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Leveraging energy-sector artificial intelligence to enhance energy security and achieve sustainable development goals

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Ensuring a secure and reliable energy supply is essential for achieving sustainable development goals. Artificial intelligence (AI) can enhance energy security by optimizing energy systems, improving efficiency, and strengthening infrastructure resilience. This study explores AI's contribution to energy security and its impact on key United Nations Sustainable Development Goals (SDGs), specifically SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 13 (Climate Action), based on data from 52 countries (2012–2021). The research constructs an energy security index, considering renewable energy adoption, availability, and environmental impact. The findings reveal significant disparities in energy security, with progress in electricity access and infrastructure, but persistent challenges in regions dependent on fossil fuels or underdeveloped systems. The study shows that no country has yet achieved universal energy security. Regression analysis indicates that Artificial Intelligence in the Energy Sector (AIPE) increases energy security by 0.446 to 6.97%. AI investments raise energy security by 1.68 to 8.39%, while AI research contributes 8.58%. These results highlight the significant role of AI investments and research in improving energy security, with AI research having the largest impact. However, socio-economic factors such as income inequality and inflation limit AI's full potential.

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Introduction

Economic development is an ongoing process, where access to energy serves as a fundamental driver of economic activity and a key factor in achieving advanced levels of development. In an unpretentious word, energy is the backbone of sustaining economies, ensuring national security, and promoting social well-being (Batra, 2023). So, a secure energy supply is every country's priority to avoid disruption in the development process. Therefore, energy security has been discussed at the global forum. The question is, "What is Energy Security (ES)?" As for now, there is no definite definition of ES. According to the International Energy Agency (IEA, 2023a; IEA, 2023b), "uninterrupted availability of energy sources at an affordable price." In other words, ES stands on four pillars: (i) Energy Availability, (ii) Energy Accessibility/Reliability, (iii) Environmental Acceptability/Sustainability, and (iv) Energy Affordability. Countries that depend on external sources of energy—especially oil, natural gas, or electricity—are vulnerable to supply disruptions (Cherp et al., 2012; Bordoff and O'Sullivan, 2023). Thus, countries prioritize energy security and invest in next-generation technologies, such as advanced grid management, and carbon capture, to accelerate the global transition to sustainable energy systems (Kabeyi et al., 2022). For instance, Japan and Germany lack significant domestic energy resources and have developed energy security strategies to diversify their energy imports, invest in energy storage, and support local renewable energy initiatives to mitigate supply risks (Wagner et al., 2021; Hager and Hamagami, 2020; Raupach-Sumiya et al., 2015). Second, countries, including the European Union, have committed to reaching "net-zero emissions" by 2050 (Shahzad et al., 2024; Obobisa, 2022), ensuring energy security in this context, which involves strengthening renewable energy systems and improving energy storage capabilities to ensure a steady energy supply while reducing reliance on fossil fuels.

In this regard, AI has been acknowledged as a transformative tool to optimize operations, improve efficiency, and address the multifaceted challenges associated with energy security (Ahmad et al., 2021). AI has the potential to enhance energy security by integrating renewable energy sources, predicting demand fluctuations, and optimizing grid operations (Ukoba et al., 2024). AI-based predictive maintenance systems can significantly reduce the risks associated with energy infrastructure failure. AI identifies inefficiencies and vulnerabilities by monitoring the distribution networks in real-time. In the oil and gas industries, AI-powered predictive models are used for equipment monitoring, detecting leaks, or detecting corrosion signs, minimizing supply chain risks. Wider implementation of AI in the energy system could optimize energy planning and generation. For instance, AI can optimize renewable energy generation. According to Matthew Sparkes. (2023), the uptake of AI in wind turbines globally would improve efficiency by 0.3%, providing enough extra energy to power a moderately sized country. The use of AI in the energy market has become more decentralized with distributed local renewable energy production. According to research organization RAND, AI could optimize the market by managing microgrids' localized pricing and peer-to-peer trading with automated real-time pricing. Further, it can identify optimal locations for new renewable energy projects. Countries are leveraging artificial intelligence to achieve energy security, and China and the USA have been at the forefront of AI adoption in the energy sector. The USA has implemented AI to optimize electricity grid operations through innovative grid technologies. The California Independent System Operator (CAISO) has used AI to predict fluctuations in renewable energy generation.

China is building one of the world's most extensive smart grids, where AI is used for real-time monitoring and helping manage the grid more efficiently. Germany is one of the leading countries in Europe using AI to enhance energy security, especially in the context of its Energiewende. For example, the Fraunhofer UMSICHT research institute in Germany has developed AI-based solutions for optimizing energy systems. The United Kingdom, Japan, South Korea, and India are leading the way in utilizing AI to achieve energy security. AI's capabilities include predictive maintenance, grid optimization, renewable energy integration, and demand-side management. AI has emerged as a pivotal force in transforming the energy sector by enabling utilities to manage fluctuations in energy demand and supply, but also offering novel pathways to achieve the Sustainable Development Goals (SDGs) set by the United Nations in 2015 for a sustainable future by 2030. SDGs are directly or indirectly linked to energy security and AI in addressing global challenges such as climate change, sustainable energy access, and socio-economic inequalities.

The question is how AI has interwoven with the energy sector to achieve SDGs goals (Șerbu and Mârza, 2024). AI has the potential to drive significant progress in the energy sector (Aysan et al., 2024), aligning with SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 13 (Climate Action). AI can accelerate the transition to clean and renewable energy by optimizing the generation and consumption of renewable energy. Further, it helps to improve energy efficiency in various sectors such as industries, households, and transportation, thereby making energy more affordable. AI-based smart grids enable cleaner and more reliable electricity systems. AI can foster innovation in energy infrastructure by allowing the development of more efficient systems. AI technologies enhance the operation of industrial processes, reducing energy consumption, minimizing waste, and allowing companies to make real-time decisions that improve production efficiency while lowering the environmental impact. AI can enhance the reliability of energy infrastructure by predicting when equipment is likely to fail and scheduling maintenance before it leads to energy disruptions. This is critical for maintaining energy security, especially in developing regions with less resilient infrastructure (Kiehbadroudinezhad et al., 2023). AI can model climate scenarios, enabling better planning for the transition to a low-carbon economy and improving the resilience of energy systems to climate impacts. Energy security is, therefore, a crucial foundation for attaining various SDGs, especially SDG 7 and SDG 13.

On the other hand, AI can significantly contribute by optimizing energy systems, enhancing energy efficiency, supporting renewable energy integration, and improving energy infrastructure resilience. These AI-driven innovations can help address the urgent need for sustainable, affordable, and accessible energy, thereby facilitating the achievement of broader sustainability goals. Further, Wang et al. (2025) highlighted that AI policies are instrumental in improving economic sustainability, underscoring the positive role of well-targeted government intervention. Wang et al. (2025) highlighted that AI affects sustainable development through three key dimensions: R&D innovation, infrastructure, and market advantage. Their findings show that AI plays a significant role in driving sustainable development, with R&D innovation having the most considerable impact.

This study aims to address a significant gap in the existing literature by analyzing the role of artificial intelligence (AI) in enhancing energy security across 52 countries between 2012 and 2021. This study differs from prior studies in terms of integrating AI as a driving factor that can directly and indirectly influence energy security. The study is innovative in many ways. First, the study captures the four dimensions of energy security: (1) Energy Availability, (ii) Energy Reliability, (iii) Energy Affordability, and (iv) Energy Sustainability. These dimensions are examined through a set of diverse indicators, including renewable energy adoption, fuel imports, energy efficiency, and environmental impact. Additionally, this study applies a standardized, normalized method to ensure the robustness of the findings. The entropy weighting method is employed to assign weights to each indicator, offering a unique advantage over traditional methods such as PCA, DEA, or equal weighting, which are not efficient in reflecting their actual influence on energy security and can obscure critical variations between dimensions. Entropy is particularly suited for this context because it reflects the relative importance of each indicator in an unbiased manner, particularly in the diverse energy landscapes of 52 countries. Furthermore, this study's novelty is further emphasized by aligning the energy security index with the SDGs. This study tracks the SDGs, aligning SDG 7 (SDG targets 7.1, 7.2 and 7.3 Affordable and Clean Energy), SDG 9 (SDG target 9.4 Industry, Innovation, and Infrastructure), and SDG 13 (SDG target 13.2 Climate Action) of each country. In the second stage, the study applies the regression analysis and assesses the impact of Artificial intelligence on the energy security of each dimension. Additionally, to make the study dynamic, it adopts the three AI indicators: (1) AI patent, which captures the technology in the energy sector directly linked to the energy sector; (2) the study used investment, which is the indirect indicator to drive energy security. 3. Research and development in terms of scholarly articles in the field of AI's impact on energy security. Additionally, the study investigates the moderating effect of AI on energy security, providing a deeper understanding of AI's role in shaping the future of global energy systems. A key distinguishing feature of this study is its incorporation of income inequality (measured using the Gini Index), which is often overlooked in previous energy security assessments. By considering this aspect, the study contributes to the literature by offering a more comprehensive view of how social factors, such as income inequality, intersect with energy security in the AI-driven era.

Literature review

This study swirls around three main domains: energy security, artificial intelligence, and AI related to energy and SDGs. Before delving into the empirical analysis, we will review the existing literature on these three domains to build a solid foundation for understanding.

Energy security. Energy security has been the subject of a vast body of literature, yet research in this area remains ongoing and continues to gain prominence. The concept of energy security is dynamic and evolving, reflecting its growing significance in academic discourse and policy development. Despite this extensive research, a universally accepted index or method for measuring energy security remains elusive. The Energy Security Index, which considers multiple dimensions, is often employed, though no singular approach has emerged as definitive.

Contemporary research demonstrates significant variation in energy security evaluation approaches among nations and geographical areas. These approaches highlight the multidimensionality of the concept. For instance, Lobova et al. (2019) employed the Z-score normalization method to develop four energy security performance dimensions using 12 indicators. Lee et al. (2024) applied the entropy method to calculate energy security composite indices, incorporating a variety of energy-related indicators and categorizing them into dimensions such as industry construction, supply security, consumption security, and environmental impact. Kartal (2022) used the Energy Security Risk Index (ESRI) to measure energy security. Similarly, Banna et al. (2023) and Iyke (2024) applied the same ESRI to capture multiple dimensions of energy security. Podbregar et al. (2020) conducted a reliability assessment of the International Index of Energy Security Risk, which tracks energy security variables across 25 selected countries. Using PCA and regression methods, the authors tested the index for statistical reliability, minimizing collinearity while maintaining comprehensive coverage of key parameters. Smal and Wieprow (2023) focused on the Energy Security Index in Poland, using a combination of financial analysis and energy market data to assess energy security. They evaluated the financial health of energy companies using indicators like Debt Ratio, Liquidity Ratio, and Return on Assets. Additionally, they employed discriminant analysis models, such as Altman's EM-Score and Gajdka's model, to predict the bankruptcy risks of energy firms. Abdullah et al. (2021) selected 39 indicators across various dimensions of energy security, including availability, affordability, efficiency, governance, and environmental sustainability. They constructed the final Energy Security Index by aggregating these standardized indicators into a composite score. In the subsequent sections, we will review the role of AI in the energy sector and SDGs.

Energy security and artificial intelligence. AI has become the central force driving the latest wave of technological revolutions and industrial transformations (Li et al., 2023; Ding et al., 2023; Qin et al., 2024). AI is a path to increasing reliability and security in the energy sectors in many ways. Such as Liu et al. (2021) evaluated the impact of Artificial intelligence on energy intensity. This study was basically about China's industrial sector. They endorsed the positive influence of AI in reducing energy intensity. Lyu and Liu (2021) highlighted that AI stands out as the most significant emerging digital technology in the energy sector, benefiting both employees and employers. Robotics as a proxy for AI was also used by Wang et al. (2022) to assess the AI impact in the energy sector. They concluded that industrial robots are highly effective in improving manufacturing energy intensity. Similarly, Ding et al. (2024) adopted robots as AI in their research and found the positive influence of AI in alleviating energy poverty. A literature-based study was done by Camacho et al. (2024). The study analyzed AI's impact on key energy systems, including production, transmission, distribution, and usage, revealing important benefits across all domains. A study by Zhao et al. (2024) conducted on the role of AI in the environment by focusing on energy conservation. They found that AI is an effective tool for China's energy conservation and carbon reduction efforts. Although this literature is less and not directly on energy security, it is valuable in assessing the AI role in energy security. Wang et al. (2026) argued that AI is rapidly shaping the global energy transition by significantly enhancing the efficiency, resilience, and integration of renewable energy systems. However, they emphasized that the successful deployment of AI in this context largely depends on the availability of strong financial support.

Sustainable development goals, implications of AI and energy. The concept of "Sustainable Development" today extends beyond environmental concerns, encompassing intergenerational equity, ecological stability, and the enhancement of human quality of life. Cheba and Bąk (2021) said there are around 500 distinct definitions of sustainable development in the literature. The Brundtland (1987) highlighted three critical aspects of sustainable development: (i)The obligation to protect the environment for future generations, (ii) Intra- and interspecies equity, and (iii) Sustainability viewed as a dynamic process rather than a static state. Thus, "Sustainable Development" is multidimensional and focuses on different dimensions of the human world, including economic, social, and ecological development. In a historic 2015 agreement, every UN nation backed the ambitious 2030 Agenda, launching 17 global goals to combat poverty, bridge inequalities, fight environmental decline, mitigate climate impacts, and promote peaceful societies. Among these SDGs, one specifically addresses energy security, focusing on both the supply of resources and the role of consumers (Elavarasan et al., 2021). Thus, many researchers have started their research on this dimension to ensure and track the progress of economies (Axon and Darton, 2021; Shyu, 2021; Stephan et al., 2018). In this regard, Luty et al. (2023) assess the energy security from the SDGs perspective. However, they did not find any sustainable consumption and energy productivity. Minas et al. (2024) evaluate the achievement of SDGs from the energy access point of view. They concluded that investments in renewable energy are seen as essential not only for ensuring "energy for all" but also for advancing other SDGs. McCollum et al. (2018) also connect the interlinkages of energy with SDGs. Leite de Almeida et al. (2021) researched energy projects regarding SDGs, and Bisaga et al. (2021) focused on solar energy sources while evaluating the SDGs. They found that solar off-grid systems are helpful in the SDGs.

Some research evaluates the SDGs status of the country through AI technologies. For example, Vinuesa et al. (2020) studied the linkages of AI and SDGs. However, their findings revealed both the beneficial and detrimental impacts of AI. They noted that AI could help achieve 134 targets across all SDGs, but may also impede progress on 59 targets. The authors stressed the importance of regulatory guidance and oversight to ensure that AI technologies promote, rather than hinder, sustainable development. Ametepey et al. (2024) investigated the influence of AI in achieving SDGs and found its positive role. Similarly, Jungwirth and Haluza (2023), Năstasă et al. (2024), Goralski et al. (2020), Di Vaio et al. (2020), and Truby (2020) also linked SDGs with AI applications.

Research gap and development of research hypothesis. The literature review above highlights AI's significant role in enhancing energy security and advancing the SDGs. However, it also reveals several gaps that this study aims to address. While prior research has explored AI's impact on energy security and the SDGs, there is a lack of in-depth studies examining the multiple dimensions of energy security. This research aims to fill this gap by incorporating four critical aspects of energy security that have not been comprehensively studied before: (1) Energy Availability, (2) Energy Reliability, (3) Energy Affordability, and (4) Energy Sustainability. A key innovation of this study is the application of the entropy method to assign weights to energy security indicators, offering a more robust analysis. Furthermore, the inclusion of SDG targets, particularly 7.1, 7.2, 7.3, 9.4, and 13.2 (which focus on energy use, energy efficiency, and climate impact), represents another important gap this study addresses. Another crucial gap is filled by the incorporation of AI indicators—specifically, AI patents, AI-related investments, and AI scholarly research in energy. These three indicators introduce both direct and indirect influences of AI on energy security. The study also explores the moderating effect of AI on energy security, offering a deeper understanding of AI's role in shaping global energy systems and the achievement of SDGs, particularly in the context of energy security in the sampled countries. Additionally, this study distinguishes itself by incorporating the income inequality index (measured using the Gini Index), which is often ignored in previous energy security assessments. By examining income inequality, this research offers a deeper insight into how social factors intersect with energy security in an AI-driven context. Addressing these gaps, this study aims to make a meaningful contribution to the field. Based on the identified research gaps, the following research hypotheses are proposed for investigation:

Research Hypothesis 1. The multidimensional evaluation of energy security through various indices influences energy policies, and AI integration enhances these evaluations.

Research Hypothesis 2. Tracking energy security for measuring progress towards SDGs.

Research Hypothesis 3. AI enhances energy security by improving availability, affordability, reliability, and sustainability.

Research Hypothesis 4. AI integration in the energy sector supports SDG targets 7.1, 7.2, 7.3, 9.4, and 13.2.

Research Hypothesis 5. Income inequality influences energy security and the achievement of SDGs.

Model, data, and methods

Theoretical linkages and model setup. Artificial intelligence (AI) systems have achieved widespread adoption across industries, with their strategic significance expanding exponentially in recent years. The global AI market, valued at nearly USD 100 billion in 2021, is expected to experience remarkable growth, expanding almost twentyfold to reach approximately USD 2 trillion by 2030 (Wang et al., 2024). As a novel scientific discipline, AI integrates advanced theories and digital technologies and is widely expected to play a pivotal role in driving the energy transition (Wang et al., 2025).

In the context of sustainable development, AI is increasingly recognized as a transformative force in the energy sector (Wang et al., 2024), offering innovative pathways to achieve the SDGs (Raman et al., 2024; Mhlanga, 2021). Specifically, AI's potential aligns with Endogenous Growth Theory, highlighting technological advancements' role in fostering long-term economic development. Within this framework, AI is seen as a key driver of sustainable development, particularly in energy systems (Wang et al., 2025). AI is powering the next wave of energy evolution, enabling smarter grids, breakthrough storage tech, and precision energy management. These advances ensure stable, affordable, and eco-friendly power—key pillars of energy security—while curbing pollution from legacy energy systems. AI plays a vital role in energy integration, ultimately driving the transition toward a sustainable energy future. Through intelligent management systems, AI can optimize energy flow, balance supply and demand, minimize waste, and ensure enhanced energy security (Kaur et al., 2024).

Linkages of AI and energy security. The integration of AI into the energy sector enhances energy security by addressing its key dimensions (also see Fig. 1).

Availability: AI optimizes energy distribution by forecasting demand and supply, ensuring efficient energy storage, and managing peak demand through smart grids.

Affordability: AI helps lower energy costs by predicting maintenance needs and reducing costly repairs, making energy systems more economically viable.

