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Exploring the Determinants of Renewable Energy Consumption: A Bayesian Monte Carlo Simulation Analysis of Technology, Economic Growth, CO_2 Emissions, and Digital Financial Inclusion

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ABSTRACT

Amid escalating climate crises and the global push for energy transition, renewable energy consumption (REC) has become a key priority for sustainable development. However, the global energy system remains heavily dependent on fossil fuels, accounting for nearly 80% of total energy use and 76.7% of greenhouse gas emissions. This reliance underscores the urgent need to promote factors driving the shift toward renewable energy, including technological innovation (TI), digital financial inclusion (DFI), economic growth (GDP), and CO_2 emission control. Addressing gaps in integrated approaches and methodological challenges in prior studies, this research applies a Bayesian Monte Carlo method to estimate the probabilistic impacts of these factors on REC, using panel data from 58 countries between 2004 and 2022. The results reveal that TI exerts a positive and highly significant influence on REC (coefficient = 0.1097; probability of effect = 100%), reaffirming its critical role in enhancing efficiency, lowering costs, and fostering advancements in smart grids and energy systems through the integration of AI, IoT, and Big Data. DFI also shows a positive, albeit moderate, effect on REC (coefficient = 0.1891; probability of effect = 67.63%), while GDP demonstrates a strong positive association with REC (coefficient = 0.8750; probability of effect = 83.44%). In contrast, CO_2 emissions have a significant negative effect on REC (coefficient = −0.2297; probability of effect = 86.13%), providing vital insights for policymakers aiming to align energy transition efforts with sustainability objectives.

Keywords: Technological Innovation, Digital Financial Inclusion, Economic Growth, CO_2 Emission.
JEL Classifications: O31, O33, O40, Q56

1. INTRODUCTION

The transition toward renewable energy has emerged as one of the most critical global imperatives in the 21st century. As nations grapple with rising environmental degradation, growing energy insecurity, and international commitments to decarbonization, renewable energy consumption (REC) has been positioned at the forefront of sustainable development agendas (Okafor-Yarwood, 2019). Despite decades of international agreements, such as the Kyoto Protocol (1997), the Paris Agreement (2015), and the Sustainable Development Goals (SDGs) under the 2030 Agenda (Fuso Nerini et al., 2018), global energy systems remain heavily reliant on fossil fuels, accounting for approximately 79.7% of total energy consumption worldwide (World Bank, 2023). This over-reliance on fossil fuels continues to exacerbate greenhouse gas (GHG) emissions, with CO_2 comprising 76.7% of total emissions, intensifying climate change risks and threatening environmental sustainability. Against this backdrop, understanding the determinants of REC has become a central focus for scholars, policymakers, and practitioners. Prior research has largely concentrated on the influence of macroeconomic and environmental variables on REC, including gross domestic product (GDP), CO_2 emissions (Tudor and Sova, 2021), per capita income (Sadorsky, 2010; Salim and Rafi, 2012), and oil prices

(Al-Maamary et al., 2017). These studies have provided valuable insights into the economic and environmental factors driving renewable energy uptake but have overlooked critical aspects of financial and technological enablers.

Investing in renewable energy infrastructure demands substantial capital and entails high initial costs, often deterring private investors and creating financing bottlenecks (Tsao et al., 2021). Therefore, the availability of a robust and inclusive financial system is indispensable to facilitate long-term investments in renewable energy (Eren et al., 2019). While conventional financial inclusion (FI) has been recognized for its role in mobilizing resources and mitigating risks in the renewable energy sector (Chen et al., 2022; Cui et al., 2020; Li et al., 2022), the rapid advancement of financial technologies has transformed the landscape of financial access. The rise of digital financial inclusion (DFI) — defined as the use of digital platforms to provide affordable, accessible, and efficient financial services to underserved populations — represents a pivotal evolution in the financial ecosystem (Le Quoc, 2024). Despite its transformative potential, empirical research on the relationship between DFI and REC remains scarce, leaving an important gap in the literature.

Simultaneously, TI plays an indispensable role in scaling up renewable energy production by improving energy efficiency, lowering production costs, and fostering technological innovations that enable the transition from fossil fuels to renewable sources (Zhou, 2010). However, many countries — particularly developing economies — face structural challenges such as limited access to clean technologies, technological dependence on foreign suppliers, high import costs, and inadequate domestic innovation capacity (Khan et al., 2021). These barriers hinder their ability to achieve renewable energy targets and deepen energy inequities across nations Despite extensive research on the determinants of REC, few empirical studies have systematically analyzed the independent effects of TI, DFI, gross domestic product (GDP), and CO_2 emissions on REC across countries within a unified empirical framework. Most prior studies have focused on isolated factors or adopted fragmented approaches, limiting the comprehensive understanding of how these key drivers individually contribute to renewable energy consumption across different national contexts (Sadorsky, 2010; Cui et al., 2020; Li et al., 2022).

Moreover, existing empirical analyses using conventional econometric methods face several methodological challenges when applied to cross-country data. Specifically, the presence of multicollinearity among explanatory variables (e.g., between GDP, CO_2 emissions, and TI), potential endogeneity (due to reverse causality between economic growth and renewable energy use), cross-sectional dependence (resulting from global integration and spillover effects), and parameter heterogeneity across countries may compromise the consistency and efficiency of parameter estimates (Bekabil, 2020). Additionally, traditional frequentist methods offer limited ability to incorporate prior information or quantify uncertainty about model parameters and predictions. To address these methodological limitations, this study employs a Bayesian Monte Carlo simulation approach, which provides a probabilistic framework to estimate the independent effects of TI, DFI, GDP, and CO_2 emissions on renewable energy consumption. By leveraging Bayesian inference, the study incorporates prior knowledge, produces full posterior distributions of parameters, and quantifies uncertainty more effectively than point estimates from frequentist approaches. The Monte Carlo simulation further facilitates estimation in the presence of multicollinearity, accounts for cross-sectional dependence, and allows for parameter heterogeneity without imposing strict homogeneity assumptions across countries. This methodological approach enables a more robust, comprehensive, and nuanced assessment of the independent contributions of technological, economic, financial, and environmental factors to renewable energy consumption at the global level. Ultimately, the findings are expected to provide more reliable insights to inform evidence-based policymaking toward sustainable energy transitions.

The objectives of this study are twofold: (1) To quantitatively assess the independent effects of TI, GDP, CO_2 emissions, and DFI on REC across a diverse sample of countries; and (2) To provide actionable policy recommendations aimed at enhancing renewable energy adoption through integrated technological, financial, economic, and environmental strategies.

