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Do Artificial Intelligence and Green Finance Accelerate Sustainable Energy Outcomes? Global Evidence

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Abstract

This study examines the impact of artificial intelligence, green finance, and environmental policy instruments on renewable energy investment and energy efficiency across 35 economies over the period 2000 to 2024. Grounded in endogenous growth theory, environmental economics, and innovation systems theory, the study explores how technological advancement interacts with financial and policy frameworks to influence sustainable energy outcomes. A comprehensive panel data approach is employed, utilising two-way fixed effects, Driscoll–Kraay standard errors, and system generalised method of moments estimation to address heterogeneity, cross-sectional dependence, and endogeneity. The model incorporates key variables including renewable energy investment, energy efficiency, green finance, artificial intelligence adoption, policy instruments, and macroeconomic controls. The empirical findings reveal that renewable energy investment has a positive and statistically significant effect when dynamic adjustments and endogeneity are accounted for, confirming its critical role in advancing sustainable energy transitions. Green finance demonstrates a strong and significant impact in static models, although its direct effect weakens in dynamic specifications, suggesting indirect transmission through technological and investment channels. Artificial intelligence exhibits a negative and statistically significant effect across robust models, reflecting short-term adjustment costs such as increased energy demand and transitional inefficiencies. However, interaction effects indicate that artificial intelligence enhances renewable energy investment and efficiency when supported by strong financial systems and effective policy frameworks. Policy instruments show mixed and often insignificant effects, highlighting limitations in implementation and enforcement.

Keywords: *Artificial Intelligence, Green Finance, Renewable Energy Investment, Energy Efficiency*

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1. INTRODUCTION

The shift to sustainable energy systems is now one of the biggest economic challenges in the world, as the world becomes more environmentally conscious, climate change becomes increasingly severe, and the economy needs to be more resilient in the long-term future. The need for economies to transition away from fossil fuels and towards more sustainable and efficient energy systems has become even more pressing due to rising greenhouse gas emissions, resource exhaustion and environmental degradation (Kabeyi & Olanrewaju, 2022; Roussel & Audi, 2024; Wang & Azam, 2024; Akpasi et al., 2025). Investment in renewable energy and energy efficiency are considered two critical pillars of this transition, as they play a role in carbon emission reduction, economic development and energy security. Technological innovation and financial development can be important determinants of the adoption of sustainable energy solutions and efficiency in energy systems (Audi & Ali, 2022; Abid et al., 2024; Ajayi et al., 2025). New ideas, knowledge creation and technological change have become crucial ingredients of long-run economic and environmental outcomes in the theoretical development of growth economics. According to the endogenous growth theory, sustained economic growth is the result of endogenous factors like technology, R&D, human capital formation and not of exogenous factors (Cvetanović et al., 2015; Marc et al., 2022; Șerban, 2025; Alka et al., 2025).

Artificial intelligence (AI) tools are considered a new generation of innovation and could significantly change the production processes, resource allocation, and efficiency of decision-making. In the context of energy systems, where efficiency and sustainability are paramount, AI can power predictive analytics, automation, and system optimisation (Abdmouleh et al, 2015; Marc et al., 2023; Duan et al., 2019; Challoumis, 2024; Khalid et al., 2025; Kumar & Shrivastava,

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2025). But the growth-promoting power of these technologies relies on other components, such as financial systems, institutional arrangements, and policy landscapes.

Carbon pricing, emissions trading systems, and environmental standards are all mechanisms that seek to internalise environmental costs, thereby encouraging lower levels of pollution and different patterns of energy use (Aldy & Stavins, 2012; Audi & Al-Masri, 2024; Guo et al., 2025). The policy tools are designed to induce investment in renewable energy and to increase energy efficiency through relative pricing and incentivising innovation (Marc et al., 2022; Abbruzzese et al., 2025). But these instruments work only if they are enforced, institutions are of good quality, and technologies are ready to use. In many economies, environmental policies have weak implementation, their policy climate is uncertain, and their regulations are inefficient, which reduces the potential impact of environmental policies to achieve sustainable outcomes (Audi et al., 2021; Liu et al., 2023; Adebayo & Özkan, 2024; Marc et al., 2025; Pata, 2025).

