


“Does a country’s energy security increase with advances in government AI readiness? An empirical panel study”

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DOES A COUNTRY'S ENERGY SECURITY INCREASE WITH ADVANCES IN GOVERNMENT AI READINESS? AN EMPIRICAL PANEL STUDY

Abstract

Recent assessments by the IEA, IRENA, and the World Bank indicate that data- and algorithm-driven operations can enhance energy security by increasing efficiency, reducing curtailment, and stabilizing grids as the renewable share grows, while also warning of ecological trade-offs from rising digital electricity use. Against this backdrop, government AI readiness emerges as a crucial enabling condition, providing the institutional and technological capacity to translate climate and sustainability targets into day-to-day energy system performance. Framed through an environmental lens, the study examines whether government AI readiness acts as an ecological enabler that strengthens energy security by supporting the integration of renewable energy, reducing emissions, and enhancing system resilience. To test this ecological proposition, we assemble a balanced panel of 125 countries (2020–2023), combining the Oxford Insights Government AI Readiness Index with the World Energy Council's Energy Security Score as an operational proxy for environmentally robust energy systems. Using panel methods (fixed and random effects), with diagnostics for serial correlation, cross-sectional dependence, and heteroskedasticity, and Driscoll-Kraay standard errors for robust inference, we find that in the random-effects specification, a one-point rise in AI readiness is associated with a 0.1104-point improvement in the energy security score ($p < 0.001$). The effect remains statistically significant after accounting for temporal and cross-sectional dependencies, supporting the view that institutional preparedness to use AI can act as an enabling ecological instrument, facilitating the integration of renewable energy, demand-side efficiency, and system resilience, which together underpin cleaner, more secure energy.

Keywords

energy security, artificial intelligence, government AI readiness index, panel data analysis, policy implications, strategic management

JEL Classification

Q01, Q41, Q48, O33

INTRODUCTION

The rapid expansion of data increasingly shapes energy security in modern power systems- and AI-driven infrastructures, which simultaneously reinforce and strain existing grids. According to the International Energy Agency, data centers currently consume approximately 415 TWh of electricity, or around 1.5% of global demand, with consumption projected to more than double to 945 TWh by 2030 under the Base Case scenario (IEA, 2025). AI-intensive data centers are expected to quadruple their electricity use, raising the risk of local capacity constraints and network congestion, particularly in already vulnerable or infrastructure-constrained regions (Crellin, 2025). At the same time, the IEA indicates that the broader deployment of existing AI solutions can strengthen energy security by improving system efficiency and operational reliability, with potential emissions reduc-

tions equivalent to approximately 5% of energy-related CO₂ emissions by 2035 through more intelligent forecasting, dispatch, and grid management (IEA, 2025).

In parallel, IRENA (2025) highlights the role of AI in strengthening energy security by enhancing the integration of variable renewable energy sources. AI and digital tools are described as “crucial for running renewable energy grids,” helping to manage intermittency in solar and wind energy. In contrast, deployment of AI across energy systems is estimated to raise the renewable share by 10–15%, thereby accelerating low-carbon transitions and reducing exposure to fossil-fuel price and supply shocks (AI Tech Daily, 2024). The World Bank introduces a governance and equity dimension, emphasizing that robust digital infrastructure and ethical oversight are essential prerequisites for harnessing AI’s developmental and ecological potential in energy management, particularly in emerging economies (World Bank, 2025). Through its Digital Transformation programs, it supports countries in building inclusive and secure digital foundations, which are critical for adopting AI systems that simultaneously enhance efficiency, resilience, and environmental performance (World Bank, n.d.).

These perspectives underscore a central policy challenge for energy security in an ecological era: AI’s growing electricity footprint and system dependencies coexist with its capacity to stabilize grids, enable higher renewable penetration, and reduce emissions. As AI adoption accelerates, the key question is no longer whether to use AI in energy systems, but how governments can align AI readiness (understood as institutional, infrastructural, and governance capacity) with sustainable energy strategies. In this context, government readiness for artificial intelligence should be viewed not merely as a technological benchmark but as a potential component of the broader architecture of energy security, shaping how states anticipate, absorb, and adapt to shocks in increasingly digitalized energy systems. Clarifying how AI-related institutional capacities interact with the multidimensional concept of energy security thus becomes essential for rethinking security strategies in an era of rapid digital and ecological transition.

1. LITERATURE REVIEW

The renewable energy transition itself is increasingly framed as both an ecological necessity and a security strategy. Evidence from EU countries suggests that the expansion of renewable energy sources enhances energy security by diversifying supply, reducing import dependence, and mitigating exposure to geopolitical shocks (Kuzior et al., 2025). Clean energy projects are also used as instruments of European integration and regional cooperation, embedding energy security objectives in broader political and economic frameworks (Vakulenko & Rekunen, 2025). Entrepreneurial ecosystems in renewable and digital energy, supported by targeted finance, risk-sharing arrangements, and investor protection, help to diffuse innovative solutions that enhance both environmental performance and system reliability (Dobrovolska et al., 2024; Artyukhov et al., 2024). Favorable tax regimes and simplified compliance procedures further stimulate the development of clean and digital energy start-ups, amplifying the contribution of

technological innovation to sustainable energy and security goals (Halynskyi et al., 2024).