By addressing these objectives, this study seeks to fill critical knowledge gaps in the empirical literature on renewable energy drivers. The findings are expected to contribute to the scholarly discourse on sustainable energy transitions and offer valuable insights for policymakers striving to balance economic growth, environmental protection, and energy equity in the global pursuit of a low-carbon future. Through a comprehensive analysis grounded in Bayesian inference, this research aims to inform evidence-based policy design and promote more effective pathways toward achieving energy sustainability at both national and international levels.

2. LITERATURE REVIEW

2.1. The Impact of DFI on REC

Renewable energy products are not always readily available at affordable prices for low-income households (Kim and Quoc, 2024). In this context, DFI can influence REC through two main theoretical frameworks:

Diamond's (1984) financial intermediary theory suggests that banks act as financial intermediaries, connecting borrowers and savers, thus bridging the gap between those who need to consume and those who have surplus financial resources. This indicates that the financial system plays a crucial role in enhancing access to capital, particularly for investments in clean and green technologies. Kim and Quoc (2024) further emphasizes that DFI can stimulate investment in renewable energy, reducing costs for consumers, even for marginalized or financially underserved groups.

George's (1970) theory of asymmetric information indicates that in financial transactions, the information asymmetry between lenders and borrowers can create risks and reduce the efficiency of credit markets. DFI helps mitigate this issue, offering lower-cost borrowing opportunities for those who find it difficult to access traditional financial services, such as small and medium enterprises or rural residents (Zhang et al., 2022). DFI creates new forms of credit, such as digital loans, which help individuals more easily access renewable energy (Li et al., 2020). One of the significant barriers to implementing renewable energy is the high upfront capital costs (Kim and Park, 2016), and DFI can alleviate this problem, thereby encouraging REC.

However, easy access to financial services through DFI could also have counterproductive effects. Specifically, expanding credit could lead to increased consumption of fossil energy products, such as cars or electronic devices, which may increase demand for fossil energy rather than renewable energy (Johnstone et al., 2010). In Porter's (1980) theory of price competition, companies with cost advantages can attract customers, leading to an increase in fossil energy usage when its costs are lower. However, in the current context, the cost of fossil energy is rising due to global political factors such as war (Martínez-García et al., 2023), which could lead to a rise in REC when fossil fuel supplies are disrupted.

Based on the above theories, the following hypothesis is proposed:

H_1: DFI has a positive impact on REC.

2.2. The Impact of TI on REC

As presented in Porter's (1980) theory of price competition, competitive strategies attract customers through cost advantages. In this regard, TI plays a crucial role in improving the performance of renewable energy systems, making them more competitive compared to traditional energy sources derived from fossil fuels. Moreover, TI consistently help reduce the costs associated with deploying renewable energy technologies, thus making renewable energy a more economically viable option and encouraging an increase in REC.

This innovation not only involves technological improvements but also encompasses human resources, scientific knowledge, and supporting resources for the creative process. However, countries may have different strategies and legal frameworks for protecting and benefiting from technological inventions (Jaumotte and Pain, 2005). Therefore, TI in the context of renewable energy is critically important and may vary depending on the country and the specific time period. According to Oanh and Dinh (2024), TI not only improves environmental quality but also enhances performance, making renewable energy solutions more attractive and easier to adopt. This drives competition in the energy market, helping renewable energy technologies become the preferred choice, especially in regions with supportive policies and favorable market conditions for renewable energy development (Wen et al., 2022; Bakhsh et al., 2023).

Based on Kuznets' environmental hypothesis (Grossman and Krueger, 1991; Panayotou, 1993), many theoretical and empirical studies suggest that economic development may lead to a reduction in environmental pollution once a certain threshold is reached (Criqui and Kouvaritakis, 2000). However, the two largest economies, the United States and China, are also among the highest polluting countries, indicating that this hypothesis may not be entirely accurate across all countries (Alvarado et al., 2021). Bekabil (2020) states that industrialization and reliance on fossil energy are the main causes of pollution. Therefore, countries are increasingly focusing on promoting renewable energy (REC) to replace fossil energy, aiming for sustainable development (Okafor-Yarwood, 2019). Previous studies (Xie et al., 2020; Bakhsh et al., 2023; Khan et al., 2023) have demonstrated that TI is a key factor in driving renewable energy use. Thus, based on these findings, the author proposes the following hypothesis:

H_2: TI has a positive impact on REC.

2.3. The Impact of GDP on REC

Over the past two decades, empirical studies have revolved around four main hypotheses regarding the relationship between economic growth and REC. The first is the growth hypothesis, which argues that REC promotes economic growth. Specifically, an increase in REC will boost output, and if REC decreases, energy-saving policies will negatively impact growth. The second is the conservation hypothesis, which focuses on the one-way causal relationship from economic growth to REC, meaning changes in REC do not impact economic growth. The third, the feedback hypothesis, refers to a two-way causal relationship between REC and growth, suggesting that growth will stimulate REC and, conversely, an increase in REC will also promote economic growth. Finally, the neutrality hypothesis asserts that these two factors are independent and have no reciprocal effect on each other (Burakov and Freidin, 2017).

Most empirical literature presents varying results regarding the relationship between growth and REC. Some studies show a one-way causal relationship from growth to REC (Menyah et al., 2010), while other studies suggest a one-way causal relationship from REC to growth. Some studies even confirm a two-way causal relationship between the two factors. The current body of literature reveals inconsistent findings regarding the impact of economic growth on REC. Some studies report a positive relationship between growth and REC (Sadorsky, 2010), while others indicate that growth has a significant negative effect on REC (Shahbaz et al., 2024).

H_3: GDP has a negative impact on REC.

2.4. The Impact of CO_2 Emissions on REC

Regarding the impact of CO_2 emissions on REC, several theories and studies suggest that an increase in CO_2 emissions may drive the demand for renewable energy in order to mitigate the negative environmental effects. According to the "Energy Transition Theory," when a country or region reaches a certain level of environmental pollution, it will seek alternative solutions, including transitioning to renewable energy as a means to reduce CO_2 emissions and improve environmental quality. This becomes more evident as the economy develops and the demand for environmental protection increases.

Sadorsky (2010) pointed out that both carbon emissions and GDP can promote REC. Specifically, as GDP and living standards rise, countries will have the financial ability to fund renewable energy initiatives. Additionally, the increasing CO_2 emissions create pressure that forces nations to seek more sustainable energy alternatives.

