INTERNATIONAL JOURNAL OF ENVIRONMENTAL, SUSTAINABILITY AND SOCIAL SCIENCE
IJESSS
ISSN 2720 - 9644 (print)
ISSN 2721 - 0871 (online)
Indexed By : GARUDA, Google Scholar, doi Crossref, ROAD, Index Copernicus International, Indonesia OneSearch, ISJD, sinta 4, EBSCO, Clarivate Analytics Web of Science

ENERGY MANAGEMENT IN COLOMBIA: EVOLUTION AND PROSPECTS FOR THE SUSTAINABLE TRANSITION (1993-2023)

Volume: 6
Number: 2
Page: 427 - 440

Juan Camilo Cardona CASTAÑO[1]
[1]PhD student in Environmental Sciences, Centro de Ciencias de Desarrollo Regional (CCDR), Universidad Autónoma de Guerrero (UAGro), Subject professor at the Autonomous University of Querétaro (UAQ), Cadereyta de Montes Campus, Mexico
Corresponding author: Juan Camilo Cardona Castaño
E-mail: juan.cardona@uaq.mx

Article History:
Received: 2025-01-24
Revised: 2025-02-15
Accepted: 2025-03-16

Abstract:
Colombia is seeking to transition to alternative energy and move towards a sustainable future. The purpose of this study was to analyze Colombia's energy management from 1993 to 2023, with the goal of establishing projection scenarios for 2030. To achieve this objective, we reviewed energy data from institutional databases at the Ministry of Mines and Energy, conducted a hemerographic analysis, and applied inferential statistics through linear regression to examine the behavior of the analyzed period. The method used is Case study, Scale and periodicity of analysis 1993-2023. Over the past three decades, comprehensive infrastructure has been developed to increase energy levels and electricity capacity for alternative energy production throughout the country. Our findings suggest that Colombia's energy sector may stabilize by 2030, but environmental pressures such as climate change, deforestation, and other factors could negatively impact the country's energy matrix. The design and implementation of Colombia's energy transition policy have faced obstacles. Ultimately, it is essential to advance towards a sustainable energy transition in Colombia, considering environmental challenges and transforming the energy matrix towards renewable energies.

Keywords: Clean Energy, Climate Change, Energy Transition, Installed Capacity, Prospects for 2030

INTRODUCTION

One of the global challenges at the energy level is the transition to renewable energy generation systems; this is a response to the global environmental crisis. It is necessary to seek alternatives that contribute to improving the planet's energy performance and invest in research and implementation of clean energy technologies (Granit, 2022).

In the case of Latin America, there is still a dependence on fossil fuels. This dependence has not been successfully dismantled, as the economies of the region are dependent on coal (Weng et al., 2020). However, in the Colombian scenario, energy production continues to depend on fossil fuels and has bet significantly on hydropower, with an average representation of 69%; although this type of energy is clean, the country faces a challenge in the energy transition (Estrada Girado et al., 2022).

Based on the foregoing, this research focuses on analyzing the country's energy landscape in the period from 1993 to 2023. This analysis is fundamental because it explores the opportunity of various scenarios and how the problem is associated with a regional context.

This research highlights the challenges of energy generation and the behavior of the energy matrix (EM), where the growth of alternative energies has had a low representation. Likewise, the challenges that the country faces in having to diversify and seek strategies to develop alternative energies, not only being dependent on fossil fuels and water, given that the latter resource supplies the country's dams, which in turn are impacted by climate variations (drought).

CATRA RESEARCH INSTITUTE
• ISSN 2720 - 9644 (print)
• ISSN 2721 - 0871 (online)
IJESSS
INTERNATIONAL JOURNAL OF ENVIRONMENTAL, SUSTAINABILITY AND SOCIAL SCIENCE
Indexed By :

Thus, the objective of the research was to analyze energy management between 1993 and 2023 to establish projection scenarios for 2030 that allow an understanding of the energy transition in Colombia.

Background: Energy generation in Colombia is primarily obtained through hydraulic dams that supply the national territory. However, the country's population growth and geography make hydraulic energy imperative within the energy mix (Pérez-Gelves et al., 2023). Currently, Colombia is experiencing growth and development of energy infrastructure to address coverage and transmission problems in remote areas and rural communities (Plazas-Niño et al., 2023). This scenario has led to three key aspects: first, a challenge and opportunity for the country's energy development to establish alternative energy sources (Torres-Morales et al., 2023). Second, there is a focus on the micro-generation of energy in rural contexts to address supply shortages (Martínez-Sierra et al., 2019; Galvís et al., 2023). Third, and finally, there is a need to overcome economic limitations to decarbonize the energy economy and transition to green and inclusive energy sources with communities (Granados et al., 2022).

Considering the above, the energy mix in Colombia faces a significant challenge in consolidating alternative energy sources and adopting new production models that do not harm the environment and achieve separation from fossil fuels (Martínez y Castillo, 2019). Moreover, the country's energy production and installed capacity are heavily dependent on water despite the planet facing a climate crisis and freshwater depletion (Weng et al., 2020). This situation highlights the need to adapt the energy mix to the vulnerability resulting from climate change and transition to a robust model of wind and solar energy, as the country's diverse geography and thermal floors would favor the construction and implementation of such technologies, facilitating better energy performance and a more resilient energy mix (Mulcué-Nieto et al., 2020; Moreno et al., 2022).

From another perspective, Colombia's energy mix has undergone significant development. However, the country still needs to adapt its installed capacity, expand generation, and reduce non-renewable energy consumption through solid policies and the implementation of a regulatory framework that obliges the Colombian State to initiate, implement, and involve communities and companies in the development of alternative energy sources and the reduction of non-renewable energy sources (Castaño y Suárez, 2021; Peña-Torres y Reina-Rozo, 2022; Rodríguez et al., 2023).

