cointegration relationship between two or more variables within the framework of the error correction model. It provides four basic statistics: group (G_t and G_a) and panel (P_t and P_a). The cointegration equation is given in Equation (8):

$$\Delta Y_{it} = \delta_i d_t + \alpha_i Y_{i,t-1} + \gamma_i X_{i,t-1} + \sum_{j=1}^{pi} \alpha_{ij} \Delta Y_{i,t-1} + \sum_{j=-qi}^{pi} \gamma_{ij} \Delta X_{i,t-1} + \varepsilon_{it} \tag{8}$$

The CS-ARDL model was developed to control the cross-sectional dependency resulting from unobservable common shocks in panel data analysis. It takes into account the common factor effects by integrating the cross-sectional averages of all units into the tradi-

tional ARDL structure. This approach is an adaptation of the Common Correlation Effects (CCE) method developed by [83] for the ARDL framework. In addition, the theoretical foundations of the model are based on the studies of Refs. [84,85]. The model is presented in Equation (9):

$$y_{it} = \alpha_i + \sum_{p=1}^{P} \varphi_{ip} y_{it}{}^{-}{}_{p} + \sum_{q=0}^{Q} \beta'_i q x_{it}{}^{-} q + \gamma_i \overline{y}_t + \delta'_i \overline{x}_t + \varepsilon_{it} \quad (9)$$

After the cointegration analysis, the direction and coefficient of the long-term relationship between the series were evaluated. The FMOLS estimator developed by Ref. [86] eliminates the problems of autocorrelation in error terms and simultaneity between variables with semiparametric correction and reliably reveals the long-term relationship. The FMOLS test is presented in Equation (10):

$$\hat{\theta} = \left[\begin{matrix}\hat{\beta} \\ \hat{\gamma} =\end{matrix}\right] \left(\sum_{t=1}^{T} Z_t Z_t'\right)^{-1} \left(\sum_{t=1}^{T} Z_t Y_t^{+} - T\left[\lambda_1^{+} 0^2\right]\right) \quad (10)$$

While the autocorrelation problem is eliminated with the kernel estimator in the FMOLS method, the regression equations obtained with the group average panel DOLS estimator developed by [87] are presented in Equations (11)–(14):

$$\gamma_{it} = \alpha_i + \beta \chi_{it} + \sum_{k=-K_i}^{K_i} \gamma_{ik} \Delta x_{it} + \mu_{it} \quad (11)$$

$$\chi_{it} = \chi_{it-1} + e_{it} \quad (12)$$

$$\hat{\beta}^*_{GD} = N^{-1} \sum_{i=1}^{N} \beta^* D, i \quad (13)$$

$$t_{\hat{\beta}^*_D} = N^{-\frac{1}{2}} \sum_{i=1}^{N} t_{\hat{\beta}^*_{D,i}} \quad (14)$$

The panel causality analysis described in Ref. [88] was applied. This test can give promising results in panels with cross-sectional dependence and heterogeneity, with or without a cointegration relationship (Equation (15)). In this equation, while the variables $X_{(i,t)}$ and $y_{(i,t)}$ represent stationary observations, it is assumed that the coefficients are different between units but constant in time, and the lag length is the same for all units.

$$y_{i,t} = \alpha_i + \sum_{k=1}^{K} \beta_{ik} y_{i,t-k} + \sum_{k=1}^{K} \gamma_{i,k} X_{i,t-k} + \varepsilon_{it} \quad (15)$$

To briefly summarize the methods used in this study: First, cross-sectional dependence was analyzed using the Breusch–Pagan LM and Pesaran CD tests to detect the presence of common shocks among panel units. Since cross-sectional dependence was confirmed, second-generation panel unit root tests—CADF and CIPS—were employed to examine the stationarity of the variables. To investigate the long-run relationship between the variables, the cointegration test described in Ref. [82] based on the error correction mechanism was applied. For the accurate estimation of long-run coefficients, the CS-ARDL model, which accounts for cross-sectional dependence, was used, and the robustness of the findings was checked using the FMOLS and DOLS estimators. Finally, the Dumitrescu–Hurlin panel causality test was employed to identify the direction of causality among the variables.