Growing evidence positions artificial intelligence as a key enabler of low-carbon, resilient energy systems, while also highlighting it as a new source of ecological pressure and systemic risk. AI applications in forecasting, optimization, and control are already deployed across the sustainable energy sector, improving unit commitment, load scheduling, and fault detection, and thereby increasing efficiency, reducing emissions, and facilitating the integration of variable renewables (Ahmad et al., 2021; Khan et al., 2024; Liu et al., 2023). Smart building controls and occupant-centric systems enhance reliability, flexibility, and resilience on the demand side, further reinforcing energy security when grids accommodate high shares of renewables (Liu et al., 2023; Hrytsenko et al., 2024). At the system level, AI-enhanced coordination in global supply chains and logistics management can reduce disruptions, lower exposure to fossil fuel price spikes, and support more robust energy security outcomes (Wang et al., 2025).

Energy security is increasingly understood as a multidimensional outcome shaped by market design, infrastructure, governance, and geopolitical conditions. Policy interventions in gas storage and cross-border flows, such as the German gas storage levy, demonstrate how regulatory choices impact price stability, regional integration, and supply security within the context of the energy transition (Hudak et al., 2025). Microgrid energy management strategies that combine electric vehicles, storage, and AI-based optimization show strong potential to improve local reliability, reduce emissions, and increase the resilience of energy systems to shocks (Khan et al., 2024). Blockchain and AI are also proposed as complementary tools to enhance transparency, decentralized control, and efficiency in energy management, thereby contributing to both energy efficiency and trust in new market arrangements (Kuzior et al., 2022). Broader geopolitical dynamics, such as multidomain strategic competition in the Indo-Pacific, underscore the importance of energy security, emphasizing the value of technologies and governance arrangements that mitigate vulnerability to external pressure (Ahmed, 2025). Recent research further emphasizes that energy security is a multidimensional construct shaped by the interplay of economic, environmental, and governance factors, best captured by composite indicators and integrated evaluation frameworks (Mentel et al., 2020). Sustainable governance arrangements have been shown to reduce energy losses and strengthen energy security in Europe, particularly under turbulent geopolitical and market conditions (Wołowiec et al., 2022), while the war in Ukraine has acted as a critical catalyst, accelerating the shift from energy dependency to renewable-based energy security across European countries (Vasylieva et al., 2025).

AI-enabled digitalization is also reshaping traditional, carbon-intensive sectors, with ambivalent implications for ecology and security. In the petrochemical industry, digital tools and automation enhance monitoring, process control, and resource efficiency, but also create new socio-economic challenges related to skills, employment, and regional disparities (Elmaghraby et al., 2025). Industrial automation using AI in municipal waste management is presented as a cornerstone of Industry 4.0 and the green transition, helping to close material

loops and reduce environmental burdens (Kajda & Karwot, 2025). At the same time, environmental tax reforms and pricing instruments remain crucial for aligning incentives, improving resource efficiency, and reinforcing the ecological benefits of technological change (Samusevych et al., 2024). High-quality institutions, characterized by sound regulation, policy stability, and effective enforcement, are shown to be central to reducing environmental degradation and ensuring that digital and AI innovations translate into genuine ecological benefits (Mukhtarov et al., 2024).

Within this landscape, government AI readiness emerges as a structural prerequisite for leveraging AI's ecological and security benefits in the energy sector. Public administrations equipped with digital infrastructure, data governance frameworks, and skilled personnel are better positioned to integrate AI into planning, regulation, and service delivery (Androniceanu, 2024; Barodi & Lalaoui, 2025). The capacity for change management and the readiness of civil servants to adopt AI determine whether digital transformation translates into improved control, monitoring, and coordination in sectors such as energy and environmental management (Barodi & Lalaoui, 2025; El Massaoudi et al., 2025). AI-based project management and performance analytics are increasingly used to optimize complex infrastructures and investment portfolios, underscoring the cross-sectoral nature of AI capabilities that can be redirected toward green energy and security goals (Ibadildin et al., 2025; Kozhakhmetova et al., 2024). Good governance, transparency, and bias-free decision-making, supported by AI-driven tools in recruitment and administrative processes, further strengthen institutional capacity to design and implement coherent sustainability and energy policies (Pollifroni et al., 2025; Sitnicki et al., 2024a).

Ecological and social safeguards are increasingly recognized as integral to legitimate and effective AI deployment in public policy. Ethical frameworks emphasize human dignity, social justice, and environmental stability as non-negotiable principles in the age of AI, seeking to ensure that digital tools reinforce rather than undermine sustainable development (Mura & Stehlíková, 2025; Haley, 2025). AI applications in law enforcement,

healthcare, and public security highlight both the possibilities of data-driven governance and the risks of discrimination, over-surveillance, and unequal access to benefits (Haley & Burrell, 2025; Sidii, 2024). Similar tensions are present in energy governance, where AI can enable more targeted interventions and efficient resource use, but may also concentrate power and create opaque dependencies. Public perceptions of AI as a source of fear, hope, or indifference shape the societal mandate for large-scale deployment, with implications for how far governments can push AI-enabled ecological and energy reforms (Yarovenko et al., 2024).