Sustainable energy management: The category of sustainable energy management has gained significant relevance over the past decade, primarily due to the climate challenges facing the world, as well as globalization and market dynamics (Galvís et al., 2023). The exploitation of energy resources has become a crucial issue, posing both economic and political challenges. It is essential to work towards finding sustainable alternatives that promote stability and balance in energy access (Calvo-Saad et al., 2023). However, the debate surrounding energy is also influenced by different political stances, often linked to economic models that favor carbon and fossil fuel exploitation. This approach raises concerns regarding the transition to cleaner and more sustainable energy sources, particularly considering the challenges posed by climate change. Therefore, according to González-Dumar et al. (2024), energy management should not only seek efficiency and resource optimization but also enable adequate adaptation to environmental changes.

Energy transition: The energy transition has recently emerged as a crucial topic in Colombia's political discourse. This category has become a central element in public debate, transcending both government and public agendas (Ramírez et al., 2022). The need to promote the construction and production of a clean and renewable energy system in the country is emphasized, reducing dependence on coal and increasing productivity based on sustainable energy sources. This transition has become a fundamental component of public and governmental policies, as well as the country's

CATRA RESEARCH INSTITUTE
• ISSN 2720 - 9644 (print)
• ISSN 2721 - 0871 (online)
IJESSS
INTERNATIONAL JOURNAL OF ENVIRONMENTAL, SUSTAINABILITY AND SOCIAL SCIENCE
Indexed By :

macroeconomic dynamics, given that Colombia is an exporter of electrical energy (Restrepo-Trujillo et al., 2020). The energy transition aims to ensure equitable access to the population, promoting a sustainable and balanced relationship with the environment. This challenge is not only social but also economic. Colombia must adapt to a more advanced and prepared energy system to face the climate and environmental crisis facing the world. It implies a transformation in both the way energy is produced and consumed, as well as in the management of environmental resources (Rodríguez et al., 2023).

METHODS

Case study, Scale and periodicity of analysis 1993-2023. Over the past three decades, a comprehensive infrastructure has been developed to increase the level of energy and electric capacity for alternative energy production throughout the country. It is essential to highlight that those efforts have also been made to standardize infrastructure and access to energy. In Colombia, a profile based on energy alternatives has been outlined, allowing citizens and companies to access them voluntarily. It is linked to the concept of decarbonization, increased operations in terms of energy demand, renewal based on renewable energy sources, and reduction of fossil fuel use. This period, from a political perspective, represents an independent trend in discourse and political ideologies, promoting renewable energy advancement with the recent incorporation of "decarbonization." However, operational and political challenges have been identified during these analysis periods.

According to the above, the following study variables were established for statistical analysis:

- Year of energy production.
- Installed capacity in energy generation in Megawatts (MW).

The present study is mixed and establishes a prospective approach as it outlines future scenarios.

Document Review: A documentary review of various technical reports from the Ministry of Mines and Energy (Minminas) was conducted to perform a macro-level analysis. Additionally, specialized websites on energy topics were consulted, and a demographic review was carried out, which constituted the basis of this study.

- Statistical Model: A statistical model was developed using simple linear regression, analyzing the regression coefficient to determine if there is a positive and significant relationship between time and installed capacity for energy generation. Subsequently, the coefficient of determination was evaluated to measure the proportion of variability between both variables explained by the passage of time.
- ANOVA: An analysis of variance (ANOVA) was then performed to determine if the relationship between the variables is statistically significant. Furthermore, a time series projection was made using a predictive model based on linear regression, extending up to the year 2030 to estimate the progress of the installed capacity for the energy generation variable.
- Time Series Prediction: To evaluate the accuracy of the model, the mean squared error was calculated, indicating the high precision of the model. Finally, a seasonality and trend analysis was performed to determine if the installed capacity for the energy generation variable shows a tendency to stabilize, increase, or decrease.

Scenario Planning. With the systematized information, three energy challenge scenarios were proposed for Colombia. These scenarios are suggested strategies based on the documentary review and the systematization of the study and aim at a prospective process. The three strategies or scenarios are:

CATRA RESEARCH INSTITUTE
• ISSN 2720 - 9644 (print)
• ISSN 2721 - 0871 (online)
IJESSS
INTERNATIONAL JOURNAL OF ENVIRONMENTAL, SUSTAINABILITY AND SOCIAL SCIENCE
Indexed By : GARUDA, Google, doi, Crossref, ROAD, INDEX COPERNICUS, OneSearch, ISJD, sinta 4, EBSCO, Clarivate Analytics

- Micro-organization of energy in localities.
- Investment and corruption control.
- Incentives for voluntary energy transition.

These elements converge with the policies that have been established in the country to facilitate the transition to cleaner energy.

Information Analysis: Two types of analysis were performed. Qualitative and quantitative. The first consisted of an integral analysis of the information obtained through the hemerographic reviews and the reports from the Ministry of Mines and Energy of Colombia. This interpretive analysis was carried out through three categories:

- Energy challenges in Colombia.
- Energy transition.
- Scenario planning.

This analysis provided a comprehensive understanding of the country's current energy challenges and limitations, as well as the necessary elements for achieving an energy transition.

The second analysis was a descriptive analysis of the energy matrix, using parametric statistics to project energy production. This analysis was complementary to the qualitative analysis, and the information was extracted from the institutional databases of the Unidad de Planeación de Minero Energética (UPME).

RESULT AND DISCUSSION

Colombia's energy matrix has experienced progressive and sustained growth, with minimal variables of growth (Figure 1). The installed energy capacity in the country has undergone significant development, with hydraulic energy being the predominant source in the energy matrix.

