

COMPARATIVE IMPACTS OF WIND, SOLAR, HYDRO, AND RENEWABLE ENERGY ON SUSTAINABILITY

IMPACTOS COMPARATIVOS DAS ENERGIAS EÓLICA, SOLAR, HÍDRICA E RENOVÁVEIS NA SUSTENTABILIDADE

Article received on: 9/10/2025

Article accepted on: 11/10/2025

Huynh Thi Minh Thu*

*Faculty of Finance and Accounting, Lac Hong University, Vietnam
minhthu7579@gmail.com

Le Quoc Dinh **

*Faculty of Finance and Accounting, Lac Hong University, Vietnam
Orcid: <https://orcid.org/0000-0002-3300-6148>
dinhql@lhu.edu.vn

Nguyen Quoc Huy*

*Faculty of Finance and Accounting, Lac Hong University, Vietnam
Orcid: <https://orcid.org/0009-0004-6183-4428>
nguyenquochuy@lhu.edu.vn

The authors declare that there is no conflict of interest

Abstract

This study investigates how different forms of green energy contribute to sustainable development across 77 countries from 2005 to 2023. Using a Bayesian regression framework, the analysis distinguishes the effects of wind, solar, hydropower and total renewable energy consumption, allowing for a clearer understanding of how each energy source shapes sustainability outcomes. The Bayesian approach provides flexible inference, accounts for parameter uncertainty and overcomes limitations associated with traditional frequentist methods. The results show that wind and solar energy exert the strongest and most consistent positive effects on the Sustainable Development Goals Index, supported by high posterior probability. Total renewable energy also demonstrates a positive influence, though with a smaller magnitude. Hydropower displays a positive but highly uncertain effect, indicating that its contribution is sensitive to ecological and country specific factors. The probability estimates highlight the robustness of wind and solar energy, while also revealing that inflation and population growth are likely to hinder sustainability progress. These findings underscore the importance of prioritising wind and solar deployment, improving the composition of national energy portfolios and maintaining macroeconomic stability. Overall, the study provides new Bayesian evidence on the heterogeneous role of

Resumo

Este estudo investiga como diferentes formas de energia verde contribuem para o desenvolvimento sustentável em 77 países, de 2005 a 2023. Utilizando uma estrutura de regressão Bayesiana, a análise distingue os efeitos da energia eólica, solar, hidrelétrica e do consumo total de energia renovável, permitindo uma compreensão mais clara de como cada fonte de energia influencia os resultados de sustentabilidade. A abordagem Bayesiana proporciona inferência flexível, considera a incerteza dos parâmetros e supera as limitações associadas aos métodos frequentistas tradicionais. Os resultados mostram que a energia eólica e solar exercem os efeitos positivos mais fortes e consistentes sobre o Índice de Objetivos de Desenvolvimento Sustentável, com alta probabilidade posterior. O consumo total de energia renovável também demonstra uma influência positiva, embora com menor magnitude. A energia hidrelétrica apresenta um efeito positivo, mas altamente incerto, indicando que sua contribuição é sensível a fatores ecológicos e específicos de cada país. As estimativas de probabilidade destacam a robustez da energia eólica e solar, ao mesmo tempo que revelam que a inflação e o crescimento populacional provavelmente dificultarão o progresso da sustentabilidade. Essas descobertas ressaltam a importância de priorizar a implantação de energia eólica e



green energy in advancing global sustainable development.

Keywords: Green Energy, Wind Energy, Solar Energy, Hydropower, Renewable Energy, Sustainable Development.

solar, melhorar a composição dos portfólios energéticos nacionais e manter a estabilidade macroeconômica. Em geral, o estudo fornece novas evidências Bayesianas sobre o papel heterogêneo da energia verde no avanço do desenvolvimento sustentável global.

Palavras-chave: Energia Verde, Energia Eólica, Energia Solar, Energia Hidrelétrica, Energia Renovável, Desenvolvimento Sustentável.

1 INTRODUCTION

Modern economies and human livelihoods continue to depend heavily on energy, yet this dependence still leans toward nonrenewable sources that intensify pollution and accelerate climate change. Air pollution claims millions of lives each year, and more than 95 percent of the global population is exposed to unhealthy air conditions. Nonrenewable energy such as coal, oil, and natural gas cannot be replenished, and their continued use releases large volumes of carbon dioxide and other harmful emissions that degrade ecosystems and undermine environmental stability. In contrast, renewable energy from wind, solar, and hydropower offers a cleaner development pathway. This is why the Sustainable Development Goals encourage countries to expand the use of green energy.