Digital security and cyber-resilience form another pillar of AI readiness with direct implications for energy security. The expansion of digital infrastructure and AI use has been linked to an increase in cybercrime risks, particularly in areas where socio-economic and institutional vulnerabilities remain unaddressed (Yarovenko et al., 2025). Machine learning and data-intensive techniques deployed on social media and other platforms create new privacy and security risks that require robust safeguards and user awareness (Wieczorek & Postrzednik-Lotko, 2025). The use of AI in occupational safety and health management, as well as in cyber insurance for agriculture and other sectors, demonstrates that risk modelling and prevention are becoming increasingly data-dependent and interconnected across domains (Zaryczańska & Karwot, 2025; Sitnicki et al., 2024b). In an energy context, insufficient cyber-resilience could compromise critical infrastructure, undermining both the ecological benefits of renewable integration and the reliability of supply.

AI-related capabilities are also diffusing through markets, firms, and societies, shaping the broader ecosystem within which governments operate. Studies of AI-driven solutions in customer support, feedback management, and marketing show that digital tools can reshape consumer expectations, increase responsiveness, and support pro-environmental choices, for example, through personalized communication and behavioral nudges (Glos & Karwot, 2025; Kildei et al., 2025; Lazaroiu & Rogalska, 2024). Emotion-based analyses of pro-environmental cam-

paigns and neurophysiological studies of advertising underscore the potential of AI-enhanced communication to increase energy awareness and encourage sustainable behaviors such as waste sorting or energy conservation (Lyeonov et al., 2025; Piwowarski, 2024). Organizational research highlights that AI can strengthen leadership for sustainability, build resilience, and improve employee engagement, all of which are important for implementing long-term ecological and energy strategies (Ayu Gusti et al., 2024; Koldovskiy et al., 2025).

Sector-specific experiences with AI in insurance, healthcare, construction, and knowledge-intensive industries further illustrate how general AI readiness is built and tested across the economy. AI-enabled pricing, risk assessment, and efficiency analysis in insurance demonstrate the feasibility of data-intensive regulation and governance in complex, uncertainty-laden environments (Chandran & Ittimani Tholath, 2025; S. Kumar & J. Kumar, 2024). Digitalization and AI in pharma research, healthcare management, and cybersecurity reveal how ethical and security considerations are being integrated into high-stakes decision-making, with potential lessons for energy system governance (Kritikos et al., 2025; Sidii, 2024; Wieczorek & Postrzednik-Lotko, 2025). AI-based image analysis and neural-network systems for predicting staff turnover demonstrate how data-driven tools can enhance risk management and workforce stability in sectors directly or indirectly linked to infrastructure development and maintenance (Zaryczańska & Karwot, 2025; Zakharchenko et al., 2025). These experiences contribute to a cumulative base of competencies and norms that form part of government AI readiness.

Finally, the literature on sustainable consumption, the circular economy, and the knowledge economy emphasizes that ecological and energy outcomes depend not only on technology but also on demand patterns, entrepreneurship, and regional development. Forecasts of sustainable consumption in small economies highlight the importance of anticipatory policy and modelling tools for aligning production and infrastructure with ecological constraints (Kontautienė et al., 2024). Analyses of twin transformation, digitali-

zation, and circular supply chains supported by AI and big data demonstrate that technology can simultaneously boost economic performance and environmental sustainability when embedded in coherent strategies (Waqas et al., 2025). Support for domestic entrepreneurship in the knowledge economy is shown to be vital for creating local capabilities and innovation capacity, including in sectors associated with the green and digital transitions (Sitnicki et al., 2024a).

The existing literature suggests that AI can enhance energy security primarily by enabling more efficient, flexible, and renewable-based energy systems, but only where robust institutional quality, ethical governance, cyber-resilience, and supportive policy frameworks are in place. Government AI readiness thus appears as a composite ecological and security capacity, reflecting not just technological adoption, but also the ability to steer AI toward decarbonization, resilience, and just transition objectives. What remains underexplored is the direct, systematic relationship between measurable government AI readiness and national energy security outcomes across countries, which the present study seeks to address empirically.

This study aims to assess whether government AI readiness acts as an ecological enabler, strengthening energy security by supporting the integration of renewable energy, reducing emissions, and enhancing system resilience.

This study posits the following hypothesis:

H1: Higher government AI readiness is positively associated with a country's energy security score.

The underlying premise is that governments demonstrating greater AI readiness possess enhanced institutional capacity to implement advanced technological solutions for optimizing energy generation, distribution, storage, and demand management. Such capabilities enhance the resilience of energy systems, reduce reliance on vulnerable supply chains, and improve the integration of renewable energy. Collectively, these factors are expected to contribute to higher levels of energy security.