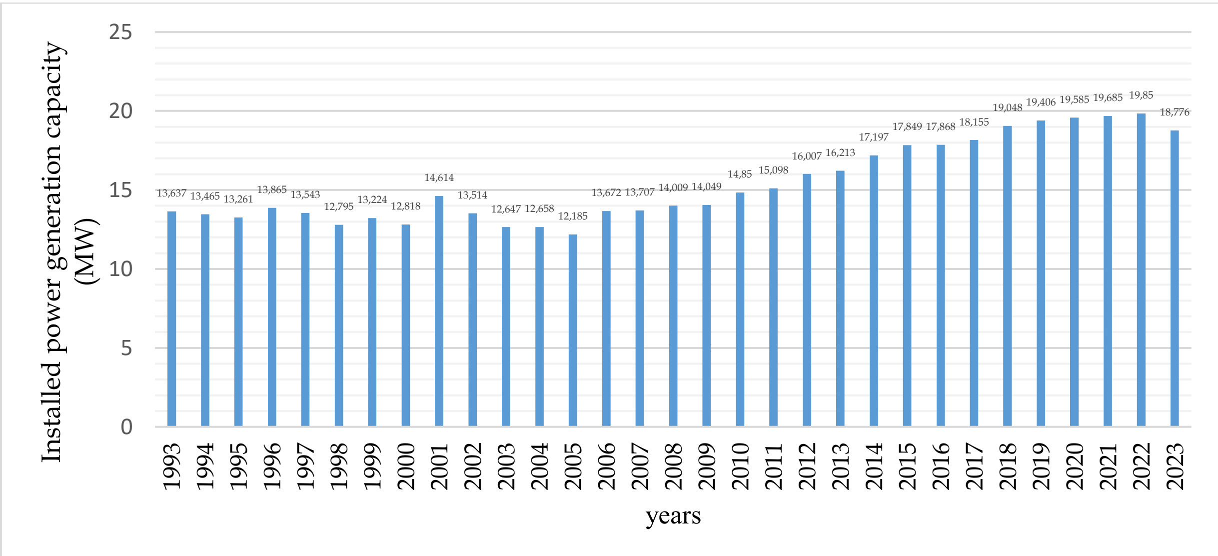


Figure 1. Installed energy generation capacity in (MW) period 1993-2023. Source: own elaboration with ARIAE data, (2022) Datamacro, (2022) and Minminas, (2024) shows the behavior in the analysis period and its fluctuations.

During the analysis of the period between 1993 and 2023, a sustained growth in Colombia's energy generation matrix was evident (Figure 2). In 2012, energy production reached 16,000 MW,

CATRA RESEARCH INSTITUTE
• ISSN 2720 - 9644 (print)
• ISSN 2721 - 0871 (online)
IJESSS
INTERNATIONAL JOURNAL OF ENVIRONMENTAL, SUSTAINABILITY AND SOCIAL SCIENCE
Indexed By :

and by 2022, it increased to 19,850 megawatts. This growth is attributed to the constant search for strategies to modernize the country's energy system despite its dependence on non-renewable sources such as coal and oil.

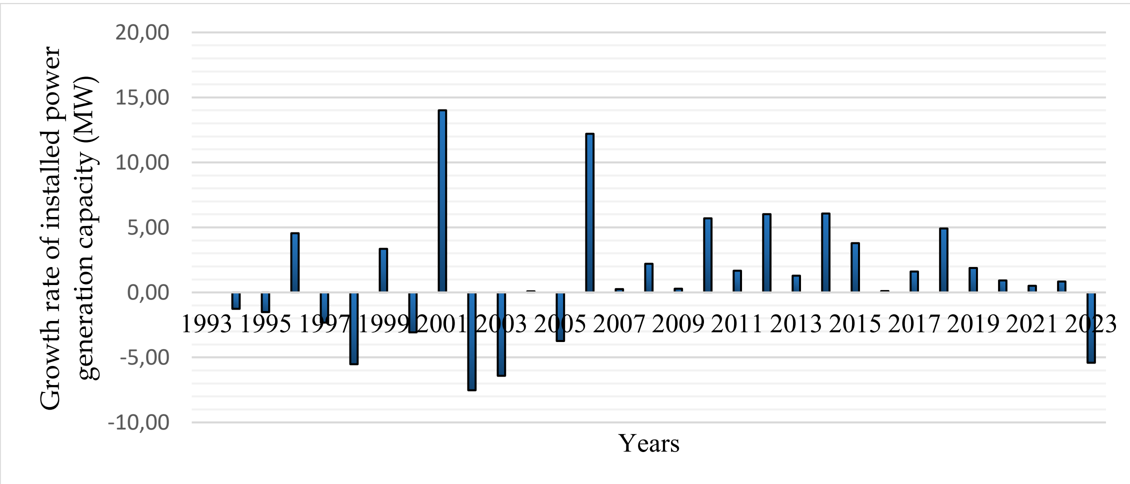
The bet on the development of alternative energies has opened up new niches, with research on the rise in terms of efficiency, effectiveness, and territorial and regional relevance. As the energy matrix has grown during this period, a profound reflection has also emerged. Colombia has been increasing its installed capacity to meet energy needs and adapt its matrix to the challenges of climate change.

However, on this path towards self-sufficiency, droughts have presented themselves as a determining external factor in energy generation, given that a large part of the country's energy demand is supplied through hydraulic energy. Approximately 70% of the energy comes from hydraulic sources, making the infrastructure of dams and reservoirs play a significant role in the generation and distribution of the energy system.

It is undeniable that there is a strong relationship between the climatic factors associated with the Colombian territory and energy production within its energy matrix. While it is recognized that more infrastructure is required to expand coverage and promote the development of alternative energies, the efforts and achievements obtained so far demonstrate that the country is moving towards greater independence in the management and generation of its energy despite the challenges it faces.

Despite these vicissitudes, the growth rate of the energy matrix has been volatile. We observe that in 2014, it reached a remarkable 6.04% growth, while in 2018, it reached a solid 4.9%. These figures are significant in terms of the progress and development of the country's energy capacity. However, it is still expected that the transition to more sustainable and renewable sources will consolidate at some point in the national energy process.

Moreover, it is worth mentioning that the average growth rate during the period from 2012 to 2022 was 2.54%, reflecting the evolution in the development of the energy matrix. Although various challenges have been faced, these numbers demonstrate constant progress in the country's ability to meet its energy demand. However, it is important to continue promoting the adoption of cleaner and more sustainable energies to ensure a more resilient and environmentally friendly energy future.



CATRA RESEARCH INSTITUTE
• ISSN 2720 - 9644 (print)
• ISSN 2721 - 0871 (online)
IJESSS
INTERNATIONAL JOURNAL OF ENVIRONMENTAL, SUSTAINABILITY AND SOCIAL SCIENCE
Indexed By : GARUDA, Google, doi Crossref, ROAD, INDEX COPERNICUS, Indonesia OneSearch, ISJD, sinta 4, EBSCO, Clarivate Analytics WEB OF SCIENCE

Figure 2. Growth rates of energy generation 1993-2023. Source: own elaboration with data from ARIAE (2022), Datamacro (2022) and Minminas (2024). It describes how energy growth has behaved over time and the positive and negative variations in energy production.