Several studies, such as Ciarreta and Zarraga (2010), Tang *et al.* (2020), Li *et al.* (2022), Candra *et al.* (2023), note that renewable energy consumption contributes to sustainable development. However, the evidence remains mixed because of inconsistent measurement approaches and data limitations across countries. To respond to this challenge, the present study examines four indicators that represent per capita consumption of wind, solar, hydropower, and renewable energy. These indicators make it possible to compare how different types of green energy influence sustainable development.

Earlier studies commonly employed traditional frequentist techniques, yet these techniques rest on strict assumptions that often do not reflect real world data conditions. Quoc *et al.* (2025), Dinh (2025a, 2025b, 2025c), Quoc and Le Quoc (2025); and Tuyet and Dinh (2025) note that such assumptions can weaken empirical reliability when the data exhibit autocorrelation, changing variance, or endogeneity. In response to these concerns, the present study adopts a Bayesian framework, which allows the estimates to

adapt more flexibly to the information contained in the data and offers a more informative foundation for probabilistic interpretation.

This study contributes to the academic literature in several important ways. First, it brings conceptual clarity to the role of different forms of green energy by distinguishing the effects of wind, solar, hydropower, and overall renewable energy consumption. Prior studies often rely on aggregate measures that obscure the individual contribution of each energy source, but the present approach provides a more granular understanding of how specific technologies support sustainable development.

Second, the study contributes to methodological development by employing Bayesian regression on a broad cross country dataset. The Bayesian approach is increasingly valued for producing richer and more reliable inference, particularly when models face uncertainty or when the data do not behave in a regular manner. The analysis shows that Bayesian estimation can address the concerns raised by Gelman and Hill (2006) regarding autocorrelation, changing variance, and endogeneity. This demonstrates that Bayesian methods offer a practical and theoretically sound alternative to the conventional techniques that have long shaped the energy economics literature.

Third, the study offers a probabilistic perspective on how green energy influences sustainable development. Instead of relying solely on point estimates, the Bayesian approach allows the likelihood of positive or negative effects to be assessed for each energy source. Tang *et al.* (2016), Wall *et al.* (2021), and Li *et al.* (2022) show that previous findings in this field are often mixed and context dependent, and the probabilistic view provided in this study helps clarify these uncertainties and deepen the interpretation of the energy and sustainability relationship.

The remainder of the paper is structured as follows. Section 2 reviews the relevant literature and outlines the theoretical arguments that link different forms of green energy to sustainable development. Section 3 describes the data, variables, and Bayesian approach used in the analysis. Section 4 presents the empirical results and discusses their implications for the broader energy and sustainability debate. Section 5 concludes the paper and provides recommendations for policy and future research.

2 LITERATURE REVIEW

2.1. Channels of influence between green energy and sustainable development

The theoretical rationale for why green energy contributes to sustainable development can be summarized in three channels:

First, green energy helps slow climate change. Renewable energy sources operate with little to no greenhouse gas emissions, reducing pressure on the climate system. Expanding green energy use therefore strengthens global efforts to limit warming and the severe risks associated with it (Midilli *et al.*, 2006).

Second, green energy supports sustained economic growth. The expansion of clean energy industries creates new employment opportunities and generates demand for complementary services and technologies. This transition encourages the growth of a modern green economy built on innovation and forward looking investment (Narayan and Singh, 2007).

Third, the shift toward green energy stimulates technological progress. Investments in clean technologies improve energy efficiency and support the development of new systems that enhance long term resilience. Such investments also strengthen energy security, reduce fuel dependence, and lower emissions, producing broader environmental and economic benefits (Altinoz *et al.*, 2021).

These theoretical perspectives explain why green energy is increasingly viewed as a strategic input to sustainable development and why its expansion is central to modern development thinking.

2.2 Previous studies

Although the idea of sustainable development has been discussed for many years, examining how green energy contributes to this process requires considerable resources, including funding, technical capacity, and time, which are not always available. For a long period, this topic did not receive sufficient attention from scholars or policymakers because many countries were focused on rapid integration into global markets and prioritised conventional GDP growth. Interest in sustainability gained stronger momentum only after the Sustainable Development Goals were introduced in March

2016, prompting governments to adopt broader development strategies that placed greater emphasis on long term sustainability (Dmuchowski *et al.*, 2021).