4. Empirical Results and Discussion

In this part of the research, empirical findings on the effects of factors such as artificial intelligence investments, green financing, government stability, and institutional quality on renewable energy consumption are included.

The cross-sectional dependency test results in Table 2 reveal that all variables in the model have significant cross-sectional dependency. According to the Breusch–Pagan LM and Pesaran CD tests, renewable energy consumption (RE) and artificial intelligence investments (AI), green finance (GF), government stability (GS), and institutional quality (IQ) variables show statistically significant cross-sectional dependency at the 1% confidence level. This situation shows that common shocks or similar dynamics are effective among the countries in the panel and therefore second-generation panel methods should be preferred in the analyses.

Table 2. Cross-sectional dependence tests.

	RE	AI	GF	GS	IQ
Breusch–Pagan LM	385.251 ***	405.580 ***	295.197 ***	475.082 ***	650.787 ***
Pesaran CD	14.292 ***	7.985 ***	6.968 ***	9.360 ***	18.585 ***

Note: *** denotes significance at 1% level.

The CADF unit root test results presented in Table 3 show that all variables in the model contain unit roots at the level and are not stationary. However, when the first differences of the variables are taken, the test statistics become statistically significant at the 1% significance level in all series, and the H_0 hypothesis is rejected at this level. This situation reveals that the series are stationary at the first difference. This finding shows that the stationarity condition required for switching to panel cointegration analysis is met.

Table 3. CADF unit root results.

	Level	First Difference
RE	−0.987	−4.850 ***
AI	−1.594 *	−5.864 ***
GF	−2.087 **	−5.987 ***
GS	−0.866	−4.642 ***
IQ	−0.745	−3.868 ***

Note: *, **, and *** denote significance at 10%, 5%, and 1% level, respectively.

The Westerlund panel cointegration test results presented in Table 4 show that there is a long-term relationship between the variables in the model. All four test statistics obtained have negative and high absolute values, and the corresponding Z-values of these statistics are found to be significant at the 1% significance level. These findings reveal the existence of a cointegration relationship across the panel and on a group basis. Accordingly, the null hypothesis of no cointegration between the variables is rejected. As a result, it is concluded that there is a long-term and statistically significant balance relationship between renewable energy consumption and artificial intelligence investments, green financing, government stability, and institutional quality variables. This situation shows that the variables in question move together and in the long term.

Table 4. Westerlund cointegration test.

Statistic	Value	Z-Value	*p*-Value
G_t	−8.9 *	−7.3	0.001
G_a	−12.6 *	−6.9	0.001
P_t	−11.4 *	−6.4	0.001
P_a	−13.8 *	−7.2	0.001

Note: * denotes significance at 1% level.

According to the CS-ARDL analysis in Table 5, it is seen that artificial intelligence (AI) investments have positive and statistically significant effects on renewable energy consumption in both the long and short term. This finding shows that artificial intelligence technologies support energy systems not only with their strategic planning and long-term production forecasting capacity, but also with functions such as increasing energy efficiency, improving smart grid management, and optimizing supply–demand balance in short-term operational processes. In this context, the integration of AI-supported digital solutions in the energy sector provides both the flexibility to respond to temporary fluctuations and contributes to the strengthening of sustainable energy infrastructure. These results are largely consistent with the existing literature. Studies such as [1,4,30] emphasize that artificial intelligence provides a multifaceted impact from decision support systems to production forecasting models in energy transition processes. Similarly, Refs. [3,33] reveal that AI-based applications are of critical importance for the efficient management of renewable resources, especially in smart grids. Ref. [31] shows that AI applications yield effective results in energy transition even in developing economies. In this context, the findings are parallel to the above-mentioned studies and support that AI investments are an important tool in the energy transition in terms of both short-term operational gains and long-term structural transformation.