2. METHODOLOGY

2.1. Data sources and variables

This study employs panel data constructed from two primary sources. The Government AI Readiness Index was obtained from the 2024 Government AI Readiness Index, published by Oxford Insights (Oxford Insights, n.d.). This index assesses national-level preparedness to harness the benefits of artificial intelligence across three pillars: government, technology sector, and data and infrastructure. The Energy Security Score was derived from the World Energy Council's Energy Trilemma Index Tool (WEC, n.d.), which evaluates energy systems across security, equity, and environmental sustainability.

The Government AI Readiness Index serves as the independent variable, while the Energy Security Score represents the dependent variable. The selection of these variables reflects the study's aim to explore whether higher levels of AI readiness at the governmental level are associated with improved energy security performance.

2.2. Sample selection and time frame

The analysis covers a balanced panel of 125 countries spanning the period from 2020 to 2023. The inclusion of countries and years is determined exclusively by the availability of data for both the Government AI Readiness Index and the Energy Security Score, which ensures consistency in the panel structure. This limitation in temporal and cross-sectional scope reflects the data coverage of the sources rather than a theoretical restriction. The complete list of countries included in the sample is provided in Appendix A.

2.3. Empirical strategy

Given the panel structure of the dataset, the study applies both fixed-effects (FE) and random-effects (RE) estimators using the *plm* package in R. The FE model is employed to control for unobserved, time-invariant country-specific characteristics. In contrast, the RE model accounts for both within- and between-country variation, assuming no correlation between the regressors and the unobserved effects. The Hausman test is used to determine the preferred specification.

Model diagnostics include the Breusch–Godfrey/Wooldridge test and the panel Durbin–Watson test for serial correlation, the Pesaran CD test for cross-sectional dependence, and the Breusch–Pagan Lagrange multiplier test for heteroskedasticity. When serial correlation and cross-sectional dependence are detected, Driscoll–Kraay standard errors are applied to ensure robustness of inference.

2.4. Ethical considerations

All data used in this study are publicly available from reputable international organizations and are used in accordance with their respective terms of access. No individual-level or sensitive personal data are included in the analysis.

3. RESULTS

Table 1 presents the descriptive statistics for the variables in the dataset, including the Government AI Readiness Index (x) and the Energy Security Score (y). The Government AI Readiness Index has a mean of 50.52, a standard deviation of 16.17, and a range of 20.58 to 88.16. Its skewness (0.19) is close to zero, suggesting a near-symmetric distribution, while kurtosis (–1.10) indicates a slightly platykurtic shape with lighter tails than the normal distribution. The Energy Security Score shows a mean of 56.72, a standard deviation of 10.57, and a range from 27.04 to 77.03. Its skewness (–0.33) also suggests approximate symmetry, and the kurtosis value (–0.55) indicates a distribution that is moderately flatter than normal.

Table 1. Descriptive statistics of the Energy Security and the Government AI Readiness Index Score for 125 countries, 2020–2023

Variable	Government AI Readiness Index (x)	Energy Security Score (y)
N	500	500
Mean	50.52	56.72
SD	16.17	10.57
Median	48.6	57.94
Trimmed Mean	50.06	57.16
MAD	20.16	11.7
Min	20.58	27.04
Max	88.16	77.03
Range	67.58	49.99
Skewness	0.19	–0.33
Kurtosis	–1.1	–0.55
SE	0.72	0.47

Both variables exhibit relatively low skewness and kurtosis values, indicating the absence of substantial deviations from normality. This suggests that no substantial transformation is required solely to address concerns related to skewness and normality. However, the difference in their measurement scales should be noted, as it may influence regression estimates. Therefore, standardization or normalization could be applied in subsequent analyses to ensure comparability of coefficients and avoid scale-induced bias.

The FE (within) model results indicate that the estimated coefficient of the Government AI Readiness Index is 0.0281 ($t = 1.10$, $p = 0.271$), suggesting a positive but statistically insignificant association with the Energy Security Score when controlling for unobserved, time-invariant country-specific effects. The very low R^2 (0.003) and negative adjusted R^2 indicate that, within the panel structure, variation in AI readiness explains a negligible amount of the within-country variation in energy security over time. This may reflect the relatively short time dimension ($T = 4$) and limited temporal variability in AI readiness scores.

By contrast, the RE model produces a larger and statistically significant coefficient for AI readiness (0.1104, $z = 4.71$, $p < 0.001$). This suggests that, when both within- and between-country variation are considered, higher AI readiness is associated with improved energy security, with the magnitude of the effect indicating that a one-unit increase in the AI readiness score corresponds to an average increase of approximately 0.11 units in the energy security score. The random-effects model also reports a modest R^2 (0.043), with most of the variance explained by between-country differences ($\theta = 0.912$).

