This is a preproof accepted article for *Global Sustainability*
This version may be subject to change during the production process
DOI: 10.1017/sus.2025.10034

Identifying the determinants of the energy transition in departments in Colombia: An analysis with spatial econometrics

Alexander Cotte-Poveda[1,*], Clara Pardo Martínez[2]
[1]Escuela Superior de Administración Pública (ESAP), Bogotá 110111, Colombia
[2]School of Administration, Universidad del Rosario, Bogotá 110111, Colombia
* Correspondence: Alexander Cotte Poveda, Email: alexander.cotte@esap.edu.co
Clara Inés Pardo Martínez: clara.pardo@urosario.edu.co

The Non-Technical Summary

This study aimed to analyse the advantages and challenges of the energy transition in an emerging economy such as Colombia via quantitative spatial panel data models using Colombian regions, which included departments from 2015 to 2023, to determine the main relationships between the energy transition and other variables, such as housing features, energy consumption and costs, fossil fuel use, mining, transportation activities, deforestation and livestock activity.

The Technical Summary

Energy transition is closely related to climate change and is helpful for achieving the main initiative in a broader strategy adopted by governments to contain global warming to 1.5 °C above preindustrial levels by the middle of the century. This study uses different empirical methods as quantitative spatial panel data models to determine variables that impact energy transition considering that the limitations of this study are related to the availability of data in every region and information on specific actions to promote energy transition in the regions. The results revealed that regions with higher levels of households, electricity coverage, energy, gasoline and diesel consumption, mining activities, transportation dynamics, deforestation rates and livestock activities generate higher carbon dioxide emissions, whereas regions with greater stable forest and electric vehicle growth rates present lower carbon dioxide emissions. The findings of this study could allow us to formulate suitable public policies to promote just energy transition that could be founded on different knowledge fields, including the industry and productive sector and its role in cleaner production, environmentally friendly infrastructure and technology, building capacities to adopt present and future technological change and create robust regulatory frameworks for their adequate operation, while considering the features and economic activities of territories and the diversification of energy sources as a strategy to promote sustainable energy transition and control climate change. Future research could concentrate on including new variables as renewable energy prices, comparative studies with other Latin American and models to promote knowledge of energy transition and clean technologies.

Summary social promotion: Energy transition in departments in Colombia: An analysis with spatial econometrics

Keywords: Energy Transition, spatial econometrics, CO_2 emissions, challenges, Colombia

Introduction

Energy transition (or energy system transformation) is defined as a transformation of the global energy sector from fossil-based systems of energy production and consumption to renewable energy sources, which requires global efforts and investments to shift from non-renewable energy sources such as oil, natural gas, and coal to renewable energy sources such as wind and solar, as well as lithium-ion batteries, generating a major structural change to energy supply and consumption by technological advancements in an energy system, which is promoted by a societal push towards sustainability, promoting decarbonization and limiting climate change (S&P Global, 2024, Kowalska-Pyzalska, 2024, IEA, 2024).

Energy transition is considered the main initiative in a broader strategy adopted by governments to return global warming to 1.5 °C above preindustrial levels by mid-century, considering that it is essential for long-term energy security, price stability, national resilience and reducing climate impacts (IRENA, 2022, 2023). To achieve an adequate energy transition, the world needs an enormous change in how the population produces and consumes energy, which could result in a reduction of nearly 37 gigatons of annual CO_2 emissions by 2050. These reductions can be achieved through 1) significant increases in generation and direct uses of renewable-based electricity; 2) substantial improvements in energy efficiency; 3) the electrification of end-use sectors (e.g., electric vehicles and heat pumps); 4) clean hydrogen and its derivatives; 5) bioenergy coupled with carbon capture and storage; and 6) the last-mile use of carbon capture and storage (IRENA, 2022, 2023; IEA, 2023).

To achieve energy transition in a just and sustainable manner, global cooperation and collective action are necessary to invest in renewable energy infrastructures, drive technology innovation, and R&D (Doumon, 2024), and consider the intrinsic link between the energy sector and government decision-making (WEF, 2024). This requires effective governances and policies based on a policy design with the following four key parameters (Chipangamate and Nwaila): i. The evaluation and analysis of potential renewable energy; ii. the development of infrastructure and the adaptation of current infrastructure; iii. successful integration into the system, iv. implications for society and the environment, where it is fundamental to determine the main factors that can influence energy transition in regions to promote adequate policies and strategies to promote energy transition, and v. to overcome the social, economic and political barriers to the energy transition and to provide incentives for the transition.

Energy transition has been studied and investigated from different perspectives, so different inputs for stakeholders such as governments, policy-makers, decision-makers, businesses, and communities, among others, have been generated to determine effective strategies to promote this transition in an effective and sustainable manner. The main approaches used in studies of energy transition are as follows:

Policies to promote energy transition: Since an integral global policy framework can provide countries with possibilities for a just transition that strengthens international finance flows, capacities and technologies, a progressive policy[1] and regulatory measures will generate greater benefits from the energy transition for all peoples, nations and regions of the world (IRENA, 2023). Some studies on policies for energy transition are as follows:

- Maghyereh et al. (2025), through a study across 16 countries from 2004 to 2019, used a nonparametric local linear dummy variable estimation (LLDVE) method, indicating the importance of a balanced approach, where well-designed policies accelerate the global energy transition.
- Li et al. (2025) quantitatively evaluated the global energy transition using indicators in 88 countries and established that energy transition is a long-term process that needs a series of conditions to support it, where capital investment, the improvement of energy infrastructure, and technological

[1] Progressive energy policies imply to ensure the shift to clean energy is equitable and beneficial for society, particularly those most vulnerable to the impacts of climate change and the energy transition itself. These policies prioritize affordability, job creation in green industries, and community benefits and infrastructure from renewable energy projects (Kuzemko et al., 2022).

https://doi.org/10.1017/sus.2025.10034 Published online by Cambridge University Press

progress need to accumulate over the long term, which implies that all countries should formulate long-term development plans, implement directed policies in all dimensions, and strive to meet the goals of climate mitigation and access to modern energy services.

