

DRIVERS OF RENEWABLE ENERGY CONSUMPTION: EVIDENCE FROM A GLOBAL PERSPECTIVE

FATORES QUE IMPULSIONAM O CONSUMO DE ENERGIA RENOVÁVEL: EVIDÊNCIAS DE UMA PERSPECTIVA GLOBAL

Article received on: 8/15/2025

Article accepted on: 11/14/2025

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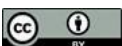
The authors declare that there is no conflict of interest

Abstract

The global shift toward renewable energy has intensified the need to understand the key factors influencing renewable energy consumption (REC) across countries. This study investigates the determinants of REC by jointly examining the roles of technological innovation, digital financial inclusion, economic growth, carbon dioxide emissions, population size, foreign direct investment, urbanization, and trade openness. Using a balanced panel of 69 countries over the period 2002–2023, the study applies a Bayesian regression framework to address common empirical challenges such as multicollinearity, parameter uncertainty, and cross-country heterogeneity. The empirical findings reveal that technological innovation is a fundamental driver of renewable energy consumption, highlighting its importance in improving efficiency and enhancing the competitiveness of clean energy technologies. Economic growth and foreign direct investment also exert positive effects, suggesting that higher income levels and capital inflows can facilitate renewable energy expansion when aligned with appropriate structural and policy conditions. In contrast, carbon dioxide emissions, population growth, urbanization, and trade openness negatively affect renewable energy consumption, indicating that fossil fuel dependence, demographic pressure, and trade-driven scale effects may constrain the energy transition. Digital financial inclusion shows a positive but conditional impact, implying that its effectiveness depends on complementary green finance policies and regulatory support. The results demonstrate that

Resumo

A mudança global em direção às energias renováveis intensificou a necessidade de compreender os principais fatores que influenciam o consumo de energia renovável (CER) em diferentes países. Este estudo investiga os determinantes do CER, examinando conjuntamente os papéis da inovação tecnológica, inclusão financeira digital, crescimento econômico, emissões de dióxido de carbono, tamanho da população, investimento estrangeiro direto, urbanização e abertura comercial. Utilizando um painel equilibrado de 69 países no período de 2002 a 2023, o estudo aplica uma estrutura de regressão Bayesiana para abordar desafios empíricos comuns, como multicolinearidade, incerteza dos parâmetros e heterogeneidade entre países. Os resultados empíricos revelam que a inovação tecnológica é um fator fundamental para o consumo de energia renovável, destacando sua importância para melhorar a eficiência e aumentar a competitividade das tecnologias de energia limpa. O crescimento econômico e o investimento estrangeiro direto também exercem efeitos positivos, sugerindo que níveis de renda mais elevados e fluxos de capital podem facilitar a expansão da energia renovável quando alinhados com condições estruturais e políticas adequadas. Em contraste, as emissões de dióxido de carbono, o crescimento populacional, a urbanização e a abertura comercial afetam negativamente o consumo de energia renovável, indicando que a dependência de combustíveis fósseis, a pressão demográfica e os efeitos de escala impulsionados pelo



renewable energy consumption is shaped by a complex interaction of economic, technological, financial, demographic, and structural factors. The study provides robust policy-relevant insights to support the design of integrated strategies for advancing a sustainable low-carbon energy transition.

Keywords: Technological Innovation. Digital Financial Inclusion. Economic Growth. CO₂ Emission.

comércio podem restringir a transição energética. A inclusão financeira digital apresenta um impacto positivo, porém condicional, o que implica que sua eficácia depende de políticas complementares de financiamento verde e de apoio regulatório. Os resultados demonstram que o consumo de energia renovável é moldado por uma interação complexa de fatores econômicos, tecnológicos, financeiros, demográficos e estruturais. O estudo fornece informações robustas e relevantes para políticas públicas, apoiando o desenvolvimento de estratégias integradas para promover uma transição energética sustentável de baixo carbono.

Palavras-chave: Inovação Tecnológica. Inclusão Financeira Digital. Crescimento Econômico. Emissão de CO₂.