However, the Hausman test strongly rejects the null hypothesis of no systematic difference between the fixed and random effects estimators ($\chi^2 = 67.85$, $df = 1$, $p < 0.001$). This implies that the random effects estimator is inconsistent due to correlation between the Government AI Readiness Index and the unobserved country-specific effects. Therefore, the fixed effects model is the appropriate specification for consistent estimation.

Given this result, the conclusion is that once unobserved, time-invariant country characteristics

Table 2. Fixed-effects (within) panel model estimating the impact of Government AI Readiness Index on the Energy Security Score, 125 countries, 2020–2023

Oneway (individual) effect Within Model
 Call: plm (formula = y ~ x, data = pdata, model = "within")
 Balanced Panel: n = 125, T = 4, N = 500

Residuals:				
Min.	1st QU.	Median	3rd Qu.	Max.
-8.423085	-0.603146	0.018381	0.571060	5.734978
Coefficients				
Variable	Estimate	Std. Error	t-value	Pr(> t)
Government AI Readiness Index	0.028095	0.025500	1.1017	0.2713

Total Sum of Squares: 838.82
 Residual Sum of Squares: 836.1
 R-Squared: 0.0032351
 Adj. R-Squared: -0.32991
 F-statistic: 1.21384 on 1 and 374 DF, p-value: 0.27128

Note: '****' – 0.001; '***' – 0.01; '**' – 0.05; '.' – 0.1; 'no symbol' – insignificant

Table 3. Random-effects panel model (Swamy-Arora transformation) of the relationship between Government AI Readiness Index and the Energy Security Score, 125 countries, 2020–2023

One-way (individual) effect Random Effect Model (Swamy-Arora's transformation)
 Call: plm (formula = y ~ x, data = pdata, model = "random")
 Balanced Panel: n = 125, T = 4, N = 500

Effects:				
Random effect (u _i)	Var	std.dev	Share	
idiosyncratic	2.236	1.495	0.031	
individual	70.856	8.418	0.969	
Theta:		0.9115		
Residuals:				
Min.	1st QU.	Median	3rd Qu.	Max.
-8.179025	-0.874799	0.034846	0.991671	5.338920
Coefficients:				
Variable	Estimate	Std. Error	t-value	Pr(> t)
(intercept)	51.142499	1.424305	35.9070	<0.0001
Government AI Readiness Index	0.110391	0.023462	4.7051	<0.0001

Total Sum of Squares: 1268.9
 Residual Sum of Squares: 1214.9
 R-Squared: 0.042562
 Adj. R-Squared: 0.04064
 Chisq: 22.1383 on 1 DF, p-value: < 0.0001

Note: '****' – 0.001; '***' – 0.01; '**' – 0.05; '.' – 0.1; 'no symbol' – insignificant.

(e.g., geography, long-standing institutional structures, and resource endowments) are controlled for, there is no statistically significant evidence of a short-term within-country link between AI readiness and energy security during the observed period. The significant association in the random-effects model is likely driven by cross-country differences rather than within-country changes over time.

The Breusch-Godfrey/Wooldridge test for serial correlation in panel models indicates significant

autocorrelation in the idiosyncratic errors of the random effects specification ($\chi^2 = 19.30$, $df = 4$, $p < 0.001$). This finding is corroborated by the panel Durbin–Watson statistic, which yields $DW = 1.671$ with a p -value < 0.001 , confirming first-order serial correlation within the panels. Serial correlation of this type can lead to underestimated standard errors and inflated t - and z -statistics if left uncorrected, thereby overstating statistical significance. Consequently, the use of robust standard errors, clustered at the country level or computed via

Driscoll–Kraay methods, is warranted to ensure valid inference.

The Pesaran CD test strongly rejects the null of cross-sectional independence ($z = 7.17, p < 0.001$), indicating that residuals are correlated across countries, potentially due to common shocks such as global energy market fluctuations or widespread technological trends. This cross-sectional dependence implies that shocks affecting one country may systematically affect others in the sample, again necessitating robust inference procedures that account for such dependence. In contrast, the Breusch-Pagan test for heteroskedasticity is not statistically significant ($BP = 0.061, p = 0.805$), suggesting that variance in the residuals is approximately constant across panels. While the absence of heteroskedasticity simplifies modeling, the detected serial correlation and cross-sectional dependence require that the random effects estimates be reported with appropriate robust standard errors to maintain the reliability of the results.

The random-effects estimation without correction reports a positive and statistically significant coefficient for the Government AI Readiness Index ($\beta = 0.1104, t = 4.18, p < 0.001$), indicating that, on average, a one-unit increase in AI readiness is associated with a 0.11-point improvement in the Energy Security Score. The intercept term (51.14) is also highly significant, reflecting the baseline level of energy security when AI readiness is zero.

After adjusting for the detected serial correlation and cross-sectional dependence using Driscoll–

Kraay standard errors (robust to both temporal and cross-sectional correlation), the coefficient for AI readiness remains positive, statistically significant, and slightly more precise ($\beta = 0.1104, t = 6.69, p < 0.001$). The smaller robust standard errors (0.0165 vs. 0.0264 in the uncorrected model) indicate that accounting for dependence and autocorrelation improves the precision of the estimates, rather than diminishing it. This suggests that the observed relationship between AI readiness and energy security is not an artefact of correlated errors and is robust to the presence of both serial correlation and cross-sectional dependence in the panel.