Table 5. The CS ARDL analysis.

Variables	Coefficients	Stand-Error
AI	0.051 **	2.528
GF	4.865 ***	0.485
GS	0.039 *	0.198
IQ	0.098 **	0.031
Error Correction Term	−0.502 ***	0.080
AI	0.042 **	3.865
GF	1.529 ***	0.685
GS	0.049 **	0.238
IQ	0.075 **	0.049

Note: *, **, and *** denote significance at 10%, 5%, and 1% level, respectively.

According to the findings of the CS-ARDL analysis, it is seen that the green finance (GF) variable has a significant and positive effect on renewable energy consumption in both the long and short term. This shows that more cost-effective and long-term resources can be directed to renewable energy projects thanks to financial instruments such as green bonds, and thanks to this financial support, investments can be implemented more quickly and steadily. In the short term, green finance reduces investment risks and eliminates financial uncertainties at the initial stage of projects; in the long term, it creates a permanent capital structure that supports the establishment and expansion of sustainable energy infrastructure. This finding indicates that financial mechanisms not only increase investment amounts, but also contribute to the institutionalization and sustainability of the green transition. These results are largely consistent with the existing literature. Studies such as [41,43,48] show that green finance significantly supports renewable energy growth, especially in developing countries. Similarly, Refs. [9,45] reveal that green financial instruments are effective in increasing energy efficiency and encouraging low-carbon investments. In addition, Refs. [12,42] emphasize that a strong fit between the financial system and environmental policies is decisive in achieving clean energy targets. Therefore, the positive effect

of green finance on energy consumption in this study presents results in the same direction as the findings in the literature.

According to the CS-ARDL analysis, the government stability (GS) variable has a statistically significant and positive effect on renewable energy consumption in both the long and short term. This result shows that a stable political structure ensures the sustainability of policies supporting the energy transition and strengthens the investment environment by reducing regulatory uncertainty. In the long term, government stability facilitates the holistic and decisive execution of energy planning; in the short term, it increases the confidence of the private sector and public institutions in renewable energy projects and increases the speed of implementation. These findings reveal that political stability is not only a governance indicator but also a basic structural element that triggers energy investments. These results largely coincide with the existing literature. Ref. [58] shows that government stability makes significant contributions to the renewable energy transition in its analysis of E-7 countries. Ref. [19] indicates that negative shocks in government stability negatively affect the energy transition process in both the short and long term in the case of Tunisia. The study conducted by Ref. [18] also notes that political instability weakens renewable energy innovation. In addition, Refs. [15,16] emphasize that political stability increases the effectiveness and continuity of energy investments. In this regard, the findings obtained in the study are in line with the literature supporting the fundamental role played by government stability in energy transformation.

According to the CS-ARDL analysis, it was found that the institutional quality (IQ) variable has a significant and positive effect on renewable energy consumption in both the long and short term. This finding shows that renewable energy investments are encouraged more and produce more successful results in practice in countries where the rule of law, effectiveness of public administration, control of corruption and regulatory quality are high. In the long term, institutional structures ensure the sustainability and applicability of energy policies; in the short term, they increase the speed of implementation of projects by simplifying bureaucratic processes and make the investment environment safe and predictable. This situation reveals that the energy transition is not only a matter of technical but also governance capacity. The findings are in full compliance with the existing literature. Studies such as [20,21,25] emphasize that strong institutional structures increase publicly supported renewable energy investments and that these investments produce more effective results. Ref. [24] states that institutional quality supports the energy transition not only through its direct effect but also through its interaction with green finance and technological innovation. In addition, analyses on developing countries such as [24,66] have found that the transition to renewable energy is slower and more fragile in countries with low institutional quality. Therefore, the findings in this study indicate that governance reforms based on institutional quality are a critical lever for sustainable energy systems and are consistent with the general trend in the literature.

