International Journal of Electrical and Computer Engineering (IJECE)
Vol. 15, No. 3, June 2025, pp. 2523~2533
ISSN: 2088-8708, DOI: 10.11591/ijece.v15i3.pp2523-2533

Analysis of geothermal technology development in the Colombian energy transition to 2050 using system dynamics

Diego Alberto Carreño[1], Isaac Dyner[1], Enrique Ángel Sanint[2], Andrés Julián Aristizábal[1]
[1]Faculty of Natural Sciences and Engineering, Universidad Jorge Tadeo Lozano, Bogotá, Colombia
[2]School of Engineering and Basic Sciences, Universidad EIA, Envigado, Colombia

Article Info

Article history:

Received Jun 12, 2024
Revised Dec 12, 2024
Accepted Jan 16, 2025

Keywords:

Clean energy
Energy transition
Geothermal energy
Renewable
System dynamics

ABSTRACT

This research analyzes the current and future prospects of geothermal energy in Colombia using a system dynamics model. The study focuses on evaluating geothermal potential linked to hydrothermal systems, surface manifestations like geysers, and areas near volcanoes. The model, projecting up to 2050, offers a comprehensive assessment of national geothermal potential, considering technical, economic, regulatory, and social factors that influence its integration into the energy matrix. Key findings highlight the need for adjustments to the existing regulatory framework, which currently lacks sufficient incentives for geothermal project development. Additionally, the study underscores the importance of implementing stronger government policies and incentives to promote this renewable energy source. Proper social and environmental management, with active involvement of local communities, is also identified as crucial for project success. The system dynamics approach effectively models the complex interrelationships between variables shaping the future of geothermal energy in Colombia. The developed model serves as a novel tool for technological foresight in this strategic field, identifying obstacles and opportunities to unlock Colombia's significant geothermal potential and providing a systemic perspective on this critical issue for the national energy transition.

Corresponding Author:

Andrés Julián Aristizábal
Faculty of Natural Sciences and Engineering, Universidad Jorge Tadeo Lozano
Cr. 4 #22-61, Bogotá, Colombia
Email: andresj.aristizabalc@utadeo.edu.co

1. INTRODUCTION

The global shift towards sustainable energy sources has become an urgent priority as nations strive to meet climate targets and reduce their dependence on fossil fuels [1]–[3]. Colombia, a country rich in natural resources, has initiated its energy transition strategy with a focus on incorporating renewable energy technologies. Among the various alternatives, geothermal energy represents a promising, yet underexplored, resource that could play a pivotal role in Colombia's energy landscape by 2050. However, the development and integration of geothermal technology within the Colombian energy mix face significant challenges that need to be thoroughly analyzed.

Despite the potential of geothermal energy to provide a stable and sustainable energy supply, its development in Colombia has been relatively slow compared to other renewable resources like hydropower and solar energy. The primary challenges include the lack of comprehensive geological surveys, high initial investment costs, and regulatory hurdles. Additionally, the absence of a clear roadmap for integrating geothermal technology into the national energy strategy exacerbates the problem, limiting the effectiveness of Colombia's transition to a low-carbon economy.

California emerged as a global leader in geothermal energy generation through development supported by federal subsidies and tax benefits [4], [5]. Similarly, Indonesia's geological explorations in Java and Sumatra led to the construction of high-capacity geothermal plants, while the Philippines successfully developed the Tiwi and Tongonan fields, reducing their dependence on imported fuels [6], [7]. Turkey's government-financed surveys in Denizli and Aydın resulted in new power plants, and Mexico expanded its geothermal program by establishing plants in Baja California and other states [8]. Legislative reforms and public policies in the United States, the Philippines, Mexico, and Indonesia further facilitated geothermal expansion through tax incentives, electricity law reforms, and laws attracting private investment [8].

Renewable energy is crucial for achieving a sustainable future, as it reduces our reliance on fossil fuels, mitigates climate change, and promotes energy security [9]–[11]. In the context of Colombia, geothermal energy presents a viable alternative due to the country's significant volcanic activity, which provides a stable and continuous energy source. Moreover, integrating geothermal technology into the national energy mix enhances resilience against fluctuations in hydropower availability, which is often affected by climate variability.