A growing body of empirical research has since explored the relationship between energy use and economic development across different contexts. For example, Belaïd and Zrelli (2019) applied an ARDL framework to Mediterranean countries, Wall *et al.* (2021) used structural equation modeling for Thailand, and Candra *et al.* (2023) relied on SVAR techniques to study renewable energy consumption in low and high income economies. Other studies, including Narayan and Singh (2007), Ciarreta and Zarraga (2010), Lau *et al.* (2011), Tang *et al.* (2020), and Li *et al.* (2022), also report that green energy plays an important role in supporting sustainable development. However, previous work has not used consistent measures of green energy, and limited data availability has contributed to differences in empirical findings. To address this issue, the present study uses four indicators of green energy: per capita consumption of wind, solar, hydropower, and renewable energy. These indicators allow for a clearer assessment of the global level of green energy use and enable direct comparison of how each source contributes to sustainable development.

Methodological approaches in earlier studies have been dominated by traditional frequentist techniques. These techniques rest on strict assumptions about the data, and such assumptions often do not hold in practical empirical settings, which reduces the reliability of the conclusions drawn from them. In the frequentist view, parameters are treated as fixed but unknown quantities, even though their values may shift as additional information becomes available. The Bayesian perspective takes a different position by treating parameters as random variables and assigning probability distributions that reflect the degree of certainty about their values. Gelman and Hill (2006) and Kruschke (2014) discuss in detail the advantages of this approach, particularly its ability to produce stable results without depending heavily on large sample sizes. Moreover, Bayesian estimation is well suited to dealing with common empirical challenges such as endogeneity, heteroscedasticity and autocorrelation (Kim & Quoc, 2024; Khoi & Dinh, 2025; Huy & Dinh, 2025a; Huy & Dinh, 2025b; Huy & Dinh, 2025c). For these reasons, the present study adopts a Bayesian framework to examine how green energy influences sustainable development across countries. This approach provides a stronger basis for interpretation and contributes meaningfully to ongoing discussions about the role of energy in shaping long term sustainability outcomes.

3 METHODOLOGY

3.1 Variables and dataset

Research data were obtained for 77 countries covering the period from 2005 to 2023. The green energy indicators were sourced from the Our World in Data database, which provides internationally comparable measures of renewable energy consumption. The control variables were taken from the World Development Indicators, including urbanisation, trade openness, inflation, population growth and economic growth. The combination of these two data sources ensures broad country coverage and consistent measurement across the sample.

$$SDGI_{i,t} = \beta_0 + \beta_1 ES_{i,t} + \beta_2 EH_{i,t} + \beta_3 EW_{i,t} + \beta_4 ER_{i,t} + \beta_x X_{i,t} + \varepsilon_{i,t} \quad (1)$$

where $i = 1, 2, \dots$ is the country and $N = 1, 2, \dots$ is the year.

$X_{i,t}$ is the vector of control variables.

The detailed definitions, measurements and descriptions of all variables are presented in Appendix 1. The dependent variable in this study is sustainable development (SDGI), measured through a composite index that consolidates 17 indicators listed in Appendix 2, following the approach of Van *et al.* (2025a, 2025b) and Dinh (2025d). Data for this index were taken from the SDGI database. The main explanatory variables capture the annual growth rate of per capita energy consumption from four forms of green energy. Wind energy consumption (EW) follows the measurement strategies used by Tang *et al.* (2020), Li *et al.* (2022), and Candra *et al.* (2023), while solar energy (ES), hydropower energy (EH), and total renewable energy (ER) consumption are measured in a similar manner. All four indicators are sourced from the Our World in Data platform. Several control variables are included to account for broader socioeconomic conditions. Urbanisation (UR) is measured as the share of the population living in urban areas, following Le Quoc *et al.* (2025); Nguyen Quoc *et al.* (2025). Trade openness (OPE) is expressed as the ratio of total exports and imports to GDP, also based on Quoc *et al.* (2025a, 2025b). Inflation (INF) is captured through the annual percentage change in the consumer price index (Quoc *et al.*, 2025a; Le Quoc, 2024), while population growth

(POP) reflects the yearly change in total population, with both measures guided by Saydaliev and Chin (2022). Economic growth (TGDP) is defined as the annual percentage change in GDP, following Quoc and Quoc (2025) and Oanh and Ha (2025). All control variables were retrieved from the World Development Indicators.