- Xiong et al. (2024) investigated the impact of energy transition policies on enterprise total factor productivity (TFP) in China, utilizing a quasinatural experiment and panel data from Chinese cities and manufacturing enterprises (2011–2021) determining that energy transition policies can help improve the TFP of enterprises and that the government should provide policy support, including financial subsidies, tax incentives, and green credit to reduce the costs and risks of green innovation for enterprises, considering that financing environment to conduct green technology R&D and tax incentives and subsidies can be provided to adopt energy conservation and emission reduction measures to increase participation in energy transition.
- Doğan et al. (2024) explored the fundamental contributors of energy transition in the context of the OECD countries during the period 1991 to 2019 using the quantile regression technique concluding that energy transition process requires the task of upgrading the quality of implementation of policies related to energy technology.
- Radtke and Renn (2024) analysed the requirements for a sustainable energy transition from governance processes and structures determining that energy transition policies require of the bottom-up and top-down strategies, which implies to managing and fostering energy participation by creating acceptance, addressing public perceptions, prioritizing civic engagement, incentivizing innovation, enhancing systemic coordination across sectors and levels, and acknowledging the causes of climate change and interrelated governance issues.

These studies show the importance of understanding the factors that impact energy transition to determine adequate and effective policies package, to reduce the costs and risks. These studies highlight the importance of understanding the factors that impact energy transition to determine adequate and effective policy packages that promote sustainable energy transition.

Relationship between energy transition and climate change: Since energy transition plays a crucial role in mitigating climate change by reducing greenhouse gas emissions and promoting economic and health benefits, increasing the share of renewable energy in the energy mix, improving energy efficiency and transforming the entire energy sector to supply more people with energy and halt climate change are necessary (Yu et al., 2024, ESPON, 2021, BMZ, 2020). Different researchers have evaluated this relationship such as:

- Bashir et al. (2025) studied the empirical impact of climate change, energy transition, and renewable energy investments on energy security risk in the 25 largest energy consuming countries from 1990 to 2021 using empirical methods establishing that energy transition and energy transformation reduce energy security risks
- Xia (2025) analysed the impact of climate actions on the energy transition applying ex-ante volatility correlations between clean energy, fossil fuels and the broad market as indicators of market linkages finding the influence of global climate actions on energy market behaviours as key elements in energy transition.
- Bretschger (2024) calculated the effects of decarbonization and technical progress in regenerative energies on the market share of new energies, the development of carbon emission, the growth of per capita income and population development through a dynamic macroeconomic model indicating that the transition can be overcompensated by more stringent climate policy at a moderate economic cost.
- Guesmi et al. (2024) developed a policy framework to support the transition to sustainable energy and evaluated three climate change policy indicators utilizing the Quantile Vector Autoregressive (QVAR) approach in the United States from 2014 to 2022 underscoring the importance of

government initiatives and climate policies in driving the energy transition and fostering environmentally sustainable financial activities.

These studies highlight the close relationship between energy transition and climate change, where it is important to determine the main relationships and strategies to promote energy transition to control global climate warming especially in emerging economies. Moreover, energy transition generates other benefits such as economic growth, environmental pollution, financial globalization, financial development, and women empowerment (Murshed, 2022).

Strategies to promote just energy transition: With the goal of minimizing negative impacts and maximizing positive opportunities to demonstrate the socioeconomic benefits afforded by energy transition, green jobs that guarantee living wages, proper workplace safety protections, and health benefits should be supported; this is connected to laying the social groundwork for a resilient net-zero economy, helping leaders focus on the task of rapid decarbonization, and striving for fair and inclusive outcomes (UNDP, 2022, IISD, 2023). Some studies on this topic include the following:

- Rio-Ocampo et al. (2025) explored the conceptual background of energy justice by analysing dimensions (energy access, energy security, energy democracy and energy poverty) to assess energy justice through the energy cycle for a just energy transition determining within an energy justice decision-making approach that energy systems should promote i) availability, ii) affordability, iii) due process, iv) transparency and accountability, v) sustainability, vi) intra- and vii) intergenerational equity and viii) responsibility.
- Azubuike et al. (2024) analysed energy justice to identify the inequalities that global energy transition determines that energy transition for the global south will (i) enable the region to address sustainability-related issues of hunger and multidimensional poverty while gradually implementing energy transition policies; (ii) present an attractive case against political and social opposition to energy transition; and (iii) and (iv) ensure that developed countries contributing the most to greenhouse gas emissions take the lead now and act while the Global South effectuates national contributions sustainably.
- Le et al. (2024) explored an integrated model encompassing the circular economy, energy justice, environmental impacts, corporate renewable energy strategies, and social life cycle assessment through a quantitative approach, data from 459 senior and middle-level managers highlighting the positive role of renewable energy in corporate strategies and the value of integrating social life cycle assessment into the circular economy framework and policymakers can promote sustainability by setting clear regulations and positioning the circular economy as a key national policy and a core element of economic strategy and energy transition.
- Fang et al. (2023) examined the cross-sectional impact of social media penetration, particularly Facebook, on energy justice in a panel of 70 countries using ordinary least square showing that Facebook penetration improves energy justice across countries and social media should be promoted to emphasize on social services equitability, climate-vulnerable economies to help civil awareness and energy resilience.
- Sovacool (2021) explored the concept of energy transitions from the unique angle of epistemic communities (innovation, practices, and justice), and applied these concepts to a set of case studies indicating that innovation has implications concerning ownership, siting, and broader societal consequences arising from design choices and social practice, and the effects on rural industrial, lifestyles and energy justice has patterns of inequality and exclusion, even at times impacts on future generations.