Apergis and Payne (2015) also confirmed the positive and significant relationship between real GDP per capita, per capita CO_2 emissions, and REC in South American countries in the long term. Countries with higher GDP will have the financial resources to invest in renewable energy technologies, and the rising CO_2 emissions push these countries to seek clean energy solutions to reduce pollution. Omri et al. (2015) further asserted that the increase in CO_2 emissions and GDP leads to higher REC. This aligns with the "Energy Transition Driver Theory," which argues that as emissions rise, countries are not only motivated by environmental concerns but also recognize the long-term economic benefits of transitioning to renewable energy.

However, Sinha and Shahbaz (2018) offered a different perspective, arguing that the high initial costs of renewable energy have made it difficult for developing economies to finance renewable energy solutions. They pointed out that while developed nations have enough resources to support the transition to renewable energy, developing countries face high upfront investment costs and competition from cheaper fossil fuel sources. As a result, REC in these countries remains limited.

Furthermore, the "Externality Theory" also plays a crucial role in explaining the link between CO_2 emissions and REC. This theory suggests that the social costs of CO_2 emissions (such as environmental pollution and climate change) are not fully reflected in the market prices of fossil fuels. Therefore, countries need policies that encourage or subsidize the use of renewable energy to reduce the costs of REC and promote it as a sustainable solution to CO_2 emissions and environmental protection. Thus, the increase in CO_2 emissions not only encourages the consumption of renewable energy but also creates incentives for countries to implement policies that promote the use of clean energy to mitigate the negative environmental impacts. However, financial barriers and costs remain factors to consider in this transition, especially for developing economies.

H_4: CO_2 emissions has a positive impact on REC.

3. RESEARCH METHODOLOGY

3.1. Data and Sample

The selection of countries was primarily guided by the availability, consistency, and reliability of relevant data throughout the study period. Data were obtained from three authoritative and widely recognized sources: The World Bank (WB), the International Monetary Fund (IMF), and Our World in Data (OWID). After applying rigorous criteria to ensure data completeness and quality, the final dataset comprises a balanced panel of 58countries spanning the period from 2002 to 2022. Comprehensive definitions, data sources, and measurement methodologies for all variables included in the analysis are systematically presented in Appendix 1.

3.2. Rationale for Variable Selection

Following Kim and Quoc (2024), REC is measured by REC per capita (in kWh), transformed using the natural logarithm to ensure normalization and improve the statistical properties of the variable. This measure reflects the extent to which renewable energy is integrated into a country's energy consumption structure on an individual basis, making it an appropriate indicator for cross-country comparisons. Given the global emphasis on sustainable energy transitions, REC serves as a key outcome variable to evaluate how economic, technological, financial, and environmental factors influence renewable energy uptake across countries and over time.

No single variable can comprehensively capture DFI due to its multifaceted nature (Le Quoc, 2024; Kim and Quoc, 2024). Therefore, following established practices in prior studies (Oanh and Dinh, 2024; Van and Le Quoc, 2024; Dinh, 2025a, 2025b, 2025c; Quoc et al., 2025a, 2025b), we adopt a composite approach to measure DFI by constructing an index using the Principal Component Analysis (PCA) method. This index incorporates 10 key components: the ratio of outstanding loans from commercial banks to GDP (OLCA), the ratio of outstanding deposits from commercial banks to GDP (ODCB), commercial bank branches per 1,000 square kilometers (CBPKM), commercial bank branches per 100,000 adults (CBP), ATMs per 1,000 square kilometers (ATMKM), ATMs per 100,000 adults (ATM), internet penetration rate (INT), mobile cellular subscriptions per 100 people (MCS), fixed telephone subscriptions per 100 people (FTS), and fixed broadband subscriptions per 100 people (FBS). Accordingly, the DFI index is constructed as follows:

$$DFI = W_1 OLCA + W_2 ODCB + W_3 CBPKM + W_4 CBP + W_5 ATMKM + W_6 ATM + W_7 INT + W_8 MCS + W_9 FTS + W_{10} FBS$$

Where DFI denotes the DFI index, and W represents the weights derived from PCA for each component's contribution.

This composite measure allows for a more holistic representation of financial inclusion by capturing both access and usage dimensions across physical and digital channels, aligning with recent literature advocating multidimensional approaches to DFI. DFI improves access to financial services through digital platforms, reducing barriers to funding for renewable energy investments, particularly in underserved areas (Le Quoc, 2024). By enabling broader participation and lowering transaction costs, higher DFI can foster greater adoption of renewable energy technologies. Based on this rationale, the study proposes the following hypothesis:

H_5: DFI has a positive impact on REC.

Similarly, drawing from Kim and Quoc (2024) and Ulucak (2021), we develop the TI variable using three essential indicators: the number of R&D researchers per million people (ADR), annual patent applications per million people (APA), and annual articles published in scientific and technical journals (AAP). These components jointly reflect both input (R&D capacity) and output (innovation outcomes) dimensions of TI, offering a comprehensive metric.

Where TI represents TI, and Z denotes the weights assigned to each variable. This multidimensional approach to measuring TI aligns with contemporary studies emphasizing both research efforts and innovation outputs (Kim and Le Quoc, 2024).

$$TI = Z_1AAP+Z_2ADR+Z_3APA$$

TI enhances renewable energy efficiency and affordability via innovations in production, storage, and distribution (Kim and Quoc; Ulucak, 2021). Increased R&D, patent activity, and scientific output facilitate technological improvements and diffusion, promoting renewable energy uptake. TI enhances renewable energy efficiency and affordability via innovations in production, storage, and distribution (Chien et al., 2021; Ulucak, 2021). Increased R&D, patent activity, and scientific output facilitate technological improvements and diffusion, promoting renewable energy uptake.

H_6: TI has a positive impact on REC.

GDP and Carbon Dioxide Emissions (CO_2) are included as explanatory variables in the model because they represent key economic and environmental factors influencing REC.

Firstly, per capita GDP serves as a vital indicator of a country's level of economic development. According to Sadorsky (2010), higher GDP can lead to increased overall energy demand while also providing greater financial capacity to invest in clean energy technologies, thereby fostering REC. Similarly, Apergis and Payne (2015) find a positive and statistically significant relationship between GDP and REC in the long run across South American countries. Therefore, incorporating GDP into the model allows for controlling the impact of economic growth on the demand for and adoption of renewable energy sources.