1 INTRODUCTION

The global transition toward renewable energy represents one of the most pressing challenges of the twenty-first century, driven by escalating environmental degradation, rising energy insecurity, and increasingly stringent international commitments to decarbonization. Within this context, renewable energy consumption (REC) has become a central pillar of sustainable development strategies worldwide (Okafor-Yarwood, 2019). Nevertheless, despite long-standing global initiatives—including the Kyoto Protocol, the Paris Agreement, and the Sustainable Development Goals (SDGs)—the global energy system remains heavily dependent on fossil fuels, which account for nearly four-fifths of total energy consumption (World Bank, 2023; Kim & Le Quoc, 2024). This persistent reliance continues to intensify greenhouse gas emissions, with carbon dioxide (CO₂) alone contributing more than three-quarters of total emissions, thereby amplifying climate risks and undermining long-term environmental sustainability.

Against this backdrop, identifying the determinants of renewable energy consumption has attracted growing attention from scholars and policymakers alike. Existing studies have largely emphasized macroeconomic and environmental factors—such as economic growth, income levels, carbon emissions, and energy prices—in explaining variations in REC across countries (Sadorsky, 2010; Tudor & Sova, 2021; Al-Maamary *et al.*, 2017). While this body of literature has enhanced understanding of how

economic expansion and environmental pressure influence renewable energy demand, it often provides a partial view by underestimating the roles of financial conditions, technological capability, demographic dynamics, and structural openness in shaping energy transition pathways.

The deployment of renewable energy typically involves substantial upfront investment, long payback periods, and exposure to technological and market risks, which may discourage private participation and create persistent financing constraints (Tsao *et al.*, 2021). Consequently, the availability of an inclusive and efficient financial system is critical for mobilizing capital toward renewable energy projects (Eren *et al.*, 2019). In recent years, the rapid diffusion of digital technologies has transformed access to financial services. Digital financial inclusion (DFI)—through mobile banking, digital payments, and fintech platforms—has the potential to reduce transaction costs, broaden access to credit, and enhance financial participation among households and firms previously excluded from formal finance (Le Quoc, 2024). Despite its increasing relevance, empirical evidence on the relationship between DFI and renewable energy consumption remains limited and inconclusive.

Technological innovation (TI) also constitutes an important determinant of renewable energy consumption, as technological progress can enhance energy efficiency, lower production and storage costs, and facilitate the substitution of fossil fuels with cleaner energy sources (Zhou, 2010). However, technological advancement is unevenly distributed across countries. Many economies—particularly developing ones—face constraints such as weak domestic innovation capacity, dependence on imported technologies, and limited research and development infrastructure (Khan *et al.*, 2021), which may slow renewable energy adoption and contribute to cross-country disparities in energy transition outcomes.

Beyond financial and technological factors, broader macroeconomic, demographic, and structural conditions may further influence renewable energy consumption. Economic growth (GDP) affects both energy demand and the capacity to invest in renewable energy infrastructure, while foreign direct investment (FDI) can support renewable energy development through capital inflows and technology transfer, depending on its sectoral orientation. Population size (POP) and urbanization (UR) shape energy demand patterns and infrastructure needs, whereas trade openness (OPEN) reflects the extent of integration into global markets, potentially facilitating access to

renewable energy technologies, inputs, and knowledge spillovers. Nevertheless, much of the existing literature examines these determinants in isolation, rather than within an integrated framework that captures their simultaneous and independent effects on renewable energy consumption.

From a methodological perspective, cross-country analyses of renewable energy consumption face several challenges, including multicollinearity among explanatory variables, endogeneity arising from bidirectional relationships between economic growth and energy use, cross-sectional dependence due to global spillovers, and heterogeneity across countries (Bekabil, 2020). Conventional frequentist approaches often struggle to address these issues comprehensively and provide limited information on parameter uncertainty. To overcome these limitations, this study adopts a Bayesian Monte Carlo simulation approach, which enables probabilistic inference, incorporates prior information, and offers robust estimation in the presence of complex data structures.

Accordingly, this study examines the determinants of renewable energy consumption by jointly assessing the roles of technological innovation (TI), digital financial inclusion (DFI), economic growth (GDP), carbon emissions (CO₂), population dynamics (POP), foreign direct investment (FDI), urbanization (UR), and trade openness (OPEN) across a broad panel of countries. By employing a Bayesian framework, the analysis provides a comprehensive and balanced evaluation of how economic, financial, technological, demographic, and structural factors interact to shape renewable energy consumption.