These researches have indicated the importance to promote energy transition including justice and social aspects to generate opportunities and welfare for different communities.

https://doi.org/10.1017/sus.2025.10034 Published online by Cambridge University Press

Modelling the energy transition: In this way, the possibilities of changes within energy systems that contribute to planning and policy formulation can be explored, hypotheses about the future of energy can be developed, a dialogue among different stakeholders on complex issues can be promoted, and the impacts of climate change, among other factors, on the energy sector can be explored; in these efforts, it is important that models capture the dynamics of the energy transition and represent policy ideas in real detail to understand what their impacts might be and how the energy transition might unfold (Hennick, 2024, Barbrook-Johnson et al., 2024). Studies related to energy transition modelling include the following:

- Mundu et al. (2024) evaluated energy system simulation modelling, emphasizing its role in analysing and optimizing energy systems for sustainable development using four simulation methodologies, Agent-Based Modelling (ABM), System Dynamics (SD), Discrete-Event Simulation (DES), and Integrated Energy Models (IEMs), determining that simulation modelling play important role for addressing energy challenges, driving innovation, and informing policy, where areas to improve implies enhancing data quality, refining modelling techniques, and strengthening validation processes.
- Bogdanov et al. (2019, 2021) described a global, 100% renewable electricity system, which can be achieved by 2050 which requires effort and investments and demonstrated that the technical feasibility and economic viability of 100% renewable energy systems including the power, heat, transport and desalination sectors in energy transition process with different benefits as 50% energy savings, universal access to fresh water and low-cost energy supply.
- Del Duca et al. (2024) conducted a systematic literature review of 115 papers to elucidate methodological approaches, variables, and assessed impacts involved in energy transition models, identifying the multifaceted environmental and economic impacts of green energy transition processes, where Agent-Based Modelling & Simulation and Statistical Methodologies predominate.
- Chang et al. (2021) identified trends in the field of energy system modelling, with different techniques recognizing three main trends of increasing modelling of cross-sectoral synergies, growing focus on open access, and improved temporal detail to address planning future scenarios with high levels of variable renewable energy sources.
- Jacobson et al. (2015, 2018) performed 100% all-sector wind, water, and solar scenarios for 20 world regions encompassing 139 countries determining low cost and zero-load-loss grid solutions in all regions for three scenarios and these transformations could lead to low-cost, reliable, 100% renewable systems in many places worldwide.
- Tovar-Facio et al. (2021) developed an analysis of mathematical models for the sustainable energy transition indicating that new models of energy systems must consider the effect of the share of resources and energy in a globalized context, and the impact associated to the climate change also is a point that must be incorporated in optimization model for energy transition.
- Bolwig et al. (2019) discussed how quantitative modelling of energy scenarios for sustainable energy transition pathways can be made more realistic applying of system dynamics modelling (SDM) determining that this model can capture the co-evolution of technology, economy, policy and behavioral factors over sufficiently long-time periods, which is necessary for the analysis of transition pathway dynamics.

These results show the importance to assess energy transition models to generate inputs, trends scenarios and framework for policymakers, businesses, and stakeholders to plan, take decisions and implement the shift towards more sustainable energy systems.

On the basis of this background and investigations of energy transition, it is important to continue the research process to determine the advances, challenges and variables that determine trends in energy transition, especially in developing countries. Considering these elements, the objective of

https://doi.org/10.1017/sus.2025.10034 Published online by Cambridge University Press

this study is to determine advances and challenges in energy transition in Colombia using spatial panel data models, which can establish the main variables and strategies that support energy transition in an emerging economy with high amounts of renewable energy sources.

This study makes the following contributions. First, the main focus is energy transition, determining the main variables that affect its penetration and changes in energy sources. This study closes a gap in the Colombian energy system to determine advances and challenges in energy transition based on the institutional decarbonization theory generating new inputs on knowledge in energy transition in emerging economies. Our second approach involves thoroughly and systematically assessing the energy transition via spatial panel data models. This method captures regional differences in Colombia from the use of energy to generate an energy transition process. Third, this study provides information on the Colombian energy transition and can help policy-makers increase the level of energy transition. Fourth, this study highlights the main challenges of energy transition in emerging economies and contributes with new theoretical approach for energy transition analyzing regional differences.

The organization of this article entails an introduction to the literature review, as well as an exploration of the theoretical framework and a comprehensive review of previous studies concerning the energy transition. The research methodology employed in this study is subsequently explained. The subsequent section presents the findings and analysis derived from the research. Finally, the article concludes with a summary of the research outcomes and further recommendations.

Research methodology and empirical model

In this section, we describe the empirical models used to investigate the effects that the energy transition can have on CO_2 emissions for departments in Colombia. Our approach is similar to that taken by Runar Brannlund and Vesterberg (2021), Dharmaratna and Harris (2012) and Gaudin et al. (2001) in the sense that we estimate functions of the Stone–Geary energy transition in translogarithmic form. This function was originally developed by Geary (1950-1951), whereas Stone (1954) used it in empirical work. This functional form has also been used in theoretical work.

For the different estimates, spatial autoregressive models for panel data were used; spatial autoregressive (SAR) models, also known as simultaneous autoregressive (SAR) models, for panel data in this work were estimated with a spatial autoregressive SAR fixed-effects model.