Reliability: AI enhances the resilience of energy systems by predicting failures and ensuring energy infrastructure can handle disruptions. Predictive algorithms in AI applications ensure

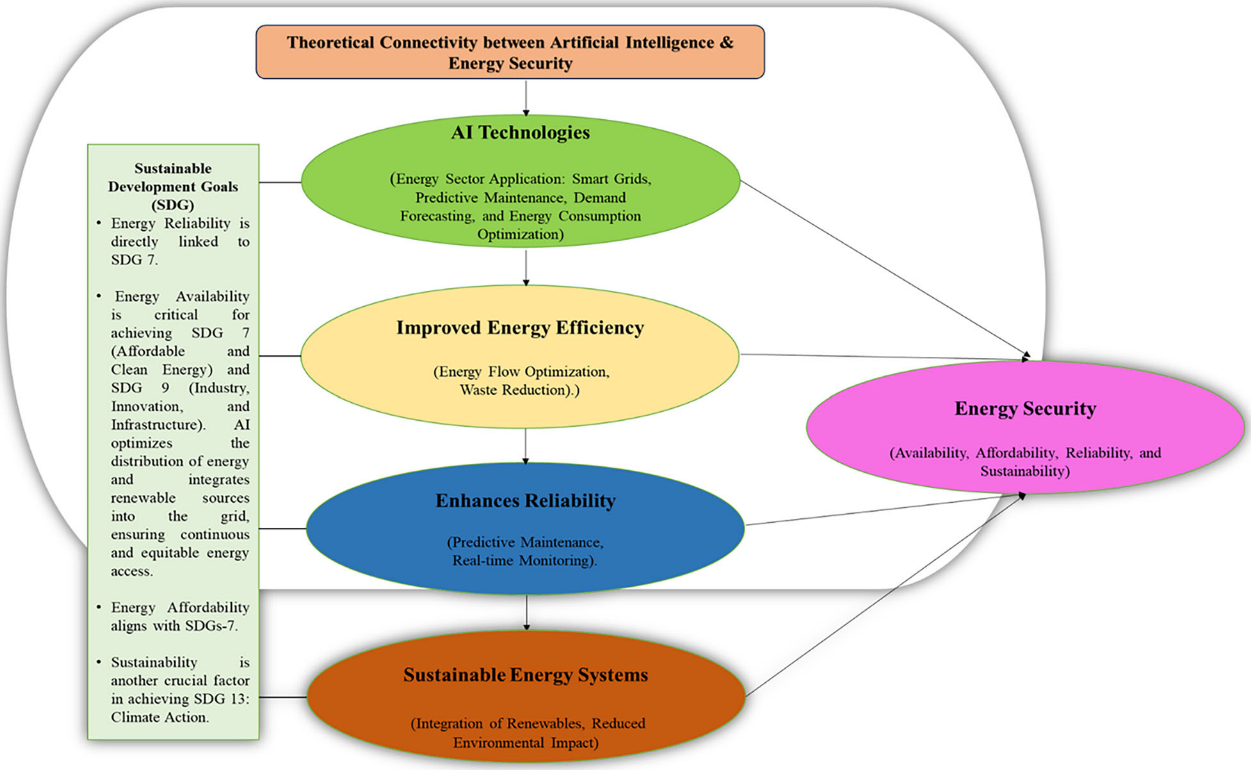


Fig. 1 Visualizing the Theoretical Connection Between AI and Energy Security.

continuous energy supply, reducing the risks of blackouts and improving grid stability.

Sustainability: AI facilitates the shift to sustainable energy systems by optimizing renewable energy usage and boosting energy efficiency. Machine learning techniques help minimize waste, reduce emissions, and improve the integration of clean energy sources into the grid.

This direct link between AI and energy security is grounded in Innovation Diffusion Theory (Rogers, 1962), which suggests that AI adoption in the energy sector is influenced by factors such as its perceived relative advantage, compatibility with existing infrastructure, complexity, trialability, and the observable benefits it offers. In the case of energy systems, AI integration in smart grids, predictive maintenance tools, and energy optimization technologies helps enhance energy security by ensuring more reliable, efficient, and resilient energy distribution. As AI adoption expands, it is expected to contribute significantly to achieving SDG 7 by improving energy efficiency. Moreover, AI supports SDG 13 (Climate Action) by optimizing energy consumption, reducing waste, and enabling the transition to more sustainable and environmentally friendly energy systems (Pimenow et al., 2024). This discussion gives us the support to build the following empirical models for panel specification:

$$ESI-Indices_{it} = \alpha_0 + \alpha_1 AIPE_{it} + \alpha_2 Gini-Index_{it} + \alpha_3 Inf_{it} + \alpha_4 GDP_{it} + \alpha_5 Ind_{it} + I_i + Y_i + \mu_{it,1} \tag{1}$$

Where $ESI-Indicies$ denotes five indices of energy security, composed of energy and environmental indicators. The leading comprehensive index, namely "The Energy Security Index (ESI)," and four sub-indices: (i) the energy Availability Index," (ii) the Energy Reliability Index, (iii) the Energy Affordability Index, (iv) the Energy Sustainability Index. $AIPE_{it}$ is the Artificial Intelligence (AI) technology in the energy sector, as estimated by AI patents in energy. This indicator calculates the direct relation of AI with the energy sector. Control variables: (i) Gross domestic product per capita [GDP] (Singh et al., 2021), (ii) Industrialization [Ind] (Li et al., 2020), (iii) income inequality [$Gini-Index$] (Azhgaliyeva et al., 2023), (iv) inflation [Inf] (Mawutor et al., 2024). I_i and Y_i used for country and year effects. μ_{it} is the error terms where it refers to the panel and year. Further, this study incorporated AI's investment and research indicators to capture the indirect relation. Panel specifications of these are as follows:

$$ESI-Indices_{it} = \alpha_0 + \alpha_1 AI\_Inv_{it} + \alpha_2 Gini-Index_{it} + \alpha_3 Inf_{it} + \alpha_4 GDP_{it} + \alpha_5 Ind_{it} + I_i + Y_i + \mu_{it,2} \tag{2}$$

$$ESI-IndicesI_{it} = \alpha_0 + \alpha_1 AI\_SR_{it} + \alpha_2 Gini-Index_{it} + \alpha_3 Inf_{it} + \alpha_4 GDP_{it} + \alpha_5 Ind_{it} + I_i + Y_i + \mu_{it,3} \tag{3}$$

Where AI_Inv & AI_SR represent the investment in the AI sector and scholarly research in the field of AI, respectively. α_0, is the constant term. α_1 to α_5 , are the coefficients to be estimated for the respective variables.

Data source. This study's main research point is to identify the energy security level of the 52 countries (see Appendix Table A1) and the role of AI in ensuring energy security, further to accomplish the goals of the United Nations SDGs 7, 9, and 13 from 2012 to 2021. For AI, the data range was limited; thus, this study period was selected based on data availability. Detailed data units and their sources are given in Table 1, and the descriptive statistics are shown in Table A2 (Appendix 1). The multicollinearity test of the model is given in Table A3.

Table 1 Variables and Data Sources.

Variable(s)	Measurement	Source of Data
AIPE	Patent applications in the field of energy management	WDI ourworldindata SWIID
AI_Inv	Investment in artificial intelligence	IEA
AI_SR	Scholarly publications on artificial intelligence per million people	
Energy Reliability Index	$\frac{\text{Value of Fuel Imports}}{\text{Value of Merchandise Imports}} \times 100$ *(FIM)* Electric power transmission and distribution losses (% of output) (EPTD)	
Energy Affordability Index	Percentage of the population with access to electricity (ACP) Gasoline Prices USD/litre (GSP) Electricity Prices (ELP)	
Energy Availability Index	Total Primary energy consumption (TWh) (TPEC) Total Primary energy supply by GDP (MJ per 2015 USD) (TES) Electricity production from oil, gas and coal sources (% of total) (ELNON)	
Energy Sustainability Index	Low-carbon electricity production (% of total) (LCEP) $\frac{\text{Annual } CO_2 \text{ Emissions(kg)}}{\text{Annual Energy Consumption kWh)}}$ *(CO_2E) Energy Intensity Level of Primary Energy (MJ/$2017 PPP GDP) (EINT)*	
Ind	$\frac{\text{Industry value added}}{GDP} \times 100$	
Inf	Inflation, consumer prices (annual %)	
Gini − Indx	Gini Index (Income Inequality)	
GDP	GDP per capita in constant 2015 US$	
Pop	Population, Total	

Estimation methods

Driscoll and Kraay (1998) (D&K). In this study, we applied a robust estimation method, "Driscoll and Kraay," developed by Driscoll and Kraay (1998). The method is helpful as it addresses heteroskedasticity, autocorrelation, and cross-sectional dependence in the error terms. This approach has become widely used in econometrics, particularly in empirical research involving panel data models where the residuals may exhibit both temporal autocorrelation and cross-sectional dependence across units (individuals, countries, firms, etc.). D&K is based on robust covariance matrix estimation, which corrects for issues related to heteroskedasticity and autocorrelation in the error terms. D&K estimator ensures consistent estimation of standard errors, even in any complications. As this research is based on a panel of countries, autocorrelation within each country is possible over time (e.g., economic shocks may have lingering effects from one year to the next). Further, there is a high chance of correlation across countries' error terms. Thus, D&K would be a robust covariance matrix in this situation.

Driscoll & Kraay covariance matrix estimator is given by:

$$C\hat{o}v\left(\hat{\beta}\right) = (X'X)^{-1}\hat{\Omega}(X'X)^{-1} \tag{4}$$

Where $\hat{\Omega}$ is the robust covariance matrix estimate defined as:

$$\hat{\Omega} = \frac{1}{T}\sum_{t=1}^{T} \hat{\varepsilon}_t\hat{\varepsilon}'_t + \sum_{s=1}^{T-1}\left(1 - \frac{s}{T}\right)\sum_{t=s+1}^{T} \hat{\varepsilon}_t\hat{\varepsilon}'_{t-s} \tag{5}$$

Development and tracking energy security index

Entropy application for weights. To assign weights, the study follows the entropy method. The detailed explanation of the entropy method is provided in the Appendix, and the entropy weights are shown in Table A6.

Development of energy Indices. This study used the standard normalized method to develop the energy security index and sub-indices. There is much literature that uses this method (European Union and Joint Research Center, 2008; Kim et al., 2025). The variables used in the indexes are mentioned in Table 1. The formula used for this estimation is:

$$Normalized\ Value = \frac{Value - Min}{Max - Min} \tag{6}$$

Where:

- *Value is the observed value of a given variable,*
- *Min is the minimum value of that variable,*
- *Max is the maximum value of that variable*

Inverted normalization indicators[1], we transformed the values as follows:

$$Normalized\ Value = 1 - \frac{(Value - Min)}{(Max - Min)} \tag{7}$$

Sub-energy security index. Weighting aggregation using entropy weights to develop energy security indexes.

(i) Energy Availability Index
This index reflects the availability of energy in the system. It is computed by taking the average of the normalized values TPES, TES, ELNON:

$$Energy\ Availability\ Index = \frac{\sum TPEC + TES + ELNON \times weights}{\sum weights_i} \tag{8}$$

(ii) Energy Reliability Index
This index is calculated as the average of the normalized values for the percentage of the EPTD and FIM.

$$Energy\ Reliability\ Index = \frac{\sum FIM + EPTD \times weights}{\sum weights_i} \tag{9}$$

(iii) Energy Affordability Index
This index is based on the normalized value of ACP, GSP, and ELP

$$Energy\ Affordability\ Index = \frac{\sum ACP + ELP + GSP \times weights}{\sum weights_i} \tag{10}$$

(iv) Energy Sustainability Index
This index measures the long-term sustainability of energy resources. It is calculated as the average of the normalized values for EINT, LCEP and CO_2E

$$Energy\ Sustainability\ Index = \frac{\sum EINT + LCEP + CO_2E \times weights}{\sum weights_i} \tag{11}$$

(v) Final Energy Security Index (ESI)

The final Energy Security Index (ESI) is the average of the four sub-indices (Energy Availability, Reliability, Affordability, and Sustainability). This gives an overall measure of energy security:

ESI index is the average of sub-indices measured as follows:

The final index is the weighted sum of all sub-indices, with weights proportional to their total entropy weight contribution.

$$ESI = \sum\left(sub_j \times Total\ weights\right) \tag{12}$$

Removing data outliers. We applied the Winsor method at 95% to remove the data outliers. The choice of 95% Winsorization was made as it is commonly used to balance reducing the influence of extreme values while retaining enough data for analysis. A 90% cutoff would remove more data, potentially losing valuable information, while 99% would leave some extreme values still influencing the results. Sensitivity tests showed that using 95% did not materially affect the results, confirming it as an effective approach to handle outliers without distorting the analysis. Figure 2 presents the data distribution of the index through box plots.

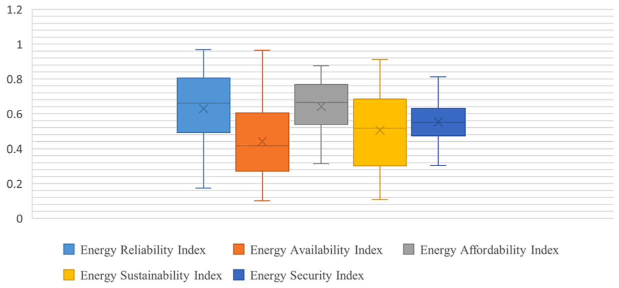


Fig. 2 Box Plots of Index' data distribution (For Outliers).

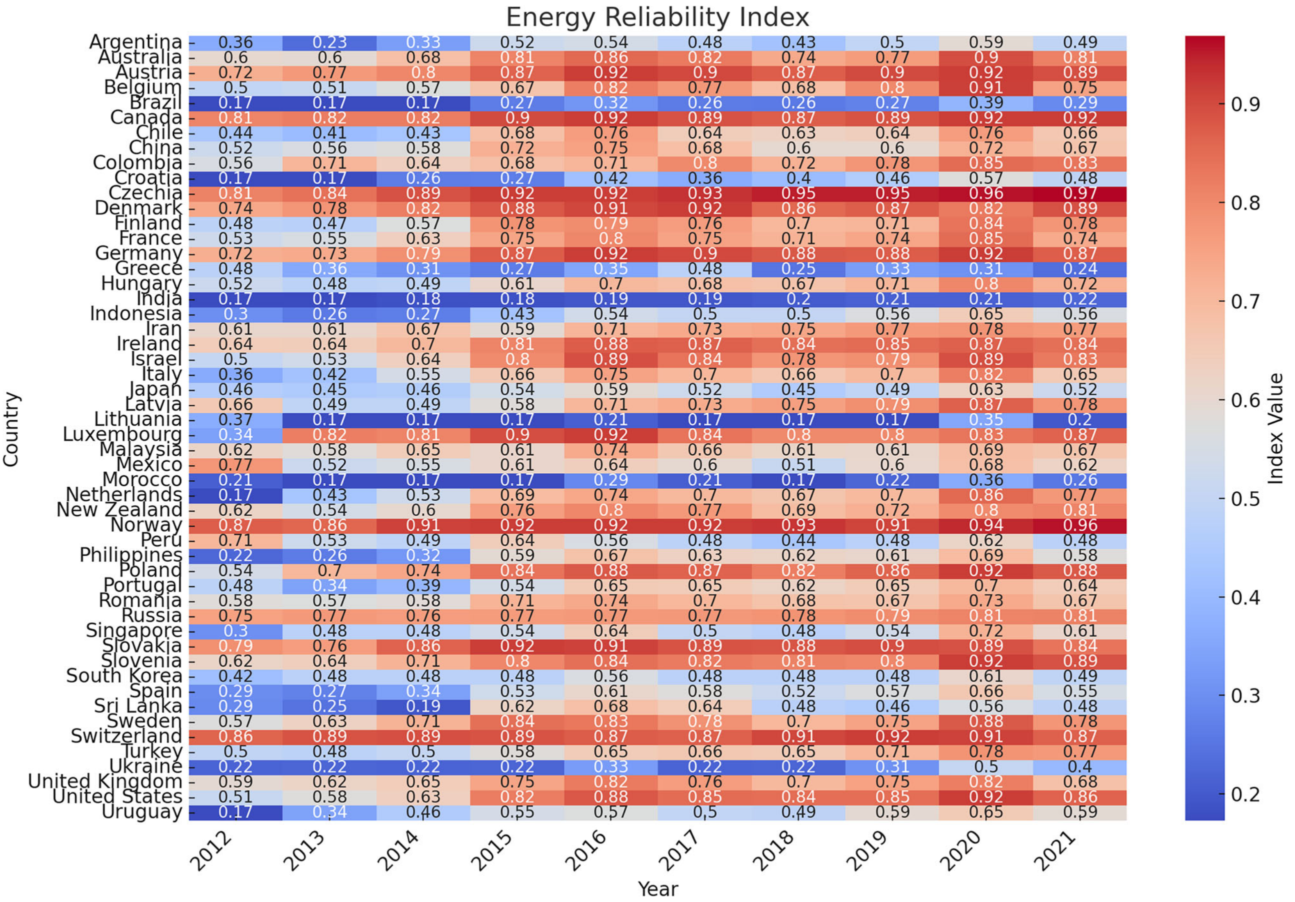
Results and discussion

The estimation of the study is based on two phases. The first phase is based on evaluating the energy security of the countries aligned with the SDG goals. In the second estimation phase, we run the regression to find the influential role of AI on energy security.

Tracking energy security and SDGs assessment

Energy Reliability Index & SDGs-7 (Target 7.1, 7.2). The Energy Reliability Index (Fig. 3) is measured by fuel import dependence and electricity transmission loss and distribution, which are directly related to SDG 7. This index is crucial for ensuring that countries can provide uninterrupted energy to households, industries, and critical services. The index value for each country across the sample years is presented in Fig. 3, where colors range from 0.2 (lower) to 0.9 (higher). Red indicates higher values, and dark blue shows lower values. The Energy Reliability Index evaluates the efficiency and dependability of energy systems in each country. In 2021, Argentina had a reliability score of 0.49. Although this reflects some improvement compared to previous years, it still indicates a relatively unreliable energy infrastructure, possibly due to aging infrastructure or challenges in securing fuel supply.