Financial development, especially the development of green finance, is a key means to enable the transition to sustainable energy systems. Green finance includes financial products and investments aimed at financing sustainable projects, such as renewable energy, energy efficiency, and low-carbon technologies. It helps allocate financing to sustainable activities, reduces financing constraints, and makes clean energy investments more scalable (Raman et al., 2025). Green finance is a key driver to speed up the use of renewable energy technologies and increase energy efficiency by mobilising resources and lowering investment risks (Bhattacharyya, 2022; Ali & Audi, 2023; Nasir & Ahmed, 2024; Madouri, 2025). But its impact is often dependent on the overall institutional and regulatory framework as well as the way it relates to technological innovation. The advent of AI introduces a fresh perspective to the sustainability conversation, with the potential to greatly improve the efficiency and effectiveness of energy systems. AI technologies can help optimise energy usage, manage the grid and integrate renewable energy into the existing energy system. Meanwhile, the use of AI is tied to significant energy consumption, including in data processing required to run AI algorithms and computational needs as AI models are deployed, which can ultimately reduce some potential environmental benefits in the short term (Sachs et al., 2019; Khan et al., 2025; Madouri, 2025; Umair et al., 2025; Erdoğdu et al., 2025). The duality of AI underscores the significance of comprehending its interplay with financial and policy structures to influence sustainable energy results. Although a significant amount of literature has been published on sustainability, technology, and finance, there is a lack of literature which examines these three factors together, taking into account the interdependencies and joint effects. Especially, the link between artificial intelligence, green finance and environmental policy instruments and their impact on renewable energy investment and on energy efficiency, has received little attention. Although the literature has investigated the positive impact of green finance on sustainability and the transformative impact of AI, there has been a lack of a unified and comprehensive empirical analysis that addresses these two aspects together. Moreover, existing work poorly addresses the dynamic and non-linear relationships among these variables and the potential for complementarities and threshold effects. In this light, this research examines how artificial intelligence, green finance and environmental policy instruments affect investments in renewable energy and energy efficiency in 35 economies from 2000 to 2024.

2. LITERATURE REVIEW

Technological progress, financial development and sustainable energy outcomes have become a focal point in recent empirical studies, especially in the field of global climate challenges and energy transitions. There has been increasing literature that underscores the significance of renewable energy investment as an important enabler of sustainable energy systems and long-term environmental performance (Capros et al., 2018; Si et al., 2020; Poudel et al., 2022; Appannan et al., 2023; Arshi et al., 2025; Han et al., 2025; Naeem et al., 2025). Empirical studies have shown that investments in renewable energy infrastructure can play a key role in enhancing energy efficiency and decreasing reliance on fossil fuels. For instance, Apergis and Payne (2010) have found that there exists a long-run relationship between renewable energy consumption and economic growth, which implies that investments in clean energy can contribute to environmental protection and economic growth. In a similar vein, Bhattacharya et al. (2016) show that energy efficiency and sustainable growth are better when renewable energy is developed in a group of countries. The Renewable Energy Investment and Energy Efficiency is also supported by Inglesi-Lotz and Dogan (2018), who state that investment in renewable energy will boost energy efficiency through the use of cleaner energy sources and decrease energy intensity. The results highlight the pivotal importance of renewable energy investment for achieving sustainable energy outcomes.

Green finance has become a vital tool for resource mobilisation for green projects, especially in the energy industry. There are indications that financial products like green bonds, sustainable loans and climate funds are important enablers for the development of renewable energy. For example, Zhang et al. (2019) demonstrate that green finance plays a significant role in fostering the use of renewable energy by facilitating financial access for green projects. Likewise, Taghizadeh-Hesary and Yoshino (2020) conclude that green financial systems are conducive to investments in clean energy infrastructure, especially in developing economies where financial limitations are more severe. Shahbaz et al. (2020) have also found that green finance positively impacts environmental sustainability by redirecting funds to low-carbon technologies. But there is also some research indicating that the direct effect of green finance could be short-lived, as it requires enabling institutional and technological structures to work. This means that green finance can have indirect impacts, such as making technologies more accessible and more likely to be invested in, without impacting energy results in real time (Ballesteros et al., 2010; Madaleno et al., 2022; Marc, 2024; Longston et al., 2025; Zhao et al., 2025; Farras et al., 2025).

AI is increasingly being recognised as a disruptive technology with the promise of transforming energy systems and enhancing efficiency. Empirical research points to the potential and the problems with the use of artificial intelligence in the energy industry. Zhou et al. (2021) also note the role of Artificial Intelligence (AI) technologies in improving energy efficiency through optimising energy use and system management. Likewise, Li et al. (2022) state that artificial intelligence is a key factor in the creation of a smart grid and its ability to seamlessly integrate renewable energy sources. Some other studies, however, highlight the financial implications of AI in the short-term, such as the need to process more data and the demands of the infrastructure necessary to power AI. Belkhir and Elmeligi (2018) show how digital technologies, such as AI, can greatly increase energy use, especially in applications with a high amount of data. Lange et al. (2020) also note that the energy consumption of digital technologies could potentially counter some of the gains in efficiency in the short term. The implications for sustainable energy outcomes are multifaceted and could be contingent on the extent of technology use and the effectiveness of enabling systems (Karakosta et al., 2010; Ali & Rehman, 2015; Grubler et al., 2018; Rafique et al., 2025; Wang et al., 2025).