The specification is shown in Equation (1), where the variables were transformed through translog:

$$\begin{aligned} lnQ_{CO_{2it}} = \alpha_1 + \alpha_2 \ln COM_{it} + \alpha_3 ln\, GDP_{it} + \alpha_4 lnEMQ_{it} + \alpha_5 lnHOM_{it} + \alpha_6 lnENC_{it} \\ + \alpha_9 lnGPG_{it} + \alpha_{10} lnGPD_{it} + \alpha_{11} lnDEF_{it} - \alpha_{12} lnSFG_{it} + \alpha_{13} lnFLI_{it} \\ + \alpha_{14} lnCAT_{it} + u_i \qquad (1) \end{aligned}$$

Notably, $Q_{CO_{2it}}$ represents greenhouse gas emissions in period *t* for Colombian department *i*, GDP_{it} represents aggregate-level production by department, EMQ_{it} represents exploitation of mines and quarries, HOM_{it} represents total homes, ENC_{it} represents energy consumption, GPG_{it} represents the gallon price of gasoline by department, GPD_{it} represents the diesel gallon price by department, DEF_{it} represents the deforestation rate by department, SFG_{it} represents the stable forest area growth rate by department, FLI_{it} represents total flights by department, EVE_{it} represents electric vehicles by department, and CAT_{it} represents cattle by department.

Data sources

Last statistics of Colombian in 2024 indicate that primary energy consumption reaching 616 TWh, electricity generation was 87.51 TWh, share of energy consumption by source is represented mainly by oil (41.61%), natural gas (22.15%), hydropower (21.89%), coal (10.14%) renewable energy (1.48%), and energy mix for electricity generation is represented mainly by hydropower (58.10%), natural gas (16.83%), coal (15.15%), solar (3.67%), oil (3.66%), bioenergy (2.59%) and for 2023 the

https://doi.org/10.1017/sus.2025.10034 Published online by Cambridge University Press

amount of CO_2 emitted per unit of energy was 0.17 kilograms of CO_2 per kilowatt-hour and represents 0.21% of global emissions (IEA, 2023, UPME, 2023, University of Exeter, 2024, Energy Institute, 2025).

We obtained annual data from various sources for every Colombian Department for the period 2015-2023 in the following manner:

- *CO_2 emissions*: Tonnes of CO_2 emissions for every department following energy consumption and fixed sources and carbon emission factors come from Resolution 181401/2004 (where natural gas is 56.1 tCO_2/TJ and electricity is 59.14 tCO_2/TJ).
- *Companies by department:* Number of active companies for every Colombian department from the Colombian Superintendence of Companies.
- *Aggregate-level production (GDP):* measured as gross domestic product (GDP) for every department from the Colombian Office of Statistics (DANE).
- *Exploitation of mines and quarries:* measured as monetary units for every department from the National Satellite Account calculated by DANE.
- *Total homes* are the number of households that have every Colombian department with public services based on data provided by the Superintendent of Public Services.
- *Total energy consumption:* electricity consumption by department from the data provided by the Superintendent of Public Services.
- *Consumption of gasoline and diesel:* in gallons based on data provided by the application for the administration of the ACPM and Gasoline surcharge of the Ministry of Finance and Public Credit.
- *The deforestation rate* is measured as the variation in forested area within a specific spatial unit of reference (department) from the initial year to the final year based on data from the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM).
- *The stable forest area growth rate* is the percentage of variation in the natural stable forested area of the territory denominated department derived from IDEAM.
- *Total flights*: measured as the number of flights by department from the data of Civil Aviation (Aerocivil)
- *Electric vehicles*: measured as the number of electric vehicles by department based on data provided by the Ministry of Transportation.
- *Cattle*: number of cattle by department from the National Agricultural Survey.

Results and discussion

First, the results were analysed from perspective of spatial dynamics in Colombia, indicating that the relationship between CO_2 emissions and income is measured, using regional GDP as a proxy. Pearson correlations are used, and the Pearson correlation coefficient shows a positive relationship between Colombia's regions and CO_2 emissions (see table 1). These results indicate that regions with more economy growth generates higher CO_2 emissions considering that the current growth model promotes higher emissions from traditional technologies and fossil energy, which implies that energy policies must promote clean energy and technologies with circular economy that are intrinsically linked and depend on one another. Moreover, energy transition must promote the minimizing its material footprint over the coming decades, which implies a new, circular, efficient energy system with policies supported by effective regulatory frameworks, effective incentives and standards applied throughout the supply chain, supported improved governance and collaboration at both national and international levels to achieve energy transition supported in circular economy (United Nations Environment Programme, 2024).

https://doi.org/10.1017/sus.2025.10034 Published online by Cambridge University Press

Table 1. Pearson correlation coefficient for the variables CO2 and GDP in the matrix of Colombian regions.

Variable	Andina region	Caribe region	Pacífica region	Orinoquía region	Amazonía region	Isalnd region
CO_2	0.5847	0.8839	0.8241	0.1863	0.0439	0.452

Second, table 2 presents the results of the 10 selected models to analysis energy transition from economic, energy, environmental and transportation perspectives demonstrating that, in all the models, the spatial autoregressive model was positively and significantly related to energy transition, suggesting that departments with higher fossil energy and economic activities increase CO_2 emissions, whereas electric vehicles and stable forest. The results from different perspectives indicate the following:

Economic variables: Energy transition could affect economic results across countries. For example, estimations of the IEA (2024) established that clean energy added approximately USD 320 billion to the world economy, which represented 10% of global GDP growth. Moreover, it is important that countries can achieve sustained economic growth with the development of their natural resources without compromising energy accessibility, affordability or reliability (WEF, 2024a). The results related to economic variables indicate that a higher number of companies, the aggregate level of production, exploitation of mines and total homes have a positive relationship with CO_2 emissions, indicating the importance of defining how energy transitions could be developed without affecting economic growth, including clean energy sources, and decreasing the environmental impacts of both productive sectors and household activities.