Secondly, CO_2 emissions are used as a proxy for environmental pollution and are closely linked to a country's energy consumption structure. Omri et al. (2015) suggest that rising CO_2 emissions can trigger policies aimed at promoting renewable energy as a means of reducing environmental degradation. Additionally, Sadorsky (2010) highlights that countries with high emissions are more likely to transition toward cleaner energy sources to meet greenhouse gas reduction targets. Including CO_2 in the model enables an assessment of the relationship between environmental pressure and REC. Based on this rationale, the following hypotheses are proposed:

H_7: GDP has a positive impact on REC.
H_8: CO_2 emissions have a positive impact on REC.

Both GDP and CO_2 are transformed using the natural logarithm to address issues of heteroskedasticity, reduce the influence of outliers, and improve the normality of the variable distributions, aligning with the assumptions of modern regression models.

3.3. Methodology

Based on previous studies by Kim and Quoc (2024) and Van and Le Quoc (2024), we propose the following research model to analyze the factors including DFI, CO_2, GDP, and TI affecting REC:

$$REC_{i,t} = \beta_0+\beta_1DFI_{i,t}+\beta_2TI_{i,t}+\beta_3GDP_{i,t}+\beta_4CO_{2i,t}+\beta xX_{i,t}+\varepsilon_{i,t} \quad (1)$$

Model (1) may experience multicollinearity between the explanatory variables, such as CO_2 and GDP, or DFI and GDP, which could reduce the accuracy of the estimates in the model. To address this issue and ensure the accuracy of the parameter estimates, we apply the Bayesian method, a robust technique that can handle uncertainties in the data and the relationships between variables. The Bayesian approach allows for the integration of prior knowledge and observed data to estimate the posterior distribution of the model parameters (Huy and Dinh, 2025).

In Bayesian statistics, research data are combined with prior information to estimate the posterior distribution. Results are interpreted as probability distributions of parameter values, regardless of sample size, allowing the Bayesian approach to overcome limitations associated with small samples (Zondervan-Zwijnenburg et al., 2017). Bayesian and frequentist methods are based on fundamentally different philosophical perspectives regarding what is considered fixed. Consequently, their interpretations also differ. The Bayesian approach assumes that the observed data are fixed, while model parameters are random variables. In contrast, the frequentist perspective treats parameters as fixed but unknown, and data as random samples drawn repeatedly. Under Bayesian inference, the posterior distribution of the parameters is computed based on the observed data and prior distributions, forming the basis for interpretation. Meanwhile, frequentist inference relies on sampling distributions or statistical properties of the data. In other words, Bayesian analysis answers questions about the conditional distribution of parameters given the observed data. Following the Bayesian framework, the author specifies a Bayesian linear regression model as:

$$y \sim N(\beta^T X, \sigma^2 I) \quad (*)$$

where y is normally distributed with a mean of $\beta^T X$ and variance $\sigma^2 I$. The mean is obtained from the product of the transposed weight matrix and the predictor matrix. In this model, both the outcome y and the parameters are assumed to follow probability distributions. The posterior probability of the model parameters conditional on the data is expressed as:

$$P(y|\beta,X) = P(y|\beta,X)P(\beta|X)$$

where $P(y|\beta,X)$ represents the likelihood, $P(\beta|X)$ is the prior distribution, and $P(y|X)$ is a normalizing constant (often omitted for estimation purposes).

To examine the hypothesized relationship between REC and explanatory variables, Bayesian regression is conducted in three steps:

Specifying priors: All regression coefficients are assigned normal prior distributions with a mean of zero, implying no prior bias toward positive or negative effects.

Defining likelihoods: Likelihood functions are assumed to follow normal distributions based on the model parameters.

Estimating posterior distributions: The Markov Chain Monte Carlo (MCMC) method with Gibbs sampling is applied, generating 12,500 posterior draws, with the first 2,500 draws discarded as burn-in to ensure convergence. MCMC is widely used to fit complex models across various disciplines. Hồi quy Bayesian được sử dụng trong nghiên cứu gần đây như Huy et al. (2025); Quoc et al. (2025c)

4. EMPIRICAL FINDINGS AND DISCUSSION

Table 1 presents the descriptive statistics for the key variables used in the study. The average REC is 7.7346, with a standard deviation of 1.4699, ranging from a minimum of 2.1423 to a maximum of 11.9294. This indicates a relatively wide variation in REC across countries and periods. The TI variable has a mean value of 8.8893 and a standard deviation of 1.5033, with values ranging from 5.4803 to 13.0691, reflecting significant differences in technological development levels. DFI shows an average of 4.8133, a relatively lower standard deviation of 0.4977, and values ranging from 2.6352 to 5.6530, suggesting moderate variation across observations. Per capita GDP (GDP) has an average of 26.5003 with a standard deviation of 1.5163, ranging from 22.4607 to 30.8673. This reflects differences in economic development levels across countries. Finally, CO_2 emissions (CO_2) have a mean of 1.5946 and a standard deviation of 0.8604, with a minimum value of −1.5143 and a maximum of 3.2430, indicating variation in environmental pollution levels among the sampled countries.

Table 2 presents the correlation analysis among the variables. It can be observed that TI, DFI, GDP, and CO_2 all exhibit significant positive correlations with REC, suggesting potential associations between these explanatory variables and REC. In addition, the relatively high correlations among independent variables—such as TI and DFI (0.4241), GDP and TI (0.8249), CO_2 and TI (0.4845), and CO_2 and DFI (0.5430)—indicate potential multicollinearity issues. High multicollinearity may inflate standard errors, reduce the precision of coefficient estimates, and complicate the interpretation of individual effects in classical regression models. To address this challenge and ensure the robustness of parameter estimation, we adopt a Bayesian regression approach. The Bayesian method offers several advantages in the presence of multicollinearity by incorporating prior distributions to stabilize estimates and accounting for parameter uncertainty through posterior distributions. This approach allows for more reliable inference and a nuanced understanding of the relationships between REC and its determinants.

Table 1: Descriptive statistics

Variables	Mean	Std.Dev	Minimum	Maximum
REC	7.7346	1.4699	2.1423	11.9294
TI	8.8893	1.5033	5.4803	13.0691
DFI	4.8133	0.4977	2.6352	5.6530
GDP	26.5003	1.5163	22.4607	30.8673
CO_2	1.5946	0.8604	-1.5143	3.2430
POP	17.1313	1.7611	12.5848	21.0719
FDI	22.8966	1.6433	15.8559	27.3215
UR	16.6931	1.6033	12.5113	20.6152
OPEN	85.1233	52.4196	22.1060	393.1412

Source: Calculations by the authors

The results indicate that TI has a positive and statistically significant impact on REC, with a coefficient of 0.1097 and a probability of effect of 100%. This confirms the pivotal role of TI in promoting REC. TI serves not only as a supportive factor but also as a central leverage, increasing the share of renewable energy through various mechanisms: (1) improving efficiency and reducing the cost of renewable energy production (such as solar panel technology and wind turbines), (2) developing storage solutions and smart grid management to address the intermittency of renewable energy, and (3) applying AI, IoT, and Big Data in forecasting output and real-time consumption management. According to Porter and Van der Linde (1995), TI not only reduces "environmental costs" but also creates "competitive advantages," helping businesses reduce long-term energy costs and access the green market. These findings support Hypothesis H1 and align with the research of Kim and Quoc (2024), which emphasizes that in the context of Industry 4.0, TI both increases REC and contributes to achieving clean energy (SDG 7) and climate action (SDG 13) goals.