A score between 0.4 and 0.7 typically represents a moderate or intermediate situation in terms of energy reliability. This range suggests that while energy supply is somewhat stable, it may still experience fluctuations or interruptions due to factors like weather, infrastructure, and policy issues. Australia's reliability score in 2021 was 0.81, indicating a more robust energy infrastructure with fewer disruptions. Norway's energy reliability is among the highest, scoring 0.96 in 2021, with its well-



Country	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Argentina	0.36	0.23	0.33	0.52	0.54	0.48	0.43	0.5	0.59	0.49
Australia	0.6	0.6	0.68	0.81	0.86	0.82	0.74	0.77	0.9	0.81
Austria	0.72	0.77	0.8	0.87	0.92	0.9	0.87	0.9	0.92	0.89
Belgium	0.5	0.51	0.57	0.67	0.82	0.77	0.68	0.8	0.91	0.75
Brazil	0.17	0.17	0.17	0.27	0.32	0.26	0.26	0.27	0.39	0.29
Canada	0.81	0.82	0.82	0.9	0.92	0.89	0.87	0.89	0.92	0.92
Chile	0.44	0.41	0.43	0.68	0.76	0.64	0.63	0.64	0.76	0.66
China	0.52	0.56	0.58	0.72	0.75	0.68	0.6	0.6	0.72	0.67
Colombia	0.56	0.71	0.64	0.68	0.71	0.8	0.72	0.78	0.85	0.83
Croatia	0.17	0.17	0.26	0.27	0.42	0.36	0.4	0.46	0.57	0.48
Czechia	0.81	0.84	0.89	0.92	0.92	0.93	0.95	0.95	0.96	0.97
Denmark	0.74	0.78	0.82	0.88	0.91	0.92	0.86	0.87	0.82	0.89
Finland	0.48	0.47	0.57	0.78	0.79	0.76	0.7	0.71	0.84	0.78
France	0.53	0.55	0.63	0.75	0.8	0.75	0.71	0.74	0.85	0.74
Germany	0.72	0.73	0.79	0.87	0.92	0.9	0.88	0.88	0.92	0.87
Greece	0.48	0.36	0.31	0.27	0.35	0.48	0.25	0.33	0.31	0.24
Hungary	0.52	0.48	0.49	0.61	0.7	0.68	0.67	0.71	0.8	0.72
India	0.17	0.17	0.18	0.18	0.19	0.19	0.2	0.21	0.21	0.22
Indonesia	0.3	0.26	0.27	0.43	0.54	0.5	0.5	0.56	0.65	0.56
Iran	0.61	0.61	0.67	0.59	0.71	0.73	0.75	0.77	0.78	0.77
Ireland	0.64	0.64	0.7	0.81	0.88	0.87	0.84	0.85	0.87	0.84
Israel	0.5	0.53	0.64	0.8	0.89	0.84	0.78	0.79	0.89	0.83
Italy	0.36	0.42	0.55	0.66	0.75	0.7	0.66	0.7	0.82	0.65
Japan	0.46	0.45	0.46	0.54	0.59	0.52	0.45	0.49	0.63	0.52
Latvia	0.66	0.49	0.49	0.58	0.71	0.73	0.75	0.79	0.87	0.78
Lithuania	0.37	0.17	0.17	0.17	0.21	0.17	0.17	0.17	0.35	0.2
Luxembourg	0.34	0.82	0.81	0.9	0.92	0.84	0.8	0.8	0.83	0.87
Malaysia	0.62	0.58	0.65	0.61	0.74	0.66	0.61	0.61	0.69	0.67
Mexico	0.77	0.52	0.55	0.61	0.64	0.6	0.51	0.6	0.68	0.62
Morocco	0.21	0.17	0.17	0.17	0.29	0.21	0.17	0.22	0.36	0.26
Netherlands	0.17	0.43	0.53	0.69	0.74	0.7	0.67	0.7	0.86	0.77
New Zealand	0.62	0.54	0.6	0.76	0.8	0.77	0.69	0.72	0.8	0.81
Norway	0.87	0.86	0.91	0.92	0.92	0.92	0.93	0.91	0.94	0.96
Peru	0.71	0.53	0.49	0.64	0.56	0.48	0.44	0.48	0.62	0.48
Philippines	0.22	0.26	0.32	0.59	0.67	0.63	0.62	0.61	0.69	0.58
Poland	0.54	0.7	0.74	0.84	0.88	0.87	0.82	0.86	0.92	0.88
Portugal	0.48	0.34	0.39	0.54	0.65	0.65	0.62	0.65	0.7	0.64
Romania	0.58	0.57	0.58	0.71	0.74	0.7	0.68	0.67	0.73	0.67
Russia	0.75	0.77	0.76	0.77	0.77	0.77	0.78	0.79	0.81	0.81
Singapore	0.3	0.48	0.48	0.54	0.64	0.5	0.48	0.54	0.72	0.61
Slovakia	0.79	0.76	0.86	0.92	0.91	0.89	0.88	0.9	0.89	0.84
Slovenia	0.62	0.64	0.71	0.8	0.84	0.82	0.81	0.8	0.92	0.89
South Korea	0.42	0.48	0.48	0.48	0.56	0.48	0.48	0.48	0.61	0.49
Spain	0.29	0.27	0.34	0.53	0.61	0.58	0.52	0.57	0.66	0.55
Sri Lanka	0.29	0.25	0.19	0.62	0.68	0.64	0.48	0.46	0.56	0.48
Sweden	0.57	0.63	0.71	0.84	0.83	0.78	0.7	0.75	0.88	0.78
Switzerland	0.86	0.89	0.89	0.89	0.87	0.87	0.91	0.92	0.91	0.87
Turkey	0.5	0.48	0.5	0.58	0.65	0.66	0.65	0.71	0.78	0.77
Ukraine	0.22	0.22	0.22	0.22	0.33	0.22	0.22	0.31	0.5	0.4
United Kingdom	0.59	0.62	0.65	0.75	0.82	0.76	0.7	0.75	0.82	0.68
United States	0.51	0.58	0.63	0.82	0.88	0.85	0.84	0.85	0.92	0.86
Uruguay	0.17	0.34	0.46	0.55	0.57	0.5	0.49	0.59	0.65	0.59

Fig. 3 Energy reliability index value by year.

maintained infrastructure, making the country resilient to energy outages. High scores in energy reliability contribute to ensuring universal access to modern energy for all, which is crucial for development and poverty reduction. Both fuel import dependence and transmission losses are key factors affecting energy system reliability. Reducing these factors increases the reliability and sustainability, all of which are central to SDG 7. SDG 7 emphasizes reliable, affordable, and sustainable energy systems for all. By addressing fuel import dependence (through local energy production and renewables) and reducing transmission losses (through grid upgrades and efficient infrastructure), countries directly contribute to SDG 7's goals of reliability and affordability. Germany (0.87 in 2021) and other European countries have heavily invested in renewable energy sources to reduce their fuel import dependence. This transition helps improve the reliability of their energy systems, minimizing risks of price volatility and supply disruptions due to external factors.

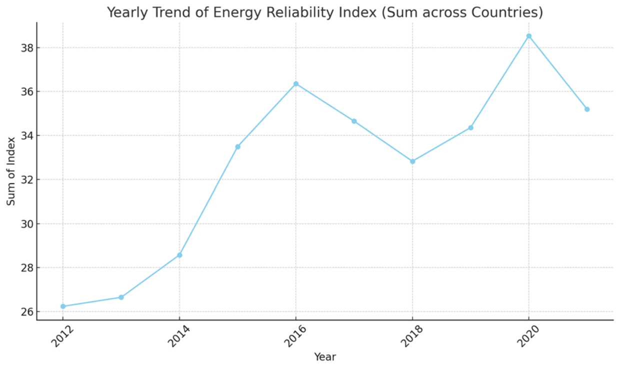


Fig. 4 Energy reliability index growth trend over the Years (2012–2021).

Figure 4 indicates an overall upward trend, reflecting improvements in energy reliability across countries. Figure 5 shows the yearly trend and progress evaluation for each country from 2012 to 2021.

Energy Availability Index & SDGs-7&9 (Target 7.1 and 9.4). The Energy Availability Index evaluates both total energy consumption and supply, along with electricity production from non-renewable sources. Figure 6 presents annual index values for each country through a detailed heatmap, illustrating nations' capacity to meet energy demands from 2012 to 2021. In 2021, Canada achieved a score of 0.96, reflecting its abundant energy supply and heavy reliance on clean energy sources like hydropower, which ensures consistently high availability. This high score can be largely attributed to Canada's position as the third-largest producer of hydroelectricity in the world. In 2022, Canada's hydroelectric stations generated a combined total of 393,789 gigawatt-hours, accounting for 61.7% of the country's total electricity generation (Natural Resources Canada, 2024). The country's hydropower dependence provides a significant advantage, as it offers a stable, renewable, and low-carbon energy source that supports both energy availability and sustainability. Furthermore, Canada's robust policy frameworks have encouraged investments in renewable energy, enhancing energy security by diversifying its energy sources and improving energy efficiency across regions. These structural advantages enable Canada to achieve high energy security scores, distinguishing it from countries with higher reliance on fossil fuels.

In contrast, India scored only 0.29 in the same year, highlighting substantial energy availability challenges, particularly in rural areas due to inconsistent power supply and continued dependence on non-renewable sources. Brazil's moderate score of 0.61 indicates progress but reveals persistent difficulties in

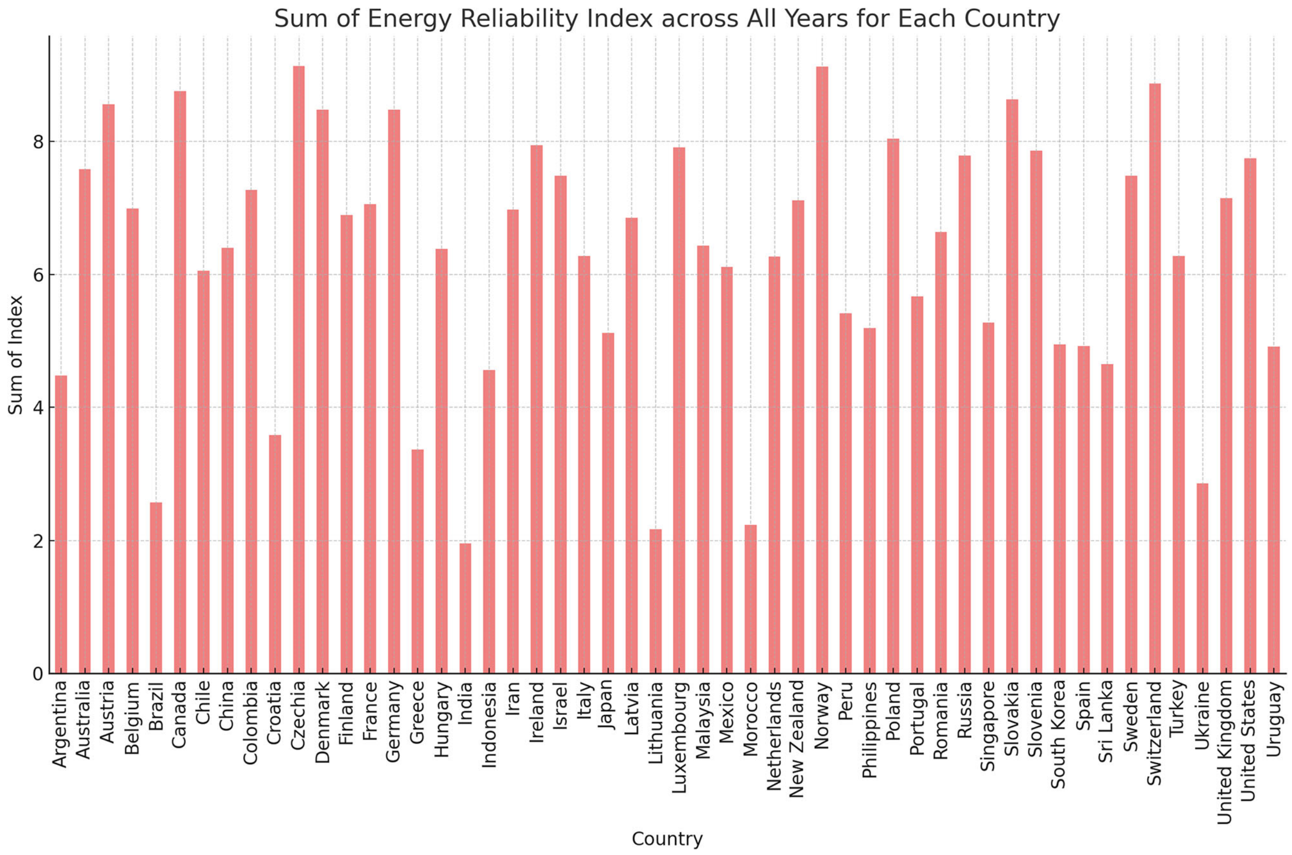
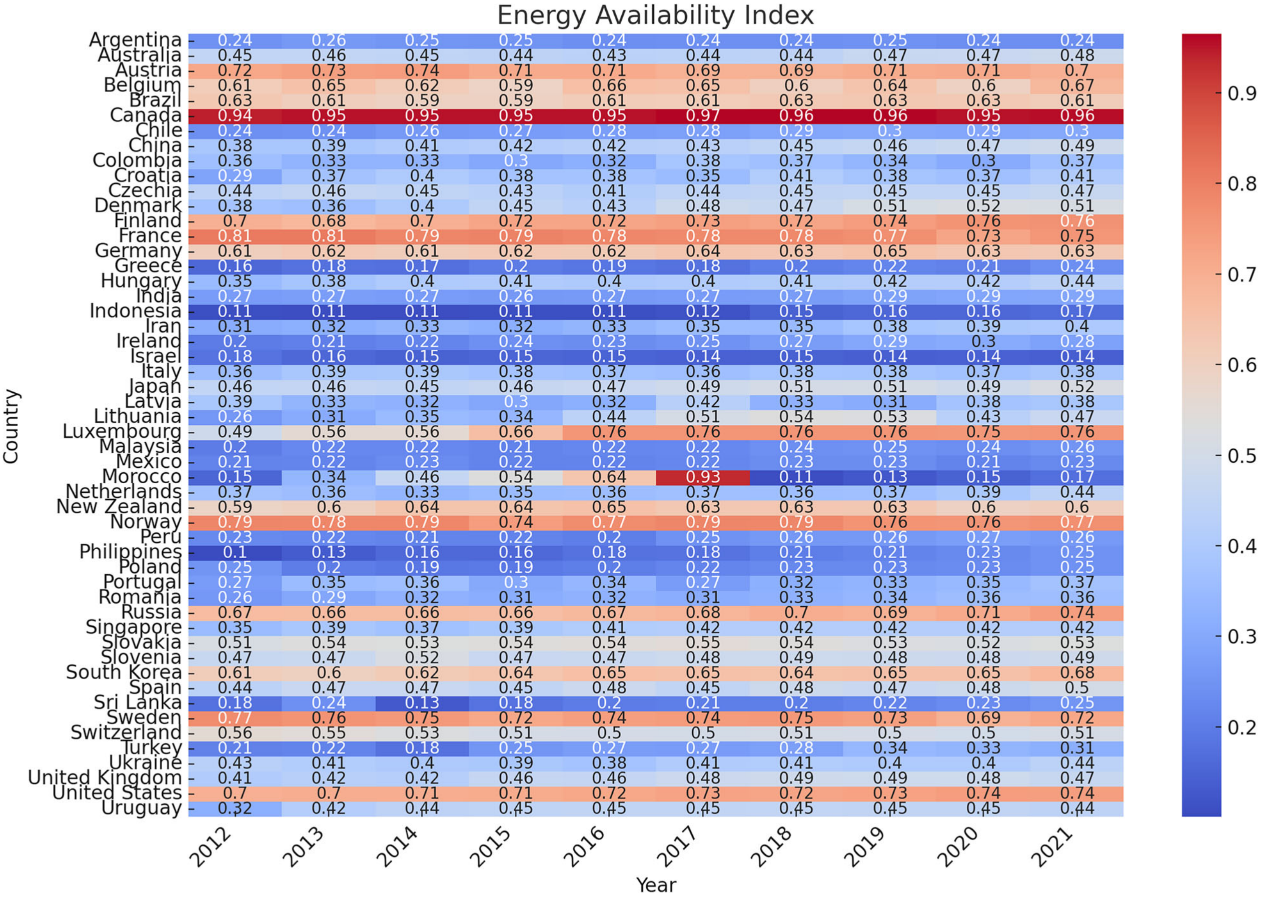


Fig. 5 Energy reliability index comparison of all countries.