Energy variables: Energy transition implies the reconstruction of energy system elements, which explicitly implies energy utilization type, structure, form, transportation mode, and spatial pattern shifting from fossil fuels to renewable energy sources (Yang et al., 2024), where hydrocarbons play an important role in enabling material transition (for example, providing feedstock in the manufacturing of renewable energy equipment and products, supporting infrastructure, etc.), and the petrochemical sector requires hydrocarbons to play a role in the value chain for lower-carbon technologies (WEF, 2024a). The results of the proposed models demonstrate that higher energy consumption, such as gasoline, diesel and reserves, generates higher CO_2 emissions, which implies the importance of determining the strategy of transitioning from fossil to renewable energy sources in a staggered manner to achieve effective transition, reduce risks and maintain energy security.

https://doi.org/10.1017/sus.2025.10034 Published online by Cambridge University Press

Table 2. Spatial autoregressive model, fixed-effects spatial regression with CO_2 emission as the dependent variable

Parameter	Model [1]	Model [2]	Model [3]	Model [4]	Model [5]	Model [6]	Model [7]	Model [8]	Model [9]	Model [10]
Companies by department	2.830** (1.247)	3.043*** (1.185)	2.945*** (1.189)	0.000*** (0.000)	0.000* (0.000)	0.000* (0.000)	0.000* (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)
The aggregate-level production (GDP) by department	4.220*** (1.310)	1.307 (1.359)	1.635 (1.412)	1.734* (1.298)	4.301*** (1.143)	4.362*** (1.146)	4.420** (1.140)	0.000*** (0.000)	0.000*** (0.000)	0.000*** (0.000)
Exploitation of mines and quarries	0.210 (0.248)	0.058 (0.237)	0.053 (0.237)	0.009 (0.205)	0.012 (0.176)	0.012 (0.176)	0.024 (0.175)	0.000 (0.000))	0.000 (0.000))	0.000 (0.000))
Total homes		5.31e-06*** (9.96e-07)	5.07e-06*** (1.04e-06)	6.03e-06*** (1.06e-06)	2.58e-06*** (9.75e-07)	2.60e06*** (9.75e-07)	2.58e-06*** (9.70e-07)	3.42e-06*** (1.17e-06)	3.27e-06*** (1.17e-06)	3.36e-06*** (1.24e-06)
Total energy consumption			5.57e-10 (6.61e-10)	3.31e-10 (5.73e-10)	4.23e-11 (4.93e-10)	4.83e-11 (4.93e-10)	1.37e-11 (4.91e-10)	4.22e-10 (4.88e-10)	3.91e-10 (4.87e-10)	3.83e-10 (4.88e-10)
Consumption of gasoline (v)				4.429*** (0.480)	0.498 (0.575)	0.505 (0.575)	0.551 (0.573)	0.186 (0.590)	0.007 (0.000)	0.013 (0.602)
Consumption of diesel (w)					0.001*** (0.000)	0.001*** (0.000)	0.001*** (0.000)	0.001*** (0.000)	0.001*** (0.000)	0.001*** (0.000)
Deforestation rate (ap)						0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)
Stable forest area growth rate (ar)							-0.015** (0.008)	-0.013* (0.008)	-0.014* (0.008)	-0.013* (0.008)
Total flights (aw)								0.083 (0.117)	0.078 (0.117)	0.078 (0.117)
Electric vehicles (ax)									-0.000* (0.000)	-0.000* (0.000)
Cattle (an)										3.96e-08 (1.79e-07)
σ_e	1.060	1.007	1.005	0.872	0.747	0.746	0.742	0.758	0.756	0.756
Number of obs	297	297	297	297	297	297	297	297	297	297
Number of groups	33	33	33	33	33	33	33	33	33	33
Wald chi²	49.59	83.38	84.31	199.40	366.84	367.69	374.97	347.77	352.19	352.31
Prob > chi²	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pseudo R²	0.42	0.43	0.43	0.25	0.31	0.31	0.31	0.11	0.10	0.10
Log likelihood	-390.00	-376.49	-376.14	-338.45	-297.73	-297.56	-296.04	-301.79	-300.83	-300.81

Note: *The figures in parentheses are the standard errors. *** Significant at the 1 percent level, ** significant at the 5 percent level and * significant at the 10 percent level*

The environmental variables analysed, such as the deforestation rate and stable forest area growth, are fundamental in the transition through the ability of forests to sequester carbon (Lundmark, 2023), and the forest sector is fundamental for implementing strategies for transforming the energy sector through a just transition towards the modern use of energy to maximize synergies and minimize trade-offs (UNDP, 2023). The results of the models confirm that stable forest area growth contributes to energy transition, whereas the deforestation rate has a negative relationship with energy transition, indicating the importance of promoting forest processes and reducing the deforestation rate as a good program to promote energy transition.

Transportation variables: The transport sector is responsible for close to a quarter of global energy-related CO_2 emissions because of its heavy reliance on fossil fuels. With the global demand for transport services expected to increase in future years, it is crucial to sustainably transform the sector and advance towards a zero-carbon sector with renewables providing a large share of the solutions (IRENA, 2023). The results of the models confirm that higher total flights increase CO_2 emissions, whereas higher penetration of electric vehicles decreases CO_2 emissions, which demonstrates the importance of new energy sources in the transportation sector, such as electricity, biofuels and hydrogen, and the implementation of efficient technologies to support the energy transition.