The results also show that DFI has a positive effect on REC, with a coefficient of 0.1891 and a probability of effect of 67.63%. While this does not reach the 95% confidence threshold, it suggests a positive trend and potential. This indicates that DFI can contribute to promoting recycling activities (REC) and the circular economy by expanding access to formal financial services for excluded groups, such as the poor, women, rural residents, and MSMEs. As a result, they can borrow funds, invest in recycling equipment, and participate in green value chains. Additionally, digital finance reduces transaction costs and promotes electronic payments for services such as waste collection, sorting, and recycling through technologies like mobile banking, e-wallets, and blockchain. However, the probability of effect being relatively low (67.63%) implies that there are still several barriers: (1) uneven digital infrastructure, with many rural and mountainous areas lacking stable internet access and having high access costs; (2) the digital skills gap and lack of digital financial knowledge that prevent certain segments of the population and small businesses from utilizing these services, leading to a "double exclusion" problem (digital divide + financial exclusion), which limits the spillover effects on REC.

The results show that GDP has a significant positive impact on REC with a coefficient of 0.8750 and a probability of effect of 83.44%, supporting Hypothesis H3 and consistent with the study of Van and Le Quoc (2024). This reflects that economic growth is a key factor driving investment and expansion in renewable energy, as it generates greater financial resources for investing in clean

Table 2: Correlation analysis

	REC	TI	DFI	GDP	CO_2	POP	FDI	UR	OPEN
REC	1								
TI	0.3461	1							
DFI	0.5119	0.4241	1						
GDP	0.1231	0.8249	0.2287	1					
CO_2	0.4870	0.4845	0.5430	0.2383	1				
POP	−0.4443	0.3798	−0.3447	0.7062	−0.3175	1			
FDI	0.1929	0.6491	0.2600	0.7489	0.3448	0.4168	1		
UR	−0.3482	0.492	−0.2503	0.7891	−0.1928	0.9815	0.5023	1	
OPEN	0.1048	−0.2179	0.2895	−0.4115	0.2918	−0.587	−0.042	−0.5869	1

Source: Calculations by the authors

energy infrastructure, green technologies, and renewable energy projects. As GDP increases, both the government and the private sector can raise more capital for sustainable energy programs, as well as improve access to advanced technologies. However, the probability of effect has not yet reached a certain threshold (only 83.44%), suggesting that the impact of GDP on REC still carries a certain degree of uncertainty. This implies that while economic growth plays an important role, it is not enough to ensure a sustainable increase in REC. In some cases, economic growth may come with increased consumption of traditional energy sources (such as thermal power and coal), unless there are clear policies guiding energy transition. If growth is mainly based on the extraction of fossil resources or heavy industry ("brown growth"), it may reduce the share of renewable energy in total energy consumption and increase greenhouse gas emissions. Previous studies also indicate that high GDP does not automatically lead to the "greening" of the energy structure, as it heavily depends on energy and environmental policies and incentives for green investment. Therefore, to ensure that economic growth goes hand-in-hand with the expansion of REC, governments need to integrate policies such as carbon taxes, subsidies for clean energy, encourage private investment in renewable energy, and develop green energy transmission and storage infrastructure. At the same time, a clear energy transition roadmap must be established to ensure that GDP growth does not lead to increased fossil fuel use, but rather drives the "greening" of the economy and long-term emissions reduction.

CO_2 emissions exert a significant negative impact on REC, with an estimated coefficient of −0.2297 and a probability of effect of 86.13%, thereby supporting Hypothesis H4 and aligning with prior findings from Kim and Quoc (2024). This result underscores the adverse relationship between CO_2 emissions and REC, as CO_2 is the principal greenhouse gas driving global climate change. Elevated CO_2 emissions contribute to rising global temperatures, triggering extreme weather events such as floods, droughts, and more intense storms, which escalate the risks of natural disasters and socioeconomic disruptions. Consequently, high CO_2 emissions not only impede progress toward Sustainable Development Goal (SDG) 13 (Climate Action) but also indirectly constrain achievements in SDG 7 (Affordable and Clean Energy), SDG 3 (Good Health), and SDG 11 (Sustainable Cities and Communities). In addition to environmental damages, CO_2 emissions impose substantial social costs. Air pollution linked to CO_2 and related emissions increases the prevalence of respiratory and cardiovascular diseases, leading to higher healthcare expenditures, reduced labor productivity, and

Table 3: Bayesian regression

Dependent variable: REC	Bayesian Regression			
	Mean	Std. Dev.	MCSE	Probability of Effect: Independent→Dependent
C	4.2185	0.6235	0.0036	100%
TI	0.1097	0.0373	0.0002	100%
DFI	0.1891	0.0876	0.0005	67.63
GDP	0.8750	0.0590	0.0003	83.44%
CO_2	−0.2297	0.0566	0.0003	86.13
POP	−1.1973	0.1271	0.0007	100%
FDI	0.0736	0.0285	0.0002	100%
UR	−0.0054	0.1375	0.0008	100%
OPEN	−0.0064	0.0008	0.0000	100%
Acceptance rate			1.0000	
Efficiency: Min			0.9612	
Max Gelman-Rubin Rc			1.0000	

Source: Calculations by the authors

negative implications for the workforce and social welfare. As highlighted by OECD (2021), economies with elevated emissions often encounter greater fiscal burdens in addressing environmental consequences, which strain national budgets and limit resources for investing in other sustainable development priorities. The negative relationship between CO_2 emissions and REC can be partly explained by structural and institutional inertia in fossil fuel-dependent economies. In these contexts, high CO_2 emissions are typically symptomatic of entrenched reliance on traditional energy sources, whereby infrastructure, policies, and investments favor fossil fuels over renewable alternatives. This dominance of carbon-intensive industries creates barriers to the expansion of renewable energy by diverting financial, institutional, and political capital away from green energy initiatives. Moreover, the environmental degradation and climate-related risks associated with high CO_2 emissions increase the costs of disaster response, recovery, and adaptation, thereby reducing fiscal space for renewable energy investments. Health impacts from air pollution further compound these challenges by raising healthcare costs and lowering workforce productivity, undermining both social welfare and long-term economic capacity to support renewable energy transitions.