Country	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Argentina	0.24	0.26	0.25	0.25	0.24	0.24	0.24	0.25	0.24	0.24
Australia	0.45	0.46	0.45	0.44	0.43	0.44	0.44	0.47	0.47	0.48
Austria	0.72	0.73	0.74	0.71	0.71	0.69	0.69	0.71	0.71	0.7
Belgium	0.61	0.65	0.62	0.59	0.66	0.65	0.6	0.64	0.6	0.67
Brazil	0.63	0.61	0.59	0.59	0.61	0.61	0.63	0.63	0.63	0.61
Canada	0.94	0.95	0.95	0.95	0.95	0.97	0.96	0.96	0.95	0.96
Chile	0.24	0.24	0.26	0.27	0.28	0.28	0.29	0.3	0.29	0.3
China	0.38	0.39	0.41	0.42	0.42	0.43	0.45	0.46	0.47	0.49
Colombia	0.36	0.33	0.33	0.3	0.32	0.38	0.37	0.34	0.3	0.37
Croatia	0.29	0.37	0.4	0.38	0.38	0.35	0.41	0.38	0.37	0.41
Czechia	0.44	0.46	0.45	0.43	0.41	0.44	0.45	0.45	0.45	0.47
Denmark	0.38	0.36	0.4	0.45	0.43	0.48	0.47	0.51	0.52	0.51
Finland	0.7	0.68	0.7	0.72	0.72	0.73	0.72	0.74	0.76	0.76
France	0.81	0.81	0.79	0.79	0.78	0.78	0.78	0.77	0.73	0.75
Germany	0.61	0.62	0.61	0.62	0.62	0.64	0.63	0.65	0.63	0.63
Greece	0.16	0.18	0.17	0.2	0.19	0.18	0.2	0.22	0.21	0.24
Hungary	0.35	0.38	0.4	0.41	0.4	0.4	0.41	0.42	0.42	0.44
India	0.27	0.27	0.27	0.26	0.27	0.27	0.27	0.29	0.29	0.29
Indonesia	0.11	0.11	0.11	0.11	0.11	0.12	0.15	0.16	0.16	0.17
Iran	0.31	0.32	0.33	0.32	0.33	0.35	0.35	0.38	0.39	0.4
Ireland	0.2	0.21	0.22	0.24	0.23	0.25	0.27	0.29	0.3	0.28
Israel	0.18	0.16	0.15	0.15	0.15	0.14	0.15	0.14	0.14	0.14
Italy	0.36	0.39	0.39	0.38	0.37	0.36	0.38	0.38	0.37	0.38
Japan	0.46	0.46	0.45	0.46	0.47	0.49	0.51	0.51	0.49	0.52
Latvia	0.39	0.33	0.32	0.3	0.32	0.42	0.33	0.31	0.38	0.38
Lithuania	0.26	0.31	0.35	0.34	0.44	0.51	0.54	0.53	0.43	0.47
Luxembourg	0.49	0.56	0.56	0.66	0.76	0.76	0.76	0.76	0.75	0.76
Malaysia	0.2	0.22	0.22	0.21	0.22	0.22	0.24	0.25	0.24	0.26
Mexico	0.21	0.22	0.23	0.22	0.22	0.22	0.23	0.23	0.21	0.23
Morocco	0.15	0.34	0.46	0.54	0.64	0.93	0.11	0.13	0.15	0.17
Netherlands	0.37	0.36	0.33	0.35	0.36	0.37	0.36	0.37	0.39	0.44
New Zealand	0.59	0.6	0.64	0.64	0.65	0.63	0.63	0.63	0.6	0.6
Norway	0.79	0.78	0.79	0.74	0.77	0.79	0.79	0.76	0.76	0.77
Peru	0.23	0.22	0.21	0.22	0.2	0.25	0.26	0.26	0.27	0.26
Philippines	0.1	0.13	0.16	0.16	0.18	0.18	0.21	0.21	0.23	0.25
Poland	0.25	0.2	0.19	0.19	0.2	0.22	0.23	0.23	0.23	0.25
Portugal	0.27	0.35	0.36	0.3	0.34	0.27	0.32	0.33	0.35	0.37
Romania	0.26	0.29	0.32	0.31	0.32	0.31	0.33	0.34	0.36	0.36
Russia	0.67	0.66	0.66	0.66	0.67	0.68	0.7	0.69	0.71	0.74
Singapore	0.35	0.39	0.37	0.39	0.41	0.42	0.42	0.42	0.42	0.42
Slovakia	0.51	0.54	0.53	0.54	0.54	0.55	0.54	0.53	0.52	0.53
Slovenia	0.47	0.47	0.52	0.47	0.47	0.48	0.49	0.48	0.48	0.49
South Korea	0.61	0.6	0.62	0.64	0.65	0.65	0.64	0.65	0.65	0.68
Spain	0.44	0.47	0.47	0.45	0.48	0.45	0.48	0.47	0.48	0.5
Sri Lanka	0.18	0.24	0.13	0.18	0.2	0.21	0.2	0.22	0.23	0.25
Sweden	0.77	0.76	0.75	0.72	0.74	0.74	0.75	0.73	0.69	0.72
Switzerland	0.56	0.55	0.53	0.51	0.5	0.5	0.51	0.5	0.5	0.51
Turkey	0.21	0.22	0.18	0.25	0.27	0.27	0.28	0.34	0.33	0.31
Ukraine	0.43	0.41	0.4	0.39	0.38	0.41	0.41	0.4	0.4	0.44
United Kingdom	0.41	0.42	0.42	0.46	0.46	0.48	0.49	0.49	0.48	0.47
United States	0.7	0.7	0.71	0.71	0.72	0.73	0.72	0.73	0.74	0.74
Uruguay	0.32	0.42	0.44	0.45	0.45	0.45	0.45	0.45	0.45	0.44

Fig. 6 Energy Availability index value by year.

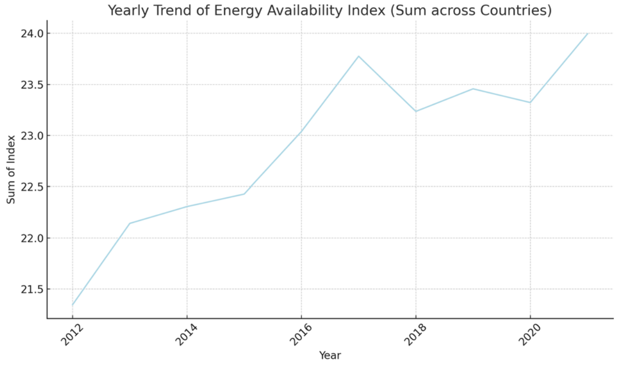


Fig. 7 Energy Availability Index comparison of all countries.

providing reliable energy access to remote regions. China's Energy Availability Index remains mid-range due to several factors. If we look back at energy consumption and supply with electricity production from non-renewables, then we might understand China's middle scores. The total energy consumption surged from 32,624.2 in 2012 to 43,847 in 2021; energy supply actually decreased from 13,020.948 to 9629.64 during the same period. Simultaneously, non-renewable electricity production declined from 77.71 to 66.25%, revealing two significant trends: first, rapidly growing demand driven by economic and population growth has created a supply-demand imbalance; second, China's gradual transition toward renewable energy (particularly solar) is evident, though meeting escalating energy needs remains challenging. These findings demonstrate stark global disparities in energy availability, emphasizing the critical need for international cooperation and innovation to achieve SDG-7 and SDG-9 targets. Figure 7 confirms this upward trajectory through collective average progress, where the overall trend continues to rise despite periodic fluctuations. Notably, many nations still prioritize non-renewable sources for meeting energy demands (see Fig. 8).

Energy Affordability Index &SDGs-7 (Target 7.3). The Energy Affordability Index (Fig. 9), measured by electricity prices, gasoline prices, and access to electricity, reflects how accessible and affordable energy is for households and industries across the country. A higher value suggests that energy is more affordable for citizens. This index aligns with SDG-7, which seeks to ensure universal access to affordable and clean energy. In 2021, Norway's affordability score was 0.74, indicating affordable energy prices. Argentina, with a score of 0.88, shows that energy is relatively affordable, possibly due to government price controls. However, economic instability may still cause fluctuating affordability for its citizens. China also scored 0.82, showing affordable energy prices and maximum electricity access. India's score of 0.38 in 2021 shows that, despite substantial improvements in access, the cost of energy remains a significant financial burden for low-income households. This index is integral to SDG-7, which advocates for affordable energy prices for all, particularly in developing nations. In India and Argentina, enhancing affordability can help improve the quality of life and reduce energy poverty (SDG-1), while in Norway, maintaining affordability ensures energy accessibility for all socioeconomic groups.

Iran consistently exhibits the highest energy affordability values, indicating low energy costs. The results align with those of Mamipour et al. (2023), who stated that Iran has long

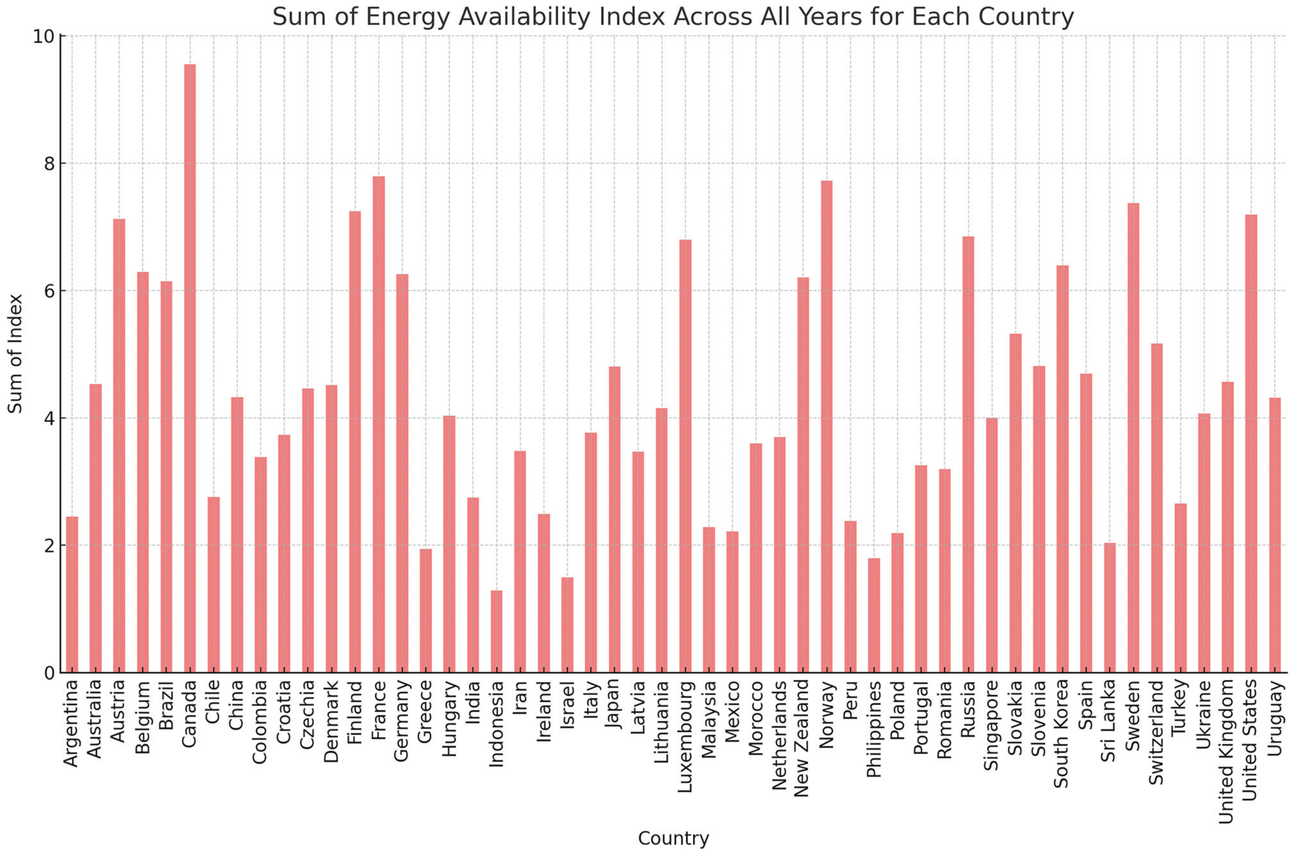


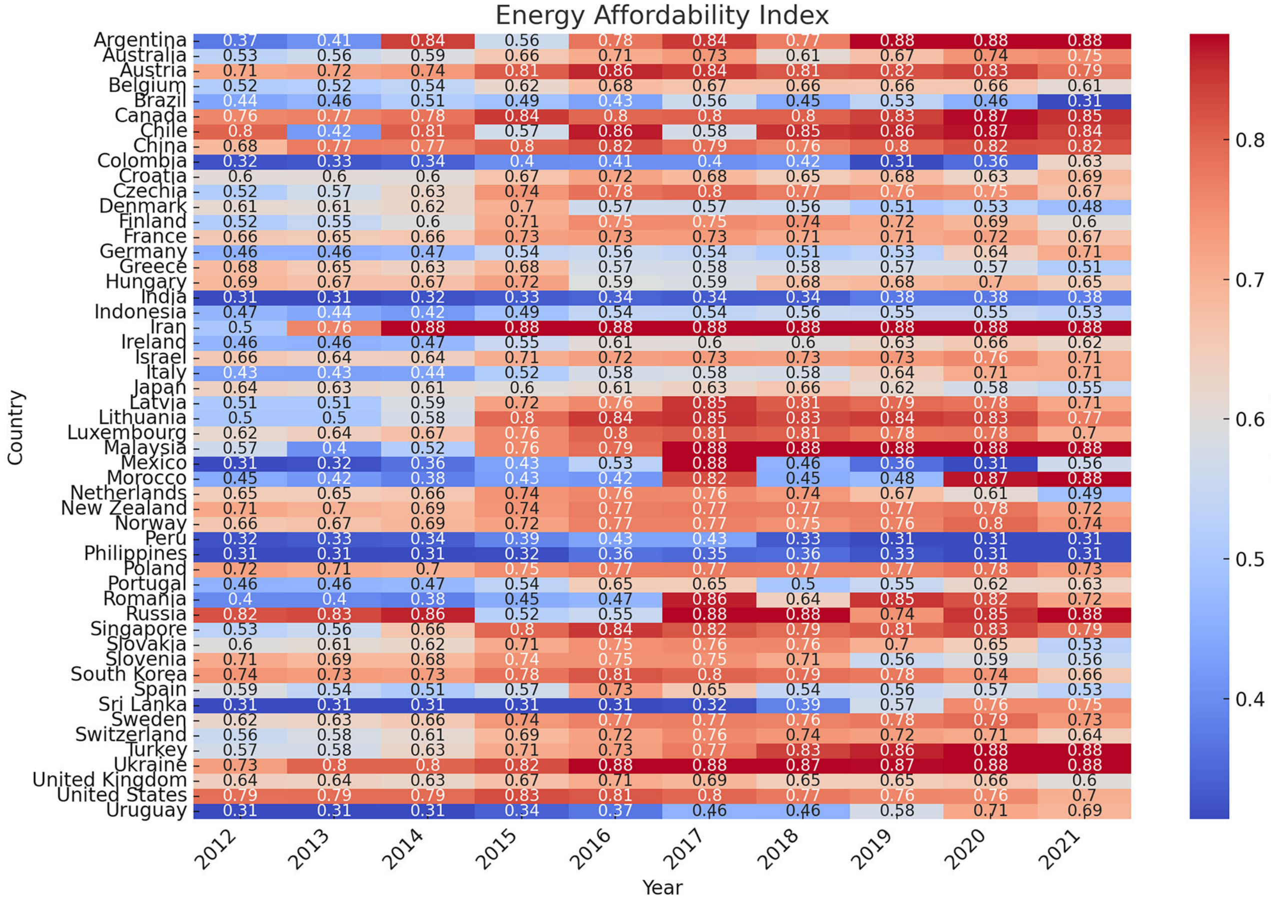
Fig. 8 Energy Availability Index growth trend over the Years (2012–2021).

maintained some of the lowest gasoline prices globally, supported by the government's significant direct and indirect subsidies. Figure 10 highlights yearly energy affordability across countries. Figure 11 shows the overall energy affordability throughout the sample period of each country.

Energy Sustainability Index &SDGs7,13 (Target 7.2 & 13.2). Figure 12 (Sustainability Index) provides a clear visualization of global energy sustainability. A higher score reflects the use of renewable energy sources and a reduction in carbon emissions. Countries like Uruguay, Austria, Denmark, and Norway are leaders in energy sustainability, as reflected by their high Energy Sustainability Index scores. Uruguay has become a model for renewable energy integration, with over 98% of its electricity from renewables. In 2005, Uruguay embarked on a major transformation of its energy sector, transitioning from fossil fuel-based electricity production to renewable sources. Despite a temporary rise in fossil fuel use during a severe drought in 2022, the country remains a global leader in renewable energy. Today, Uruguay generates more than 98%[2] of its electricity from renewables, with wind and hydropower as the primary contributors. Similarly, Austria's reliance on hydropower and Denmark's global leadership in wind energy further contribute to their high scores. Norway's energy system, almost entirely based on hydropower, ensures a low carbon footprint. These countries also prioritize energy efficiency and have set ambitious goals to achieve carbon neutrality by 2050. Their success in transitioning to clean energy sources not only advances SDG 7 but also supports SDG 13, positioning them as exemplary models for sustainability and climate change mitigation.

Despite substantial investments in renewable energy, China remains the world's largest emitter of CO_2, primarily because it relies on coal for electricity generation. However, India has made strides in renewable energy (especially solar). However, renewable sources still account for a small proportion of the overall energy mix compared to non-renewable sources like coal. Energy intensity in India is high due to inefficient energy use, poor energy infrastructure, and large-scale industrial energy consumption. In summary, India's, Iran's, and Ukraine's low values reflect their ongoing reliance on non-renewable energy, the slow pace of transitioning to renewable energy, and the inefficiencies in their energy systems. Addressing these challenges is essential for these countries to improve their energy sustainability and meet global climate targets. This factor weighs heavily in the Energy Sustainability Index, as inefficient energy use leads to a higher environmental impact. Figure 13 shows the ups and downs of overall global progress or challenges in achieving sustainable energy systems in the sample countries. On the other hand, Fig. 14 showed the country's overall energy sustainability and at the same time.

Energy Security Index & SDGs7,9,13(Target 7.1, 7.2, 7.3), 9 (Target 9.4), 13 (Target 13.2). As shown in Fig. 15, the Energy Security Index is a composite metric that combines multiple dimensions of energy sustainability, availability, affordability, and reliability, closely aligning with SDGs 7, 9 and SDG 13. This index reflects a country's ability to ensure reliable and adequate energy supplies while minimizing environmental and economic risks. The Energy Security Index provides a comprehensive assessment of a country's ability to maintain stable, affordable, and sustainable energy supplies, measured across four key dimensions: reliability, availability, affordability, and sustainability. Between 2012 and 2021, global trends revealed significant disparities in energy security performance. Top-performing nations like Norway, Sweden, and