The results of the 10 models indicate that achieving an adequate energy transition depends on different variables where it is necessary to determine adequate energy policies that require major

https://doi.org/10.1017/sus.2025.10034 Published online by Cambridge University Press

investment by governments, businesses, and households to deliver greater affordability, optimal distribution of benefits and costs, more equity in energy systems, the distributional aspects and wider social impacts of a policy and ensures that everyone has access to affordable clean energy technologies (IEA, 2024), considering that energy transition could imply (IEA, 2024): i. efforts to promote efficient and affordable appliances; ii. to provide targeted support to vulnerable households, resulting in wider social benefits; and iii. the electrification of public transport and incentives for electric two- and three-wheelers can promote affordable clean transport for all, iv. the challenges of reforming fossil fuel subsidies while promoting affordable clean energy consumption, v. to design a process that is orderly and inclusive, among other, to achieve an energy transition that promotes development, economic and social aspects, and the conservation of natural resources and to control and mitigate climate change.

The results of the models confirm that the energy transition is closely related to the business sector, level of production, and households; decreases in fossil fuels; and guarantees the quality of forest resources, the transportation sector and castle production, indicating the importance of analysing energy policies differentiated by sector and requirements in infrastructure and energy use. IRENA (2020) considers that to maximize the socioeconomic benefits of an energy transition; policies should include the following: i. Ambition: scale-up targets under NDCs and accelerating energy transition-related plans; ii. Public intervention: Launch public investment plans, provide strategic guidance; iii. Industry: Develop local industries and supply chains for energy transition-related technologies; iv. Employment and livelihoods: Create jobs, offer labour market measures, provide social protection, and v. skills and education: expand education and vocational training to avoid skill gaps, reskill fossil fuel workers, indicating that a holistic approach to accelerate a low-carbon economy should include enabling, deploying, and integrating policies that complement each other, which guarantees increases in GDP, employment, and welfare; decreases in CO_2 emissions; and the control and mitigation of climate change.

Conclusions

This study analysed the energy transition from spatial panel data models to determine advances and challenges in the context of an emerging economy through different models that include economic, energy, environmental and transportation variables.

The results indicate that the variables selected are significantly related to energy transition, implying that regions that have higher levels of production, exploitation of mines and quarries, total homes, energy consumption, consumption of gasoline and diesel, deforestation rates, total flights and cattle generate higher CO_2 emissions, whereas stable forest area growth rates and electric vehicles decrease CO_2 emissions. For these results, it is important to determine adequate energy policies that allow effective and just energy transition without comprising development and support the control and mitigation of climate change.

The limitations of this study are related to the availability of data in every region and information on specific actions to promote energy transition in the regions. Future research could concentrate on including new variables and models to promote knowledge of energy transition and clean technologies.

The findings of this study demonstrate the importance of promoting adequate and effective energy transition, especially in emerging economies with limited resources and technologies, as a strategy for promoting sustainable development, just energy transition and control and mitigating climate change, which are fundamental for generating clean jobs, new infrastructure, technologies and energy sources that allow the decarbonization of the economy. Moreover, suitable public policies to promote energy transition could be founded on different knowledge fields, including the industry and productive sector and its role in cleaner production, environmentally friendly infrastructure and technology, promotion of circular economy, building capacities to adopt present and future

https://doi.org/10.1017/sus.2025.10034 Published online by Cambridge University Press

technological change and create robust regulatory frameworks for their adequate operation to achieve energy security and environmental sustainability (Murshed and Masud, 2020, Barragan et al., 2025).

Acknowledgements. The authors thank anonymous reviewers of this research in following events: the first annual workshop on Regional Sustainable Economic Development around the Globe, the Third Annual International Conference on Empirical Economics at PSU-Altoona, and the 31st Annual Conference of International Sustainable Development Research Society (ISDRS).

Author contributions. Clara Inés Pardo Martínez: Conceived and designed the analysis, wrote the paper and performed the analysis. Alexander Cotte Poveda: Conceived and designed the analysis, contributed to data or analysis tools and performed the analysis.

Financial support. This study was financed by Escuela Superior de Administración Pública (ESAP) through of Resolution No. SC – 2295, ID E6_2024_08

Conflict of interest. We wish to confirm that there are no known conflicts of interest associated with this publication and that there has been no significant financial support for this work that could have influenced its outcome.

Research transparency and reproducibility. The authors confirm the research transparency and reproducibility according to the journal's policy.

References

Azubuike, S., Emeseh, E., Amakiri, D. (2024). Climate change, energy transition, and the Global South: learnings from the international framework on the ozone layer. Journal of Energy & Natural Resources Law 42(3), 255–277. https://doi.org/10.1080/02646811.2024.2345012

Barbrook-Johnson, P., Mercure, JF., Sharpe, S. et al. (2024). Economic modelling fit for the demands of energy decision makers. Nature Energy 9, 229–231, https://doi.org/10.1038/ s41560-024-01452-7

Barragán, A., Cecilio-Ayala, E., Silva-Borjas, P., Cortés-Ruiz, J., Hernandez-Cardona, E. (2025). Policies and sustainable energy transition in the global environment: Challenges for Latin America. Heliyon 11 (6), e42295. https://doi.org/10.1016/j.heliyon.2025.e42295.

Bashir, M., Pata, U., Shahzad, L. (2025). Linking climate change, energy transition and renewable energy investments to combat energy security risks: Evidence from top energy consuming economies. Energy 314, 134175, https://doi.org/10.1016/j.energy.2024.134175.

BMZ (2020). Energy and climate. https://www.bmz.de/en/issues/climate-change-and-development/energy-and-climate

Bogdanov, D., Farfan, J., Sadovskaia, K. et al. (2019). Radical transformation pathway towards sustainable electricity via evolutionary steps. Nat Commun 10, 1077. https://doi.org/10.1038/s41467-019-08855-1

Bogdanov, D., Manish R., Arman A., Ashish G., Ayobami S., Michael C., Upeksha C., Kristina Sadovskaia K., Farfan J., De Souza L., Barbosa N., Fasihi M., Khalili S., Traber T., Breyer C. (2021). Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. Energy 227, 120467, https://doi.org/10.1016/j.energy.2021.120467.