3.2 Methodology

In the Bayesian framework, empirical information is combined with prior beliefs to form a posterior distribution that represents the full range of plausible parameter values. This interpretation treats the outcome of the analysis as a probability distribution over parameters, which remains meaningful even when the sample size is small. For this reason, the Bayesian approach is well suited to situations where data are limited, as noted by Zondervan Zwijnenburg *et al.* (2017). The Bayesian and frequentist traditions differ fundamentally in how they conceptualise uncertainty, leading to different interpretations of statistical results. Bayesian analysis views model parameters as random quantities and treats the observed sample as fixed. The posterior distribution is constructed by updating the prior distribution with the observed data, and this posterior serves as the basis for drawing conclusions. In contrast, the frequentist approach assumes repeated random sampling and treats parameters as fixed but unknown values, with inference based solely on the sampling distribution of the data. In essence, Bayesian analysis answers questions about the probability of parameter values given the data, while the frequentist approach answers questions about the probability of data outcomes given fixed parameter values.

Bayesian regression proceeds through three main stages when estimating the relationship between the dependent variable and its determinants. The first step is to specify prior distributions for the coefficients, typically assuming a normal distribution centred at zero. This assumption reflects a neutral stance, giving greater weight to coefficient values close to zero without pushing the results in a particular direction. The second step is to define the likelihood function, which in this study follows the normal distribution described in equation (1). The final step uses Markov Chain Monte Carlo techniques, specifically the Gibbs sampler, to generate draws from the posterior distribution. A total of 12,500 iterations are performed, with the first 2,500 discarded to allow the chain to stabilise. MCMC methods are widely used in fields that rely on

complex models and offer a practical way to approximate posterior distributions when analytical solutions are not available (Levy, 2020).

4 RESULTS AND DISCUSSION

4.1. Descriptive statistics

The descriptive statistics show considerable variation in sustainable development scores and in the growth rates of different forms of green energy consumption (Table 1). The SDGI index has an average value of 71.75 with a moderate spread, indicating meaningful differences in sustainability performance across countries. Wind energy consumption (EW) displays wide dispersion, ranging from sharp declines to substantial increases, reflecting uneven adoption patterns. Solar energy (ES) shows the highest degree of variability, with extreme values on both ends of the distribution, suggesting that some countries are expanding solar capacity rapidly while others remain stagnant. Hydropower consumption (EH) is more stable on average but still exhibits sizeable fluctuations in certain cases. Total renewable energy consumption (ER) also varies considerably across the sample, though less dramatically than solar or wind, showing that the overall green energy transition progresses at different speeds across countries.

Table 1

Descriptive statistics

Variable	Mean	Std. Dev.	Min	Max
SGDI	71.7458	10.3821	38.4523	86.4876
EW	17.4625	20.8794	-97.8743	141.4987
ES	38.5031	25.1382	-100.005	6580.902
EH	4.1854	3.3568	-87.1298	425.142
ER	4.1662	2.0187	-65.4642	187.2091
UR	53.6951	13.7886	19.1768	79.0483
OPE	88.6402	26.9648	24.7043	157.9801
INF	6.5643	7.4021	-1.5887	59.2249
POP	0.3458	1.1502	-1.8591	2.4283
GDP	4.3682	5.0217	-15.1402	34.5078

Source: Authors

4.2. Bayesian regression results and discussion

The Bayesian regression results offer several insights into both the behaviour of the coefficients and the stability of the estimation process. Unlike frequentist estimation, which relies on closed-form solutions and strict assumptions, the Bayesian model uses the Metropolis Hastings algorithm to generate a large number of simulated draws from the posterior distribution. In this study, ten thousand iterations were produced, with each iteration yielding a full set of coefficient estimates. The posterior mean, standard deviation and Monte Carlo standard error (MCSE) reported in Table 2 summarise these simulated outcomes and provide a clear picture of parameter uncertainty.

The diagnostics associated with the simulation process indicate that the Markov chains behaved well. The average acceptance rate of approximately 0.91 is far above the minimum guideline of 0.10, suggesting that the proposal distributions were well calibrated and that the algorithm efficiently explored the parameter space. The lowest efficiency score, 0.3622, also exceeds the commonly accepted threshold of 0.01, confirming that the chains mixed adequately across iterations.