Country	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Argentina	0.37	0.41	0.84	0.56	0.78	0.84	0.77	0.88	0.88	0.88
Australia	0.53	0.56	0.59	0.66	0.71	0.73	0.61	0.67	0.74	0.75
Austria	0.71	0.72	0.74	0.81	0.86	0.84	0.81	0.82	0.83	0.79
Belgium	0.52	0.52	0.54	0.62	0.68	0.67	0.66	0.66	0.66	0.61
Brazil	0.44	0.46	0.51	0.49	0.43	0.56	0.45	0.53	0.46	0.31
Canada	0.76	0.77	0.78	0.84	0.8	0.8	0.8	0.83	0.87	0.85
Chile	0.8	0.42	0.81	0.57	0.86	0.58	0.85	0.86	0.87	0.84
China	0.68	0.77	0.77	0.8	0.82	0.79	0.76	0.8	0.82	0.82
Colombia	0.32	0.33	0.34	0.4	0.41	0.4	0.42	0.31	0.36	0.63
Croatia	0.6	0.6	0.6	0.67	0.72	0.68	0.65	0.68	0.63	0.69
Czechia	0.52	0.57	0.63	0.74	0.78	0.8	0.77	0.76	0.75	0.67
Denmark	0.61	0.61	0.62	0.7	0.57	0.57	0.56	0.51	0.53	0.48
Finland	0.52	0.55	0.6	0.71	0.75	0.75	0.74	0.72	0.69	0.6
France	0.66	0.65	0.66	0.73	0.73	0.73	0.71	0.71	0.72	0.67
Germany	0.46	0.46	0.47	0.54	0.56	0.54	0.51	0.53	0.64	0.71
Greece	0.68	0.65	0.63	0.68	0.57	0.58	0.58	0.57	0.57	0.51
Hungary	0.69	0.67	0.67	0.72	0.59	0.59	0.68	0.68	0.7	0.65
India	0.31	0.31	0.32	0.33	0.34	0.34	0.34	0.38	0.38	0.38
Indonesia	0.47	0.44	0.42	0.49	0.54	0.54	0.56	0.55	0.55	0.53
Iran	0.5	0.76	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Ireland	0.46	0.46	0.47	0.55	0.61	0.6	0.6	0.63	0.66	0.62
Israel	0.66	0.64	0.64	0.71	0.72	0.73	0.73	0.73	0.76	0.71
Italy	0.43	0.43	0.44	0.52	0.58	0.58	0.58	0.64	0.71	0.71
Japan	0.64	0.63	0.61	0.6	0.61	0.63	0.66	0.62	0.58	0.55
Latvia	0.51	0.51	0.59	0.72	0.76	0.85	0.81	0.79	0.78	0.71
Lithuania	0.5	0.5	0.58	0.8	0.84	0.85	0.83	0.84	0.83	0.77
Luxembourg	0.62	0.64	0.67	0.76	0.8	0.81	0.81	0.78	0.78	0.7
Malaysia	0.57	0.4	0.52	0.76	0.79	0.88	0.88	0.88	0.88	0.88
Mexico	0.31	0.32	0.36	0.43	0.53	0.88	0.46	0.36	0.31	0.56
Morocco	0.45	0.42	0.38	0.43	0.42	0.82	0.45	0.48	0.87	0.88
Netherlands	0.65	0.65	0.66	0.74	0.76	0.76	0.74	0.67	0.61	0.49
New Zealand	0.71	0.7	0.69	0.74	0.77	0.77	0.77	0.77	0.78	0.72
Norway	0.66	0.67	0.69	0.72	0.77	0.77	0.75	0.76	0.8	0.74
Peru	0.32	0.33	0.34	0.39	0.43	0.43	0.33	0.31	0.31	0.31
Philippines	0.31	0.31	0.31	0.32	0.36	0.35	0.36	0.33	0.31	0.31
Poland	0.72	0.71	0.7	0.75	0.77	0.77	0.77	0.77	0.78	0.73
Portugal	0.46	0.46	0.47	0.54	0.65	0.65	0.5	0.55	0.62	0.63
Romania	0.4	0.4	0.38	0.45	0.47	0.86	0.64	0.85	0.82	0.72
Russia	0.82	0.83	0.86	0.52	0.55	0.88	0.88	0.74	0.85	0.88
Singapore	0.53	0.56	0.66	0.8	0.84	0.82	0.79	0.81	0.83	0.79
Slovakia	0.6	0.61	0.62	0.71	0.75	0.76	0.76	0.7	0.65	0.53
Slovenia	0.71	0.69	0.68	0.74	0.75	0.75	0.71	0.56	0.59	0.56
South Korea	0.74	0.73	0.73	0.78	0.81	0.8	0.79	0.78	0.74	0.66
Spain	0.59	0.54	0.51	0.57	0.73	0.65	0.54	0.56	0.57	0.53
Sri Lanka	0.31	0.31	0.31	0.31	0.31	0.32	0.39	0.57	0.76	0.75
Sweden	0.62	0.63	0.66	0.74	0.77	0.77	0.76	0.78	0.79	0.73
Switzerland	0.56	0.58	0.61	0.69	0.72	0.76	0.74	0.72	0.71	0.64
Turkey	0.57	0.58	0.63	0.71	0.73	0.77	0.83	0.86	0.88	0.88
Ukraine	0.73	0.8	0.8	0.82	0.88	0.88	0.87	0.87	0.88	0.88
United Kingdom	0.64	0.64	0.63	0.67	0.71	0.69	0.65	0.65	0.66	0.6
United States	0.79	0.79	0.79	0.83	0.81	0.8	0.77	0.76	0.76	0.7
Uruguay	0.31	0.31	0.31	0.34	0.37	0.46	0.46	0.58	0.71	0.69

Fig. 9 Energy Affordability Index value by year.

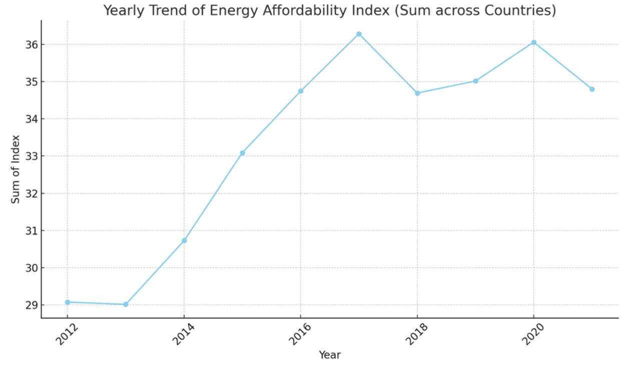


Fig. 10 Energy Affordability Index growth trend over the Years (2012–2021).

Canada consistently scored above 0.70 due to their diversified energy portfolios, strong renewable energy adoption, and robust infrastructure. These countries demonstrated how abundant domestic resources, particularly hydropower and wind energy, coupled with efficient long-term energy stability.

Meanwhile, several nations made remarkable improvements during this period, with Uruguay standing out as a success story by increasing its index from 0.36 to 0.67 through a strategic transition to 98% renewable electricity generation from wind and hydropower. Other countries like Turkey and Germany also showed significant progress through renewable energy expansion and grid modernization efforts. However, many developing nations continued to face challenges, with countries like India, the Philippines, and Morocco struggling with scores below 0.50 due to high fuel import dependency, and limited access to affordable electricity. Countries relying heavily on fossil fuels, such as Mexico and Russia, experienced more volatility in their energy security scores, particularly when facing geopolitical tensions or policy instability. The findings underscore the importance of diversified energy sources, modernized infrastructure, and stable policy frameworks in achieving energy security. The index highlights both the progress made and the significant work remaining, particularly in developing economies where energy access and affordability remain pressing concerns. The most successful cases demonstrate that long-term planning, investment in renewable energy, and regional cooperation are essential components of a robust energy security strategy.

Low-performing countries face a dual challenge: addressing energy poverty while transitioning to cleaner, more secure energy systems. Investments in renewable energy, grid modernization, and energy efficiency will be critical for these nations to improve their energy security index. For instance, India has made substantial strides in expanding solar energy capacity, but it still faces considerable energy reliability and affordability challenges. Overall, the growth trend shown in Fig. 16 and the global landscape depicted in Fig. 17. This emphasizes that no country has yet achieved comprehensive (full) energy security, and substantial work is needed to meet the targets SDGs.

Regression findings and discussion

Initial require validation testing approaches. Before proceeding with any econometric analysis, one must pass some basic tests for authentic findings. Thus, the study applied the cross-dependence Pesaran (2003 and 2015) to confirm whether the panel data set involves inter-dependence. The findings are given in Table A4.

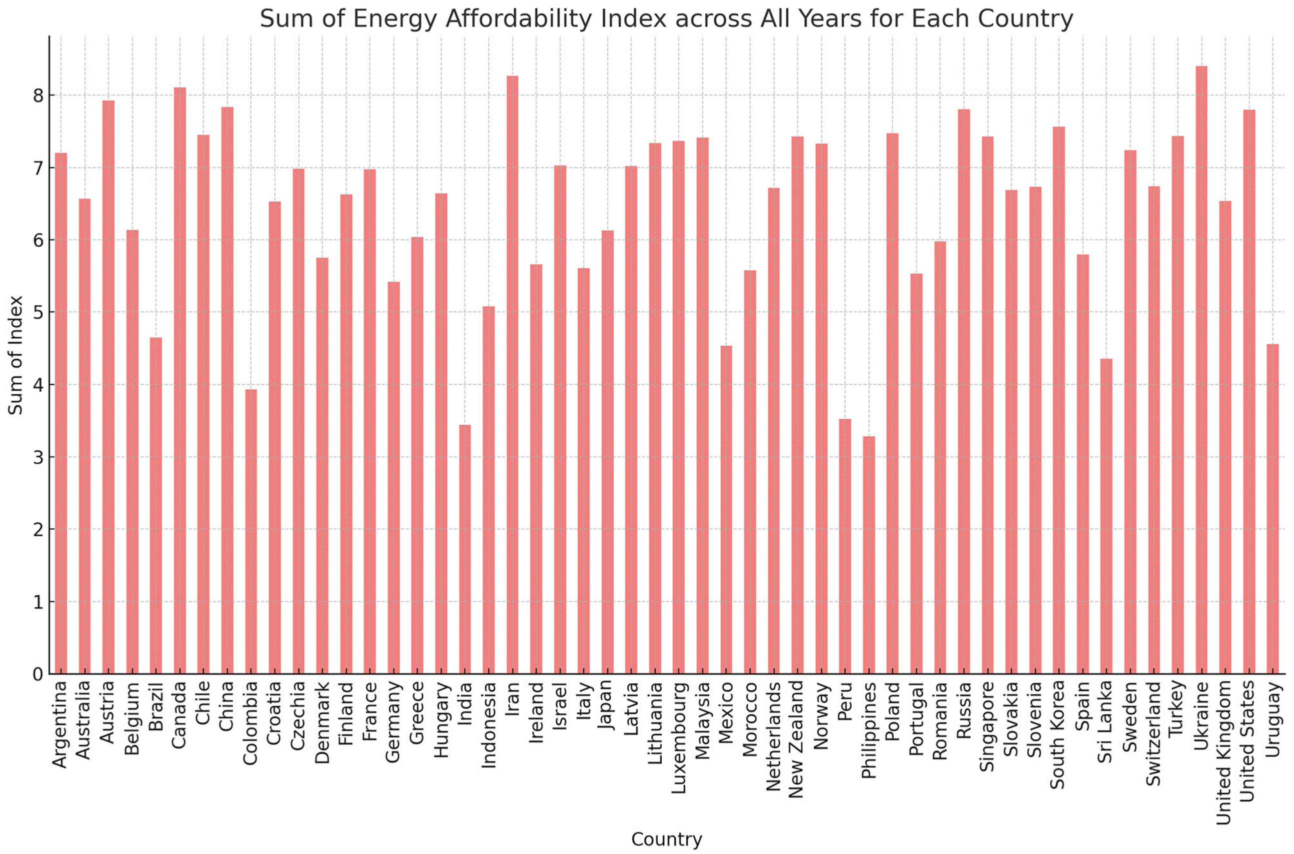


Fig. 11 Energy Affordability Index comparison of all countries.

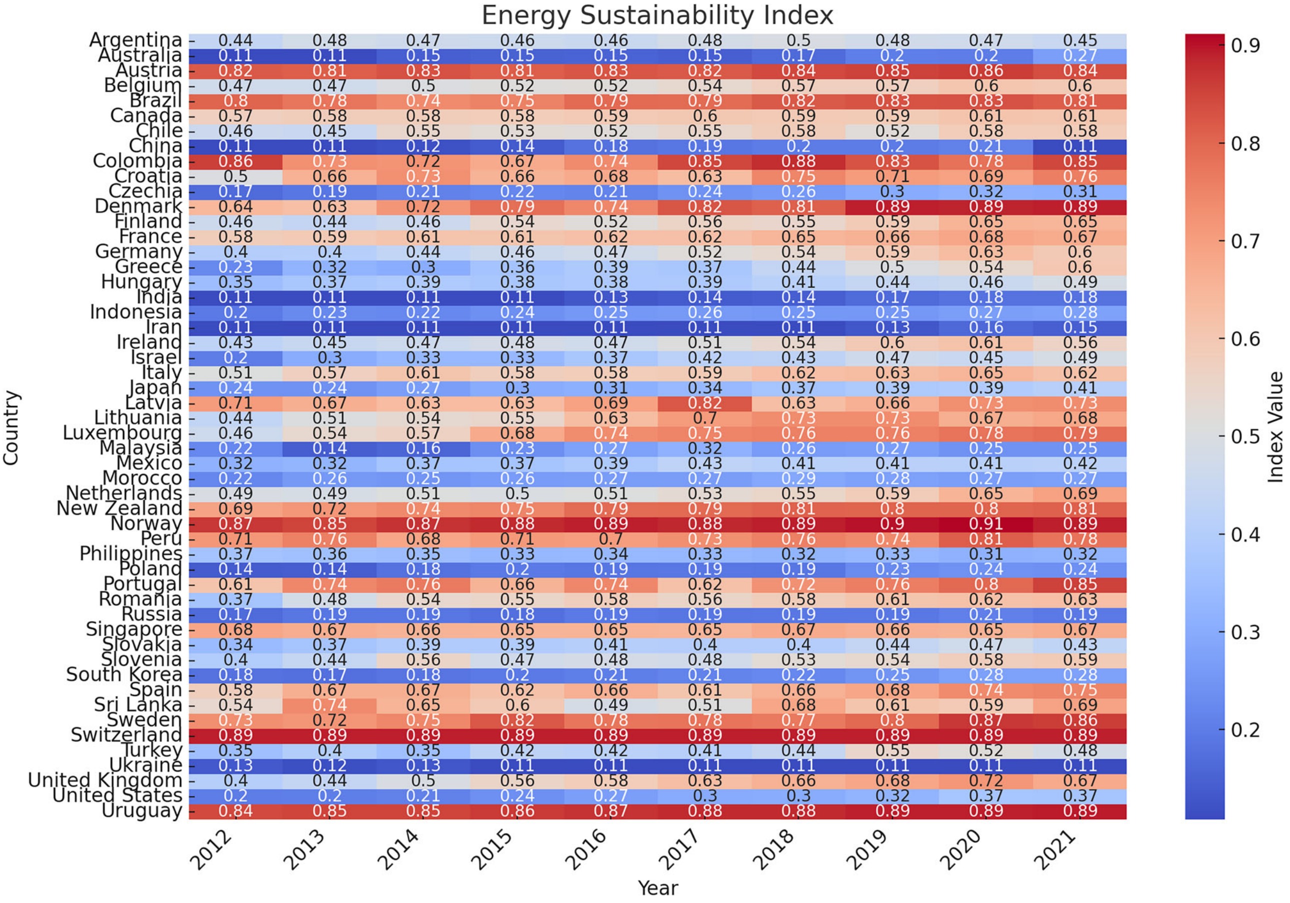
The p-values of all parameters confirmed cross-dependence in the panel data set, as they are below 5%. This test leads us to test the unit root level. Due to the CD presence, applying cross-sectionally augmented panel unit root CIPS Pesaran (2007) is valid. The results are given in Table A5, which confirms that the concerned variables are involved in first-difference stationarity.

The previous section showed a mixed scenario (not fully achieved SDGs) of the sampled countries moving towards achieving the universal SDGs. Thus, the study incorporated the role of AI to assess whether the advanced technology would be leveraged to achieve the SDGs. For that, we perform the econometric method to determine their relationship direction. First, this study checks the direct relationship between the parameters. We used the “Scatter Plot Matrix of Correlations” (Fig. 18). It shows the direction of the relation and the correlation value between the two parameters. The results showed that the Energy indexes positively correlate with “scholarly publication on artificial intelligence” (AI_SR) (0.399, 0.373, 0.258, 0.343 and 0.511). AIPE and “Investment in Artificial Intelligence” (AI_Inv) also positively correlated in most of the energy index. However, among AI indicators, AI_SR shows a stronger relation than others. However, the Gini_index relation is negative with the energy indices. It implies that as income inequality (represented by a higher Gini index) increases, access to modern energy services tends to become more restricted, especially for lower-income groups (Sonora, 2022; Igawa and Managi, 2022).

The affordability index shows a negative relation with AI_Inv and AI_SR. It means that AI can play a significant role in improving energy efficiency by minimizing the use of energy per output. However, surprisingly, AIPE shows a positive impact; however, the correlation is weak. It shows that AIPE is not very effective or direct in reducing energy consumption. Further, inflation reduces sustainability while GDP increases energy security indexes. However, Ind showed a mixed pattern. The overall impact of AI parameters on energy security is positive, as the graph shows an upward trend. However, income inequality and inflation are not favorable to securing energy.

Driscoll & Kraay’s findings. In this step, the study determines the significant magnitude of the association of AI with energy security, and the study applies the D&K. D&K is justifiable as the study data involved cross-dependence. Thus, D&K is suitable for authentic findings. The study runs a separate regression for each energy index for comprehensive and detailed analysis. Findings for the energy availability index are given in Table 2. The first column incorporates the AI impacts without including controlling factors. However, the second column’s findings endorsed the first column by controlling for other factors. The study also controls for the year and country-specific effects for robustness estimation. Table findings reveal that a 1% increase in energy patent AI can enhance the availability (measured by total energy consumption & supply, electricity production from non-renewables) of energy significantly up to (0.0137 to 1.53%). While these results are meaningful, the effects’ economic magnitude is modest. However, even improvements in energy availability can have meaningful long-term impacts on energy systems.