Bolwig, S., Bazbauers, G., Klitkou, A., Lund, P., Blumberga, A., Gravelsins, A., Blumberga, D. (2019). Review of modelling energy transitions pathways with application to energy system flexibility. Renewable and Sustainable Energy Reviews 101, 440-452, https://doi.org/10.1016/j.rser.2018.11.019.

Brannlund, R., Vesterberg, M. (2021). Peak and off-peak demand for electricity: Is there a potential for load shifting?. Energy Economics 102, 105466.

Bretschger, L. (2024). Energy transition and climate change abatement: A macroeconomic analysis. Resource and Energy Economics 76, 101423, https://doi.org/10.1016/ j.reseneeco.2023.101423.

https://doi.org/10.1017/sus.2025.10034 Published online by Cambridge University Press

Chang, M., Thellufsen, J., Zakeri, B., Pickering, B., Pfenninger, S., Lund, H., Østergaard, P. (2021). Trends in tools and approaches for modelling the energy transition. Applied Energy 290, 116731, https://doi.org/10.1016/j.apenergy.2021.116731.

Chipangamate, N., Nwaila, G. (2024). Assessment of challenges and strategies for driving energy transitions in emerging markets: A socio-technological systems perspective. Energy Geoscience 5, Issue 2, 100257, https://doi.org/10.1016/j.engeos.2023.100257.

Dharmaratna, D., Harris, E. (2012). Estimating Residential Water Demand Using the Stone-Geary Functional Form: The Case of Sri Lanka. Water Resour Manage 26, 2283–2299 https://doi.org/10.1007/s11269-012-0017-1

Del Duca, V., Ponsiglione, C., Primario, S., Strazzullo, S. (2024). Towards economic, environmental, and societal sustainable world: Reviewing the interplay of methodologies, variables, and impacts in energy transition models. Journal of Cleaner Production 479, 144074, https://doi.org/10.1016/j.jclepro.2024.144074.

Doğan, B., Chu, L., Khalfaoui, R., Ghosh, S., Shahbaz, M. (2024). Strategy towards sustainable energy transition: The effect of policy uncertainty, environmental technology and natural resources rent in the OECD nations. Resources Policy 98, 105333, https://doi.org/10.1016/j.resourpol.2024.105333.

Energy Institute (2025). Statistical Review of World Energy. https://www.energyinst.org/ statistical-review.

ESPON (2021). The energy transition and climate change resilience: ESPON evidence. https://archive.espon.eu/sites/default/files/attachments/Topic%20paper%20%235%20-%20The%20energy%20transition%20and%20climate%20change%20resilience%20-%20ESPON%20evidence.pdf

Fang, M., Njangang, H., Padhan, H., Simo, C., Yan, C. (2023). Social media and energy justice: A global evidence. Energy Economics 125, 106886, https://doi.org/10.1016/ j.eneco.2023.106886.

Gaudin, S., Griffin, R., Sickles, R., 2001. Demand specification for municipal watermanagement: evaluation of the Stone-Geary form. Land Econ. 77 (3), 399e422.

Geary, Roy C. (1950-1951). A Note on 'A Constant-Utility Index of the Cost of Living'. Review of Economic Studies. 18 (2): 65–66.

Guesmi, K., Mohammed, K., Tiwari, S. (2024). Green horizons: Enabling the energy transition through climate change policies. International Review of Economics & Finance 94, 103409, https://doi.org/10.1016/j.iref.2024.103409.

Hennick, C. (2024). The role of modeling in the energy transition. https://energy.mit.edu/news/the-role-of-modeling-in-the-energy-transition/#:~:text="%5BModels%5D%20can%20simply%20be,different%20stakeholders%20on%20complex%20issues.

IEA (2024). Global Energy Transitions Stocktake. Tracking progress toward the Paris Agreement. https://www.iea.org/topics/global-energy-transitions-stocktake#:~:text=The %20IEA's%20 Net%20Zero%20by,rise%20to%201.5oC.

IEA (2024). Clean energy is boosting economic growth. https://www.iea.org/commentaries/ clean-energy-is-boosting-economic-growth

IEA (2024). Affordable and Fair Clean Energy Transitions. https://iea.blob.core.windows.net/assets/86f2ba8c-f44b-494a-95cc-e75863cebf95/ StrategiesforAffordableandFairCleanEnergyTransitions.pdf

IEA (2023). Net Zero Roadmap. A Global Pathway to Keep the 1.5 °C Goal in Reach. https://iea.blob.core.windows.net/assets/8ad619b9-17aa-473d-8a2f-4b90846f5c19/NetZeroRoadmap_AGlobalPathwaytoKeepthe1.5CGoalinReach-2023Update.pdf

https://doi.org/10.1017/sus.2025.10034 Published online by Cambridge University Press