Research highlights key success factors for geothermal energy development, emphasizing the identification of suitable geological conditions, rigorous financial analyses, and the importance of a clear legal and regulatory framework [12]–[14]. Reusing depleted oil and gas wells is also considered a cost-effective option for geothermal generation, with demonstrated technical feasibility in Europe and North America [15]–[17]. This approach significantly reduces costs, as demonstrated by successful projects in Bavaria, Germany, and North Dakota, USA, where old wells were converted into geothermal plants [18]–[22] .

The potential for scaling this solution is enormous, with over 3 million oil and gas wells worldwide that could be converted to generate geothermal capacity [23]. For instance, the United States alone could add up to 16 gigawatts of geothermal capacity by converting inactive wells, equivalent to the capacity of 16 large power plants. These developments highlight the growing role of geothermal energy in achieving sustainable energy goals globally.

While previous studies have laid the groundwork for understanding geothermal energy's potential in Colombia, several unresolved issues remain. These include the need for more detailed geological surveys to accurately assess the resource potential, the development of financial mechanisms to attract investment, and the formulation of policies that facilitate the integration of geothermal energy into the national grid. Furthermore, there is a lack of dynamic modeling approaches that can simulate the long-term impacts of geothermal technology on Colombia's energy transition, particularly under various policy scenarios.

This manuscript aims to address these gaps by employing a system dynamics approach to model the development of geothermal technology within the context of Colombia's energy transition to 2050. Unlike previous studies, this research will integrate geological, economic, and policy variables into a comprehensive model that simulates different scenarios. The novelty of this approach lies in its ability to provide policymakers with actionable insights into how various factors interact over time, thus enabling more informed decisions regarding geothermal energy development.

The following sections of this manuscript will elaborate on the methodology, data sources, and the system dynamics model developed for this study. The results section will present the outcomes of the different scenarios simulated, highlighting the potential contributions of geothermal energy to Colombia's energy transition. Finally, the discussion will interpret these findings in the context of existing literature and policy frameworks, demonstrating the relevance and applicability of the proposed model in shaping Colombia's energy future.

2. METHOD

The focus of the model is to analyze the behavior of geothermal energy through system dynamics, using the Vensim tool for its simulation. The specific data collected support the formulation and analysis in the development of this model. This study comprehensively considers various aspects such as technological, economic, political, and environmental factors to ensure a faithful reflection of the complexity of the environment.

The chosen period for studying the system is 2023-2050. This period was strategically selected to thoroughly analyze the behavior and development of geothermal energy over significant time horizons. By focusing on this extended period, long-term trends can be identified, and a comprehensive assessment can be made of how geothermal energy may evolve in response to technological, economic, political, and environmental factors.

The scenarios established to evaluate the model are shown in Table 1. These scenarios consider different levels of geothermal energy adoption, ranging from a baseline case with minimal implementation to an ambitious transition scenario with significant geothermal integration. Each scenario incorporates key variables such as investment costs, technological advancements, and policy incentives to assess their impact on Colombia's energy transition.

The values and descriptions of the parameters for each scenario are shown in Table 2. These parameters include factors such as geothermal capacity growth rates, investment costs, and environmental impact coefficients, which are essential for accurately simulating the energy transition. Figure 1 shows the model developed in Vensim. Illustrating the interconnections between key system components, including energy supply, demand, and policy interventions.

Table 1. Scenarios proposed for the model

Uncertainty	Scenario (+,+)	Scenario (+,-)	Scenario (-,+)	Scenario (-,-)
Name	Green democracy	Renewable extractivism	Greta	Burning house
Policy orientation towards energy transition	Promotes	Fluctuates	Slows down	Slows down
Political situation in Colombia	Series of presidents who drive local mitigation initiatives	Policies towards the transition oscillate back and forth as governments alternate	Series of presidents who drive local mitigation initiatives	Policies towards the transition oscillate back and forth as governments alternate
Geothermal energy entry	Strategies are designed to encourage the emergence of geothermal projects. The learning curve is accelerated	Geothermal projects are left to their own fate. The learning curve is slow	Strategies are designed to encourage the emergence of geothermal projects. The learning curve is accelerated	Circumstances never arise for it to enter on equal terms.