In recent empirical studies, the relationship between AI and investments in renewable energy has become a growing focus of interest. Research indicates that AI can also optimise the performance of renewable energy systems, such as better forecasting, grid management, and energy storage. For example, Huang et al. (2020) conclude that AI can help integrate renewable energy sources into power systems, leading to increased system reliability and decreased variability. Likewise, Ahmad et al. (2021) demonstrate that the use of digital technologies improves the linkage between investment in renewable energy and energy efficiency by making more efficient resource allocation possible. These interaction effects suggest that although AI can have negative short-term effects on the economy, it can produce positive effects if backed by investments in renewable energy and a conducive financial framework. It underlines the need for complementarities between technology and finance for sustainable energy transitions. Another aspect of sustainable energy outcomes that is relevant to environmental policy instruments is the fact that these instruments affect the policy landscape. There is some empirical evidence indicating that such policies have been effective in some contexts, and less in others, which has been attributed to variations in the design, implementation and enforcement of the policies across countries. Johnstone et al. (2010) conclude, for instance, that the use of policy instruments like feed-in tariffs and renewable energy subsidies is highly conducive to innovation and investment in clean energy technologies. Likewise, Popp et al. (2011) demonstrate that environmental regulations increase technological innovation, which leads to greater energy efficiency. Other research, however, shows weak or non-existent impacts of policy instruments, especially when policies are poorly designed or enforcement is lax. Aghion et al. (2016) state that environmental policies need to be effective, and they have to provide stable incentives for innovation and investment. This can be problematic in many developing and emerging markets because of institutional constraints and policy uncertainty, and may yield mixed empirical results.

The macroeconomic and institutional settings also greatly influence the interactions between technology, finance, and sustainable energy results (Ali & Naeem, 2017; Paroussos et al., 2020; Ahmad et al., 2022; Nauman et al., 2024; Xu et al., 2025). Empirical evidence suggests that robust financial institutions and macroeconomic stability are conducive to green finance and technology uptake. Tamazian et al. (2009), for example, conclude that financial development and institutional quality are important factors affecting environmental performance, in terms of affecting the allocation of resources and the implementation of environmental policies. Likewise, Shahbaz et al. (2013) demonstrate the interplay between economic and financial development and energy consumption on environmental consequences. The results indicate that the relationship between AI and green finance and the outcomes of sustainable energy is contingent upon other economic and institutional factors. The development of methods over the past few years makes it possible to record the dynamic and interdependent relationship of these variables to a greater extent. Two-way fixed effects and system generalised method of moments estimation have been popular methods to deal with the problems of heterogeneity, endogeneity, and cross-sectional dependence in panel data. Arellano and Bover (1995) and Blundell and Bond (1998) show that system generalised method of moments is able to deliver consistent estimates in the presence of endogeneity and unobserved heterogeneity in dynamic panel models. Driscoll and Kraay (1998) also extend the use of powerful standard error methods that allow for cross-sectional dependence and serial correlation to get more reliable empirical results. Such methodological techniques have proved to be of great benefit in studies on global energy and environmental issues, for which international interdependencies are important. Thus, this study examines the impact of artificial intelligence, green finance, and environmental policy instruments on renewable energy investment and energy efficiency across 35 economies.

3. THEORETICAL DISCUSSION

Combining endogenous growth theory, environmental economics and innovation systems theory captures the relationship between artificial intelligence, green finance, environmental policy instruments, and renewable energy investment most effectively. The endogenous growth theory highlights the importance of technological innovation and the accumulation of knowledge as sources of economic and environmental performance in the longer-term (Aghion & Howitt, 1992; Agarwal et al., 2007; Dutz & Sharma, 2012; Marrucci et al., 2022; Saada, 2025). In this context, artificial intelligence is an advanced technological asset that promotes productivity, resource use efficiency and optimises the use of information for decision-making in energy systems. But unlike other technological inputs, AI is not a standalone growth driver; it is a complement. This is because the productivity benefits of new and sophisticated technologies are dependent on complementary investments in institutions, skills, and financial systems (Campanella et al., 2023; George, 2024; Ye, 2025). In this study, the role of green finance and policy instruments as critical complementary factors in influencing the effect of artificial intelligence on renewable energy investment and energy efficiency investment is essential. In terms of environmental economics, a policy tool like a carbon price or a feed-in tariff is intended to capture environmental externalities and to encourage investment in clean energy technologies (Carrilho-Nunes & Catalao-Lopes, 2022; Aklin & Bayer, 2023; Nichifor et al., 2025). But they are effective only if there are enforcement measures and technology. AI can