On the other hand, the variability in the growth rate may be related to various factors, such as the country's economic situation, changes in energy policies, investment in infrastructure, and climatic conditions, among others. The historical dependence on non-renewable sources such as coal and oil may also influence this fluctuation, as these resources can be affected by changes in international prices and global demand. Regarding energy management in Colombia, it is possible to observe certain advances, especially in years of higher growth. The energy generation capacity has been increasing, indicating greater infrastructure and capacity to meet the country's energy needs.

Between 1993 and 2023, hydraulic energy has been predominant in the energy generation process in Colombia. The installed capacity of hydraulic energy has maintained an average of 60%, which poses challenges for the conservation and sustainability of water bodies in the country. While hydraulic energy is a clean option, its exploitation involves limitations and changes in the water bodies where this energy is extracted. However, despite these challenges, the use of alternative technologies to meet energy demand in Colombia has lagged behind hydraulic energy and even non-renewable fuels. The Colombian energy matrix still largely depends on oil and coal, making it a highly carbonized economy. Although efforts are being made to decarbonize the economy, this also poses a challenge in terms of public policy and government management of energy.

It is necessary to promote the development of new energy technologies that can be implemented in strategic regions to increase the presence of alternative energies in the country's energy matrix. It would allow for meeting territorial needs in terms of consumption and coverage. This approach will require careful planning and the promotion of viable projects that foster sustainable energy in Colombia and reduce dependence on fossil fuels. In conclusion, although hydraulic energy has been essential in energy generation in Colombia, it is crucial to advance towards greater diversification and development of alternative technologies to address the country's environmental and energy challenges. The promotion of public policies and investment in new technologies will be key to achieving a more sustainable and balanced energy matrix in the future.

Modeling of Information. The linear regression analysis model showed a positive and significant relationship between the variable's "years" (independent variable) and "installed capacity of energy generation in MW" (dependent variable), with a regression coefficient of 0.41, a t-value of 15.616, and a significance level of 0.000. The coefficient of determination would be approximately 0.969, suggesting that changes over time directly affect energy production in megawatts, with a growth trend. It means that, in general, the analyzed information suggests a strong relationship between the increasing amount of energy in megawatts in Colombia during the examined years, which could be due to an increase in population demanding more energy, greater efficiency in generation, or a combination of both factors. According to statistics, the relationship between time and production is positive, meaning that the number of megawatts will increase as time passes, which could also be due to the country's industrialization.

1) Linear regression. The linear regression showed a significant and positive relationship between the dependent variable "installed capacity in MW" and the independent variable "year," suggesting that as time advances, there is a greater demand for energy, and it is necessary to improve the installed capacity of electric power generation. The Pearson correlation between the variables is

ISSN 2720 - 9644 (print)
ISSN 2721 - 0871 (online)
IJESSS
INTERNATIONAL JOURNAL OF ENVIRONMENTAL, SUSTAINABILITY AND SOCIAL SCIENCE
Indexed By : GARUDA, Google Scholar, doi Crossref, ROAD, INDEX COPERNICUS, Indonesia OneSearch, ISJD, sinta 4, EBSCO, Clarivate Analytics

0.88 (Table 1), indicating a substantial relationship between both variables, with a bilateral significance of 0.00, suggesting that the correlation is statistically significant at the 1% level.

The explanatory model of linear regression has a coefficient of determination R-squared of 0.188, indicating that 78.8% of the variability of MW is explained by external agents that occur in a year and the passage of time.

The ANOVA showed an F-value of 107.602 (Table 2), sufficient to demonstrate that the "year" variable has a significant impact on the installed capacity of megawatts of energy. As for the beta coefficient, it was 0.88, indicating that there is an 88.8% possibility that the year and its implications can generate variations in the installed capacity of energy (Table 3).

Table 1. Correlations of the installed energy capacity variables in MW/year

Variable	Tests	Year	Megawatts
Year	Pearson correlation	1	,888
	Sig. (bilateral)		,000
	N	31	31
Megawatts	Pearson correlation	,888	1
	Sig. (bilateral)	,000	
	N	31	31

Source: own elaboration

Table 2. ANNOVA

Model		Sum of squares	gl	Quadratic means	F	Sig.
1	Regression	153,919	1	153,919	107,602	,000
	Residual	41,483	29	1,430		
	Total	195,403	30			

Source: own elaboration

Table 3. Correlation Coefficient

Model		Unstandardized coefficients		Standardized coefficients	t	Sig.
		B	Typical error	Beta		
1	Constante	-484,852	48,226		-10,054	,000
	Year	,249	,024	,888	10,373	,000

Source: own elaboration

Table 4. Model settings

Model	Number of predictors	Model fit statistics	Ljung-Box Q(18)			Number of outliers
		Stationary R-squared	Statistics	GL	Sig.	
MegaWattios-Modelo_1	0	,527	12,636	17	,760	0

Source: own elaboration

2) Projection model to 20230. The predictive model, which started from the analysis period between 1993 and 2023, projected to 2030, showed a seasonality of 0.527, indicating a good fit, and an R-squared of 0.929. It allows us to assert that approximately 52.7% of the variability of the

CATRA RESEARCH INSTITUTE
• ISSN 2720 - 9644 (print)
• ISSN 2721 - 0871 (online)
IJESSS
INTERNATIONAL JOURNAL OF ENVIRONMENTAL, SUSTAINABILITY AND SOCIAL SCIENCE
Indexed By :
GARUDA Google doi Crossref ROAD INDEX COPERNICUS oneSearch ISJD sinta 4 EBSCO Clarivate Analytics WEB OF SCIENCE

dependent variable is explained by the seasonal variability and 92.9% of the total variability (Tables 4 and 5).