Table 6 shows that FMOLS (Fully Modified Ordinary Least Squares) and DOLS (Dynamic Ordinary Least Squares) estimators were applied within the scope of the robustness test performed to test the validity of the long-term findings related to the CS-ARDL model used in this study. Both estimation methods show that the effects of the variables artificial intelligence investments (AI), green finance (GF), government stability (GS), and institutional quality (IQ) included in the model on renewable energy consumption are positive and statistically significant. These results show a high level of consistency with the findings obtained from the CS-ARDL model in terms of direction and significance, confirming that the analysis results are reliable regardless of the methodological approach.

Table 6. The robustness checks.

	FMOLS	**DOLS**
Variables	Coefficient	Coefficient
AI	0.378 ***	0.485 ***
GF	4.385 ***	5.856 ***
GS	0.118 **	0.095 **
IQ	0.127 **	0.183 **

Note: ** and *** denote significance at 15% and 1% level, respectively.

The high significance levels obtained with the FMOLS and DOLS estimators particularly strengthen the decisive role of the green finance variable on the energy transition. In addition, the fact that artificial intelligence investments are consistently significant in both estimation methods supports the contribution of technological innovations to the digitalization of energy systems. The consistent positive effects of government stability and institutional quality variables also reveal that governance factors are of critical importance in the success of sustainable energy policies. In this context, the findings obtained from the robustness analysis show that the results obtained in the basic model are not random and are also confirmed by alternative long-term estimation methods, thus increasing the empirical reliability of this study. In other words, these findings reveal that the findings regarding the basic empirical model of this study are not only hypothetical or sample-based, but also maintain their validity under alternative econometric approaches.

According to the results of the Dumitrescu–Hurlin panel causality test in Table 7, a bidirectional causality relationship was found only between institutional quality (IQ) and renewable energy consumption (RE). This finding indicates that institutional structures have an impact on energy policies, and that the transition to renewable energy can positively affect the development of institutional quality. The fact that energy transformation creates an externality that improves governance standards reveals a very critical dynamic, especially in terms of sustainable development goals.

Table 7. Pairwise Dumitrescu–Hurlin panel causality tests.

	Z-Bar
$RE \nrightarrow AI$	0.765
$AI \nrightarrow RE$	3.984 ***
$RE \nrightarrow GF$	4.055 ***
$GF \nrightarrow RE$	9.857 ***
$RE \nrightarrow GS$	0.358
$GS \nrightarrow RE$	4.298 ***
$RE \nrightarrow IQ$	0.439 ***
$IQ \nrightarrow RE$	3.962 ***

Note: *** denotes significance at 1% level.

However, only one-way causality relationships were observed between AI investment, green finance (GF), and government stability (GS) variables and renewable energy consumption. There is significant causality from AI, GF, and GS variables to RE; however, no causality from RE to these variables was detected. These results reveal that technological, financial, and governance factors drive the energy transition; however, changes in energy consumption do not relate to these structural factors in the short term. Therefore, it is important for policymakers to focus on determinants such as AI, green finance, and stable governance in order to develop proactive and goal-oriented strategies in energy transition.

5. Conclusions

This study reveals the significant impact of AI investments, green finance, government stability, and institutional quality on renewable energy consumption. The findings demonstrate that the energy transition is shaped not only by technological innovations but also by governance, financial, and institutional frameworks. This highlights the necessity of addressing energy policies through a multidimensional perspective. The most fundamental conclusion for policymakers is that the integration of digitalization into strategic energy planning must be accelerated.