Table 2. Values and description of parameters

Scenario	Level of Political and Social Favorability	Maximum growth rate	Capacity under construction	Max. Installed power to 2050	Efficiency factor geothermal plant	Cost x MW installed
Green democracy	100% The favorability of the political and social orientation towards the energy transition is 100% favorable.	4.5% The maximum technology growth rate is assumed [24]	100 MW Government takes the initiative and installs the first 100 MW to boost this type of energy	1170 MW This is the maximum geothermal generation capacity of the country.	85% It is determined by research, being the current maximum efficiency factor.	5.19 M USD It is determined by research, with the minimum costs determined for this scenario.
Renewable Extractivism	75%	3.5%	0 MW	1170 MW	85%	5.19 M USD – 7.76 MUSD/MW
	Politically, there is not much stability on whether the implementation of this type of energy is good or bad.	The maximum growth rate decreases to one percentage point taking as a value the annual growth rate between 2000-2018 [24]	The government does not risk investing in this first geothermal project to prove that it works, thus delaying its implementation.	The same maximum installed power is maintained because it is the potential that the country has.	The efficiency factor remains the same but technological development will be affected.	The cost of MW ranges from 7.76 M USD/MW to 5.19 M USD/MW.
Greta	25%	3.5%	50 MW	1170 MW	85%	5.19 M USD – 7.76 MUSD/MW
	There is favorability on the part of society, some politicians motivate, but there is not total support from both sides.	The maximum growth rate decreases to one percentage point taking as a value the annual growth rate between 2000-2018 [24]	Some presidents, by encouraging the emergence of geothermal projects, are promoting the first 50 MW	The same maximum installed power is maintained because it is the potential that the country has.	The efficiency factor remains the same but technological development will be affected.	The cost of MW ranges from 7.76 M USD/MW to 5.19 M USD/MW.
Burning house	0%	2.03%	0	585 MW	80%	7.76 M USDMW – 6.15 M USD/MW
	Society and government never agree with the implementation of geothermal plants throughout the country.	The growth rate remains the smallest on record, based on growth data for Mexico [24]	No capacity is under construction because the conditions and circumstances are not present.	Construction capacity is reduced by half as exploration is also not carried out in the different zones.	The efficiency factor is reduced to 80%, being the most obsolete technology.	The lowest cost is not achieved because the conditions for this technology to be more economical are never met.

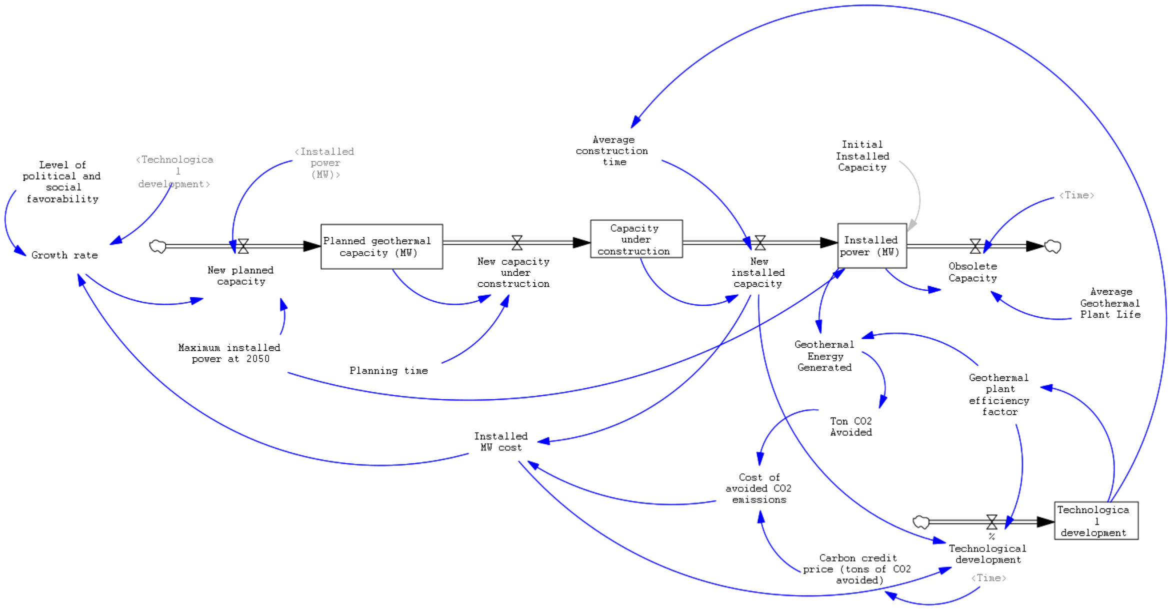


Figure 1. Model to evaluate the integration of geothermal energy into the Colombian market by 2050