Regarding the time series of projections up to 2030, a slight, imperceptible increase was observed, which tends to stabilize between 2024 and 2030. According to statistics, the installed capacity of energy generation in MW will stabilize between 2024 and 2030 since the forecast line does not present any pronounced inclination, neither positive nor negative (Figure 3)

Table 5. Statistical model

Fit statistic	Media	ET	Minimum	Maximum	Percentile						
					5	10	25	50	75	90	95
Stationary R-squared	,527	.	,527	,527	,527	,527	,527	,527	,527	,527	,527
R- squared	,929	.	,929	,929	,929	,929	,929	,929	,929	,929	,929
RMSE	,682	.	,682	,682	,682	,682	,682	,682	,682	,682	,682
MAPE	3,354	.	3,354	3,354	3,354	3,354	3,354	3,354	3,354	3,354	3,354
MaxAPE	12,593	.	12,593	12,593	12,593	12,593	12,593	12,593	12,593	12,593	12,593
MAE	,499	.	,499	,499	,499	,499	,499	,499	,499	,499	,499
MaxAE	1,840	.	1,840	1,840	1,840	1,840	1,840	1,840	1,840	1,840	1,840
BIC normalized	-,655	.	-,655	-,655	-,655	-,655	-,655	-,655	-,655	-,655	-,655

Source: own elaboration

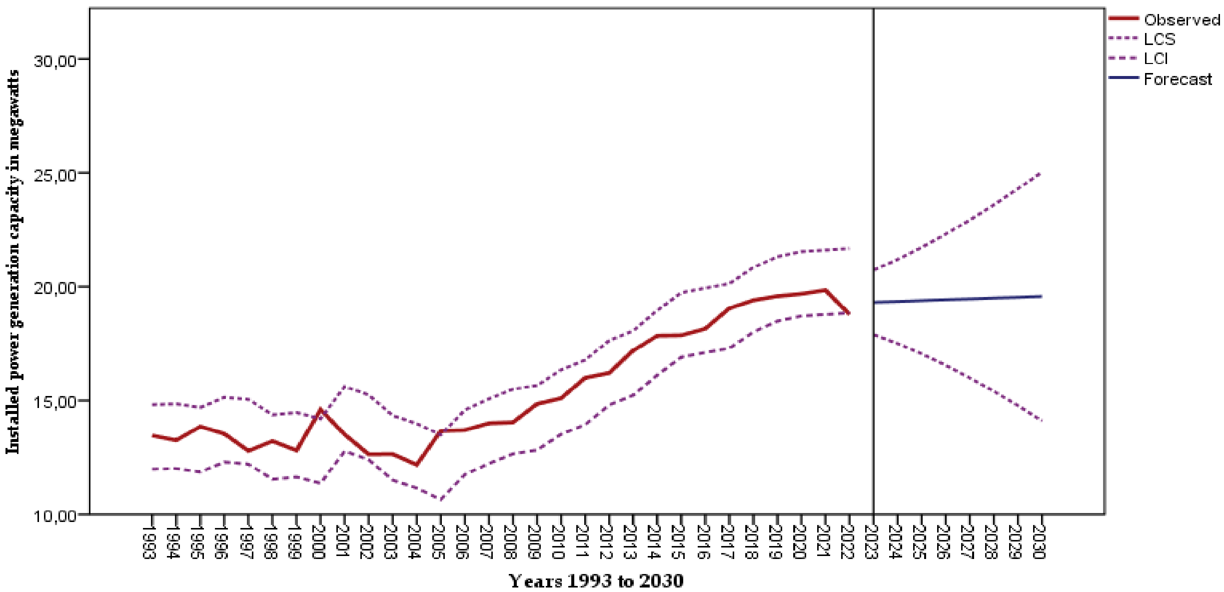


Figure 3. Historical behavior of the variables installed energy generation capacity started in 1993 and with a projection to 2030. Source: own elaboration. The image shows how the supply line is tending toward stabilization, although it shows imperceptible growth.

The results of the regression model and the projection for 2030 allow us to conclude that each year has external factors, usually of environmental origin, that can affect the variations in the installed capacity of energy in Colombia. Although alternative energy in the country is under development, improvements and adaptations are still required in the infrastructure. The country's energy matrix mainly depends on hydraulic energy, which is generated through water bodies.

CATRA RESEARCH INSTITUTE
• ISSN 2720 - 9644 (print)
• ISSN 2721 - 0871 (online)
IJESSS
INTERNATIONAL JOURNAL OF ENVIRONMENTAL, SUSTAINABILITY AND SOCIAL SCIENCE
Indexed By :

However, the current global crisis, caused by climate change, deforestation, and land-use changes, is generating losses and affecting hydrological stability in the country. Additionally, the El Niño phenomenon in the last year has raised concerns about a possible energy and water shortage, which can significantly impact the variable of installed energy generation capacity. If the trend of environmental degradation continues, although the predictive model showed slight increases in the projection period, considering the factors that each year brings, it is possible to envision a scenario of energy decline and scarcity.

Challenges and opportunities in Colombia's energy transition. Colombia has made significant progress in its transition towards alternative energies. Hydraulic energy accounts for approximately 60% of the installed capacity. However, energy challenges persist, demanding solutions. Among them, the need to optimize and expand electrical coverage throughout the territory stands out, especially in areas and sectors that lack access and still rely on fossil fuels or biomass.

To address these challenges, technological development is crucial to harness clean energies, such as wind and solar power. Colombia has great potential in winds and solar radiation, highlighting the importance of promoting the necessary infrastructure to cover the current deficiencies in alternative energies. The Colombian government faces the challenge of adopting cleaner and more sustainable energies, considering its rich biodiversity. However, this transition is hindered by the high demand and production of oil and coal in the industry. It is essential to establish a solid and participatory regulation and alternative energy policy involving communities and considering diverse local perspectives on energy generation. Addressing this transition from multiple sectors will enable the implementation of sustainable actions and strategies that mitigate the impact of non-clean sources.