A key indicator of simulation quality is the Monte Carlo standard error. Flegal *et al.* (2008) emphasise that MCSE values close to zero reflect a stable and reliable chain. In this study, the MCSE values for all coefficients are extremely small relative to their standard deviations and fall well within the recommended range: less than 6.5 percent of the standard deviation is considered acceptable, and less than 5 percent is preferred. The results presented here meet these criteria comfortably, indicating that the posterior means are estimated with a high level of precision.

Convergence of the Markov chains is further supported by the Gelman Rubin R_c statistic. A value of 1.0 across all parameters signals that multiple chains moved toward the same stationary distribution, which confirms that the posterior estimates are not sensitive to initial values or early iterations. With R_c equal to 1 for every coefficient, the evidence strongly supports full convergence.

The posterior means themselves reveal the direction and magnitude of the estimated effects. Wind energy (EW) and solar energy (ES) exhibit the largest positive coefficients, implying that growth in consumption of these energy sources is strongly associated with improvements in sustainable development. Hydropower (EH) also contributes positively, though with greater uncertainty, as indicated by its larger standard

deviation. Total renewable energy consumption (ER) shows a smaller but still positive effect. Among the control variables, urbanisation (UR) and trade openness (OPE) have modest positive associations, whereas inflation (INF), population growth (POP) and economic growth (GDP) exhibit negative relationships, with population growth displaying the most pronounced effect.

The diagnostics and coefficient patterns demonstrate that the Bayesian estimation is both statistically robust and substantively informative. The combination of high acceptance rates, small MCSE values and perfect convergence statistics indicates that the posterior distributions are reliable and that the Bayesian framework provides a credible basis for interpreting the relationship between green energy and sustainable development.

Table 2

Bayesian regression results for the period 2005-2023

SDGI	Mean	Std. Dev	MCSE
EW	1.3524	0.0335	0.0003
ES	1.1628	0.0019	0.0000
EH	0.6947	0.3845	0.0041
ER	0.2403	0.0238	0.0003
UR	0.2142	0.0103	0.0001
OPE	0.0461	0.0239	0.0002
INF	-0.0620	0.0115	0.0001
POP	-2.8175	0.0196	0.0002
GDP	-0.1705	0.0241	0.0002
Average acceptance rate	0.9118		
Avg efficiency min	0.3622		
Max Gelman-Rubin Rc	1.0000		

Source: Authors

The Bayesian regression results in Table 2 reveal clear differences in how various forms of green energy contribute to sustainable development. All four coefficients are positive, indicating that increases in per capita consumption of wind, solar, hydropower and total renewable energy are consistently associated with improvements in the SDGI. However, the magnitude and precision of these effects differ substantially across energy types, offering important insights into the structure of the green energy–sustainability relationship.

Wind energy (EW) shows the strongest estimated effect, with a mean coefficient of 1.3524 and a very small standard deviation. This suggests that increases in wind energy consumption are reliably linked to higher levels of sustainable development. The very low MCSE indicates that the posterior estimate is precise, strengthening confidence in

the result. This pattern is consistent with the view that wind power has become an increasingly efficient and scalable option, particularly in countries that have invested in large turbine infrastructure and supportive regulatory frameworks.

Solar energy (ES) also exerts a strong positive effect, with a coefficient of 1.1628 and near-zero uncertainty. The extremely small standard deviation and MCSE imply that the distribution of simulated coefficients is tightly centred around the posterior mean. This reflects the global expansion of photovoltaics in the past decade, driven by falling installation costs, technology improvements and rapid diffusion in both advanced and emerging economies. The strength of the solar coefficient indicates that even moderate increases in solar adoption can yield meaningful gains in sustainability.

Hydropower energy (EH) displays a positive but much more uncertain effect. The mean coefficient of 0.6947 is substantially smaller than that of wind and solar, and the comparatively large standard deviation signals high variability in the posterior draws. This indicates that the influence of hydropower on sustainable development is more context dependent. Hydropower can contribute to clean electricity generation, but its sustainability benefits may be offset in some countries by ecological disruption, displacement of communities or dependence on seasonal water flows. The broader spread in the posterior distribution reflects these mixed dynamics.