2.1. Growth rate

It represents an adaptive and conditional approach to modeling the growth rate of geothermal energy, taking into account important variables such as installation costs, levels of political and social acceptance, and technological developments. This approach reflects the complexity of the environment in which geothermal energy projects operate and provides a dynamic picture of how these factors interact to influence the expansion and development of geothermal energy. Each condition captured in the equation contains a specific set of conditions that can adjust the growth rate under different scenarios. The conditional relationship between installation costs and growth rates acknowledges that the productivity and adoption of geothermal energy are closely tied to economic considerations. Additionally, the inclusion of social and political factors highlights the importance of contextual and technical aspects for the sustainable expansion of energy sources. These values are determined by a study that analyzes the market size and share of geothermal energy trends and growth forecasts (2023-2028) [24].

2.2. Average life of geothermal plant

The estimated lifespan of a geothermal plant, whether at a domestic or large scale, is notably long. While exact values vary, heat pumps typically have a lifespan of 15 to 20 years, whereas large geothermal power plants are generally designed with an expected lifespan of around 30 years. However, it is common for many plants to exceed 60 years of operation, and those built recently demonstrate an extraordinary longevity of 80 to 100 years. This exceptional lifespan is attributed both to the accumulated experience in these technologies and the absence of combustion, which eliminates the risk of fires. Additionally, geothermal systems require relatively low maintenance, and components with shorter lifespans can be replaced at the end of their useful life. In this case, the maximum reference value is 25 years in the most promising scenario.

Equation (1) calculates the expected new planned capacity. It is the difference between the projected maximum installed capacity in 2050 and the current installed capacity, multiplied by the growth rate. This formula provides an estimate of the new capacity expected to be added over a given period, based on the difference between the maximum planned capacity and the current capacity and the expected growth rate. This equation not only quantifies the planned expansion in geothermal energy capacity but also integrates the dynamics of growth over time, allowing for more informed and strategic planning for the continuous development of this renewable energy source.

$$New\ planned\ cap. = \left(Max.\ Ins.Pow.\ at\ 2050 - Ins.Pow.\ (MW)\right) \times Growth\ rate \tag{1}$$

Once the new geothermal energy is planned, a scheduled construction period elapses before the final installation. Equation (2) introduces us to a crucial concept in the implementation of geothermal energy projects: the time lag between planning and the effective construction of the projected capacity. This specific model, which incorporates the "DELAY3" time delay function, provides us with a unique window to understand and address a unique reality in the development of geothermal infrastructure. By adopting a time lag approach, this time lag that separates the planning phase from the moment geothermal capacity is realized in construction is accurately captured. It is more than just a mathematical formula; it is a modeled representation of the complex and often unpredictable reality of geothermal projects.

$$New\ cap. under\ const. = DELAY3\left(\left(\frac{Geothermal\ plan.\ cap.(MW)}{Planned\ time}\right)\right) \tag{2}$$

Equation (3) allows for calculating the new installed capacity by dividing the capacity currently under construction by the average construction time. In simple terms, this formula provides an estimate of how much new capacity is expected to be added to the geothermal energy system based on the capacity currently under construction and the estimated average time to complete the construction. In short, it assesses how much additional capacity is expected to be added to the geothermal energy system during a time interval defined by the average construction time.

$$New\ ins. cap. = \frac{Cap. under\ construction\ (MW)}{Average\ const.time} \tag{3}$$

Equation (4) allows for estimating the effective contribution of geothermal energy to the system. It considers both the installed capacity and efficiency, which are fundamental elements for understanding the actual production of geothermal energy.

$$Generated\ Geoth. energy = Installed\ Pow.\ (MW) \times Geoth.\ eff. factor\ plant. \tag{4}$$

Equation (5) allows for calculating the percentage of technological development, which is fundamental for evaluating the effectiveness and efficiency of implementing new capacities in the geothermal energy sector. By adjusting the new installed capacity by the plant's efficiency and then dividing this figure by the cost per installed megawatt, the equation provides a clear perspective on how technological improvements are influencing the expansion of geothermal capacity. A higher percentage indicates that greater technological development is being achieved in geothermal energy generation, suggesting efficiency in implementation and possibly greater competitiveness in the energy landscape.