Over time, there has been a lack of planning in the implementation of alternative energies across the territory despite the current government's efforts to correct this situation. Problems persist, requiring further development of actions to achieve adequate planning tailored to the needs and potential of each Colombian department. It is also essential to recognize and support community-based and rural energy enclaves, which have developed their generation systems but often do not receive the recognition they deserve. The analysis of Colombia's energy matrix between 1993 and 2023 has highlighted advances and challenges in the country's energy transition, demanding a greater push in the development of alternative technologies and increased state investment to achieve a more sustainable and environmentally friendly energy matrix.

It is essential to emphasize that all energy improvement processes involve raising awareness and education about the importance of energy sustainability. Fostering a culture of responsible and efficient energy use among the population is key to reducing demand and promoting environmentally friendly practices. It is also crucial to promote research and development of innovative technologies in clean energies, facilitating access to financing and resources for sustainable energy projects at the local and regional levels.

An additional challenge in Colombia's energy matrix transition to alternatives is the resistance or lack of support from certain sectors within the traditional energy industry. The adoption of clean and renewable energies may involve changes in business models and affect deeply rooted economic interests. Addressing potential political and economic challenges during this transition is crucial, including the promotion of incentives and policies that favor the adoption of clean energies and ensure a just and equitable transition for all parties involved. Moreover, the infrastructure and technical capacity required to integrate alternative energies into the national electric grid efficiently should be taken into account, ensuring a safe and stable transition.

Towards an energy transition. In the current government of President Gustavo Petro, one of the pillars of his government plan is the decarbonization of the economy and the transition to renewable energy. However, this transition has faced difficulties due to the El Niño phenomenon. A wave of drought has affected the country's largest dams, which are an important source of hydroelectric energy. This situation has confirmed two fundamental aspects: first, the need to advance towards an alternative energy system, whether through wind, solar, or tidal energy. Second, the importance of managing strategies that ensure efficient energy supply. Despite efforts, Colombia's energy system, which heavily relies on hydroelectric energy, proves insufficient to guarantee a constant supply, especially in regions like the Caribbean Coast, which face connectivity and energy supply problems. Moreover, the country's most ambitious energy project, Hidroituango, has faced numerous setbacks in its development and implementation, including inoperability, technical issues, and corruption allegations. However, other limitations have hindered the energy transition, such as political polarization and lack of financing to improve the necessary infrastructure for the adoption of renewable energy sources.

1) Scenario development. Based on the obtained information, three scenarios are proposed as an alternative to the energy transition processes and to overcome the current challenges faced by the ME:

Scenario 1: Micro-generation of energy in localities

One alternative that could be proposed for energy supply in the country is to promote micro-generation of energy. It involves producing energy on a small scale (20 Kilowatt) and can be implemented in communities not connected to the electrical grid. Additionally, it could be a possible alternative that combines both traditional energy and alternative energy systems. The development of this type of energy and technologies at the local level would not only allow for a small-scale energy transition but also help reduce dependence on hydroelectric energy. It would be especially beneficial during times of water scarcity, as it would provide a solution during drought seasons when energy production from dams decreases.

Scenario 2: investment and corruption control

Another strategy involves exercising control over the country's energy security, which entails advancing technologies related to solar, wind, and tidal energy. However, it is essential to conduct a citizen oversight exercise and implement a transparent policy regarding the management of the country's energy landscape, particularly considering that most corruption cases are linked to large-scale hydroelectric projects like Hidroituango.

Scenario 3: incentives for voluntary energy transition

Incentivizing the installation of solar panels and wind turbines in rural areas, as well as promoting the use of Pelton wheels for hydroelectric energy generation, is another strategy. The focus should be on directing these initiatives towards small rural producers and micro-entrepreneurs, offering subsidies and incentives for a voluntary transition to these technologies. It could trigger a positive domino effect on the country's energy development, facilitating a progressive and tangible transition towards more sustainable and accessible energy sources for rural communities.

Theoretical discussion of the results. According to Pérez-Gelves et al. (2023), Latin America faces significant challenges in accessing non-renewable energy resources, which has resulted in minimal contributions to social, economic, and human development across various territories. Based on the authors' findings, this study highlights that Latin America has a strong dependency on fossil fuels, leading to limited solutions at the territorial level and in energy transformation.

CATRA RESEARCH INSTITUTE
• ISSN 2720 - 9644 (print)
• ISSN 2721 - 0871 (online)
IJESSS
INTERNATIONAL JOURNAL OF ENVIRONMENTAL, SUSTAINABILITY AND SOCIAL SCIENCE
Indexed By :

Raihan (2023) points out that the Colombian context is unique. The country's energy matrix has made significant advancements in hydropower. However, it is crucial not only to move away from non-renewable energy sources but also to consider increasing wind and solar energy due to the climate crisis. As proposed by the authors, Colombia must shift towards solutions that enhance the generation of wind and solar energy. The climate crisis directly impacts water resources, which are essential for sustaining the 69% average of hydroelectric power generation in Colombia.

Given the above, Colombia has a regulatory and planning framework in place. Nevertheless, ambiguities are evident: on the one hand, a clean energy matrix is proposed, with a need for diversification; on the other hand, there is a progressive decarbonization of the energy matrix. Considering the energy production patterns in the country, transitioning to a high level of alternative energy production becomes challenging. According to Ramírez et al. (2022), one of the issues facing the energy matrix is the lack of consolidation of clean technologies that contribute to responsible diversification in harmony with communities and the environment. For this to be feasible, a solid regulatory framework must be constructed, capable of responding fairly to the energy needs of each region.

Therefore, Colombia's energy matrix faces a significant challenge in strengthening solar and wind energy while adapting hydropower to potential vulnerabilities resulting from the climate crisis (Villa-Loaiza et al., 2023). In light of the reflections in this research and considering the author's perspective, the energy matrix must explore greater growth in alternative energy as a response to the climate crisis.

Regarding the challenges of an energy transition, the government will need to make decisions aimed at increasing wind and solar energy, which would be a strategy to counteract climate impacts and the variations brought by the El Niño phenomenon. Therefore, this research finds similarities with the studies of Restrepo-Trujillo et al. (2020), suggesting that the implementation of alternative energies would enhance the country's energy competitiveness alongside a climate change adaptation strategy addressing the El Niño phenomenon. This adaptation must focus on resilience and contingency measures against the potential energy shortages in the country.