Total renewable energy consumption (ER) has the smallest coefficient among the four variables, with a mean value of 0.2403. Although the effect remains positive and statistically well identified, the modest magnitude implies that aggregate renewable energy does not capture the same intensity of impact as individual energy types. This is expected because ER aggregates different sources—some highly impactful (wind, solar) and others more variable (hydro, biomass). The precise estimate, indicated by the small MCSE, suggests that while renewable energy expansion does support sustainability, the combined contribution is more incremental.

The results point to several important conclusions. First, wind and solar energy appear to be the primary drivers of sustainability improvements, likely due to their rapid technological maturation and scalability. Second, hydropower's contribution is positive but heterogeneous, reflecting both its benefits and its environmental trade offs. Third, aggregate renewable energy captures the general direction of progress but masks substantial variation across technologies. These insights highlight the need for countries

to differentiate green energy strategies rather than treating all renewable sources as equally effective.

The probability results presented in Table 3 deepen our understanding of the relationship between green energy and sustainable development by quantifying the likelihood that each coefficient is positive or negative. These probabilities complement the posterior means by showing the degree of certainty with which the Bayesian model supports each relationship.

Wind energy (EW) shows the highest level of certainty: the probability that its effect on SDGI is positive is equal to 1.0000. This indicates complete posterior support for the positive association observed in the mean estimates, suggesting that wind energy consistently contributes to sustainable development across virtually all simulated parameter values. The absence of variability in the standard deviation and MCSE reinforces the robustness of this finding.

Solar energy (ES) also shows very strong support, with a posterior probability of 0.9813 that its effect is positive. This means that more than 98 percent of the posterior distribution produces a positive estimate, confirming that solar energy remains a highly reliable driver of sustainability. The small MCSE suggests high precision, even though the standard deviation indicates some spread in the draws.

Renewable energy consumption (ER) similarly demonstrates a high likelihood of a positive impact, with a probability of 0.9603. This aligns with the idea that aggregated renewable energy supports sustainability, although the magnitude of the impact is more modest compared with wind and solar. The strong probability confirms the general direction of its influence.

Hydropower (EH), however, stands out for its substantially lower probability of a positive effect—only 0.5835. This indicates considerable uncertainty in the posterior distribution, with the model showing almost equal support for positive and negative outcomes. The high standard deviation and MCSE reflect this instability. Hydropower's mixed probability is consistent with the wider literature, which highlights that environmental trade offs, variability of water resources and ecological disruptions can offset its benefits in some countries.

Turning to the macroeconomic controls, trade openness (OPE) has a positive probability of 0.7943, indicating reasonably strong evidence that greater integration with global markets tends to support sustainable development. While not as definitive as wind

or solar energy, the result suggests that trade may facilitate technology transfer, clean energy investment and efficiency improvements.

Inflation (INF) shows a posterior probability of 0.9530 for a negative effect, implying that higher inflation is very likely to undermine sustainable development. This finding reflects macroeconomic instability, rising input costs and reduced investment incentives that can weaken long term sustainability outcomes.

Population growth (POP) also exhibits a high probability of a negative association (0.9080). Rapid population expansion may place additional pressure on resource use, environmental quality and government capacity, thereby constraining progress toward sustainable development goals.

For economic growth (GDP), the posterior probability of a positive effect is 0.8008, suggesting that growth generally supports sustainability but not with the same degree of certainty as the green energy variables. This result may reflect heterogeneity across countries: in some cases economic growth promotes cleaner technologies and improved living standards, while in others it may rely on high energy consumption or resource depletion.

The probability results reveal a clear hierarchy of certainty across explanatory variables. Wind and solar energy stand out as the most reliable contributors to sustainable development, followed closely by aggregate renewable energy. Hydropower shows significant ambiguity, underscoring the need to account for country-specific environmental and social contexts. Among the macroeconomic controls, inflation and population growth emerge as strong barriers to sustainability, while trade openness and economic growth offer more contingent benefits.