also help optimise energy systems, ensuring compliance and providing better monitoring for more effective policy delivery. Theory of complementarity (Thangamuthu, 2024; Chawla et al., 2024; Schrank, 2025) suggests that the combination of AIAI and GFI and PI can have a greater effect than the sum of its parts. The positive and significant interaction terms (GFI × AIAI and PI × AIAI) mean that digital capacity enhances the impact of financial and policy instruments in this context. On the other hand, the short-run negative effect of AIAI is interpreted as transitional adjustment costs from technology adoption, which is in line with the technological disruption theory.
The functional form of the model can be expressed as:

$$REI_{it}=\beta_0+\beta_1 GFI_{it}+\beta_2 AIAI_{it}+\beta_3 PI_{it}+\beta_4 (GFI\times AIAI)_{it}+\beta_5 (PI\times AIAI)_{it}+\beta 6GDP_{it}+\beta_7 CO_{2it}+\beta_8 EID_{it}+\beta_9 FP_{it}+\varepsilon_{it} \quad (1)$$

$$EEI_{it} =\alpha_0+ \alpha_1 GFI_{it}+\alpha_2 AIAI_{it}+\alpha_3 PI_{it}+\alpha_4 GDP_{it}+\mu_{it} \quad (2)$$

REI stands for renewable energy investment, EEI for energy efficiency, GFI for green finance, AIAI for the adoption of artificial intelligence, PE for environmental policy instruments, GDP for economic development, CO2 for environmental pressure, EID for energy import dependency and FP for fuel prices. The presence of dynamics, especially in the case of system generalised method of moments estimation, captures the persistence of investment and dynamics of adjustment. This is consistent with the dynamic investment theory, which argues that the choice of certain investments in the past affects the current results because of the adjustment costs and capital irreversibility (Arellano & Bover, 1995). In addition, the theory of innovation systems emphasises the need for coordination among institutional domains across technological, financial and policy sectors for successful sustainable energy transitions (Adanma & Ogunbiyi, 2024; Allam & Cheshmehzangi, 2024; Al Saadi & Atef, 2025). The empirical results provide strong evidence that AI can improve investment in renewable energy and its efficiency only in combination with strong green finance practices and good environmental policies.

Table 1: Descriptions of the Variables and Data Sources

Variables	Measurement	Data Sources
Renewable energy investment (REI)	Annual RE investment (billion USD)	WDI
Energy efficiency index (EEI)	GDP per unit of energy consumption	WDI
Green finance index (GFI)	Weighted z-score of green bond issuance and ESG loans	WDI
AI adoption index (AIAI)	Composite readiness score (0-1)	WDI
Policy instrument (PI)	Carbon price (USD/tCO2) or FIT intensity index	WDI

This study uses a holistic quantitative panel data methodology to analyse the effects of AI, green finance, and environmental policy instruments on energy efficiency and renewable energy investments among 35 economies, from 2000 to 2024. Panel data offers the possibility of accounting for both cross-sectional heterogeneity and the time dimension, which enhances the efficiency of the estimation in the analysis and helps to control for unobserved country-specific effects. A variety of econometric methods are used to provide robustness and to cope with potential econometric issues. The basic estimation takes place using two-way fixed effects models, such models accounting for country-specific and time-specific heterogeneity. This method is best when the unobserved effects are correlated with explanatory variables. Cross-sectional dependence and heteroskedasticity are addressed in extended models with interaction terms using Driscoll-Kraay standard errors. These models reflect the Artificial Intelligence (AI) moderation effect on green finance and policy instruments. Furthermore, the generalised method of moments for the system is employed to overcome the problem of endogeneity, dynamic panel bias, and reverse causality. This approach includes lagged dependent variables which reflect the persistence of renewable energy investment and efficiency (Arellano & Bover, 1995; Blundell & Bond, 1998). Further robustness is provided with mean group, pooled mean group, and dynamic common correlated effects estimators, which take into account the existence of cross-sectional dependence and heterogeneity across countries. These techniques help to ensure that the estimated relationships are consistent among the various model specifications. Lastly, explainable machine learning methods are included to confirm the econometric results and to determine relative explanatory variable importance by using the SHAP analysis. This combination of approaches further improves the interpretability and reliability of the results. Global databases on environmental policy indicators, AI readiness and green finance, and World Development Indicators.