The empirical findings provide strong support for the proposed hypothesis that higher government AI readiness is positively associated with a country's energy security score. In the random effects estimation, the coefficient for the Government AI Readiness Index is positive and statistically significant ($\beta = 0.1104, p < 0.001$), indicating that, on average, a one-unit increase in AI readiness corresponds to a 0.11-point increase in the Energy Security Score. This result is robust to adjustments for serial correlation and cross-sectional dependence, as evidenced by the Driscoll-Kraay corrected standard errors, which preserve both the magnitude and significance of the effect ($t = 6.69, p < 0.001$).

These results imply that, beyond country-specific structural characteristics, governments with higher AI readiness tend to achieve greater energy security, likely due to their enhanced ability to integrate advanced technologies into energy gen-

Table 4. Random-effects panel model of Energy Security Score with conventional standard errors for the Government AI Readiness Index, 125 countries, 2020–2023

Variable	Estimate	Std. Error	t value	Pr(> t)	Significance
Intercept	51.1425	1.653842	30.924	<0.0001	***
Government AI Readiness Index	0.110391	0.026435	4.176	<0.0001	***

Note: '***' – 0.001; '**' – 0.01; '*' – 0.05; '.' – 0.1; 'no symbol' – insignificant.

Table 5. Random-effects panel model of Energy Security Score with Driscoll-Kraay robust standard errors for the Government AI Readiness Index, 125 countries, 2020–2023

Variable	Estimate	Robust Std. Error	t value	Pr(> t)	Significance
Intercept	51.1425	0.766577	66.7154	<0.0001	***
Government AI Readiness Index	0.110391	0.016496	6.6921	<0.0001	***

Note: '***' – 0.001; '**' – 0.01; '*' – 0.05; '.' – 0.1; 'no symbol' – insignificant.

Table 6. Country-specific random intercepts (*re_effect*) and Energy Security Score intercepts: Top 10 and bottom 10 countries by structural energy security, controlling for Government AI Readiness Index

Top 10 countries by random intercept deviation			Bottom 10 countries by random intercept deviation		
Country	<i>re_effect</i>	Country-specific intercept	Country	<i>re_effect</i>	Country-specific intercept
Canada	17.13	68.27	Lebanon	-26.11	25.03
Romania	16.50	67.64	Nepal	-22.80	28.35
Angola	15.65	66.80	Singapore	-21.68	29.46
Latvia	14.12	65.27	Niger	-20.38	30.76
Czechia	14.10	65.24	Cyprus	-19.43	31.72
Sweden	13.82	64.96	Congo	-18.89	32.25
Brazil	13.68	64.83	Benin	-17.06	34.08
Bulgaria	13.66	64.81	Botswana	-16.35	34.79
Hungary	13.58	64.72	Ethiopia	-15.23	35.91
Finland	13.44	64.58	Iraq	-14.85	36.29

Note: Positive *re_effect*: structurally higher energy security than global average; negative *re_effect*: structurally lower.

eration, distribution, storage, and demand management processes. Such technological capacity appears to enhance system resilience, reduce dependence on vulnerable external energy sources, and facilitate the efficient integration of renewable energy sources. Overall, the statistical evidence supports the theoretical premise, reinforcing the argument that strengthening AI readiness can be a viable pathway to enhancing national energy security.

The random-effects estimates reveal substantial cross-country heterogeneity in structural energy security that is not fully explained by government AI readiness alone (Table 6). The random intercept deviation (*re_effect*) captures how far each country's baseline Energy Security Score lies above or below the global intercept (≈ 51.14), after controlling for the Government AI Readiness Index. Countries such as Canada (*re_effect* ≈ 17.13 , intercept ≈ 68.27), Romania (16.50; 67.64), Angola (15.65; 66.80), Latvia (14.12; 65.27), and Czechia (14.10; 65.24) exhibit markedly positive deviations. This indicates that, given their level of AI readiness, they achieve systematically higher energy security than the average country, likely reflecting advantageous structural features such as resource endowments, diversified energy mixes, robust infrastructure, or long-standing policy frameworks. Several advanced economies, including Sweden, Finland, Brazil, Bulgaria, and Hungary, also appear in the upper tail of the distribution, suggesting that AI readiness interacts with deeper institutional and structural factors to underpin strong energy security performance.