Coefficients improved when country and year-specific effects were included, indicating that controlling for these factors enhances the robustness of the findings. Additionally, the analysis supports correlation rather than causality; therefore, any causal interpretation of these findings should be toned down. Nevertheless, these relationships highlight the potential for AI to contribute to energy security, though further research. Energy-related innovations derived from AI patents often lead to more



Country	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Argentina	0.44	0.48	0.47	0.46	0.46	0.48	0.5	0.48	0.47	0.45
Australia	0.11	0.11	0.15	0.15	0.15	0.15	0.17	0.2	0.2	0.27
Austria	0.82	0.81	0.83	0.81	0.83	0.82	0.84	0.85	0.86	0.84
Belgium	0.47	0.47	0.5	0.52	0.52	0.54	0.57	0.57	0.6	0.6
Brazil	0.8	0.78	0.74	0.75	0.79	0.79	0.82	0.83	0.83	0.81
Canada	0.57	0.58	0.58	0.58	0.59	0.6	0.59	0.59	0.61	0.61
Chile	0.46	0.45	0.55	0.53	0.52	0.55	0.58	0.52	0.58	0.58
China	0.11	0.11	0.12	0.14	0.18	0.19	0.2	0.2	0.21	0.11
Colombia	0.86	0.73	0.72	0.67	0.74	0.85	0.88	0.83	0.78	0.85
Croatia	0.5	0.66	0.73	0.66	0.68	0.63	0.75	0.71	0.69	0.76
Czechia	0.17	0.19	0.21	0.22	0.21	0.24	0.26	0.3	0.32	0.31
Denmark	0.64	0.63	0.72	0.79	0.74	0.82	0.81	0.89	0.89	0.89
Finland	0.46	0.44	0.46	0.54	0.52	0.56	0.55	0.59	0.65	0.65
France	0.58	0.59	0.61	0.61	0.62	0.62	0.65	0.66	0.68	0.67
Germany	0.4	0.4	0.44	0.46	0.47	0.52	0.54	0.59	0.63	0.6
Greece	0.23	0.32	0.3	0.36	0.39	0.37	0.44	0.5	0.54	0.6
Hungary	0.35	0.37	0.39	0.38	0.38	0.39	0.41	0.44	0.46	0.49
India	0.11	0.11	0.11	0.11	0.13	0.14	0.14	0.17	0.18	0.18
Indonesia	0.2	0.23	0.22	0.24	0.25	0.26	0.25	0.25	0.27	0.28
Iran	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.13	0.16	0.15
Ireland	0.43	0.45	0.47	0.48	0.47	0.51	0.54	0.6	0.61	0.56
Israel	0.2	0.3	0.33	0.33	0.37	0.42	0.43	0.47	0.45	0.49
Italy	0.51	0.57	0.61	0.58	0.58	0.59	0.62	0.63	0.65	0.62
Japan	0.24	0.24	0.27	0.3	0.31	0.34	0.37	0.39	0.39	0.41
Latvia	0.71	0.67	0.63	0.63	0.69	0.82	0.63	0.66	0.73	0.73
Lithuania	0.44	0.51	0.54	0.55	0.63	0.7	0.73	0.73	0.67	0.68
Luxembourg	0.46	0.54	0.57	0.68	0.74	0.75	0.76	0.76	0.78	0.79
Malaysia	0.22	0.14	0.16	0.23	0.27	0.32	0.26	0.27	0.25	0.25
Mexico	0.32	0.32	0.37	0.37	0.39	0.43	0.41	0.41	0.41	0.42
Morocco	0.22	0.26	0.25	0.26	0.27	0.27	0.29	0.28	0.27	0.27
Netherlands	0.49	0.49	0.51	0.5	0.51	0.53	0.55	0.59	0.65	0.69
New Zealand	0.69	0.72	0.74	0.75	0.79	0.79	0.81	0.8	0.8	0.81
Norway	0.87	0.85	0.87	0.88	0.89	0.88	0.89	0.9	0.91	0.89
Peru	0.71	0.76	0.68	0.71	0.7	0.73	0.76	0.74	0.81	0.78
Philippines	0.37	0.36	0.35	0.33	0.34	0.33	0.32	0.33	0.31	0.32
Poland	0.14	0.14	0.18	0.2	0.19	0.19	0.19	0.23	0.24	0.24
Portugal	0.61	0.74	0.76	0.66	0.74	0.62	0.72	0.76	0.8	0.85
Romania	0.37	0.48	0.54	0.55	0.58	0.56	0.58	0.61	0.62	0.63
Russia	0.17	0.19	0.19	0.18	0.19	0.19	0.19	0.19	0.21	0.19
Singapore	0.68	0.67	0.66	0.65	0.65	0.65	0.67	0.66	0.65	0.67
Slovakia	0.34	0.37	0.39	0.39	0.41	0.4	0.4	0.44	0.47	0.43
Slovenia	0.4	0.44	0.56	0.47	0.48	0.48	0.53	0.54	0.58	0.59
South Korea	0.18	0.17	0.18	0.2	0.21	0.21	0.22	0.25	0.28	0.28
Spain	0.58	0.67	0.67	0.62	0.66	0.61	0.66	0.68	0.74	0.75
Sri Lanka	0.54	0.74	0.65	0.6	0.49	0.51	0.68	0.61	0.59	0.69
Sweden	0.73	0.72	0.75	0.82	0.78	0.78	0.77	0.8	0.87	0.86
Switzerland	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
Turkey	0.35	0.4	0.35	0.42	0.42	0.41	0.44	0.55	0.52	0.48
Ukraine	0.13	0.12	0.13	0.11	0.11	0.11	0.11	0.11	0.11	0.11
United Kingdom	0.4	0.44	0.5	0.56	0.58	0.63	0.66	0.68	0.72	0.67
United States	0.2	0.2	0.21	0.24	0.27	0.3	0.3	0.32	0.37	0.37
Uruguay	0.84	0.85	0.85	0.86	0.87	0.88	0.88	0.89	0.89	0.89

Fig. 12 Energy Sustainability Index value by year.

efficient energy production technologies that enhance domestic production capabilities. These innovations also improve energy distribution and consumption efficiency, optimizing resource use and ensuring more reliable access to energy across both production and consumption sectors. This implies that AIPE is valuable if it goes in the right direction and aligns with environmental policy.

AI_Inv is also positive and improves energy availability by (0.819 to 2.13%). Investing in AI technologies for energy is a strategic move to improve energy efficiency, reduce waste, and enable more sustainable energy (Nižetić et al., 2019). Investment in AI-powered clean tech can reduce costs and increase renewable energy solutions. However, the role of AI_SR is significant and increases from (0.0863% to 0.0946) when controlled by other factors. AI-based scholarly research, such as machine learning, can analyze vast energy consumption data, predict demand patterns, and identify energy generation and distribution inefficiencies. By processing information through logical channels—where data is collected, filtered, and analyzed based on defined rules—AI-based research can offer actionable insights for energy providers to optimize grid management, enhance renewable energy integration, and reduce waste (Rao et al., 2024). This dynamic, data-driven approach helps ensure that energy resources are available, distributed efficiently, and utilized sustainably, ultimately improving energy access and reliability. The positive impact of AI on energy can be defended by (Lee et al., 2024; Tao et al., 2024). So, the results imply that AI significantly improves energy availability. For instance, AI-powered smart grids have transformed energy systems using real-time data to allocate energy efficiently and quickly detect faults, ensuring that energy is consistently available when and where needed.

A notable example is Pacific Gas and Electric in the U.S., which uses AI to monitor grid infrastructure and predict faults before they result in outages, thereby reducing the number of blackouts and enhancing grid reliability. Additionally, AI helps enhance energy generation by enabling more efficient use of renewable resources. AI optimizes the integration of solar and wind energy by predicting fluctuations in weather patterns. Germany's energy transition has successfully implemented AI technologies to manage renewable energy and reducing reliance on fossil fuels.

Economic growth (13.8%) and industrialization (2.77%) are the most influential factors in increasing energy availability. As an economy grows, energy demand increases due to higher consumption by businesses, transportation, and households. Further economic expansion often drives investments in energy infrastructure, technologies, and innovations that can improve the overall energy supply (Ahmed et al., 2022). Similarly, industrialization typically leads to greater energy needs for manufacturing processes, machinery, and transportation networks. This encourages investments in more sustainable energy sources and technologies, improving energy availability. However, income inequality (0.31%) and inflation (4.9%) reduce the availability. In societies with high income inequality, lower-income households often lack the financial means to access reliable energy sources, leading to disparities in energy availability. As a result, economic inequality can contribute to energy poverty, where a significant portion of the population struggles to

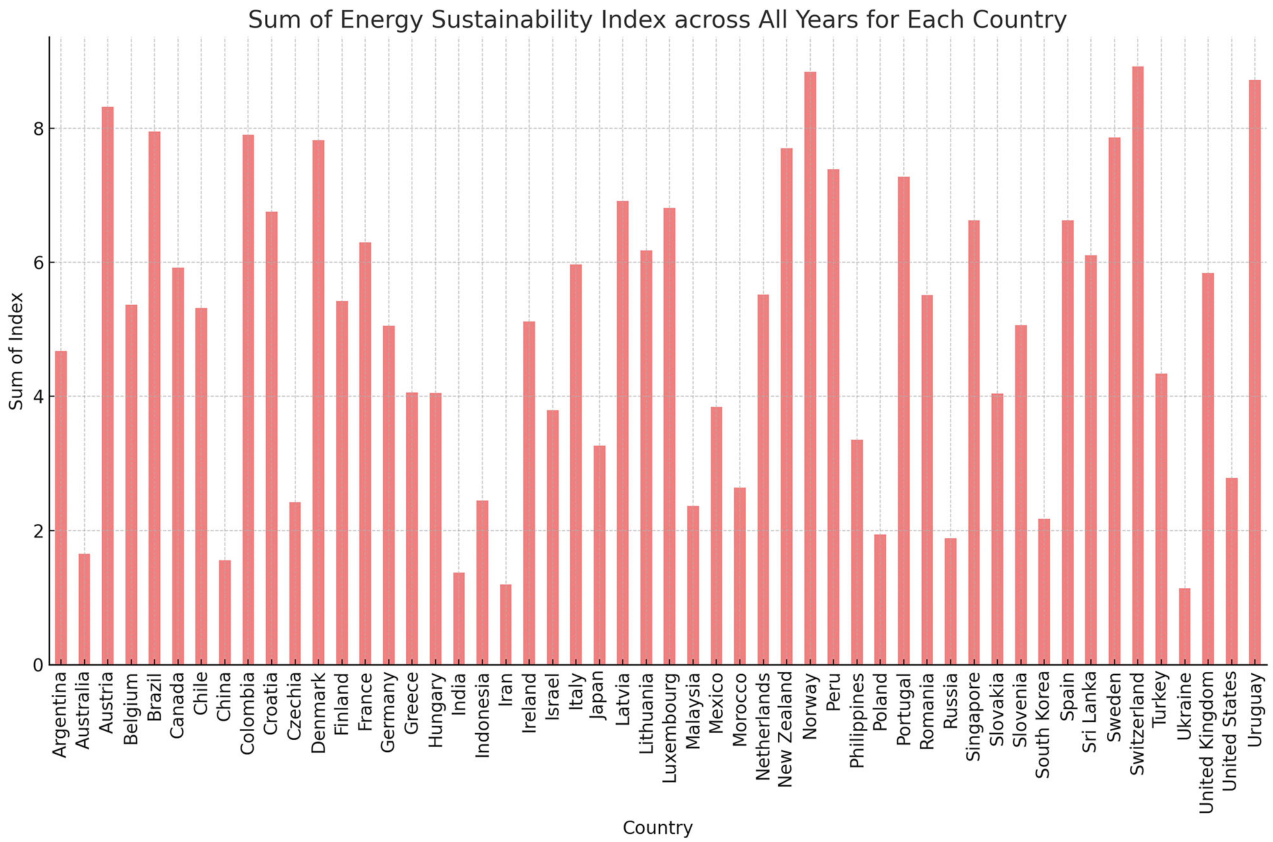


Fig. 13 Energy Sustainable Index growth trend over the Years (2012–2021).

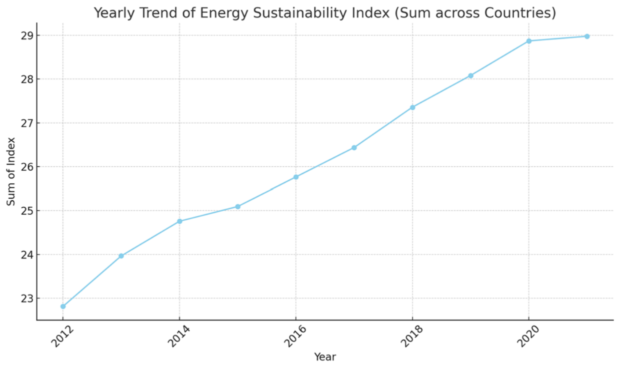


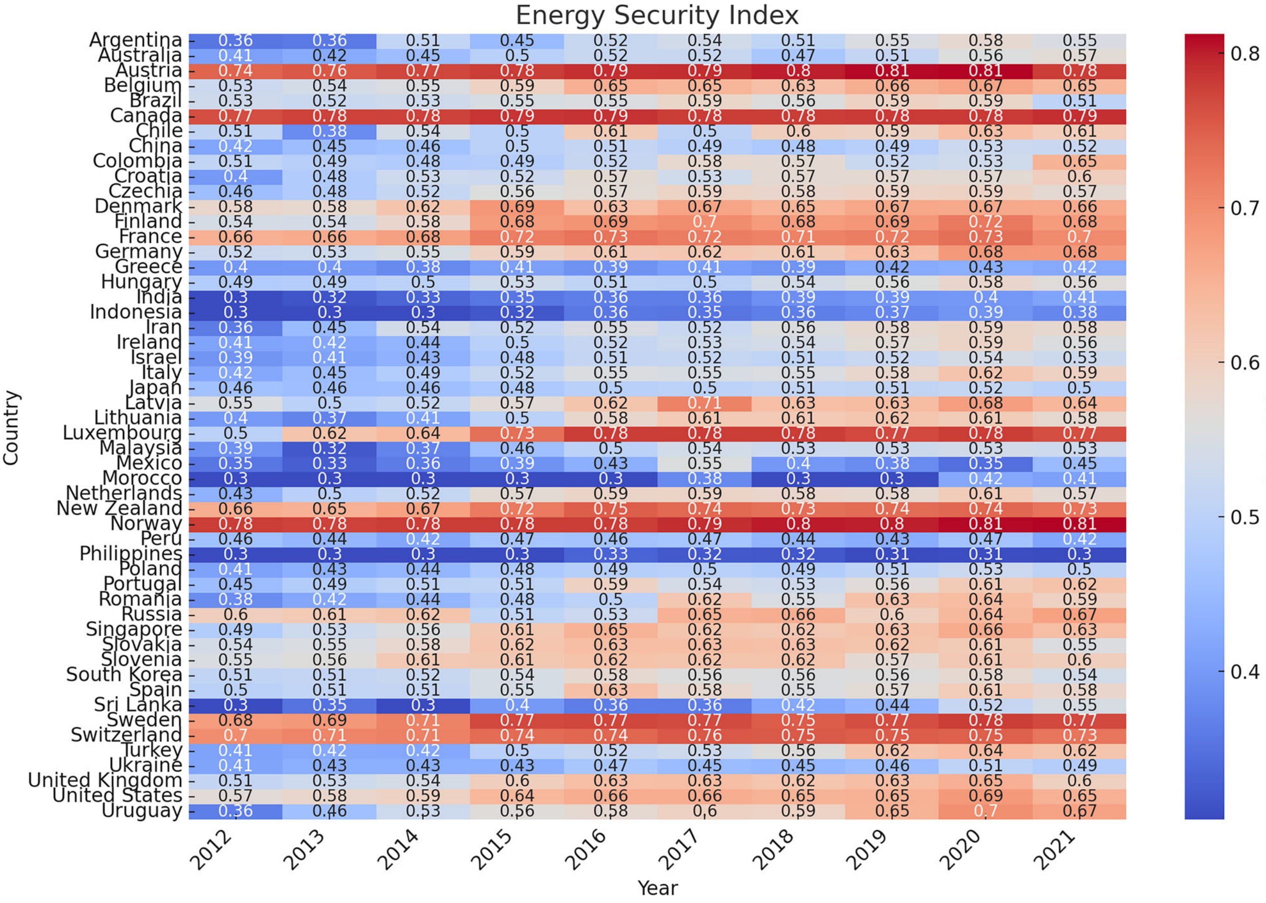
Fig. 14 Energy Sustainability Index comparison of all countries.

afford or access consistent energy services. Further, high Gini index countries often involve unequal distribution of resources for infrastructure development. Energy projects are frequently concentrated in wealthier areas or urban centers, leaving rural and low-income regions without proper access to energy infrastructure. This increases the gap between those with energy access and those without, reinforcing existing economic inequalities (Song et al., 2023; Opoku et al., 2024). Inflation also reduces people's access to electricity. This indicates that higher prices reduce society's purchasing power, thereby preventing households from being able to afford electricity. Inflation means that the cost of raw materials, transportation, and labor increases, which can directly lead to higher energy prices. This makes energy less affordable for consumers and businesses, potentially limiting access to reliable energy sources, especially for lower-income populations.

Table 3 describes the findings of the energy reliability index and AI indicators. The reliability index showed that AI indicators are significant in improving the infrastructure of electricity efficiency status/reducing the electric power transmission distribution, as the coefficient impact of AIPE and research in AI is positive and significant. However, the AI_Inv is insignificant, while the research in AI magnitude is a little higher than AIPE. AI improves energy reliability by making systems more resilient and capable of adapting to demand fluctuations or failures. AI's ability to perform predictive maintenance has been particularly transformative. By monitoring equipment health and predicting potential failures before they occur, AI systems reduce the chances of prolonged outages. For example, companies like National Grid in the UK use AI-driven algorithms to detect potential grid issues and proactively adjust operations, thus maintaining uninterrupted service.

Moreover, AI supports energy demand-side management, enabling energy producers and utilities to balance energy supply with consumption, particularly during peak demand periods. Hawaii has adopted AI systems to optimize grid performance, particularly during natural disasters like hurricanes, by dynamically adjusting energy distribution, ensuring access to electricity in affected regions. Income inequality and inflation lower the access to electricity by (1.22%, 2.92%). However, GDP (economic growth) and industrialization significantly increase energy reliability by 18.1 and 7.42%, respectively.