By addressing these issues, the study contributes to the literature on energy transition by offering a more integrated and methodologically robust understanding of the drivers of renewable energy consumption. The findings are expected to inform policymakers in designing coordinated strategies that align economic development, financial inclusion, technological progress, and environmental sustainability in the global transition toward a low-carbon energy future.

2 LITERATURE REVIEW

2.1 The impact of DFI on REC

Renewable energy technologies are often associated with high upfront costs, which limits their affordability for low-income households and financially constrained users (Kim & Le Quoc, 2024). In this context, digital financial inclusion (DFI) may influence renewable energy consumption (REC) through financial intermediation and information efficiency channels.

From the perspective of financial intermediation theory (Diamond, 1984), DFI enhances the allocation of financial resources by connecting savers and borrowers more efficiently, thereby improving access to capital for clean energy investments. By lowering transaction costs and expanding credit availability, digital financial services can facilitate investment in renewable energy technologies, particularly for underserved households and small firms (Kim & Le Quoc, 2024).

Similarly, asymmetric information theory (George, 1970) suggests that credit markets are often constrained by information gaps between lenders and borrowers. DFI can reduce these frictions by leveraging digital data and alternative credit scoring, enabling lower-cost financing and improving access to renewable energy-related credit (Li *et al.*, 2020; Zhang *et al.*, 2022). This is particularly relevant given that high initial capital requirements remain a major barrier to renewable energy adoption (Kim & Park, 2016).

However, the expansion of digital credit may also generate unintended effects. Easier access to finance can stimulate broader consumption, including fossil energy-intensive goods, potentially offsetting gains in renewable energy use (Johnstone *et al.*, 2010). Under price competition dynamics (Porter, 1980), fossil fuels may retain demand advantages when relative costs are lower. Nonetheless, recent geopolitical disruptions and rising fossil fuel prices have weakened this cost advantage, potentially shifting consumption toward renewable energy alternatives (Martínez-García *et al.*, 2023).

Based on these arguments, the following hypothesis is proposed:

H1: Digital financial inclusion has a positive impact on renewable energy consumption.

2.2 The impact of TI on REC

Technological innovation (TI) is widely recognized as a key driver of renewable energy consumption by enhancing efficiency and reducing the relative costs of clean energy technologies. According to Porter's (1980) price competition theory, cost advantages play a decisive role in shaping market preferences. In this sense, technological progress improves the performance of renewable energy systems, strengthens their competitiveness against fossil-based energy sources, and facilitates wider adoption.

Beyond technical improvements, TI reflects broader innovation capacity, including human capital, scientific knowledge, and institutional support for research and development. However, the effectiveness of TI varies across countries due to differences in innovation systems, legal frameworks, and policy environments (Jaumotte & Pain, 2005). Empirical evidence suggests that stronger technological capability not only improves environmental quality but also enhances the economic attractiveness and operational feasibility of renewable energy solutions, particularly in regions with supportive regulatory and market conditions (Oanh, 2024; Wen *et al.*, 2022).

From a broader development perspective, while the Environmental Kuznets Curve hypothesis posits that economic growth may eventually reduce environmental degradation (Grossman & Krueger, 1991; Panayotou, 1993), empirical patterns remain inconsistent across countries. High levels of pollution in major economies indicate that technological progress, rather than income growth alone, is crucial for decoupling energy consumption from environmental damage (Alvarado *et al.*, 2021; Bekabil, 2020). In this context, technological innovation plays a central role in enabling the transition from fossil-based energy systems toward renewable alternatives. Consistent empirical evidence confirms that countries with stronger innovation capacity tend to exhibit higher levels of renewable energy consumption (Xie *et al.*, 2020; Bakhsh *et al.*, 2023; Khan *et al.*, 2023).

Based on these arguments, the following hypothesis is proposed:

H2: Technological innovation has a positive impact on renewable energy consumption.

2.3 The impact of GDP on REC

The relationship between economic growth and renewable energy consumption (REC) has been extensively debated in the literature, with empirical evidence yielding mixed conclusions. Prior studies commonly classify this nexus into four competing hypotheses: the growth, conservation, feedback, and neutrality hypotheses, reflecting different causal directions between economic activity and renewable energy use (Burakov & Freidin, 2017). These frameworks suggest that economic growth may either stimulate REC through higher investment capacity, respond to REC via energy-led growth, reinforce REC through mutual feedback, or remain largely independent of renewable energy dynamics.