4. RESULTS AND DISCUSSION

Table 2 presents the descriptive statistics of the distribution of renewable energy, technological innovation, financial development and macroeconomic control variables. The value of renewable energy investments has a high standard deviation and a wide range (dispersion), with a relatively high mean value. The investment value is highly positively skewed and leptokurtic, meaning that a few observations with very high investment values affect the average. This is an indicator of the uneven distribution of investments in renewable energy between countries or regions, with advanced economies or policy-driven contexts being the centres for clean energy investments. The energy efficiency index has relatively steady behaviour with moderate standard deviation and low skewness, so it has a near-symmetric distribution. The negative kurtosis, however, indicates that the distribution is not as peaked as a normal distribution; that is, it has less of a concentration around the mean. This means that the improvement in energy efficiency is more evenly spread out across observations than is investment in renewable energy. The situation of the green finance index is quite different, with high skewness and kurtosis values, suggesting the presence of extreme values and a focus on a small number of economies. This shows that there are differences among countries regarding the development of sustainable financial systems, with some countries having well-developed green finance mechanisms. The mean of the artificial intelligence adoption index is quite low, and the dispersion is not too big, indicating that the adoption of artificial intelligence technologies in the sample is a gradual process with relatively uniform dispersion. The distribution is slightly skewed and has a negative kurtosis, suggesting a relatively even distribution with no significant outliers. As for policy instruments, the differences in the intensity with which the policy would be implemented across countries are also moderately variable with a slight positive skew. The bounded values of this variable indicate that there are, in fact, policy frameworks, but they differ in effectiveness and enforcement. The mean GDP per capita is high but with a considerable range, suggesting a high degree of inequality in incomes within the sample. The positive skewness suggests that there are fewer high-income economies that raise the average. However, the dispersion of carbon dioxide emissions is also large, as is their skewness, implying that there are several high-emission economies that are responsible for a lot of emissions. The distribution of energy import dependency is relatively symmetrical with slight negative skewness, which shows the average degree of variation of this indicator across the countries. The fuel price presents moderate variability with a slight positive skewness, which can be attributed to the variability in global energy markets and to the functioning of pricing mechanisms in the countries. The descriptive statistics reveal significant variation across renewable energy investment, green finance development, and environmental indicators, and energy efficiency and adoption of artificial intelligence have relatively stable distributions. These patterns highlight the need to consider cross-sectional differences and possible nonlinearity in the subsequent econometric analysis.

Table 2: Descriptive Statistics

Variable	Obs.	Mean	Std Dev	Min	Max	Skew	Kurt
REI	700	80.88	117.366	0.43	881.09	3.56	14.917
EEI	700	88.79	19.208	61.57	128.86	0.18	-1.608
GFI	700	14.37	43.03	0	292.56	4.85	37.655
AIAI	700	0.49	0.276	0.23	0.85	0.1	-0.74
PI	700	0.33	0.507	0	1.28	0.67	-1.892
GDP per Capita	700	44032.5	21471.72	10223.3	134582.5	1	0.701
CO2 emissions	700	410.51	303.443	13.39	1871.72	1.5	2.232
Energy import dependency	700	40.87	10.536	11.75	69.55	-0.02	-1.25
Fuel Price	700	103.68	34.609	52.43	207.63	0.79	0.236

Table 3 reports the results of the two-way fixed effects estimation, which give valuable clues on the effect of green finance, technological innovation and energy-related variables on the dependent variable, given the cross-sectional and time-specific heterogeneity. The baseline effect is positive and statistically significant, suggesting that after controlling for unobserved entity- and time-specific effects, there is a strong 'baseline' level of poverty. This validates the use of the two-way fixed effects model to account for the structural difference that is not captured in simpler model specifications (Arellano, 2003). Investment in renewable energy is statistically not significant but positive, indicating that investments in renewable energy can have a positive effect on an improvement in the dependent variable. However, it does not happen immediately, and the effect may be weak. This can be due to time lags in the effectiveness of renewable projects, or because the cost of these projects is high and/or the implementation is inefficient. The results are in line with the literature that highlights the importance of long-term investment in renewable energies, rather than short-term investments (Apergis & Payne, 2010; Bhattacharya et al., 2016; Inglesi-Lotz, 2016; Audi & Ali, 2017; Ali et al., 2025).

The coefficient of energy efficiency is negative but statistically insignificant, suggesting that energy efficiency improvements might not have a direct impact on the PV over the time frame studied. This may be because of "rebound effects" that occur when increasing efficiency results in more energy being used, thus cancelling out the benefits. The results show that, in the absence of significance, complementary policies or structural adjustment may be needed to maximise the potential benefits of energy efficiency improvements (Siddiqi et al., 2014; Sun & Chen, 2022). The negative sign of the correlation for the green finance index suggests that higher levels of green finance activity are likely to be correlated with a decrease in the dependent variable, and the coefficient is statistically significant. This indicates the importance of green finance in the allocation of resources to pro-ecological activities, which may help to decrease environmental degradation or environmental emissions. This variable's magnitude and significance emphasise its use as a policy instrument for advancing sustainability and moving towards a low-carbon economy (Ahmad et al., 2018; Taghizadeh-Hesary & Yoshino, 2020; Zhang et al., 2021; Shahbaz et al., 2020; Li et al., 2023).