This research explores the importance of developing alternative scenarios in response to the energy crisis and the transition toward clean and sustainable energy sources. This topic is intrinsically linked to emerging global needs, driven by environmental challenges and the urgent need to shift from a coal-based energy matrix to more sustainable options. Granados et al. (2022) propose that addressing these issues within the territorial context is crucial, considering both the challenges and the opportunities for mitigating them. In this regard, their findings highlight the urgent need for an energy transition.

González-Dumar et al. (2024) approach the transition from a business perspective, focusing on processes carried out in the rural sector. According to the authors Esquivel García and Toro-García (2024), although the research considers the particularities of rural areas, it does not concentrate its efforts on the rural sector. Instead, it views this sector as part of the broader energy problem facing the country.

This research emphasizes the importance of developing alternative scenarios in the face of the energy crisis, climate change, and the transition to clean and sustainable energy. This topic is closely tied to global emerging needs resulting from environmental challenges and the urgency to transition from a coal-based energy matrix to more sustainable options. It aligns with the findings of Calvo-Saad et al. (2023), who emphasize the importance of addressing these issues within the territorial context, considering both the challenges of the transition and the opportunities for mitigating them. Their findings underscore the pressing need for an energy transition.

• ISSN 2720 - 9644 (print)
• ISSN 2721 - 0871 (online)
IJESSS
INTERNATIONAL JOURNAL OF ENVIRONMENTAL, SUSTAINABILITY AND SOCIAL SCIENCE
Indexed By : GARUDA, Google, doi Crossref, ROAD, Index Copernicus, Indonesia OneSearch, ISJD, sinta 4, EBSCO, Clarivate Analytics

Additionally, discussing the historical energy landscape in Colombia requires addressing the country's dependence on hydropower as a primary source of energy supply. However, energy demand has increased over time, as detected in the statistical analysis and linear regression conducted in this study, suggesting that energy production may stabilize and grow only slightly at best. These findings align with those of García-Estévez et al. (2024). Moreover, while there has historically been a trend of increased energy generation, this does not exempt Colombia from global issues and the current environmental crisis. Therefore, it is essential to establish an energy security response. In the view of Ramírez et al. (2022), this involves the democratization of energy within a sustainability framework for peace and territorial integrity.

CONCLUSION

The research successfully achieved its objective. The linear regression analysis revealed a regression coefficient of 0.41 and a t-value of 15.616, indicating a significant relationship between time and the installed energy generation capacity in Colombia. Both variables are closely interlinked, posing considerable challenges in terms of energy production and the transition to renewable sources such as wind and solar.

Additionally, Pearson's correlation showed a substantial relationship between the variables, with a value of 0.88, indicating a strong correlation between time and the installed energy generation capacity. The linear regression model explained 88% of the variability in installed energy generation capacity, highlighting a significant opportunity for energy conversion. However, the reliance on hydropower for 70% of the country's energy matrix makes the energy system vulnerable to climate change and global warming. Moreover, the El Niño phenomenon has affected water resource availability and, consequently, the energy production capacity of reservoirs.

Despite the consistent growth in installed energy generation capacity since 1993, it is insufficient to significantly reduce dependence on non-renewable sources such as coal and oil. The transition to clean energy is crucial to drive a decarbonized economy and achieve energy sustainability. However, the country faces significant challenges in this energy transition, including corruption, resistance from certain traditional sectors, and the need for an inclusive approach to the adoption of alternative energies. Furthermore, the country may face the risk of energy stagnation by 2030. According to the projections made in this research, the time series provision line indicated stability; however, factors such as environmental changes and alterations in water bodies could disrupt this balance, suggesting that the scenario remains volatile.

REFERENCES

Ariae, A. I. De E. R. De E. (2022). Balance Energético Colombiano - Beco. Contiene 2006-2021 | ARIAE. https://www.ariae.org/servicio-documental/balance-energetico-colombiano-beco-contiene-2006-2021

Calvo-Saad, M. J., Solís-Chaves, J. S., & Murillo-Arango, W. (2023). Suitable Municipalities for Biomass Energy Use in Colombia Based on a Multicriteria Analysis from a Sustainable Development Perspective. *Heliyon, 9*(10), e19874. https://doi.org/10.1016/j.heliyon.2023.e19874

Castaño, J. C. C., & Suárez, F. A. C. (2021). Sustentabilidad Rural, Perspectiva Y Gobernanza Energética: Estudio de caso, Meta- Colombia. *Revista Contacto, 1*(2), Article 2.

Datosmacro. (2022). Generación de electricidad en Colombia 2022. https://datosmacro.expansion.com/energia-y-medio-ambiente/electricidad-generacion/colombia

Esquivel García, C. L., & Toro-García, G. L. (2024). Multidimensional Energy Poverty in Colombia: A department-level review from 2018 to 2022. *Heliyon, 10*(14), e34395. https://doi.org/10.1016/j.heliyon.2024.e34395

Estrada Girado, S. A., Martínez Ruiz, F. S., & Vides Prado, C. D. (2022). Estudio del Potencial Eólico Offshore De La Zona Costera Caribe De Colombia. Ciencia E Ingeniería: Revista De Investigación Interdisciplinar En Biodiversidad Y Desarrollo Sostenible, Ciencia, Tecnología E Innovación Y Procesos Productivos Industriales, 9(2), 5.