$$\%\ tech. develop. = \frac{New\ inst.cap.\ \times Geoth.eff.factor\ plant.}{MW\ inst.\ cost} \tag{5}$$

Equation (6) allows for calculating the tons of carbon dioxide (CO_2) avoided per megawatt-hour (MWh) of geothermal energy generated. It starts by multiplying the amount of geothermal energy generated by a specific factor, 0.16438 tons of CO_2/MWh, representing the CO_2 emissions that would have been produced if the electricity had been generated by the interconnected system's conventional power generation. This figure is then subtracted from the product of the amount of geothermal energy generated and another factor, 0.091 tons of CO_2/MWh, representing the emissions avoided by using geothermal energy instead of conventional sources. The subtraction of these terms provides the net amount of CO_2 avoided. In summary, the equation precisely quantifies the positive environmental impact of using geothermal energy by calculating the CO_2 emissions avoided per unit of energy generated.

$$CO_2\ avoided\ Tons \times MWh\ = \\ (Geoth. gen. energy \times 0.16438) - (Geoth. gen. energy \times 0.091) \tag{6}$$

3. RESULTS AND DISCUSSION

Figure 2(a) shows the behavior of planned geothermal capacity under different scenarios, highlighting notable variations based on external conditions (political, social, economic, and growth rate). In the most favorable scenario, known as "Green democracy," optimal results are evident due to favorable political, social, and economic conditions, along with a favorable growth rate for this technology. The planned geothermal capacity shows accelerated growth, reaching its peak in 2046 with a projected capacity of 511 MW. In contrast, the least favorable scenario, called "House on Fire," reveals more limited development, with a maximum planned capacity of 64 MW that remains constant over time. These contrasts clearly illustrate the critical influence of external conditions on the planning and development of geothermal capacity, underscoring the importance of considering multidisciplinary factors in strategic decision-making in the energy sector.

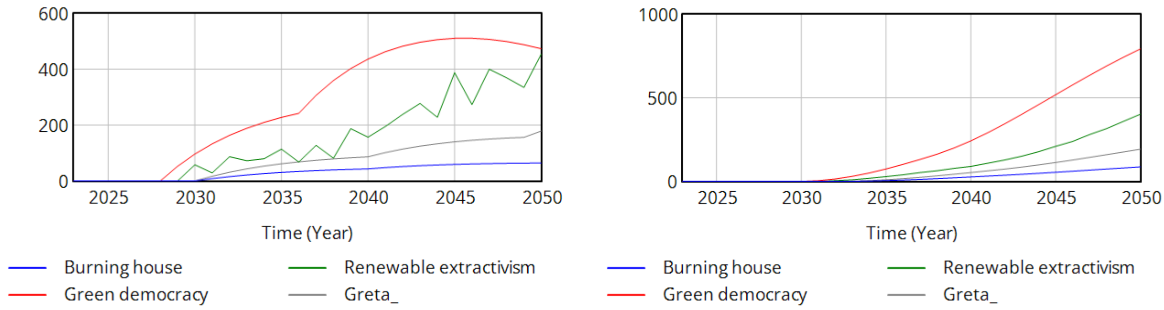
A greater planned capacity results in a higher construction capacity, as seen in Figure 2(b), where the same behavior is observed for the “Green democracy” and “House on Fire” scenarios. Here, a different behavior is presented for “Renewable Extractivism,” where some variations, rises, and falls can be seen. The fact that the curves for “Renewable Extractivism” show abrupt changes demonstrates that political stability and the continuity of government policies are crucial elements for the development and consolidation of renewable energy sources. The uncertainty generated by political changes can result in unstable decisions regarding the implementation of renewable technologies, highlighting the importance of considering not only technical but also political factors when planning the transition to a more sustainable energy model. This is clearly evident in the case of geothermal energy in Colombia. The lack of continuity in government policies and programs has hindered the advancement of this technology. Initiatives implemented during certain periods have suffered interruptions or changes in direction with changes in government, generating uncertainty and making it difficult to attract large-scale investments in geothermal projects.