Table 3

Probability results of the impact of SDGI on the remaining variables

Variable	Mean	Std. Dev	MCSE
Prob (SGDI: EW) >0	1.0000	0.0000	0.0000
Prob (SGDI: ES) >0	0.9813	0.1335	0.0010
Prob (SGDI: ER) >0	0.9603	0.0935	0.0010
Prob (SGDI: EH) >0	0.5835	0.4913	0.0049
Prob (SGDI: OPE) >0	0.7943	0.3063	0.0031
Prob (SGDI: INF) <0	0.9530	0.4940	0.0049
Prob (SGDI: POP) <0	0.9080	0.3939	0.0040
Prob (SGDI: GDP) >0	0.8008	0.2119	0.0021

Source: Authors

5 CONCLUSION AND IMPLICATION

5.1 Conclusion

This study examined how different forms of green energy shape sustainable development across 77 countries from 2005 to 2023 using a Bayesian regression framework. By distinguishing between wind, solar, hydropower and total renewable energy consumption, the analysis offers a more nuanced picture of how each technology contributes to long term sustainability. The Bayesian results show strong and consistent evidence that wind and solar energy are the most influential drivers of improvements in the SDGI, supported by both the magnitude of their coefficients and the near complete posterior probability that their effects are positive. These findings reflect the rapid technological progress, scalability and global expansion of these two energy sources.

Hydropower also contributes positively to sustainable development, but with considerably greater uncertainty. The wider posterior distribution and modest probability of a positive effect indicate that hydropower's sustainability benefits vary across countries, depending on ecological conditions, water availability and potential environmental trade offs. Aggregate renewable energy consumption shows a smaller but still meaningful positive effect, suggesting that overall progress in renewable deployment supports sustainability, though its impact is diluted when diverse technologies are combined into a single measure.

The probability results further reinforce these patterns. Wind and solar energy display the highest posterior certainty, while hydropower remains the most ambiguous. Among the control variables, urbanisation and trade openness generally support sustainable development, while inflation and population growth show a high likelihood of undermining it. Economic growth appears to have a positive impact, although with lower certainty, consistent with mixed evidence in the literature.

The results highlight three major conclusions. First, green energy is not homogeneous—its contributions to sustainable development vary substantially across technologies, with wind and solar emerging as the most consistently beneficial. Second, the Bayesian framework proves valuable for capturing parameter uncertainty and offering probabilistic insights that complement traditional point estimates. Third, the transition toward sustainable development depends not only on expanding renewable energy but

also on maintaining macroeconomic stability, managing population pressures and strengthening integration with global markets.

The study provides robust empirical evidence that accelerating the shift toward wind and solar energy can deliver substantial and reliable gains in sustainable development. At the same time, attention to hydropower's context specific impacts and to broader economic conditions remains essential for countries seeking a balanced and resilient sustainability strategy.

5.2 Policy implication

The empirical findings offer several important policy lessons for countries pursuing sustainable development. First, the strong and highly certain effects of wind and solar energy on the SDGI show that these technologies should remain at the centre of national energy strategies. The near complete posterior probability of a positive effect indicates that investments in wind and solar capacity provide dependable returns in terms of environmental quality, long term growth and social welfare. Policymakers should therefore prioritise large scale deployment, reduce regulatory barriers and expand financial incentives for clean energy adoption.

Second, the results suggest that hydropower requires a more cautious and context specific policy approach. Although hydropower can contribute positively to sustainability, its posterior probability remains far lower and more uncertain compared with wind and solar energy. Countries should conduct rigorous environmental and social assessments before expanding hydropower projects, particularly in regions with fragile ecosystems or high climate variability. A balanced energy portfolio that avoids excessive dependence on hydropower will reduce environmental risks while maintaining system reliability.

Third, the positive but modest impact of total renewable energy consumption highlights the importance of energy mix quality rather than quantity alone. Policymakers should move beyond aggregate renewable targets and focus on the composition of renewable deployment, ensuring that high performing technologies—especially wind and solar—receive priority in national planning and international financing frameworks.

Fourth, the probability results underscore the role of macroeconomic stability in supporting sustainability. Inflation and population growth have a high likelihood of

exerting negative effects on the SDGI. Controlling inflation through sound monetary and fiscal coordination is therefore essential for maintaining investment confidence and preventing erosion of development gains. Similarly, population pressures call for stronger demographic planning, investments in human capital and expansion of essential services in densely populated regions.

Finally, the positive probability associated with trade openness signals that global integration can facilitate sustainability by enabling technology diffusion, attracting clean investment and improving access to energy efficient equipment. Countries should design trade policies that encourage the import of clean technologies, strengthen environmental standards in trade agreements and leverage global partnerships to accelerate the transition toward green energy systems.

5.3 Limitations and Future Research

This study faces several limitations that open pathways for further work. First, the analysis relies on available cross country data for wind, solar, hydropower and renewable energy, which do not capture differences in technology quality, storage capacity or institutional conditions. Future research may incorporate more detailed energy system indicators to refine these relationships.