Empirical findings, however, remain inconclusive. Some studies document a positive association, arguing that higher income levels enhance the financial capacity to invest in renewable energy infrastructure and technologies (Sadorsky, 2009). In contrast, other evidence indicates that economic growth may increase overall energy demand and reinforce dependence on conventional fossil fuels, thereby constraining renewable energy consumption, particularly in growth models driven by industrialization and energy-intensive production (Menyah *et al.*, 2010; Shahbaz *et al.*, 2024). These conflicting outcomes suggest that economic growth does not automatically translate into a cleaner energy structure and may, under certain conditions, hinder the expansion of renewable energy.

In this context, economic growth may exert a negative effect on renewable energy consumption when growth relies heavily on carbon-intensive sectors and fossil energy inputs. Accordingly, the following hypothesis is proposed:

H3: Economic growth has a negative impact on renewable energy consumption.

2.4 The impact of CO₂ emissions on REC

Carbon dioxide (CO₂) emissions are commonly viewed as a key environmental pressure influencing renewable energy consumption (REC). From the perspective of energy transition theory, rising emission levels increase the urgency to adopt cleaner energy sources as a means of mitigating environmental degradation and improving long-

term sustainability. As environmental damage becomes more pronounced, countries are incentivized to shift away from fossil fuels toward renewable energy alternatives.

Empirical evidence largely supports this argument. Prior studies suggest that higher CO₂ emissions, particularly when accompanied by economic growth, can stimulate renewable energy consumption by increasing policy pressure and financial capacity for clean energy investment (Sadorsky, 2009). Long-run analyses further confirm a positive association between CO₂ emissions and REC, indicating that emission-intensive economies are more likely to pursue renewable energy solutions to offset environmental costs (Apergis & Payne, 2015; Omri *et al.*, 2015). This pattern reflects a transition mechanism in which environmental stress acts as a catalyst for cleaner energy adoption.

However, this relationship is not uniform across countries. In developing economies, high initial investment costs and limited access to finance may constrain renewable energy expansion, even under rising emission pressure (Sinha & Shahbaz, 2018). In such contexts, continued reliance on relatively cheaper fossil fuels can delay the transition toward renewable energy. From an externality perspective, the social and environmental costs of CO₂ emissions are often not fully internalized in market prices, implying that policy intervention is required to promote renewable energy adoption through subsidies, carbon pricing, or regulatory measures.

Overall, while rising CO₂ emissions may generate incentives to expand renewable energy consumption, the strength and direction of this effect depend on economic capacity and policy support. Based on these considerations, the following hypothesis is proposed:

H4: CO₂ emissions have a positive impact on renewable energy consumption.

2.5 The impact of population size on renewable energy consumption

Population size (POP) is a fundamental determinant of energy demand and consumption patterns. A larger population generally increases total energy requirements, which may place pressure on existing energy systems and influence the energy mix. On the one hand, population growth can stimulate renewable energy consumption by expanding demand and justifying large-scale investment in renewable infrastructure. On the other hand, rapid population growth—particularly in developing economies—may

reinforce reliance on fossil fuels due to cost considerations and infrastructure constraints (Nguyen Quoc *et al.*, 2025).

Empirical evidence on the population–renewable energy nexus remains mixed, suggesting that population dynamics may either support or hinder renewable energy adoption depending on economic capacity and policy orientation. In contexts where energy demand growth is met primarily through conventional energy sources, population expansion may reduce the relative share of renewable energy consumption.

Based on these considerations, the following hypothesis is proposed:

H5: Population size has a negative impact on renewable energy consumption.

2.6 The impact of foreign direct investment on renewable energy consumption

Foreign direct investment (FDI) plays a potentially important role in shaping renewable energy consumption through capital inflows, technology transfer, and managerial spillovers. FDI can facilitate renewable energy development when investment is directed toward clean energy sectors, supporting access to advanced technologies and financing (Dinh, 2025c). However, the effect of FDI is highly conditional on its sectoral composition.

In many cases, FDI flows are concentrated in energy-intensive and carbon-based industries, particularly in developing countries seeking rapid industrialization. Such investment patterns may increase fossil energy consumption and crowd out renewable energy development. As a result, the net impact of FDI on renewable energy consumption remains ambiguous and context-dependent.