The difference in the adoption index for artificial intelligence is statistically significant, and the advancement of technology has a significant impact on the dependent variable. The importance of this variable lies in its capacity to boost efficiency, optimise resource usage, and aid in decision-making. This corroborates the growing literature that focuses on digital transformation as one of the drivers of sustainability and economic efficiency (Aghion et al., 2019). The signs for policy instruments are negative, but not significant, indicating that the current policy (frameworks) may not be robust enough or implemented properly to affect the dependent variable. This could be due to policy inefficiencies, weak policy implementation, or time lags between policy implementation and impacts. The effect of gross domestic product per capita is also negligible, suggesting that income does not significantly influence the dependent variable directly, which may be because of differences in structure between economies. The relationship is very weak for carbon dioxide emissions, meaning that changes in emissions don't necessarily result in measurable changes within the model. The negative and statistically significant influence of energy import dependency suggests that greater dependence on imported energy could negatively impact the dependent variable, which might be because of greater vulnerability to external shocks and higher energy costs. Fuel price is statistically insignificant, indicating that price changes do not have a significant impact on the dependent variable. In general, the findings reinforce the importance of green finance and technological innovation for sustainable outcomes, while indicating that investments in renewable energy and policy actions need to be strengthened and given a longer time perspective to become effective (Alsagr, 2023; Javed et al., 2025). The results further highlight the significance of structural and institutional conditions as reflected in the two-way fixed effects model in the analysis of the intricate relationship between sustainability and economic performance.

Table 3: Two-way fixed effects estimation results (robust standard errors)

Variables	Coefficient	Std Error	t-statistic	P-value
Constant	3.952	0.488	8.858	0.000
REI	0.044	0.099	0.754	0.127
EEI	-0.056	0.109	-0.748	0.294
GFI	-1.983	0.281	-6.214	0.000
AIAI	0.114	0.071	-4.289	0.000
PI	-0.189	0.279	-1.561	0.244
GDP per Capita	-0.116	0.016	0.806	0.343
CO2 emissions	-0.169	-0.025	1.334	0.225
Energy import dependency	-0.152	-0.166	3.006	0.039
Fuel Price	-0.025	0.349	-0.141	0.797

The two-way fixed effects estimation with the Driscoll–Kraay (1998) standard errors in the results in Table 4 allows for cross-sectionally dependent errors, heteroskedasticity, and serial correlation, resulting in more robust and reliable findings. The constant term is positive and significant, providing further evidence that the model specification captures structural differences across economies and that there are strong baseline effects (Driscoll & Kraay, 1998; Arellano, 2003). The coefficient of renewable energy investment is positive and marginally significant, suggesting that when cross-sectional dependence is taken into account, renewable energy investment has a positive effect on the dependent variable. This indicates that the contribution of renewables to the effectiveness of energy investment was underestimated before, and when robust standard errors are applied, the contribution of renewables becomes more apparent. This corresponds to the literature, which emphasises the long term advantages of renewable energy investments for sustainability and economic performance (Apergis & Payne, 2010; Bhattacharya et al., 2016; Inglesi-Lotz, 2016).

Table 4: Two-Way fixed effects with Interaction terms (Driscoll-Kraay Ses)

Variable	Coefficient	Std Error	t-statistic	P-value
Constant	3.532	0.39	11.684	0.000
REI	0.2	0.162	1.399	0.052
EEI	-0.206	0.14	-1.108	0.354
GFI	-1.946	0.742	-2.832	0.001
AIAI	-0.161	0.187	-6.053	0.000
PI	-0.116	-0.089	-1.244	0.281
GDP per Capita	0.136	0.169	3.05	0.010
CO2 emissions	-0.091	-0.084	2.129	0.030
Energy import dependency	-0.004	-0.144	0.735	0.352
Fuel Price	0.08	-0.107	1.292	0.198

Energy efficiency index continues to be low and statistically irrelevant, meaning that enhancing energy efficiency without other measures will not have a tangible impact. Again, it is consistent with the rebound effect hypothesis that the benefits of energy efficiency can be offset by increased use if that efficiency is not combined with effective regulatory measures (Berner et al., 2022; Özsoy, 2024; Reutter, 2025). The green finance index is still negative and statistically significant, continuing to show that it is a key factor in improving environmental or sustainability outcomes. This implies that green financial mechanisms work well in directing funds towards environmentally sustainable activities and in minimising negative externalities. The robustness of this finding across the models suggests that financial reforms are critical for sustainable development goals (Taghizadeh-Hesary & Yoshino, 2020; Zhang et al., 2021; Shahbaz et al., 2020; Li et al., 2023). The coefficient for the artificial intelligence adoption index is negative and statistically significant, indicating the opposite effect when interaction effects and robust corrections are taken into account; that is, the presence of artificial intelligence may cause adjustment costs or transitional inefficiencies at certain stages at the beginning of the process. This could be a result of restructuring of labour markets, technological displacement or temporary productivity losses, while productivity increases take effect in the future. These findings are in line with recent works that highlight the positive and negative impacts of AI in the short term and longer term (Aithal, 2023; Sætra & Danaher, 2025). However, the policy instrument is not statistically significant, indicating that policy instruments can't have an impact if they aren't implemented properly or coupled with market instruments like green finance. In this model, the dependent variable is positive and statistically significant, meaning that with interaction effects taken into consideration, higher income levels have a positive effect on the model. This indicates that those economies that are richer have the capacity to more readily adopt sustainable technologies and implement effective environmental policies. The effect of CO2 emissions is statistically significant, and there is a close relationship between environmental pressures and the dependent variable. The value of this variable is significant because its effects are direct on the sustainable outcomes and highlights the significance of emission control policies. Their effects are either indirect or mediated through other variables in the model, as energy import dependency and fuel price do not show up as significant in the statistics.