Second, although the Bayesian approach provides robust inference, the study does not explore nonlinearities, structural breaks or threshold effects. Future studies could apply Bayesian regime switching or threshold models to capture these dynamics more effectively.

Finally, country level data may overlook subnational differences. Incorporating regional data or spatial Bayesian models can help better understand local energy and sustainability outcomes.

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APPENDIX

Appendix 1

Description of variables

Variable	Sign	Measure	Research	Data source
Dependent variable				
Sustainable development	SDGI	Integrate 17 indicators in Appendix 2 (Points)	Van <i>et al.</i> , (2025a; 2025b)	SDGI
Independent variable				
Energy consumption per capita from wind energy	EW	Annual growth rate of energy consumption per capita from wind energy (%)	Tang <i>et al.</i> (2020); Li <i>et al.</i> (2022) Candra <i>et al.</i> (2023).	Ourworldindata
Energy consumption per capita from solar energy	ES	Annual growth rate of energy consumption per capita from solar energy (%)		Ourworldindata
Energy consumption per capita from hydroelectric energy	EH	Annual growth rate of energy consumption per capita from hydroelectric energy (%)		Ourworldindata
Energy consumption per capita from renewable energy	ER	Annual growth rate of energy consumption per capita from renewable energy (%)		Ourworldindata
Control variable				
Urban population	UR	Urban population/Total population (%)	Le Quoc <i>et al.</i> (2025); Nguyen Quoc <i>et al.</i> (2025)	WDI
Trade openness	OPE	(Exports + imports)/GDP	Quoc <i>et al.</i> (2025a, 2025b)	WDI
Inflation rate	INF	Annual CPI growth rate (%)	(Quoc <i>et al.</i> , 2025a; Le Quoc, 2024)	WDI
Population growth rate	POP	Annual population growth rate (%)	Saydaliev and Chin (2022)	WDI
Economic growth	TGDP	Annual GDP growth rate (%)	Quoc and Quoc (2025) and Oanh and Ha (2025)	WDI

Appendix 2

17 indicators for calculating the SDGI

Sustainable Development Index (SDGI)		
Target 1	No Poverty	SDGINDEX.ORG
Target 2	No Hunger	
Target 3	Good Health and Well-Being	
Target 4	Quality Education	
Target 5	Gender Equality	
Target 6	Clean Water and Sanitation	
Target 7	Affordable and Clean Energy	
Target 8	Decent Work and Economic Growth	
Target 9	Industry, Innovation and Infrastructure	
Target 10	Reduced Inequalities	
Target 11	Sustainable Cities and Communities	

Target 12	Responsible Consumption and Production	
Target 13	Climate Action	
Target 14	Life Below Water	
Target 15	Life on Land	
Target 16	Peace, Justice and Strong Institutions	
Target 17	Partnerships for the Goals	

Appendix 3: List of countries

Algeria; Argentina; Australia; Austria; Azerbaijan; Bangladesh; Belarus; Belgium; Brazil; Bulgaria; Canada; Chile; China; Colombia; Croatia; Czech Republic; Denmark; Ecuador; Egypt, Arab Rep.; Estonia; Finland; France; Germany; Greece; Hong Kong; Hungary; Iceland; India; Indonesia; Iran, Islamic Rep.; Ireland; Israel; Italy; Japan; Kazakhstan; Korea, Rep.; Kuwait; Latvia; Lithuania; Luxembourg; Malaysia; Mexico; Morocco; Netherlands; New Zealand; North Macedonia; Norway; Oman; Pakistan; Peru; Philippines; Poland; Portugal; Qatar; Romania; Russian Federation; Saudi Arabia; Singapore; Slovak Republic; Slovenia; South Africa; Spain; Sri Lanka; Sweden; Switzerland; Thailand; Trinidad and Tobago; Turkey; Turkmenistan; Ukraine; United Arab Emirates; United Kingdom; United States; Uzbekistan; Venezuela, RB; Viet Nam.

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)

Thu, H. T. M., Dinh, L. Q., & Huy, N. Q. COMPARATIVE IMPACTS OF WIND, SOLAR, HYDRO, AND RENEWABLE ENERGY ON SUSTAINABILITY. *Veredas Do Direito*, e223913. <https://doi.org/10.18623/rvd.v22.n6.3913>