Given the prevalence of FDI in conventional energy and industrial sectors, the following hypothesis is proposed:

H6: Foreign direct investment has a negative impact on renewable energy consumption.

2.7 The impact of urbanization on renewable energy consumption

Urbanization (UR) significantly influences energy demand, infrastructure development, and consumption behavior. Urban areas typically benefit from economies of scale, improved infrastructure, and higher energy efficiency, which can facilitate the

integration of renewable energy technologies. At the same time, rapid urban expansion often leads to increased energy demand driven by construction, transportation, and industrial activities (Nguyen Quoc *et al.*, 2025).

When urban growth is dominated by energy-intensive development and fossil fuel-based infrastructure, renewable energy consumption may be constrained. Conversely, well-planned urbanization supported by sustainable energy policies can enhance renewable energy deployment. The mixed theoretical arguments suggest that urbanization does not automatically promote renewable energy consumption.

In the absence of strong green urban planning, the following hypothesis is proposed:

H7: Urbanization has a negative impact on renewable energy consumption.

2.8 The impact of trade openness on renewable energy consumption

Trade openness (OPEN) reflects a country's degree of integration into global markets and may influence renewable energy consumption through multiple channels. Greater openness can improve access to renewable energy technologies, intermediate inputs, and international knowledge spillovers. However, trade liberalization may also increase energy demand through expanded production, transportation, and export-oriented industrial activity (Nguyen Quoc *et al.*, 2025).

In economies where trade expansion is driven by energy-intensive manufacturing and fossil fuel-based production, trade openness may reinforce conventional energy use and reduce the relative share of renewable energy. Without complementary environmental and energy policies, the scale effect of trade may dominate its technology transfer benefits.

Accordingly, the following hypothesis is proposed:

H8: Trade openness has a negative impact on renewable energy consumption.

3 RESEARCH METHODOLOGY

3.1 Data and sample

Country selection was based on data availability, consistency, and reliability over the study horizon. The dataset was compiled from three reputable sources: the World Bank (WB), the International Monetary Fund (IMF), and Our World in Data (OWID). Following strict screening procedures to ensure data completeness and quality, the final sample consists of a balanced panel of 69 countries covering the period from 2002 to 2023. Detailed variable definitions, data sources, and measurement approaches are provided in Appendix 1.

3.2 Methodology

Building on the frameworks developed by Kim & Le Quoc (2024) and Van & Le Quoc (2024), this study specifies a research model to examine the determinants of automobile consumption. The model incorporates digital financial inclusion (DFI), technological innovation (TI), economic growth (GDP), carbon emissions (CO₂), population size (POP), foreign direct investment (FDI), urbanization (UR), and trade openness (OPEN) as key explanatory variables. The baseline specification is expressed as follows:

$$REC_{i,t} = \beta_0 + \beta_1 DFII_{i,t} + \beta_2 TI_{i,t} + \beta_3 GDP_{i,t} + \beta_4 CO2_{i,t} + \beta_5 POP_{i,t} + \beta_6 FDI_{i,t} + \beta_7 UR_{i,t} + \beta_8 OPEN_{i,t} + \beta_x X_{i,t} + \varepsilon_{i,t} \quad (1)$$

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-Zwijenburg *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:

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

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:

$$P(\beta|y, X) = P(y|\beta, X)(P(\beta|X)) \quad (3)$$

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

The descriptive statistics indicate substantial cross-country variation in the key variables. Renewable energy consumption (REC) exhibits a moderate average level, with a relatively wide range between the minimum and maximum values, reflecting heterogeneous stages of energy transition across countries. Technological innovation (TI) and economic growth (GDP) display higher mean values and relatively stable dispersion, suggesting notable differences in innovation capacity and income levels among the sampled economies. Digital financial inclusion (DFI) shows limited variability compared to other variables, indicating a more homogeneous level of digital financial access across countries. Carbon dioxide emissions (CO₂) present considerable dispersion, highlighting divergent emission profiles and energy structures. Population size (POP) and urbanization (UR) also vary substantially, implying differences in demographic pressure and urban development patterns that may influence energy demand. Foreign direct investment (FDI) demonstrates moderate dispersion, reflecting unequal distribution of international capital flows, while trade openness (OPEN) exhibits the largest variability, underscoring significant differences in global market integration. Overall, the observed heterogeneity supports the use of a flexible estimation approach capable of capturing cross-country differences in the determinants of renewable energy consumption.