The results for the affordability index are given in Table 4. AI plays a significant role in improving energy affordability by reducing the energy cost of production. The results show that AIPE increases the affordability by 5.68%. Also, AI_Inv beneficially plays a role and helps increase the energy affordability (0.811%). Similarly, AI_SR significantly improves



Country	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Argentina	0.36	0.36	0.51	0.45	0.52	0.54	0.51	0.55	0.58	0.55
Australia	0.41	0.42	0.45	0.5	0.52	0.52	0.47	0.51	0.56	0.57
Austria	0.74	0.76	0.77	0.78	0.79	0.79	0.8	0.81	0.81	0.78
Belgium	0.53	0.54	0.55	0.59	0.65	0.65	0.63	0.66	0.67	0.65
Brazil	0.53	0.52	0.53	0.55	0.55	0.59	0.56	0.59	0.59	0.51
Canada	0.77	0.78	0.78	0.79	0.79	0.78	0.78	0.78	0.78	0.79
Chile	0.51	0.38	0.54	0.5	0.61	0.5	0.6	0.59	0.63	0.61
China	0.42	0.45	0.46	0.5	0.51	0.49	0.48	0.49	0.53	0.52
Colombia	0.51	0.49	0.48	0.49	0.52	0.58	0.57	0.52	0.53	0.65
Croatia	0.4	0.48	0.53	0.52	0.57	0.53	0.57	0.57	0.57	0.6
Czechia	0.46	0.48	0.52	0.56	0.57	0.59	0.58	0.59	0.59	0.57
Denmark	0.58	0.58	0.62	0.69	0.63	0.67	0.65	0.67	0.67	0.66
Finland	0.54	0.54	0.58	0.68	0.69	0.7	0.68	0.69	0.72	0.68
France	0.66	0.66	0.68	0.72	0.73	0.72	0.71	0.72	0.73	0.7
Germany	0.52	0.53	0.55	0.59	0.61	0.62	0.61	0.63	0.68	0.68
Greece	0.4	0.4	0.38	0.41	0.39	0.41	0.39	0.42	0.43	0.42
Hungary	0.49	0.49	0.5	0.53	0.51	0.5	0.54	0.56	0.58	0.56
India	0.3	0.32	0.33	0.35	0.36	0.36	0.39	0.39	0.4	0.41
Indonesia	0.3	0.3	0.3	0.32	0.36	0.35	0.36	0.37	0.39	0.38
Iran	0.36	0.45	0.54	0.52	0.55	0.52	0.56	0.58	0.59	0.58
Ireland	0.41	0.42	0.44	0.5	0.52	0.53	0.54	0.57	0.59	0.56
Israel	0.39	0.41	0.43	0.48	0.51	0.52	0.51	0.52	0.54	0.53
Italy	0.42	0.45	0.49	0.52	0.55	0.55	0.55	0.58	0.62	0.59
Japan	0.46	0.46	0.46	0.48	0.5	0.5	0.51	0.51	0.52	0.5
Latvia	0.55	0.5	0.52	0.57	0.62	0.71	0.63	0.63	0.68	0.64
Lithuania	0.4	0.37	0.41	0.5	0.58	0.61	0.61	0.62	0.61	0.58
Luxembourg	0.5	0.62	0.64	0.73	0.78	0.78	0.78	0.77	0.78	0.77
Malaysia	0.39	0.32	0.37	0.46	0.5	0.54	0.53	0.53	0.53	0.53
Mexico	0.35	0.33	0.36	0.39	0.43	0.55	0.4	0.38	0.35	0.45
Morocco	0.3	0.3	0.3	0.3	0.3	0.38	0.3	0.3	0.42	0.41
Netherlands	0.43	0.5	0.52	0.57	0.59	0.59	0.58	0.58	0.61	0.57
New Zealand	0.66	0.65	0.67	0.72	0.75	0.74	0.73	0.74	0.74	0.73
Norway	0.78	0.78	0.78	0.78	0.78	0.79	0.8	0.8	0.81	0.81
Peru	0.46	0.44	0.42	0.47	0.46	0.47	0.44	0.43	0.47	0.42
Philippines	0.3	0.3	0.3	0.3	0.33	0.32	0.32	0.31	0.31	0.3
Poland	0.41	0.43	0.44	0.48	0.49	0.5	0.49	0.51	0.53	0.5
Portugal	0.45	0.49	0.51	0.51	0.59	0.54	0.53	0.56	0.61	0.62
Romania	0.38	0.42	0.44	0.48	0.5	0.62	0.55	0.63	0.64	0.59
Russia	0.6	0.61	0.62	0.51	0.53	0.65	0.66	0.6	0.64	0.67
Singapore	0.49	0.53	0.56	0.61	0.65	0.62	0.62	0.63	0.66	0.63
Slovakia	0.54	0.55	0.58	0.62	0.63	0.63	0.63	0.62	0.61	0.55
Slovenia	0.55	0.56	0.61	0.61	0.62	0.62	0.62	0.57	0.61	0.6
South Korea	0.51	0.51	0.52	0.54	0.58	0.56	0.56	0.56	0.58	0.54
Spain	0.5	0.51	0.51	0.55	0.63	0.58	0.55	0.57	0.61	0.58
Sri Lanka	0.3	0.35	0.3	0.4	0.36	0.36	0.42	0.44	0.52	0.55
Sweden	0.68	0.69	0.71	0.77	0.77	0.77	0.75	0.77	0.78	0.77
Switzerland	0.7	0.71	0.71	0.74	0.74	0.76	0.75	0.75	0.75	0.73
Turkey	0.41	0.42	0.42	0.5	0.52	0.53	0.56	0.62	0.64	0.62
Ukraine	0.41	0.43	0.43	0.43	0.47	0.45	0.45	0.46	0.51	0.49
United Kingdom	0.51	0.53	0.54	0.6	0.63	0.63	0.62	0.63	0.65	0.6
United States	0.57	0.58	0.59	0.64	0.66	0.66	0.65	0.65	0.69	0.65
Uruguay	0.36	0.46	0.53	0.56	0.58	0.6	0.59	0.65	0.7	0.67

Fig. 15 Energy Security Index value by year.

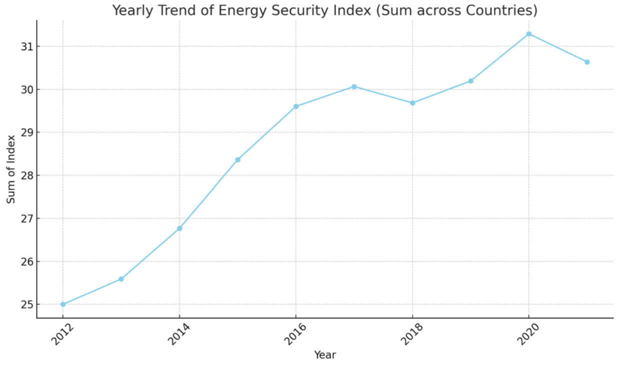


Fig. 16 Energy Security Index growth trend over the Years (2012–2021).

access to energy and reduces the cost by 5.61%. By optimizing buildings, manufacturing, and data centers, AI lowers energy consumption, ultimately cutting costs. For example, Google DeepMind's AI application in its data centers, where machine learning algorithms optimize the cooling process, results in significant cost savings. Further, AI technologies that manage energy consumption patterns, such as machine learning models for predicting energy usage, are helping companies like Siemens and Schneider Electric reduce waste and improve operational efficiency. These energy savings can lead to lower costs for consumers, making energy more affordable for households and businesses alike.

Industrialization significantly decreases the energy affordability or increases the cost of energy by 5.84%. However, GDP leads economies to increase access and reduce the cost by 6.10%. Inflation and income inequality hinder the affordability increment.

The energy sustainability index, which comprises CO_2 (carbon intensity), low carbon electricity generation and energy efficiency (energy intensity), is presented in Table 5. According to the findings, AIPE is negative but insignificant in column (2). This might be due to the higher CO_2 effect of renewable energy. So, the index impact is not beneficial. In contrast, investment and research increase sustainability up to (3.06%, 6.62%). AI technologies are instrumental in increasing the efficiency of solar, wind, and other renewable energy sources. For example, Google has successfully integrated AI to predict wind patterns more accurately, optimizing wind farm energy output. Furthermore, AI can help manage hybrid energy systems that combine renewable energy with traditional energy sources, enhancing grid stability. In Denmark, AI-driven systems predict wind and solar power output, ensuring that the national grid remains balanced and reducing the reliance on coal and gas for backup power. These AI-driven innovations are crucial for transitioning to cleaner, more sustainable energy systems. In the context of climate change and the push toward carbon neutrality, AI can help governments implement policies that balance economic growth with sustainability. For instance, AI can be used to simulate the impacts of various policy scenarios, helping decision-makers understand how best to encourage the use of renewable energy without compromising economic development.

Income inequality, inflation, and industrialization negatively reduce energy sustainability. However, economic growth positively increases energy sustainability. As economies grow, they tend to have more financial resources to invest in clean energy technologies. This allows for developing solar, wind, and

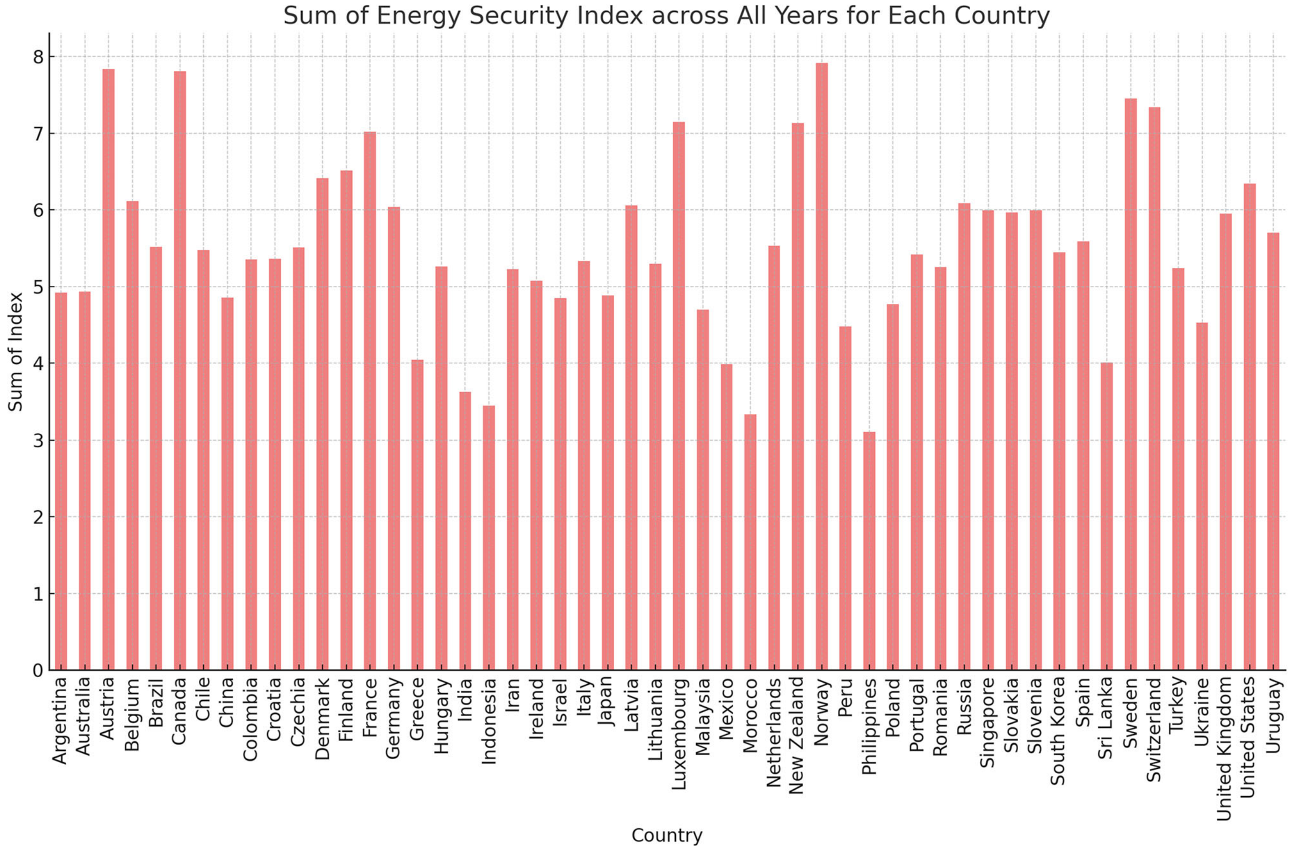


Fig. 17 Energy Security Index comparison of all countries.

hydropower, which are more sustainable. Economic growth also fosters research and innovation in sustainable energy technologies, making them more efficient and cost-effective (Elfarra et al., 2024; Shah et al., 2024). The collective index approach to secure energy security through AI and other economic factors is given in Table 6. The results showed that the overall impact of AIPE, AI_Inv, and AI_SR is positive to ensure energy security and improve energy security by (0.446–6.97, 1.68, and 8.39–8.58%, respectively). However, income inequality reduces energy security. Economic growth has the most magnitude impact (10.9%) on increasing energy security. Income inequality reduces energy security, and Ind also eventually increases the energy security by (3.47%).

In summary, AI improves energy security by enhancing energy availability, reliability, affordability, and sustainability. Its ability to optimize energy production and consumption, predict demand, and manage renewable energy resources makes AI essential in addressing the world's growing energy challenges. As we continue to develop and integrate AI technologies across energy systems, we can expect even more advancements that will help achieve a more sustainable, efficient, and equitable global energy landscape.

Benchmark analysis of indexes for robustness. To assess the robustness of the Energy Security Indexes, we compared them with the World Energy Council's (WEC) Energy Trilemma Index, which consists of three categories: (i) Energy Security (import dependence, electricity generation diversity, and energy storage), (ii) Energy Equity (access to electricity, electricity prices, and gasoline and diesel prices), and (iii) Environmental Sustainability (final energy intensity, low-carbon electricity generation, and CO_2 emissions per capita). While the variables in our study are not identical to those in the WEC index, they serve as a valid benchmark for assessing the robustness of our constructed indices, particularly in the Environmental Sustainability category, which shares common variables. Notably, the weighting of subcategories in our study may differ, as we employed the entropy method for weighting.

To ensure robustness, we first combined the WEC index into a single composite index and compared it against our Energy Security Index. For further validation, the Energy Sustainability Index was cross-checked against the Environmental Sustainability Index (WEC). To align the scales, we divided the WEC index values by 100 to match our study's scale. We applied several statistical tests to assess the strength and significance of the relationships between the indices.

The Spearman Rank Correlation results in Table 7 demonstrate a strong, statistically significant monotonic relationship between the Energy Sustainability Index and the Environmental Sustainability Index (WEC), with a Spearman's rho of 0.7784. Similarly, the Energy Security Index showed a strong correlation of 0.7648 with the Composite WEC Index. These results confirm the high degree of similarity and consistency between the constructed indices and the WEC benchmarks.

The accompanying Figs. 19 and 20 visually represent these relationships, with the scatter plots and fitted regression lines indicating a positive linear correlation between the indices. The country-specific analysis (Figs. 21 and 22) confirms that the constructed indices are comparable to the WEC index, supporting the robustness of our methodology. Although variations in index values can arise due to differences in measurement units, weights, and methodology, the correlation tests and visual evidence validate that our indices are designed for the same purpose and reflect similar trends across countries. Therefore, the robustness

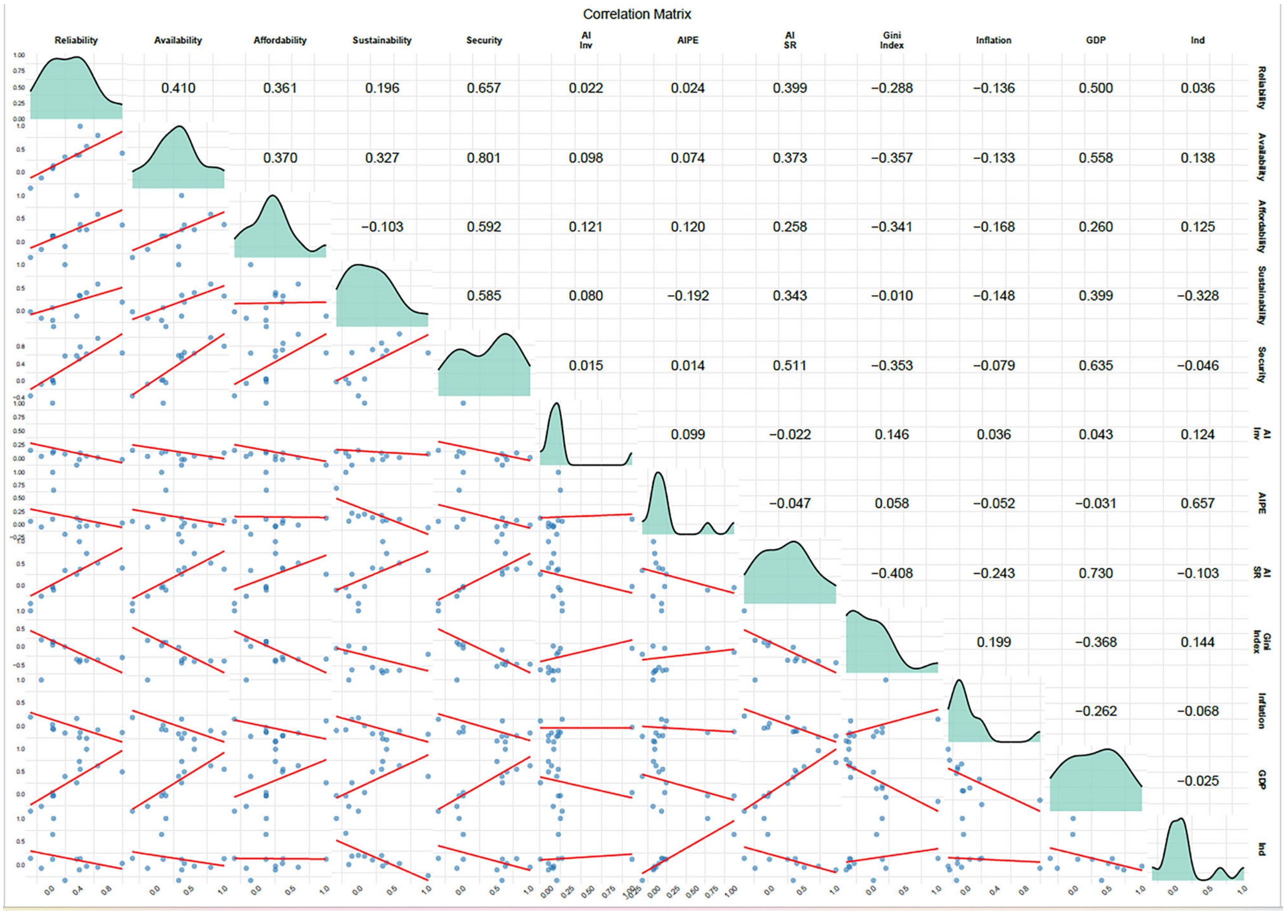


Fig. 18 Scatterplots for all pairs of dependent and independent variables.

Table 2 Impact of Artificial Intelligence on Energy Availability Index and SDG$_S$.

Variable(S)	Dependent (Energy Availability Index)	
AIPE	0.000137*	0.0153**
	(7.38e-05)	(0.00583)
AI_Inv	0.00819**	0.0213***
	(0.00384)	(0.00642)
AI_SR	0.000863***	0.000946***
	(0.000176)	(0.000187)
Gini − Index		−0.00310***
		(0.000661)
Inf		−0.0490***
		(0.0155)
GDP		0.138***
		(0.0112)
Ind		0.0277***
		(0.00908)
Country − Effect		Yes
Years − Effect		Yes
Constant	0.209***	−0.408***
	(0.0613)	(0.141)
Observations	510	510
R − squared	0.159	0.464
Number of Country	52	52

Standard errors in parentheses***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Table 3 Impact of Artificial Intelligence on Energy Reliability Index and *SDG$_S$*.

Variable(*S*)	Dependent (Energy Reliability Index)	
AIPE	0.00117***	0.000590**
	(0.000169)	(0.000257)
AI_Inv	0.00307	0.00539
	(0.00889)	(0.00556)
AI_SR	0.0182**	0.0249***
	(0.00770)	(0.00379)
Gini − Index		−0.0122***
		(0.00155)
Inf		−0.0292*
		(0.0153)
GDP		0.181***
		(0.0230)
Ind		0.0742***
		(0.0247)
Country − Effect		Yes
Years − Effect		Yes
Constant	0.460***	−48.93***
	(0.165)	(7.798)
Observations	510	510
R − squared	0.156	0.599
Number of Country	52	52

Standard errors in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$..

Table 4 Impact of Artificial Intelligence on Energy Affordability Index and SDG_S.

Variable(*S*)	Dependent (Energy Affordability Index)	
AIPE	0.00109***	0.0568***
	(0.000128)	(0.00490)
AI_Inv	−0.00908	0.00811***
	(0.00781)	(0.00182)
AI_SR	0.0409***	0.0561***
	(0.00391)	(0.00412)
Gini − Index		−0.00244
		(0.00187)
Inf		−0.0306**
		(0.0145)
GDP		0.0610***
		(0.0108)
Ind		−0.0584***
		(0.00244)
Country − Effect		Yes
Years − Effect		Yes
Constant	0.671***	1.467***
	(0.169)	(0.160)
Observations	510	510
R − squared	0.355	0.477
Number of Country	52	52

Standard errors in parentheses $^{***}p < 0.01$; $^{**}p < 0.05$.