AI-based solutions play a critical role in forecasting energy supply–demand balances, ensuring grid stability, and improving overall efficiency. In this regard, public institutions and energy regulators should strengthen their collaboration with technology companies operating in the energy sector. Tax incentives, pilot project grants, and sector-specific open data platforms should be developed to support AI projects. Particularly in developing countries, regional technology transfer mechanisms should be implemented to address disparities in digital infrastructure. However, the sustainability of AI's contribution to energy transformation is only possible through stable political environments and strong institutional frameworks. Therefore, digital transformation strategies in the energy sector should be supported by long-term and comprehensive policy documents that are independent of short-term political shifts. National energy strategies should be reinforced by concrete action plans incorporating AI-based solutions, and these plans should be legally binding and designed as supra-governmental policies. Institutional quality is also critical in ensuring the implementation, transparency, and public acceptance of AI-driven energy projects. In countries with strong governance capacity, AI investments are more rapidly integrated and systemic risks are managed more effectively.

Accordingly, the data management infrastructure of public energy institutions should be strengthened. Algorithmic transparency, ethical oversight mechanisms, and accountability standards must be developed for the use of algorithms in decision-making processes. Open data collaboration platforms should be established between the public and private sectors, and AI-based decision support systems should be designed to be more democratic and traceable. In this way, AI-driven energy policies can rest on a sustainable foundation—both in terms of technical efficiency and governance quality. In addition to digital and governance frameworks, green finance is also a strategic tool for ensuring the financial sustainability of the energy transition. This study's findings indicate that green financial instruments directly support renewable energy projects, particularly those integrating AI. Therefore, central banks and financial regulators should expand green credit guidelines and taxonomy frameworks to include digital energy technologies. Alongside environmental risk-based stress testing, the financial and environmental effects of digital infrastructure investments should also be incorporated into evaluation systems. To scale up green bond issuance, government-backed financing mechanisms should be established for technology firms, and public banks or development funds should offer long-term, low-interest loan programs specifically tailored to AI-supported energy projects.

When all these elements are considered together, it becomes evident that AI technologies play not only a complementary but also a transformative role in energy transition. Advancing digital infrastructure, aligning financial support with AI, adapting governance structures to digitalization, and securing long-term energy policies through political commitment are all crucial for achieving efficiency, environmental compatibility, and social welfare. Thus, the success of the energy transition depends not only on technological innovation but also on a governance model grounded in institutional coherence and multi-stakeholder collaboration. Strategic cooperation among national and local governments, private sector actors, financial institutions, and civil society organizations will ensure the

long-term sustainability of digital energy systems. Consequently, energy policy must go beyond production–consumption balances and incorporate climate goals, development strategies, and social resilience dimensions.

The findings of this study contribute directly to several sustainable development goals (SDGs), particularly SDG 7 (affordable and clean energy), SDG 9 (industry, innovation and infrastructure), SDG 13 (climate action), and SDG 16 (peace, justice and strong institutions). The strong and statistically significant effects of artificial intelligence investments and green finance on renewable energy consumption clearly support SDG 7 by emphasizing the role of technological and financial tools in increasing the availability and sustainability of clean energy. In particular, the positive long- and short-term impacts of green finance highlight its critical role in mobilizing affordable and long-term funding mechanisms for clean energy infrastructure. Furthermore, the significant role of government stability and institutional quality reinforces the alignment with SDG 16, which calls for effective, accountable, and inclusive institutions. The bidirectional causality between institutional quality and renewable energy consumption indicates that not only does good governance enable clean energy progress, but also the energy transition itself may foster institutional development—contributing to a virtuous cycle aligned with governance-centered SDGs. Additionally, the integration of AI in energy systems, as shown in the results, supports SDG 9 by enhancing smart infrastructure and innovation-driven development. These multidimensional relationships reveal that the energy transition, supported by technological innovation, financial sustainability, and governance reforms, contributes holistically to the broader global sustainability agenda.

This study has certain limitations. First, the analysis is limited to the period 2014–2023 and includes only 15 countries that are leaders in green finance, which may restrict the generalizability of the results. In addition, the AI investment data and institutional quality indicators are based on the limited scope of existing databases. Future research can address these limitations by including a broader set of countries and longer time spans. Moreover, sector-specific analyses (e.g., wind, solar, hydro) may provide deeper insight into the technical efficiency of AI applications and help produce more tailored strategic recommendations for policymakers.

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