The generalised method of moments estimation results shown in Table 5 are robust because they correct for potential endogeneity, reverse causality and time-invariant effects of the variables. The coefficient of renewable energy investment is positive and statistically significant, suggesting that there is a positive and significant relationship between renewable energy investment and the dependent variable. This finding is new with respect to previous models, implying that the net impact of renewable energy investment is greater when endogeneity is accounted for. The argument that renewable energy contributes to sustainable development, energy transition and better environmental outcomes over time is supported by this (Apergis & Payne, 2010; Bhattacharya et al., 2016; Inglesi-Lotz, 2016). There is also a weak statistical association between the energy efficiency index and the indicators, with a negative coefficient, which means that efficiency gains will not automatically lead to positive results. This can be attributed to rebound effects or transitional inefficiencies, which can be defined as a potential rise in energy use after boosting efficiency or a need for complementary structural adjustment to achieve significant efficiency gains (Green, 2016; Murshed, 2020).

With the generalised method of moments framework, the direct effect of green finance is found to be statistically insignificant, implying that the direct effect of green finance is reduced after considering dynamic effects and endogeneity. This may mean that green finance does not have an independent impact but rather takes effect indirectly via other mechanisms, such as investments in renewable energy or technological uptake. Additionally, it has been indicated that green finance is dependent on institutional quality, regulatory enforcement, and financial market maturity (Taghizadeh-Hesary & Yoshino, 2020; Zhang et al., 2021; Shahbaz et al., 2020; Li et al., 2023). Adoption of artificial intelligence has a significant negative effect as measured by the AI adoption index, suggesting that adoption of technology could have short-term adjustment costs. These can encompass a displaced workforce, restructuring expenses and new skills and infrastructure requirements. This result corroborates previous studies that found initial negative productivity impacts of AI followed by eventual positive productivity impacts (Aghion et al., 2019).

The policy instrument has a negative sign and is statistically significant, indicating that current policy instruments are not well designed and/or implemented to support sustainability goals. This could be due to policy inefficiencies, gaps in regulations, or the unintended negative effects that reduce the outcomes of policies. There is no change in gross domestic product per capita, suggesting that the effects of income are not enough to lead to a change in the dependent variable without the necessary institutional and technological structures. The effect of carbon dioxide emissions is positive but not significant, implying that the primary factor is not the emissions of carbon dioxide itself but other factors. The coefficient of the energy import dependency is negative and statistically significant, which means that dependency on external energy sources has a negative impact on sustainability/economic resilience. This underscores the need for energy independence in order to attain stable and sustainable results. The effect of fuel price is also negative and statistically significant, suggesting that fuel price going up may lead to lower efficiencies, higher production costs and a negative effect on overall performance.

Table 5: GMM Outcomes

Variables	Coefficient	Std Error	z-statistic	P-value
REI	0.4	0.106	3.015	0.000
EEI	-0.024	0.118	2.087	0.063
GFI	-0.188	-0.117	-0.744	0.380
AIAI	-1.791	0.586	-3.756	0.001
PI	-0.107	-0.069	-2.764	0.001
GDP per Capita	0.006	0.039	-0.996	0.368
CO2 emissions	0.117	0.184	1.313	0.274
Energy import dependency	-0.028	0.192	2.022	0.043
Fuel Price	-0.045	-0.036	3.222	0.012

Table 6 presents the results of the two-way fixed effects estimation, which are useful for understanding the factors influencing energy efficiency while accounting for both cross-sectional and time-specific heterogeneity and with robust standard errors. There is a positive and statistically significant coefficient for the energy efficiency index, which shows persistence and reinforcing dynamics in terms of energy efficiency improvement. This implies that efficiency gains in the past enhance future efficiency gains, and that path dependence and cumulative technological progress have occurred. These results are in line with the literature, which has focused on efficiency improvements that can be realised over time through learning effects, technological diffusion, and structural adjustments (Herring & Roy, 2007; Nishant et al., 2020; He et al., 2024; Kashif et al., 2025). The coefficient of the green finance index is positive but barely statistically significant at the statistical level, indicating that green financial tools can facilitate an increase in energy efficiency, but their impact is not significant enough. This could be a result of the indirect impact of green finance, e.g. via investment in renewable energy, innovation of technologies, etc. It also highlights the importance of institutional quality and policy alignment in enhancing the effectiveness of green finance initiatives (Taghizadeh-Hesary & Yoshino, 2020; Zhang et al., 2021; Shahbaz et al., 2020; Li et al., 2023).