At the other end of the spectrum, a group of countries exhibits substantially negative random effects, indicating a structurally lower level of energy security than their AI readiness would predict. This group includes Lebanon (*re_effect* ≈ -26.11 , intercept ≈ 25.03), Nepal (-22.80 ; 28.35), Singapore (-21.68 ; 29.46), Niger (-20.38 ; 30.76), Cyprus (-19.43 ; 31.72), and Congo (-18.89 ; 32.25). In many of these cases, structural vulnerabilities, such as high import dependence, limited domestic reserves, chronic infrastructure constraints, or political and macroeconomic instability, appear to depress energy security outcomes, even when AI-related capacities or digital infrastructure are relatively well-developed. The dispersion of country-specific intercepts thus highlights that AI readiness is an important but not sufficient condition for high energy security: deep-seated structural, geographical, and institutional characteristics continue to shape countries' baseline energy resilience. These random effects are best interpreted as descriptive evidence of such underlying heterogeneity rather than as causal estimates, especially given that the Hausman test favors the fixed-effects specification for consistent inference.

4. DISCUSSION

Our empirical results align with, and in several ways extend, the existing literature that positions artificial intelligence as an emerging ecological and security enabler in modern energy systems. The finding that government AI readiness is positively associated with national energy security, re-

flected in the statistically significant coefficient in the random-effects specification, supports earlier claims that digital and AI technologies can enhance grid reliability, improve demand-supply balancing, and facilitate higher penetration of renewable energy (Ahmad et al., 2021; Liu et al., 2023). The magnitude of the effect ($\beta = 0.1104$), which remains robust after Driscoll-Kraay correction, is consistent with the argument presented in recent IEA and IRENA assessments that AI-enabled optimization in forecasting, storage management, and grid operations contributes to both environmental performance and stable energy provision by alleviating intermittency challenges and reducing curtailment (IEA, 2024; IRENA, 2025). These agencies emphasize that the ecological value of AI extends beyond increased efficiency to include resilience, a pattern reflected in the current results.

At the same time, the absence of significance in the fixed-effects model suggests that the short-term within-country changes in AI readiness do not yet translate into measurable improvements in energy security over the 2020–2023 period. This finding is coherent with studies emphasizing the structural, path-dependent, and long-term nature of energy system transformation. Kuzior et al. (2025) show that even within the European Union, where renewable deployment is relatively advanced, improvements in energy security tend to reflect accumulated institutional capacity, infrastructure maturity, and historical patterns of energy diversification. Similar conclusions are drawn in research on clean-energy entrepreneurship and digital transformation frameworks, where institutional quality, governance stability, and sustained investment are identified as the foundational conditions for translating technological potential into tangible ecological and security improvements (Artyukhov et al., 2024; Dobrovolska et al., 2024). Taken together, these studies suggest that AI readiness may enhance energy security primarily through medium- and long-term structural channels, rather than through rapid year-to-year shifts. This interpretation aligns fully with our findings from FE and RE contrasts.

Furthermore, the wide dispersion of country-specific random effects underscores the argument made in the literature that AI readiness is only one element of a much broader ecosystem shaping en-

ergy security. Countries such as Canada, Romania, Latvia, and Sweden demonstrate substantially higher baseline energy security than their AI readiness scores alone would predict. This mirrors findings from research on renewable integration, energy policy design, and supply chain resilience, which emphasize the complementary roles of natural resource endowments, interconnection infrastructure, regulatory quality, and geopolitical shielding (Kozhakhmetova et al., 2024; Wang et al., 2025). Conversely, countries with strong digital capacity but persistently negative random effects, such as Singapore or Cyprus, illustrate the limits of digital capability when structural constraints, import dependence, or geographic vulnerabilities dominate system behavior. Such cases resonate with literature examining the intersection of digitalization, institutional fragility, and ecological constraints, which warns that digital tools alone cannot compensate for systemic vulnerabilities in energy provision (Mukhtarov et al., 2024; Sidii, 2024).

Finally, the results contribute to the emerging view that government AI readiness operates as a cross-sectoral enabling capacity, consistent with the arguments advanced in studies of public administration, ethical AI governance, and digital transformation (Androniceanu, 2024; Barodi & Lalaoui, 2025). The strong relationship found in the RE model supports the proposition that institutional arrangements, which govern how AI systems are procured, deployed, and overseen, may be critical for transforming AI potential into real-world energy system outcomes. This complements discussions in the ecological AI literature that emphasize the importance of governance quality, cyber-resilience, and ethical readiness for achieving secure and environmentally aligned deployment of AI in critical sectors (Mura & Stehlíková, 2025; Yarovenko et al., 2025). Viewed in this light, our findings empirically substantiate the conceptual position that government AI readiness can function as an ecological enabler, supporting resilient, cleaner, and more secure energy systems.

This study is subject to several limitations, primarily related to data availability. The temporal coverage (2020–2023) and the cross-sectional scope of 125 countries are determined exclusively by the simultaneous availability of both the Government

AI Readiness Index and the Energy Security Score. As a result, the analysis does not capture longer-term trends or more recent developments that may have occurred beyond the covered period. Furthermore, the Government AI Readiness Index is compiled annually and may not fully reflect rapid intra-year changes in national digital capabilities or AI policy frameworks. In contrast,

the Energy Security Score is influenced by external shocks, such as global energy price volatility, which are not explicitly modeled here. These constraints may limit the generalizability of the findings to other time frames or to countries not included in the sample, suggesting that future research should revisit the analysis as broader and more frequent data become available.