Table 3*Descriptive statistics*

Variables	Mean	Std.Dev	Minimum	Maximum
REC	7.4289	1.5562	2.2714	11.3846
TI	9.2147	1.4279	5.7528	12.6043
DFI	4.5679	0.5234	2.7146	5.3112
GDP	27.8324	1.4287	23.8941	29.9658
CO2	1.5073	0.9038	-1.4326	3.0185
POP	16.2148	1.8925	12.1136	20.0427
FDI	24.3419	1.5216	16.7824	26.1889
UR	15.9216	1.6748	12.0345	19.2146
OPEN	90.6842	49.1375	23.7719	366.2845

Source: Calculations by the authors

The Bayesian regression results provide robust evidence on the determinants of renewable energy consumption (REC), with all parameters exhibiting strong convergence and stability, as reflected by a high acceptance rate (1.0000), minimum efficiency above conventional thresholds (0.9612), and a Gelman–Rubin statistic equal to unity. These diagnostics confirm the reliability of the posterior estimates and support meaningful interpretation of the estimated effects.

DFI shows a positive coefficient (0.1754) with a moderate probability of effect (64.28%), providing partial support for H1. This suggests that while digital financial inclusion contributes to renewable energy consumption, its effect is weaker and less certain than that of technological innovation. The finding is broadly consistent with Kim & Le Quoc (2024) and Li *et al.* (2020), who argue that digital finance lowers transaction costs and improves access to credit for clean energy investment. However, the relatively lower probability indicates that the benefits of DFI may be constrained by uneven digital infrastructure, limited financial literacy, or the diversion of digital credit toward non-energy consumption. This result highlights that digital finance alone is insufficient to guarantee higher REC unless accompanied by targeted green finance policies.

Technological innovation exerts a positive and highly significant effect on renewable energy consumption, with a posterior mean of 0.1168 and a probability of effect of 100%. This finding strongly supports H2, confirming that technological progress plays a critical role in promoting REC. The result is consistent with prior studies (Xie *et al.*, 2020; Bakhsh *et al.*, 2023; Khan *et al.*, 2023), which emphasize that innovation enhances energy efficiency, reduces production and storage costs, and improves the reliability of renewable energy systems. From a theoretical perspective, this outcome aligns with Porter's (1980) competitiveness argument, suggesting that cost-reducing

innovations increase the relative attractiveness of renewable energy compared to fossil-based alternatives. The result underscores that technological capability is a fundamental prerequisite for accelerating the energy transition.

Economic growth exhibits a strong positive effect on renewable energy consumption, with a coefficient of 0.9417 and a high probability of effect (86.02%). This finding contradicts H3, which hypothesized a negative impact, and instead suggests that higher income levels enhance the capacity to invest in renewable energy infrastructure. The result is consistent with Sadorsky (2009) and Apergis & Payne (2015), who report that economic growth facilitates renewable energy adoption through greater fiscal space and private investment. This outcome implies that, in the sample considered, growth has not been predominantly driven by fossil-fuel-intensive activities, but rather supports energy transition efforts when accompanied by adequate policy frameworks.

CO₂ emissions are found to have a negative effect on renewable energy consumption (−0.2141) with a high probability of effect (83.67%), thereby rejecting H4, which expected a positive relationship. This result suggests that higher emission levels reflect structural dependence on fossil fuels, which may crowd out renewable energy development. The finding aligns with Sinha & Shahbaz (2018) and Bekabil (2020), who argue that emission-intensive economies often face lock-in effects due to existing fossil-fuel infrastructure. Rather than acting as a catalyst for clean energy adoption, rising emissions may signal institutional and technological inertia that delays the energy transition.

Population size has a strong and negative impact on renewable energy consumption, with a coefficient of −1.1346 and a probability of effect of 100%, supporting H5. This indicates that population growth tends to increase overall energy demand, which is often met through conventional energy sources rather than renewables. The result is consistent with arguments that demographic pressure, particularly in developing economies, intensifies reliance on fossil fuels due to cost and scalability considerations. Without adequate renewable infrastructure, population expansion may hinder the growth of renewable energy consumption.