Table 6 Impact of Artificial intelligence on Energy Security Index and SDG_S.

Variable(*S*)	Dependent (Energy Security Index)	
AIPE	0.00446**	0.0697***
	(0.00171)	(0.00204)
AI_Inv	0.0149	0.0168***
	(0.0107)	(0.00340)
AI_SR	0.0839***	0.0858***
	(0.00718)	(0.00815)
Gini − Index		−0.0861*
		(0.0427)
Inf		−0.0159**
		(0.00711)
GDP		0.109***
		(0.0137)
Ind		0.0347***
		(0.00692)
Country − Effect		Yes
Years − Effect		Yes
Constant	0.00250	−8.502**
	(0.170)	(3.438)
Observations	510	510
R − squared	0.460	0.608
Number of Country	52	52

Standard errors in parentheses $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Table 5 Impact of Artificial Intelligence on Energy Sustainability Index and SDG_S.

Variable(*S*)	Dependent (Energy Sustainability Index)	
AIPE	0.0565***	−0.0107
	(0.00443)	(0.0257)
AI_Inv	0.0237***	0.0306**
	(0.00582)	(0.0145)
AI_SR	0.0610***	0.0662***
	(0.0108)	(0.0119)
Gini − Index		−0.362***
		(0.131)
Inf		−0.0264**
		(0.0100)
GDP		0.131***
		(0.0163)
Ind		−0.0761***
		(0.0233)
Country − Effect		Yes
Years − Effect		Yes
Constant	1.467***	−31.14***
	(0.160)	(5.409)
Observations	510	530
R − squared	0.477	0.628
Number of Country	52	52

Standard errors in parentheses $^{***}p < 0.01$; $^{**}p < 0.05$.

of our Energy Security Index and Energy Sustainability Index is well-supported by the benchmark comparisons with the WEC indices.

Conclusion

Ensuring a secure and reliable energy supply is a fundamental priority for nations, as it underpins sustainable development and poverty reduction. The role of artificial intelligence in advancing energy security is particularly pertinent in the context of the United Nations' Sustainable Development Goals, specifically SDGs 7 (Affordable and Clean Energy), SDGs 9 (Industry, Innovation, and Infrastructure), and SDGs 13 (Climate Action). This study explores the intersection of AI and energy security across 52 countries from 2012 to 2021, analyzing the impact of AI on enhancing energy access, availability, affordability, sustainability, and overall security. The study offers a novel approach by constructing an energy security index incorporating multiple dimensions, including renewable energy use, fuel imports, energy intensity, and environmental impact.

The study evaluates energy security across countries using several indices aligned with SDG goals, focusing on energy reliability, availability, affordability, sustainability, and overall energy security. The *Energy Reliability Index* assesses a country's ability to provide uninterrupted energy, considering fuel import dependence and electricity transmission loss. Countries like Australia and Norway score high, reflecting their robust energy infrastructures, while Argentina's moderate score indicates challenges such as aging infrastructure and fuel supply issues. The *Energy Availability Index* measures a country's energy consumption, supply, and reliance on non-renewable sources. Canada, with its high reliance on clean energy like hydropower, scores the highest. At the same time, India struggles with lower availability due to power supply inconsistencies and high dependency on non-renewable energy. The *Energy Affordability Index* measures the affordability of energy through electricity & gasoline prices and access, with Norway and Argentina offering affordable energy, whereas India faces significant affordability issues despite progress in energy access. The *Energy Sustainability Index* evaluates the use of renewable energy and efforts to reduce carbon emissions, with countries like Sweden, Switzerland, and Uruguay leading in renewable energy adoption and sustainability efforts.

In contrast, China and India's reliance on fossil fuels results in lower sustainability scores. The overall Energy Security Index

Table 7 Spearman Rank Correlation Results.

Index Pair	No. Observations (N)	Spearman's ρ (rho)	p-value	Interpretation
ESI vs Composite WEC index	510	0.7648	<0.0001	Strong monotonic relationship, highly significant
Energy sustainability index vs. Environmental Sustainability Index	510	0.7784	<0.0001	Strong monotonic relationship, highly significant

Ukraine skipped as WEC index is not included.

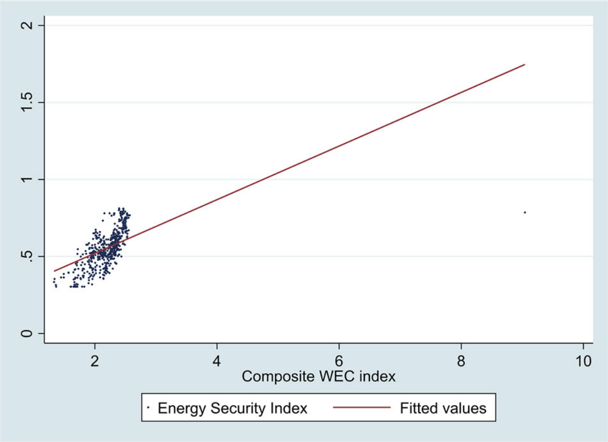


Fig. 19 Correlation WEC Trilemma Index (Composite) vs Energy Security Index.

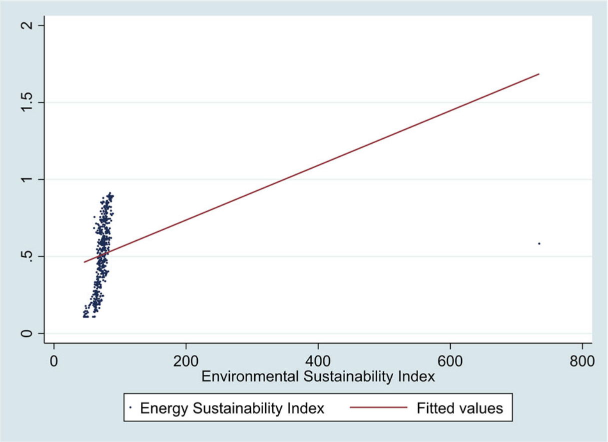


Fig. 20 Correlation WEC Environmental Index vs Energy Sustainability Index.

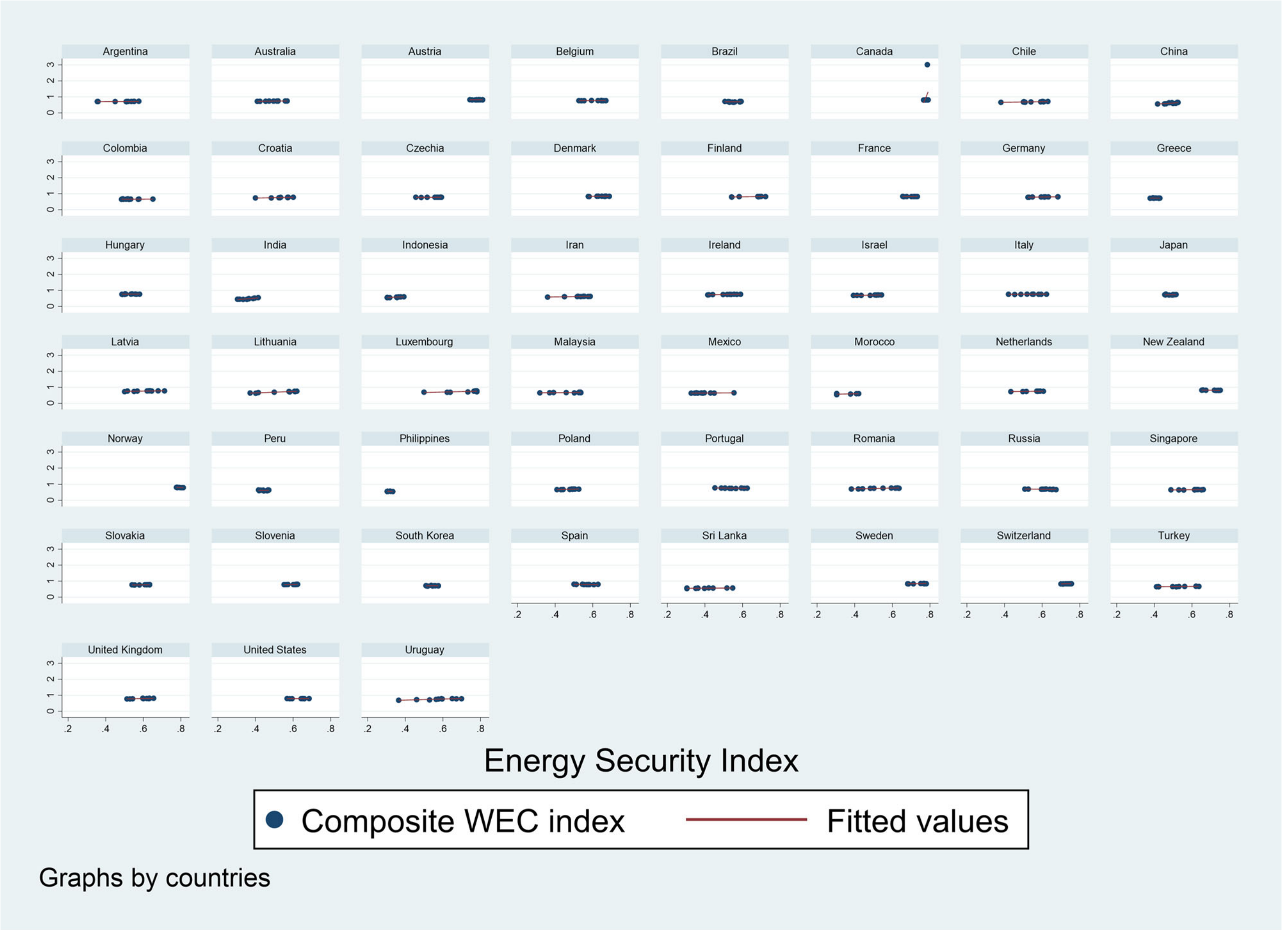


Fig. 21 Country's Correlation WEC Trilemma Index (Composite) vs Energy Security Index.

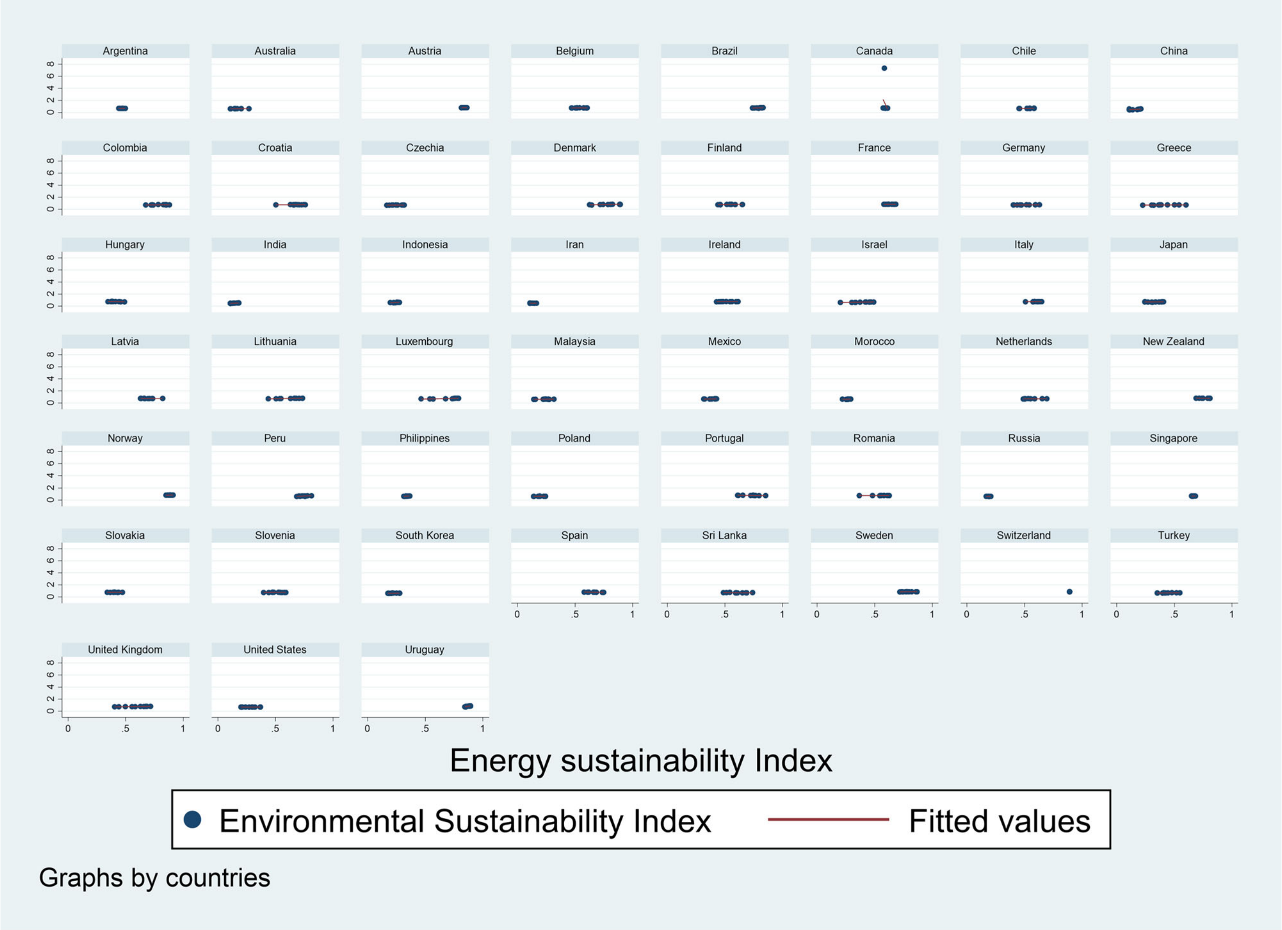


Fig. 22 Country's Correlation WEC Environmental Index vs Energy Sustainability Index.

combines these elements, showing that top-performing countries like Norway, Sweden, and Canada have diversified, sustainable, and reliable energy systems, while developing countries like India and Morocco face challenges due to fuel import dependence and inefficient energy infrastructure. The study highlights the importance of diversified energy sources, renewable energy investments, and modernized infrastructure to improve energy security globally, stressing the need for international cooperation and long-term planning to meet SDGs 7, 9, and 13. Despite progress, no country has fully achieved energy security.

The study evaluates the impact of Artificial Intelligence (AI) on energy security across various indices, including energy availability, reliability, affordability, and sustainability. The findings reveal that AI significantly enhances energy availability by optimizing production, distribution, and consumption, with AI-powered innovations improving energy efficiency. Specifically, AI patents (AIPE) increase energy availability by up to 1.53%, while AI investments (AI_Inv) improve availability by up to 2.13%. AI-based research (AI_SR) also plays a crucial role, with an increase of up to 0.0946%. The study emphasizes the role of AI in enhancing energy systems, particularly through smart grid management and renewable energy integration. Moreover, economic growth and industrialization are found to positively impact energy security, with economic growth having the most significant effect. On the other hand, income inequality and inflation hinder energy security by limiting access to affordable energy, especially for low-income populations. The Energy Sustainability Index showed that AI investments and research significantly contribute to sustainability, with an increase of 3.06% and 6.62%, respectively. However, income inequality and industrialization negatively impact sustainability. The study highlights AI's potential in optimizing energy systems, reducing costs, and enhancing sustainability, making it a key tool in achieving global energy security and meeting SDGs 7, 9, and 13. Robustness tests with an additional control variable (population) confirm the validity of the previous results, suggesting that AI can optimize energy systems and reduce inefficiencies. The moderation effect analysis indicates that targeted investments in AI are crucial to accelerating progress toward universal energy security. By aligning AI development with policy goals, particularly in sustainability and energy efficiency, countries can leverage AI to transition to more secure, sustainable, and affordable energy systems.

The policy recommendations provided in the study focus on leveraging AI to enhance energy security and contribute to achieving SDG 7, SDG 9, and SDG 13. Governments should focus on AI investments that cater to the unique energy challenges of different regions or country clusters. For example, Canada, with abundant renewable resources, should prioritize AI optimization in renewable energy systems, while India and China should focus on AI-driven transitions to renewable energy and energy efficiency technologies, addressing the growing demand and supply imbalances in these nations. Regarding AI measures, AIPE (Patent Applications in the Field of Energy Management), investments, and AI research have varying impacts depending on the country's development stage. Developed economies such as Germany and Norway should focus on AI research to optimize their advanced energy systems. Meanwhile, emerging economies like Brazil and India would benefit from focusing on AI investments and AIPE to enhance energy-saving technologies, smart grids, and infrastructure improvements. Addressing socioeconomic barriers such as income inequality and inflation is vital for equitable energy access. AI can play a key role in optimizing energy pricing and distribution systems, improving affordability for underserved populations. Finally, effective governance and international cooperation are crucial for aligning AI strategies with both national energy goals and global climate objectives. In conclusion, while AI has significant potential to enhance energy security and contribute to the SDGs, its success depends on strategic investments, coherent policy frameworks, and context-specific interventions. With the right approach, AI can accelerate progress toward a sustainable and equitable energy future.

This study is limited by data constraints, particularly the reliance on global datasets that may not fully capture regional variations in energy access and AI adoption. Furthermore, regional disparities, especially between developed and developing nations, were not fully explored, which may affect the generalizability of the findings. Future studies could delve into the application of deep learning models for more accurate energy forecasting, particularly in predicting renewable energy generation. Additionally, research focused on AI's role in improving energy security in Africa, or in transitioning fossil-fuel-dependent economies to renewables, would provide valuable insights. Investigating AI-driven policy simulation models and addressing regional disparities in AI adoption could further refine strategies for improving energy security globally.

Data availability

The datasets used in this study are publicly available and can be accessed through the following sources: • World Development Indicators (WDI): https://databank.worldbank.org/source/world-development-indicators. • Our World in Data: https://ourworldindata.org/. • Socioeconomic World Inequality Database (SWIID): https://fsolt.org/swiid/. • International Energy Agency (IEA): https://www.iea.org/.

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Notes

1 This inversion ensures consistent interpretation: a normalized value closer to 0 denotes poor performance (e.g., high emissions), while a value closer to 1 represents optimal performance (e.g., low emissions). Without inversion, the directionality of the index would be misleading, as it would suggest that lower values indicate better performance in some cases and worse performance in others.

2 https://www.trade.gov/country-commercial-guides/uruguay-renewable-energy-equipment.

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Author contributions

Rizwana Yasmeen wrote the entire manuscript, while Rui Tao contributed to the methodology, estimation, and literature sections

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The authors declare no competing interests.

Ethical approval

This study does not involve human participants or their data, therefore, ethical approval was not required.

Informed consent

As this study does not involve human participants, therefore, informed consent was not required.

Additional information

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