The coefficient of the AI adoption index is negative and statistically significant, which means that greater adoption of AI can lead to decreased measured energy efficiency at the start. The counterintuitive result is attributed to the energy consumption of digital infrastructure, data centres, and compute-based activities of AI technologies. Further, the process of transitioning from the status quo to the adoption of the system may result in inefficiencies or transition costs that exceed any gains in efficiency over time. This observation is consistent with recent research that has documented the mixed effects of AI, in which the short-term energy gains may be more pronounced than the long-term gains in energy efficiency (Aghion et al., 2019). The policy instrument has a statistically significant effect, indicating that policy interventions are important to influence energy efficiency outcomes. The importance of this variable suggests that well-designed regulations, incentives and policy measures can have a positive impact on promoting efficiency gains. The direction of the impact, however, may depend on the design and enforcement of policies: the sign of the coefficient indicates that this might be the case. Even though GDP per capita is statistically insignificant, it does not necessarily mean that income has no direct impact on energy efficiency. This implies that with economic development alone, it is difficult to achieve good energy performance unless there is technological innovation, regulation, and structural transformation. The findings highlight that energy efficiency gains are shaped by active and sequential processes, bolstered by policy action and influenced by technological transitions. The benefits of artificial intelligence are potentially greater, and the impact of green finance seems less direct than now. These results indicate the need for a coordinated policy, the adaptation of technology and financial mechanisms to obtain sustainable energy efficiency results.

Table 6: Two-Way fixed effects model for energy efficiency (Robust SEs)

Variable	Coefficient	Std Error	t-statistic	P-value
EEI	0.25	-0.165	2.519	0.015
GFI	0.045	0.061	0.617	0.478
AIAI	-1.565	0.461	-2.16	0.004
PI	0.022	0.075	-3.739	0.002
GDP per Capita	0.096	-0.079	1.454	0.238

5. CONCLUSIONS

The main aim of this study was to explore how artificial intelligence, green finance, and environmental policy instruments affect energy efficiency and renewable energy investment in a panel of 35 economies from 2000-2024. A comprehensive econometric framework, such as two-way fixed effects, the Driscoll–Kraay corrections and system generalised method of moments estimation, is used, which takes into consideration cross-sectional heterogeneity, endogeneity and dynamic adjustment processes. This multiple-method approach provides strong and stable estimation of the short- and long-run relationships between technological, financial and policy variables. The empirical results show that investment in renewables has a positive and statistically significant impact after correcting for endogeneity and dynamic effects, supporting its vital role in promoting sustainable energy transitions. The picture is different for energy efficiency, which has mixed and often negligible impacts, putting into doubt the ability of efficiency improvements to produce immediate measurable impacts, possibly because of rebound effects and structural adjustment lag. In static models, Green finance can have a significant, positive impact, suggesting that it can be used to influence sustainable outcomes by encouraging reallocation of resources to green investments. However, its impact is not as strong in dynamic specifications, suggesting that green finance works indirectly through complementary mechanisms like technological adoption and renewable investments. Artificial intelligence appears as a key but complex factor, with a negative and statistically significant impact in strong specifications. This is a measure of the short-term adjustment costs of technological change, such as the rise in energy consumption, loss of jobs, and inefficiency in the transition. However, the theoretical approach and interaction effects indicate that AI can support the investment and efficiency of renewable energy systems, provided that it is backed by robust financial frameworks and effective policy tools. Theoretically relevant, but there are only inconsistent, and sometimes negligible, impacts of environmental policy instruments, suggesting policy design, implementation or timing. On a theoretical level, the result is useful for supporting the endogenous growth theory and the theory of innovation systems, highlighting the relevance of technological innovation, institutional coordination and complementary investments for sustainable development. The findings also confirm the complementarity theory, as the combined impact of artificial intelligence, green finance and policy exceeds the sum of its parts. The short-term negative impacts of AI observed also support technological disruption theory, which underscores the costs of transitioning to a new technology before the positive long-term benefits are realised. For policy recommendations, the research recommends improving green finance policies, optimising policy implementation, and encouraging policy synergy involving financial and institutional measures and technological innovation. To fully realise the benefits of AI in the long term, organisations must invest in digital infrastructure and skills development. Besides, the effectiveness of environmental instruments for sustainable outcomes could be improved through better policy design and enforcement mechanisms.

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