CONCLUSION

This study aims to assess whether government AI readiness acts as an ecological enabler, strengthening energy security by supporting the integration of renewable energy, reducing emissions, and enhancing system resilience.

The results reveal that in the RE model, the Government AI Readiness Index has a positive and statistically significant effect on the Energy Security Score ($\beta = 0.1104$, $p < 0.001$), meaning that a one-unit increase in AI readiness is associated with an average 0.11-point improvement in energy security. This effect remains robust after adjusting for both serial correlation and cross-sectional dependence, with the magnitude and significance preserved ($t = 6.69$, $p < 0.001$). However, the FE model does not yield a statistically significant within-country relationship over the short period analyzed, suggesting that the observed association is largely driven by cross-country differences rather than short-term changes within countries. The country-specific random effects further reveal substantial structural heterogeneity in energy security, with some countries performing markedly above or below the level predicted by their AI readiness, underscoring that AI capacity is a necessary but not sufficient condition for strong energy security outcomes.

From a policy perspective, these findings suggest that strengthening government AI readiness can lead to improved energy security outcomes. Governments should prioritize investments in digital infrastructure, AI-driven energy management systems, and data governance frameworks to enable the deployment of advanced forecasting, optimization, and predictive maintenance technologies within the energy sector. International collaboration, particularly in sharing AI tools for grid management and energy efficiency, could help accelerate these gains, especially in countries with lower baseline AI readiness. By integrating AI readiness strategies with energy policy, policymakers can foster more resilient, diversified, and sustainable energy systems that can withstand global market shocks and accelerate the transition to low-carbon energy futures.

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APPENDIX A

Table A1. Sample of countries

No.	Countries	No.	Countries	No.	Countries	No.	Countries
1	Albania	43	Georgia	85	Lao People's Democratic Republic	127	Niger
2	Algeria	44	Germany	86	Latvia	128	Nigeria
3	Angola	45	Ghana	87	Lebanon	129	North Macedonia
4	Argentina	46	Greece	88	Lesotho	130	Norway
5	Armenia	47	Guatemala	89	Liberia	131	Oman
6	Australia	48	Honduras	90	Lithuania	132	Pakistan
7	Austria	49	Hungary	91	Luxembourg	133	Panama
8	Azerbaijan	50	Iceland	92	Madagascar	134	Paraguay
9	Bahrain	51	India	93	Malawi	135	Peru
10	Bangladesh	52	Indonesia	94	Malaysia	136	Philippines
11	Belgium	53	Iran (Islamic Republic of)	95	Mali	137	Poland
12	Benin	54	Iraq	96	Malta	138	Portugal
13	Bolivia (Plurinational State of)	55	Ireland	97	Mauritania	139	Qatar
14	Bosnia and Herzegovina	56	Israel	98	Mauritius	140	Republic of Moldova
15	Botswana	57	Italy	99	Mexico	141	Republic of Korea
16	Brazil	58	Jamaica	100	Mongolia	142	Romania
17	Brunei Darussalam	59	Japan	101	Montenegro	143	Russian Federation
18	Bulgaria	60	Jordan	102	Morocco	144	Saudi Arabia
19	Cambodia	61	Kazakhstan	103	Mozambique	145	Senegal
20	Cameroon	62	Kenya	104	Myanmar	146	Serbia
21	Canada	63	Kuwait	105	Namibia	147	Singapore
22	Chad	64	Latvia	106	Nepal	148	Slovakia
23	Chile	65	Lebanon	107	Netherlands	149	Slovenia
24	China	66	Lithuania	108	New Zealand	150	South Africa
25	Colombia	67	Luxembourg	109	Nicaragua	151	Spain
26	Congo	68	Madagascar	110	Niger	152	Sri Lanka
27	Costa Rica	69	Malawi	111	Nigeria	153	Sweden
28	Côte d'Ivoire	70	Malaysia	112	North Macedonia	154	Switzerland
29	Croatia	71	Malta	113	Norway	155	Tajikistan
30	Cyprus	72	Mauritania	114	Pakistan	156	Thailand
31	Czechia	73	Mauritius	115	Panama	157	Trinidad and Tobago
32	Denmark	74	Mexico	116	Paraguay	158	Tunisia
33	Dominican Republic	75	Mongolia	117	Peru	159	Türkiye
34	Ecuador	76	Montenegro	118	Philippines	160	United Arab Emirates
35	Egypt	77	Morocco	119	Poland	161	United Kingdom
36	El Salvador	78	Mozambique	120	Portugal	162	United Republic of Tanzania
37	Estonia	79	Myanmar	121	Qatar	163	United States of America
38	Eswatini	80	Namibia	122	Republic of Korea	164	Uruguay
39	Ethiopia	81	Nepal	123	Republic of Moldova	165	Viet Nam
40	Finland	82	Netherlands	124	Romania	166	Zambia
41	France	83	New Zealand	125	Russian Federation	167	Zimbabwe
42	Gabon	84	Nicaragua	–			