IEA (2023). Colombia 2023. Energy Policy Reviews. https://www.iea.org/reports/colombia-2023.
IRENA (2023). Energy transition and transport. https://www.irena.org/Energy-Transition/Technology/Transport#energy-transition
IRENA (2023). World Energy Transitions Outlook 2023: 1.5°C Pathway, International Renewable Energy Agency, Abu Dhabi. www.irena.org/publications
IRENA (2022). World Energy Transitions Outlook 2022: 1.5°C Pathway, International Renewable Energy Agency, Abu Dhabi. www.irena.org/publications
IRENA (2020). Energy Transition Policies to Maximise Socio-economic Benefits. https://www.irena.org/News/articles/2020/Oct/Energy-Transition-Policies-to-Maximise-Socio-economic-Benefits
ISSD (2023). Just Transition. https://www.iisd.org/topics/just-transition
Jacobson, M., Delucchi, M., Cameron, M., Frew, B. (2015). Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes. Proc. Natl. Acad. Sci. U.S.A. 112 (49) 15060-15065, https://doi.org/10.1073/pnas.1510028112 (2015).
Jacobson, M., Delucchi, M., Cameron, M., Mathiesen, B. (2018). Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes. Renewable Energy 123, 236-248. https://doi.org/10.1016/j.renene.2018.02.009.
Kowalska-Pyzalska, A. (2024). Introduction to innovative energy services (IES) in transitioning energy markets. Chapter 1. Editor(s): Anna Kowalska-Pyzalska, Diffusion of Innovative Energy Services, Academic Press, Pages 1-19, ISBN 9780128228821, https://doi.org/ 10.1016/B978-0-12-822882-1.00007-X.
Kuzemko, C., Mitchell, C., Goldthau, A., Nadaï, A., Managi, S. (2022). Progressive Energy Policy. ISSN 2946-3939.
Le, T., Tran, P., Dhar, B. (2024). Circular economy and social life cycle assessment: The role of corporate renewable energy strategies, environmental justice, and environmental impacts. Journal of Cleaner Production 485, 144387, https://doi.org/10.1016/j.jclepro.2024.144387.
Li, Z., Niu, S., Wang, J., Tan, Y., Wang, Z. (2025). Multidimensional assessment of energy transition and policy implications. Renewable Energy 238, 121870, https://doi.org/10.1016/j.renene.2024.121870.
Lundmark, R. (2023). The role of forests in the energy and climate transition. https://snsse.cdn.triggerfish.cloud/uploads/2023/09/the-role-of-forests-in-the-energy-and-climate-transition-english-summary.pdf
Maghyereh, A., Boulanouar, Z., Essid, L. (2025). The dynamics of green innovation and environmental policy stringency in energy transition investments. Journal of Cleaner Production 487, 144649, https://doi.org/10.1016/j.jclepro.2024.144649.
Mundu, M. M., Nnamchi, S.N., Sempewo, J.I. et al. (2024). Simulation modeling for energy systems analysis: a critical review. Energy Informatics 7, 75, https://doi.org/10.1186/ s42162-024-00374-8
Murshed, M. (2022). Pathways to clean cooking fuel transition in low and middle income Sub-Saharan African countries: The relevance of improving energy use efficiency. Sustainable Production and Consumption 30, 396-412, https://doi.org/10.1016/j.spc.2021.12.016.
Igeland, P., Schroeder, L., Yahya, M., Okhrin, Y., Uddin, G. (2024). The energy transition: The behavior of renewable energy stock during the times of energy security uncertainty. Renewable Energy 221, 119746, https://doi.org/10.1016/j.renene.2023.119746.
Radtke, J., Renn, O. (2024). Participation in Energy Transitions: A Comparison of Policy Styles. Energy Research & Social Science 118, 103743, https://doi.org/10.1016/j.erss.2024.103743.

https://doi.org/10.1017/sus.2025.10034 Published online by Cambridge University Press

Sovacool, B., Hess, D., Cantoni, R. (2021). Energy transitions from the cradle to the grave: A meta-theoretical framework integrating responsible innovation, social practices, and energy justice. Energy Research & Social Science 75, 102027, https://doi.org/10.1016/ j.erss.2021.102027.

Stone, R. (1954) Linear expenditure systems and demand analysis: an application to the British demand, The Economic Journal,64(255), 511–27.

S&P Global (2024). What is Energy Transition?. https://www.spglobal.com/en/research-insights/market-insights/what-is-energy-transition

Tovar-Facio, J., Martín, M., Ponce-Ortega, J. (2021). Sustainable energy transition: modeling and optimization. Current Opinion in Chemical Engineering 31,100661, https://doi.org/10.1016/j.coche.2020.100661.

UNDP (2023). Issue Brief: Forest, Energy, and Livelihoods. https://www.un.org/esa/ forests/wp-content/uploads/2023/03/ISSUE-BRIEF-Forests-Energy-Livelihoods-March2023-FINAL.pdf

UNDP (2022). What is just transition? And why is it important?. https://climatepromise.undp.org/news-and-stories/what-just-transition-and-why-it-important

United Nations Environment Programme (2024). Critical Transitions: Circularity, equity, and responsibility in the quest for energy transition minerals - Working Paper. https://wedocs.unep.org/20.500.11822/46623.

University of Exeter (2024). Global Carbon Budget. https://globalcarbonbudget.org

UPME (2023). Colombian energy balance. https://www1.upme.gov.co/Demanday Eficiencia/Paginas/BECO.aspx

WEF (2024). The biggest barriers to energy sector growth are often policy-related. Here's how to overcome them. https://www.weforum.org/stories/2024/10/5-of-the-10-biggest-barriers-to-energy-sector-growth-are-policy-related-here-s-how-to-overcome-them/

WEF (2024a). Why realism is key as we balance the energy transition with global growth. https://www.weforum.org/stories/2024/05/the-world-needs-a-new-strategy-for-the-energy-transition/

Xia, Q. (2025). Market perspective on climate actions and clean energy transition. Energy Policy 198, 114470, https://doi.org/10.1016/j.enpol.2024.114470.

Xiong, Z., Hu, J., Li, W. (2024). From policy to practice: Enhancing enterprise productivity through energy transition initiatives. Energy 311, 133361,https://doi.org/10.1016/ j.energy.2024.133361.

Yu, H., Wen, B., Zahidi, I., Chow, M., Liang, D., Madsen, D. (2024). The critical role of energy transition in addressing climate change at COP28. Results in Engineering 22, 102324, https://doi.org/10.1016/j.rineng.2024.102324.

https://doi.org/10.1017/sus.2025.10034 Published online by Cambridge University Press