Galvís, V. D. N., Duque, S. O. M., & Gómez, C. J. A. (2023). Technical and economic analysis of a photovoltaic solar system in Norte de Santander, Colombia. *Journal of Applied Engineering Science, 21*(1), 275-284. https://doi.org/10.5937/jaes0-40308

García-Estévez, J., Vargas-Prieto, A., & Ariza, J. (2024). Mining-Energy Boom and Local Institutional Capacities—The Case of Colombia. *The Extractive Industries and Society, 17*, 101387. https://doi.org/10.1016/j.exis.2023.101387

González-Dumar, A., Arango-Aramburo, S., & Correa-Posada, C. M. (2024). Quantifying Power System Flexibility for the Energy Transition in Colombia. *International Journal of Electrical Power & Energy Systems, 155*, 109614. https://doi.org/10.1016/j.ijepes.2023.109614

Granados, C., Castañeda, M., Zapata, S., Mesa, F., & Aristizábal, A. J. (2022). Feasibility Analysis for the Integration of Solar Photovoltaic Technology to the Colombian Residential Sector Through System Dynamics Modeling. *Energy Reports, 8*, 2389-2400. https://doi.org/10.1016/j.egyr.2022.01.154

Granit, I. (2022). Microgrids through the Energy-Water-Food Security Nexus in La Guajira, Colombia: Increasing Water and Food Security or Jeopardizing Groundwater Levels? *Energy Research & Social Science, 93*, 102814. https://doi.org/10.1016/j.erss.2022.102814

Martínez, V., & Castillo, O. L. (2019). Colombian Energy Planning—Neither for Energy Nor for Colombia. *Energy Policy, 129*, 1132-1142. https://doi.org/10.1016/j.enpol.2019.03.025

Martínez-Sierra, D., García-Samper, M., Hernández-Palma, H., & Niebles-Núñez, W. (2019). Gestión Energética en el Sector Salud en Colombia: Un Caso de Desarrollo Limpio y Sostenible. *Información tecnológica, 30*(5), 47-56. https://doi.org/10.4067/S0718-07642019000500047

Minminas, M. de M. y E. de C. (2024). BECO – MEQ EFICIENCIA ENERGÉTICA. https://www.meq.com.co/beco/

Moreno, J., Cobo, M., Barraza-Botet, C., & Sanchez, N. (2022). Role of Low Carbon Emission H2 in the Energy Transition of Colombia: Environmental Assessment of H2 Production Pathways for a Certification Scheme. *Energy Conversion and Management: X, 16*, 100312. https://doi.org/10.1016/j.ecmx.2022.100312

Mulcué-Nieto, L. F., Echeverry-Cardona, L. F., Restrepo-Franco, A. M., García-Gutiérrez, G. A., Jiménez-García, F. N., & Mora-López, L. (2020). Energy Performance Assessment of Monocrystalline and Polycrystalline Photovoltaic Modules in the Tropical Mountain Climate: The Case for Manizales-Colombia. *Energy Reports, 6*, 2828-2835. https://doi.org/10.1016/j.egyr.2020.09.036

Peña-Torres, J. A., & Reina-Rozo, J. D. (2022). Agroecology and Communal Innovation: Labcampesino, A Pedagogical Experience from the Rural Youth in Sumapaz Colombia.

CATRA RESEARCH INSTITUTE
• ISSN 2720 - 9644 (print)
• ISSN 2721 - 0871 (online)
IJESSS
INTERNATIONAL JOURNAL OF ENVIRONMENTAL, SUSTAINABILITY AND SOCIAL SCIENCE
Indexed By : GARUDA, Google, doi Crossref, ROAD, INDEX COPERNICUS, Indonesia OneSearch, ISJD, sinta 4, EBSCO, Clarivate Analytics

Current Research in Environmental Sustainability, *4*, 100162. https://doi.org/10.1016/j.crsust.2022.100162

Pérez- Gelves, J. J., Østergaard, P. A., & Díaz- Flórez, G. A. (2023). Energy Poverty Assessment and the Impact of Covid-19: An Empirical Analysis of Colombia. *Energy Policy*, *181*, 113716. https://doi.org/10.1016/j.enpol.2023.113716

Plazas-Niño, F. A., Ortiz-Pimiento, N. R., & Quirós-Tortós, J. (2023). Supporting Energy System Modelling in Developing Countries: Techno-Economic Energy Dataset for Open Modelling of Decarbonization Pathways in Colombia. *Data in Brief*, *48*, 109268. https://doi.org/10.1016/j.dib.2023.109268

Raihan, A. (2023). The Influences of Renewable Energy, Globalization, Technological Innovations, and Forests on Emission Reduction in Colombia. *Innovation and Green Development*, *2*(4), 100071. https://doi.org/10.1016/j.igd.2023.100071

Ramirez, J., Angelino Velázquez, D., & Vélez-Zapata, C. (2022). The Potential Role of Peace, Justice, and Strong Institutions in Colombia's Areas of Limited Statehood for Energy Diversification Towards Governance in Energy Democracy. *Energy Policy*, *168*, 113135. https://doi.org/10.1016/j.enpol.2022.113135

Restrepo-Trujillo, J., Moreno-Chuquen, R., & Jimenez-Garcí-a, F. N. (2020). Strategies of Expansion for Electric Power Systems Based on Hydroelectric Plants in the Context of Climate Change: Case of Analysis of Colombia. *International Journal of Energy Economics and Policy*, *10*(6), Article 6.

Rodríguez, T., Reu, B., Bolívar-Santamaría, S., Cortés-Aguilar, A., & Buendía, C. (2023). A Framework for Participatory Scenario Planning to Guide Transitions Towards Sustainability in Mountain Social-Ecological Systems: A Case Study from the Colombian Andes. *Land Use Policy*, *132*, 106817. https://doi.org/10.1016/j.landusepol.2023.106817

Torres-Morales, E., Khatiwada, D., Xylia, M., & Johnson, F. X. (2023). Investigating Biochar as a Net-Negative Emissions Strategy in Colombia: Potentials, Costs, and Barriers. *Current Research in Environmental Sustainability*, *6*, 100229. https://doi.org/10.1016/j.crsust.2023.100229

Villa-Loaiza, C., Taype-Huaman, I., Benavides-Franco, J., Buenaventura-Vera, G., & Carabalí-Mosquera, J. (2023). Does Climate Impact the Relationship Between the Energy Price and the Stock Market? The Colombian Case. *Applied Energy*, *336*, 120800. https://doi.org/10.1016/j.apenergy.2023.120800

Weng, W., Becker, S. L., Lüdeke, M. K. B., & Lakes, T. (2020). Landscape Matters: Insights from the Impact of Mega-Droughts on Colombia's Energy Transition. *Environmental Innovation and Societal Transitions*, *36*, 1-16. https://doi.org/10.1016/j.eist.2020.04.003