Bayesian regression analysis shows that the average acceptance rate is 1.000, while the minimum model efficiency rate is 0.9612, both exceeding the minimum threshold of 0.01. This demonstrates that the research model meets the requirements for both groups of countries. When compared to traditional frequency-based research methods, Bayesian analysis stands out as an effective alternative, particularly when dealing with small sample sizes. This method also addresses issues such as autocorrelation, variance heterogeneity, and endogeneity within the model. The results from Bayesian regression provide Monte Carlo Standard Error (MCSE) parameters, which help assess the stability of the MCMC chain. According to Flegal et al. (2008), when the MCSE value approaches zero, the MCMC chain becomes stronger. An MCSE under 6.5% standard deviation is considered acceptable, and under 5% is ideal. Table 3 shows that the MCSE values for both groups of countries gradually decrease to near zero, with all MCSE values below 5%, confirming the robustness of the Bayesian model. Furthermore, the Max Gelman-Rubin value of Rc = 1.0 proves that the MCMC chains have fully converged, ensuring that the analysis results are stable and reliable. With Rc = 1.0, the chains no longer show significant differences, indicating that the model has achieved homogeneity and the Bayesian inference results can be trusted.

5. CONCLUSION AND POLICY RECOMMENDATIONS

5.1. Conclusion

In the context of a global climate crisis, environmental degradation, and the pressure for energy transition, the consumption of renewable energy (REC) has become a central goal in the sustainable development agendas of many countries. Despite numerous international commitments such as the Kyoto Protocol (1997), the Paris Agreement (2015), and the Sustainable Development Goals (SDGs) for 2030, the global energy system remains heavily reliant on fossil fuels, accounting for nearly 80% of total energy consumption (World Bank, 2023), which in turn contributes to CO_2 emissions that make up 76.7% of total greenhouse gas emissions (IPCC, 2013). This situation presents an urgent challenge in promoting factors that support the transition to renewable energy, including TI, DFI, economic growth (GDP), and CO_2 emission control. However, previous studies have mostly focused on individual factors without a comprehensive approach and have been limited in methodology when addressing issues such as multicollinearity, endogeneity, cross-dependence, and parameter heterogeneity across countries. Building on this gap, this study applies the Bayesian Monte Carlo method to provide a comprehensive, reliable, and probabilistic assessment of the impacts of these factors on REC, contributing additional empirical evidence for policy formulation aimed at achieving a sustainable global energy transition. Data collected from 58 countries worldwide from 2004 to 2022 show that TI has a positive and highly significant impact on REC (coefficient = 0.1097; probability of effect = 100%), confirming the central role of TI in driving renewable energy by improving efficiency, reducing costs, advancing storage solutions, smart grid management, and the application of AI, IoT, and Big Data. DFI also positively impacts REC (coefficient = 0.1891; probability of effect = 67.63%), suggesting the potential to boost REC by expanding financial access for vulnerable groups, although it is still constrained by weak digital infrastructure and skill gaps. Economic growth (GDP) shows a significantly positive association with REC (coefficient = 0.8750; probability of effect = 83.44%), suggesting that higher GDP levels create favorable conditions for renewable energy investment, although such growth may not inherently ensure sustainability without targeted energy transition policies. In contrast, CO_2 emissions exhibit a significant negative relationship with REC (coefficient = −0.2297; probability of effect = 86.13%), indicating that higher emissions are linked to lower renewable energy uptake and pose substantial challenges to sustainable development by exacerbating environmental risks, increasing healthcare costs, and hindering the achievement of several Sustainable Development Goals (SDGs).

5.2. Policy Recommendations

Based on the research findings and the global context, several important policy implications can be drawn to promote REC and support the transition to sustainable energy.

First, there is a need to prioritize investment and encourage TI in the renewable energy sector through policies that support research and development (R&D), tax incentives for innovative companies, and the development of technological infrastructure such as smart grids and energy storage. At the same time, promoting the application of advanced technologies like AI, IoT, and Big Data in the management and operation of energy systems should be encouraged.

Second, it is important to promote DFI to expand access to capital for renewable energy projects, particularly for vulnerable groups and small businesses. This can be achieved by developing digital infrastructure, promoting digital skills, and encouraging fintech platforms, mobile banking, and crowdfunding to reduce financial barriers.

Third, economic growth (GDP) should be closely linked to sustainable development and energy transition by integrating economic development policies with emission reduction goals. This includes prioritizing green investment, transitioning the industrial structure to low-emission sectors, and enhancing environmental risk management in production processes.

Fourth, strict CO_2 emission controls should be implemented alongside the development of renewable energy, using tools such as carbon taxes, emissions trading schemes, stringent emission standards, and incentives for companies to reduce emissions. Additionally, investment in carbon capture and storage technologies is essential.

Finally, a comprehensive and integrated policy framework should be established that addresses technology, finance, economy, and environmental factors simultaneously, rather than taking a fragmented approach. Strengthening international cooperation and sharing technology and green finance, especially with developing countries, is crucial to ensuring that the energy transition is both fair and effective.

REFERENCES

Al-Maamary, H.M., Kazem, H.A., Chaichan, M.T. (2017), The impact of oil price fluctuations on common renewable energies in GCC countries. Renewable and Sustainable Energy Reviews, 75, 989-1007.

Alvarado, R., Deng, Q., Tillaguango, B., Méndez, P., Bravo, D., Chamba, J., Ahmad, M. (2021), Do economic development and human capital decrease non-renewable energy consumption? Evidence for OECD Countries. Energy, 215, 119147.

Apergis, N., Payne, J.E. (2015), Renewable energy, output, carbon dioxide emissions, and oil prices: Evidence from South America. Energy Sources Part B Economics Planning and Policy, 10(3), 281-287.

Bakhsh, S., Zhang, W., Ali, K., Anas, M. (2023), Can digital financial inclusion facilitate renewable energy consumption? Evidence from nonlinear analysis. Energy Environment, 36, 2049-2079.

Bekabil, U.T. (2020), Industrialization and environmental pollution in Africa: An empirical review. Journal of Resources Development and Management, 69, 18-21.