FDI exhibits a positive and statistically strong effect on REC (0.0791; probability = 100%), leading to a rejection of H6, which anticipated a negative impact. This finding suggests that FDI in the sample countries is likely directed toward technology-intensive or cleaner sectors, facilitating capital inflows, technology transfer, and managerial

spillovers that support renewable energy development. The result contrasts with studies emphasizing the pollution-haven effect but aligns with more recent evidence indicating that FDI can promote clean energy when host countries possess sufficient absorptive capacity and environmental regulation.

Urbanization displays a negative effect on renewable energy consumption (-0.0058) with full probability, supporting H7. This suggests that rapid urban expansion increases energy demand primarily through construction, transportation, and industrial activities, which may rely heavily on fossil fuels. In the absence of green urban planning and renewable-friendly infrastructure, urbanization may constrain the expansion of renewable energy, consistent with findings in energy-intensive urban growth literature.

Trade openness also exerts a negative effect on renewable energy consumption (-0.0060 ; probability = 100%), confirming H8. This result implies that increased integration into global markets may raise energy demand through export-oriented production and logistics, reinforcing fossil energy use. Although trade openness can facilitate technology transfer, the negative sign suggests that scale effects dominate technology spillovers in the absence of strong environmental and energy policies.

Table 4

Bayesian Regression

Dependent variable: REC	Bayesian Regression			
	Mean	Std. Dev.	MCSE	Probability of Effect: Independent → Dependent
C	4.4821	0.5897	0.0033	100%
TI	0.1168	0.0349	0.0002	100%
DFI	0.1754	0.0931	0.0005	64.28%
GDP	0.9417	0.0556	0.0003	86.02%
CO2	-0.2141	0.0602	0.0003	83.67%
POP	-1.1346	0.1359	0.0008	100%
FDI	0.0791	0.0269	0.0002	100%
UR	-0.0058	0.1464	0.0009	100%
OPEN	-0.006	0.0009	0.0000	100%
Acceptance rate	1.0000			
Efficiency: min	0.9612			
Max Gelman-Rubin Rc	1.0000			

Source: Calculations by the authors

5 CONCLUSION AND POLICY RECOMMENDATIONS

5.1 Conclusion

This study examines the determinants of renewable energy consumption using a Bayesian regression framework applied to a balanced panel of countries. By jointly considering technological innovation, digital financial inclusion, economic growth, carbon emissions, population dynamics, foreign direct investment, urbanization, and trade openness, the analysis provides a comprehensive and probabilistic assessment of the drivers shaping renewable energy consumption across heterogeneous economies. The Bayesian approach ensures robust inference by explicitly accounting for parameter uncertainty, multicollinearity, and cross-country heterogeneity.

The empirical findings highlight technological innovation as a central enabler of renewable energy consumption, underscoring the importance of innovation capacity in improving efficiency, reducing costs, and enhancing the competitiveness of renewable energy relative to fossil fuels. Economic growth and foreign direct investment also emerge as significant positive contributors, suggesting that higher income levels and capital inflows can facilitate renewable energy expansion when supported by appropriate structural and institutional conditions. In contrast, carbon dioxide emissions, population growth, urbanization, and trade openness are found to exert negative effects on renewable energy consumption, indicating that demographic pressure, carbon-intensive development patterns, and trade-driven scale effects may hinder the transition toward cleaner energy systems.

Digital financial inclusion plays a supportive but conditional role. While it contributes positively to renewable energy consumption, its effect is weaker and less certain than those of technological innovation and economic growth, implying that digital finance alone is insufficient to drive the energy transition without complementary green finance policies and regulatory support. Overall, the results reveal that renewable energy consumption is shaped by a complex interaction of economic, technological, financial, demographic, and structural factors, rather than by a single dominant driver.

By providing a balanced and integrated perspective, this study contributes to the growing literature on energy transition and sustainable development. The findings emphasize that promoting renewable energy consumption requires coordinated strategies

that simultaneously foster technological innovation, channel investment toward clean sectors, and address structural constraints associated with population growth, urbanization, and trade expansion. These insights offer a foundation for evidence-based policy design aimed at advancing a sustainable and resilient low-carbon energy future.

5.2 Policy Recommendations

5.2.1 Technological innovation (TI)

Policymakers should prioritize investment in research and development, promote technology diffusion, and strengthen innovation ecosystems related to renewable energy. Supporting clean energy patents, smart grids, and energy storage technologies can enhance efficiency and reduce costs, thereby accelerating renewable energy adoption.

5.2.2 Digital financial inclusion (DFI)

Policies should integrate digital finance with green finance objectives by incentivizing fintech platforms to channel digital credit toward renewable energy projects. Improving digital infrastructure and financial literacy is essential to ensure that digital financial inclusion effectively supports clean energy investment rather than general consumption.

5.2.3 Economic growth (GDP)

Economic growth strategies should be aligned with energy transition goals. Governments should encourage green investment, integrate renewable energy targets into development planning, and prevent growth from being locked into fossil fuel-intensive sectors.

5.2.4 Carbon dioxide emissions (CO₂)

Emission reduction policies, such as carbon pricing, emission trading schemes, and stricter environmental regulations, are necessary to weaken fossil fuel dependence.

Revenues from carbon policies should be reinvested in renewable energy infrastructure and clean technology development.

5.2.5 Population size (POP)

Energy planning should account for population growth by expanding renewable energy capacity and improving energy efficiency. Long-term demographic and energy strategies are required to prevent rising energy demand from being met primarily by fossil fuels.

5.2.6 Foreign direct investment (FDI)

Governments should attract and screen FDI toward renewable energy and low-carbon industries. Strengthening environmental standards and local absorptive capacity can ensure that foreign investment contributes positively to renewable energy development.

5.2.7 Urbanization (UR)

Urban development policies should emphasize sustainable city planning, including renewable energy integration, green buildings, and low-carbon transport systems. Well-designed urbanization can mitigate energy pressure and support renewable energy consumption.

5.2.8 Trade openness (OPEN)

Trade policies should be complemented by environmental regulations to prevent trade-driven expansion from increasing fossil energy use. Facilitating imports of renewable energy technologies and promoting green trade agreements can enhance the positive effects of openness on clean energy adoption.

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APPENDIX

Table 1

Description of variables in the model

Variables	Symb ol	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 & Le Quoc (2024); Nguyen Quoc <i>et al.</i> , 2025	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 & Le Quoc (2024); Oanh & Dinh (2024); Van & Le Quoc (2024); Dinh (2025a, 2025b, 2025c, 2025d); Quoc <i>et al</i> (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 km ²)	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 km ²)	ATM KM	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.		WB
+ Number of R&D researchers	ADR	Number of research and development (R&D) researchers per million people in the population.	Kim & Le Quoc (2024); Ulucak (2021)	
+ 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); Khoi & Dinh (2025)	WB
Environmental pollution	CO2	Total carbon dioxide emissions (million metric tons), expressed in natural logarithmic form.	Kim & Le Quoc (2024); Dinh <i>et al.</i> (2025c)	WB
Control variable				
Urbanization rate	UR	The proportion of the urban population to the total population, transformed using the natural logarithm.	Kim & Le Quoc (2024); Huy <i>et al.</i> (2025a, 2025b); Quoc <i>et al.</i> , 2025c	WB
Population growth rate	POP	The total population residing in a specific area within a year, expressed in natural logarithmic form.	Kim & Le Quoc (2024); Quoc & Quoc (2025)	WB
Trade openness	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	Kim & Le Quoc (2024); Huy & Loan (2022); Huy <i>et al.</i> (2023a, 2023b); Huy & Tam (2025);	WB

		summing the value of exports and imports of goods and services and dividing by GDP; a natural logarithmic transformation is applied for statistical robustness.		
Foreign direct investment	FDI	The total inflow of foreign direct investment into a country (in US dollars), transformed using the natural logarithm.	Sadorsky (2010), Lei <i>et al.</i> (2020); Van <i>et al.</i> (2025a, 2025b), Tuyet & Dinh (2025)	WB

Source: Compiled by the authors

Authors' Contribution

All authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

How to cite this article (APA)

Huy, N. Q., & Dinh, L. Q. DRIVERS OF RENEWABLE ENERGY CONSUMPTION: EVIDENCE FROM A GLOBAL PERSPECTIVE. *Veredas Do Direito*, e223995. <https://doi.org/10.18623/rvd.v22.n6.3995>