Burakov, D., Freidin, M. (2017), Financial development, economic growth and renewable energy consumption in Russia: A vector error correction approach. International Journal of Energy Economics and Policy, 7(6), 39-47.

Chen, H., Shi, Y., Zhao, X. (2022), Investment in renewable energy resources, sustainable financial inclusion and energy efficiency: A case of US economy. Resources Policy, 77, 102680.

Cui, L., Weng, S., Song, M. (2022), Financial inclusion, renewable energy consumption, and inclusive growth: Cross-country evidence. Energy Efficiency, 15(6), 43.

Criqui, P., and Kouvaritakis, N. (2000), World energy projections to 2030. International journal of global energy issues, 14(1-4), 116-136.

Dinh, L.Q. (2025a), The impact of digital financial inclusion on income inequality amid economic complexity: A GMM and Bayesian regression approach. Social Responsibility Journal, 21, 1383-1400.

Dinh, L.Q. (2025b), The optimal inflation threshold in digital financial inclusion: A key to sustainable development. SN Business and Economics, 5(5), 1-20.

Dinh, L.Q. (2025c), Reassessing the impact of foreign direct investment on environmental quality in 112 Countries: A Bayesian quantile regression approach. International Social Science Journal. https://doi.org/10.1111/issj.12577

Diamond, D.W. (1984), Financial intermediation and delegated monitoring. Review of Economic Studies, 51(3), 393-414.

Eren, B.M., Taspinar, N., Gokmenoglu, K.K. (2019), The impact of financial development and economic growth on renewable energy consumption: Empirical analysis of India. Science of the Total Environment, 663, 189-197.

Jaumotte, F., Pain, N. (2005), From Ideas to Development: The Determinants of R&D and Patenting (No. 457). Paris: OECD Publishing.

Johnstone, N., Haščič, I., Popp, D. (2010), Renewable energy policies and technological innovation: Evidence based on patent counts. Environmental and Resource Economics, 45, 133-155.

Flegal, J.M. (2008), Monte Carlo Standard Errors for Markov Chain Monte Carlo. United States: University of Minnesota.

Fuso Nerini, F., Tomei, J., To, L.S., Bisaga, I., Parikh, P., Black, M., Borrion, A., Spataru, C., Broto, V.C., Anandarajah, G., Milligan, B., Mulugetta, Y. (2018), Mapping synergies and trade-offs between energy and the sustainable development goals. Nature Energy, 3(1), 10-15.

George, A. (1970), The Market for Lemons: Quality Uncertainty and the Market Mechanism. The Quarterly Journal of Economics, 84, 488-500.

Grossman, G., Krueger, A. (1991), Environmental Impacts of a North American Free Trade Agreement. National Bureau of Economic Research, Working Paper No. w3914.

Huy, N.Q., Dong, N.V.H., Dinh, L.Q. (2025), Examining the roles of monetary and fiscal policies in Vietnam’s economic growth amid global challenges: A Bayesian VAR and wavelet coherence approach. International Journal of Innovative Research and Scientific Studies, 8(2), 2758-2769.

Huy, N. Q., and Dinh, L. Q. Balancing Bank Profits With Sustainable Development Goals: Examining the Pivotal Role of Financial Stability. Sustainable Development. https://doi.org/10.1002/sd.70057

Le Quoc, D. (2024), The relationship between digital financial inclusion, gender inequality, and economic growth: Dynamics from financial development. Journal of Business and Socio Economic Development, 4(4), 370-388.

Le Quoc, D., Nguyen Quoc, H., Nguyen Van, H. (2025), Evaluating the influence of digital financial inclusion on financial crises and economic cycles: A Bayesian logistic regression insight. Journal of Financial Regulation and Compliance, 33(2), 280-301.

Li, J., Dong, X., Dong, K. (2022), How much does financial inclusion contribute to renewable energy growth? Ways to realize green finance in China. Renewable Energy, 198, 760-771.

Li, J., Wu, Y., Xiao, J.J. (2020), The impact of digital finance on household consumption: Evidence from China. Economic Modelling, 86, 317-326.

Kim, O.T.T., Quoc, D.L. (2024), Exploring the influence of digital financial inclusion and technological progress on renewable energy consumption: A Bayesian quantile regression analysis. Environment Development and Sustainability, 1-30. https://doi.org/10.1007/s10668-024-05675-2

Kim, J., Park, K. (2016), Financial development and deployment of renewable energy technologies. Energy Economics, 59, 238-250.

Khan, A., Chenggang, Y., Hussain, J., Kui, Z. (2021), Impact of technological innovation, financial development and foreign direct investment on renewable energy, non-renewable energy and the environment in belt & road initiative countries. Renewable Energy, 171, 479-491.

Khan, Z., Faraz Raza, S.M., Dong, K., Haouas, I. (2023), How do remittance inflows cause the dutch disease in the financial sector? The role of financial risk and human capital. Annals of Financial Economics, 18(04), 2340001.

Martínez-García, M.Á., Ramos-Carvajal, C., Cámara, Á. (2023), Consequences of the energy measures derived from the war in Ukraine on the level of prices of EU Countries. Resources Policy, 86, 104114.

Menyah, K., Wolde-Rufael, Y. (2010), Energy consumption, pollutant emissions and economic growth in South Africa. Energy Economics, 32(6), 1374-1382.

Panayotou, T. (1993), Empirical Tests and Policy Analysis of Environmental Degradation at Different Stages of Economic Development. International Labour Organization, Working Paper No. 992927783402676.

Porter, M.E. (1980), Industry structure and competitive strategy: Keys to profitability. Financial Analysts Journal, 36(4), 30-41.

Okafor-Yarwood, I. (2019), Illegal, unreported and unregulated fishing, and the complexities of the sustainable development goals (SDGs) for countries in the Gulf of Guinea. Marine Policy, 99, 414-422.

Omri, A., Mabrouk, N.B., Sassi-Tmar, A. (2015), Modeling the causal linkages between nuclear energy, renewable energy and economic growth in developed and developing countries. Renewable and Sustainable Energy Reviews, 42, 1012-1022.

Oanh, T.T.K., Dinh, L.Q. (2024), Digital financial inclusion, financial stability, and sustainable development: Evidence from a quantile on quantile regression and wavelet coherence. Sustainable

Development, 32(6), 6324-6338.

Quoc, H.N., Le Quoc, D., Van, H.N. (2025a), Assessing digital financial inclusion and financial crises: The role of financial development in shielding against shocks. Heliyon, 11(1), e41231.

Quoc, D.L., Duy, T.T., Hai, A.N.H., Van, H.N. (2025c), Unveiling the impact of digital financial inclusion and financial development on global unemployment: A Bayesian quantile regression approach. Edelweiss Applied Science and Technology, 9(4), 2862-2876.

Quoc, H.N., Van, H.N., Le Quoc, D. (2025c), Unraveling the nexus between sustainable development, bank profitability, and loan loss provisions in Vietnam: A Bayesian vector autoregression perspective. Research on World Agricultural Economy, 6(2), 123-139.

Salim, R. A., and Rafiq, S. (2012), Why do some emerging economies proactively accelerate the adoption of renewable energy?. Energy economics, 34(4), 1051-1057.

Shahbaz, M., Topcu, B.A., Sarıgül, S.S., Doğan, M. (2024), Energy imports as inhibitor of economic growth: The role of impact of renewable and non-renewable energy consumption. The Journal of International Trade and Economic Development, 33(4), 497-522.

Sadorsky, P. (2010), The impact of financial development on energy consumption in emerging economies. Energy Policy, 38(5), 2528-2535.

Sinha, A., Shahbaz, M. (2018), Estimation of environmental Kuznets curve for CO_2 emission: Role of renewable energy generation in India. Renewable Energy, 119, 703-711.

Tudor, C., Sova, R. (2021), On the impact of GDP per capita, carbon intensity and innovation for renewable energy consumption: Worldwide evidence. Energies, 14(19), 6254.

Tsao, Y.C., Vu, T.L., Lu, J.C. (2021), Pricing, capacity and financing policies for investment of renewable energy generations. Applied Energy, 303, 117664.

Ulucak, R. (2021), Renewable energy, technological innovation and the environment: A novel dynamic auto-regressive distributive lag simulation. Renewable and Sustainable Energy Reviews, 150, 111433.

Van, H.N., Le Quoc, D. (2024), Assessing the impact of digital financial inclusion on sustainable development goals: Analyzing differences by financial development levels across Countries. Journal of the Knowledge Economy, 1-24. https://doi.org/10.1007/s13132-024-02515-6

Van, H.N., Quoc, H.N., Le Quoc, D. (2025), The role of green credit in promoting sustainable development in Vietnam: Evidence from quantile-ON-quantile regression. Research on World Agricultural Economy, 6(1), 88-99.

World Bank. (2023), World Development Indicators. Available from: https://data.worldbank.org/indicator/eg.use.comm.fo.zs

Wen, Y., Onwe, J.C., Haseeb, M., Saini, S., Matuka, A., Sahoo, D. (2022), Role of technological innovation, renewable and non-renewable energy, and economic growth on environmental quality. Evidence from African countries. Frontiers in Energy Research, 10, 958839.

Xie, F., Liu, Y., Guan, F., Wang, N. (2020), How to coordinate the relationship between renewable energy consumption and green economic development: From the perspective of technological advancement. Environmental Sciences Europe, 32, 1-15.

Zhou, N., Levine, M.D., Price, L. (2010), Overview of current energy-efficiency policies in China. Energy Policy, 38(11), 6439-6452.

Zhang, J., Zhang, H., Gong, X. (2022), Mobile payment and rural household consumption: Evidence from China. Telecommunications Policy, 46(3), 102276.

APPENDIX

Appendix 1: Description of variables in the model

Variables	Symbol	Measurement	Studies	Data source
Dependent variable				
Renewable energy consumption	REC	This variable represents the per capita consumption of renewable energy, measured in kilowatt-hours (kWh). The data are transformed using the natural logarithm (ln) for analysis.	Kim and Quoc (2024)	Our world in data
Independent variable				
Digital financial inclusion	DFI	PCA score		Authors' calculation
Loan Outstanding of Commercial Banks (CBs)	OLCB	The ratio of the total credit extended by commercial banks (CBs) in a country to its GDP.	Le Quoc (2024); Kim and Quoc (2024); Oanh and Dinh (2024); Van and Le Quoc (2024); Dinh (2025a, 2025b, 2025c); Quoc et al (2025a, 2025c)	WB, IMF
Outstanding deposits with CBs	ODCB	The ratio of total deposits held by commercial banks in a country to its GDP.		WB, IMF
Bank branch density (per 1,000 km²)	CBBP	The number of commercial bank branches per 1,000 square kilometers of land area.		FAS
Banking penetration	CBP	The number of commercial bank branches per 100,000 adults in the population.		WB, IMF
ATM density (per 1,000 km²)	ATMKM	The number of automated teller machines (ATMs) per 1,000 square kilometers of land area.		FAS
ATM accessibility	ATM	The number of automated teller machines (ATMs) per 100,000 adults in the population.		WB, IMF
Percentage of internet users	INT	The percentage of individuals in a country or region who have access to and use the Internet.		WB
Mobile subscription density	MCS	The number of mobile phone subscriptions per 100 people.		
Fixed telephone density	FTS	The number of fixed telephone subscriptions per 100 people.		
Fixed broadband penetration rate	FBS	The number of fixed broadband subscriptions per 100 people.		
Technological innovation	TI	PCA score		
Number of scientific articles published	AAP	Annual number of articles published in scientific and technical journals.	Kim and Quoc (2024); Ulucak (2021)	WB
Number of R&D researchers	ADR	Number of research and development (R&D) researchers per million people in the population.		
The yearly submissions for patents	APA	Annual number of patent applications submitted per million people.		
Gross Domestic Product	GDP	Per capita gross domestic product (current US dollars), transformed using the natural logarithm.	Ibrahim and Ajide (2021)	WB
Environmental pollution	CO_2	Total carbon dioxide emissions (million metric tons), expressed in natural logarithmic form.	Kim and Quoc (2024); Dinh et al. (2025c)	WB
Control variable				
Urbanization rate	UR	The proportion of the urban population to the total population, transformed using the natural logarithm.	Kim and Quoc (2024)	WB
Population growth rate	POP	The total population residing in a specific area within a year, expressed in natural logarithmic form.	Kim and Quoc (2024)	WB
Trade openess	OPEN	The ratio of total merchandise and service exports plus imports to GDP, serving as an indicator of a country's openness to trade. This ratio is calculated by summing the value of exports and imports of goods and services and dividing by GDP; a natural logarithmic transformation is applied for statistical robustness.	Kim and Quoc (2024)	WB
Foreign direct investment	FDI	The total inflow of foreign direct investment into a country (in US dollars), transformed using the natural logarithm.	Sadorsky (2010), Li et al. (2020)	WB

Source: Compiled by the authors