Figure 3(a) shows the installed geothermal power by 2050 for the 4 scenarios analyzed: The installed capacity is closely related to what is observed in Figures 2(b) and 3(a), where greater planning and installed capacity also correspond to higher installed power. In this context, the most promising scenario is the “Green democracy” with 793 MW of installed power. However, for a complete understanding of the situation, it is essential to compare these results with the projections established by the Unidad de Planeación Minero Energética (UPME in Spanish), which introduces geothermal energy as a significant source with an installed capacity of 937 MW. The similarity between the results obtained in the “Green democracy” scenario and the UPME projections highlights the robustness and reliability of the proposed model. This congruence could indicate a convergence of approaches and strategies between the model used and the government's projections, providing a solid basis for decision-making. The proximity of the results obtained to the UPME projections not only supports the effectiveness of the model but also suggests that strategic planning based on models can be a valuable tool for guiding energy policy decisions and investment in the sector.

Figures 3(b) and 4(a) show the technological development of geothermal power and its installed MW cost by 2050 for the 4 scenarios analyzed. Technological development and the cost of installed MW are directly related. On one hand, lower costs lead to an increase in technological development, and similarly, greater technological development results in reduced costs. The most promising scenario in terms of technological development and low costs is the “Green democracy” scenario because, as mentioned, it is the ideal scenario where the maximum potential of this technology can be realized, and all conditions are favorable for this to happen, achieving an installed MW cost of 5.16 million USD. This direct relationship between technological development and costs is due to innovations and advancements in technology that optimize processes, improving efficiency and reducing production, installation, and maintenance costs. As more resources are invested in research and development, new techniques and cheaper, more durable materials are discovered, which in turn further drives technological development by making the technology more accessible and cost-effective. It is a virtuous circle where technological progress and cost reduction feed into each other, creating an environment conducive to the widespread adoption of geothermal technology.

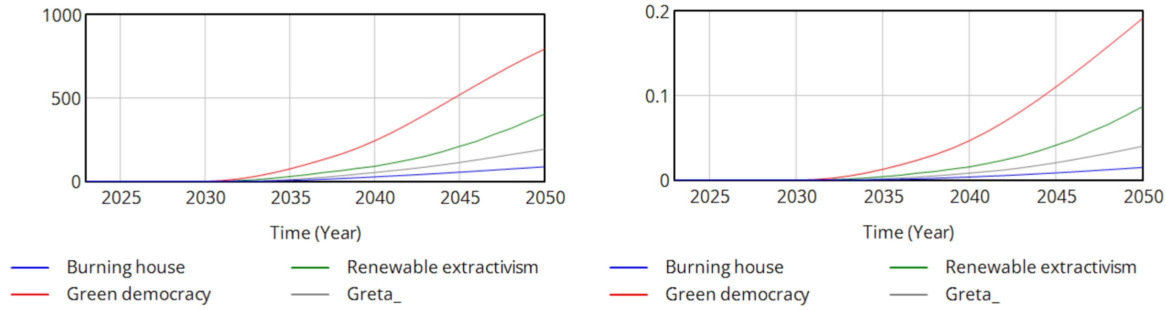
The significant reduction of 58.2 tons of CO_2 per megawatt-hour in the best-case scenario underscores its crucial role in mitigating the environmental impacts associated with electricity production. This value not only demonstrates the effectiveness of geothermal generation in reducing greenhouse gas emissions but also highlights its direct contribution to combating climate change. By opting for this renewable source, Colombia is not only advancing towards the decarbonization of its energy matrix but also setting an inspiring example for other nations seeking cleaner and more sustainable ways to generate electricity. Moreover, geothermal generation is notable not just for its positive environmental impact but also for offering a constant and reliable energy source, independent of weather conditions. This stability in electricity production helps strengthen the country's energy security, reducing dependence on more variable and volatile sources.

Figure 4(b) shows the tons of CO_2 per MWh avoided by 2050 for the 4 scenarios proposed. The system dynamics model revealed that while geothermal energy has significant potential to contribute to Colombia's renewable energy mix by 2050, it remains underutilized compared to other renewable sources like hydropower and solar energy [25], [26]. This underutilization is largely due to the high initial costs, regulatory challenges, and the absence of a comprehensive national strategy. By comparing these challenges with countries that have successfully integrated geothermal energy, such as Iceland [27] and Indonesia [28], it becomes clear that targeted policy reforms, financial incentives, and public-private partnerships are critical enablers [29]–[33]. For instance, Indonesia's success in geothermal development was driven by substantial government investment and the establishment of clear regulatory frameworks that attracted private investment [34].



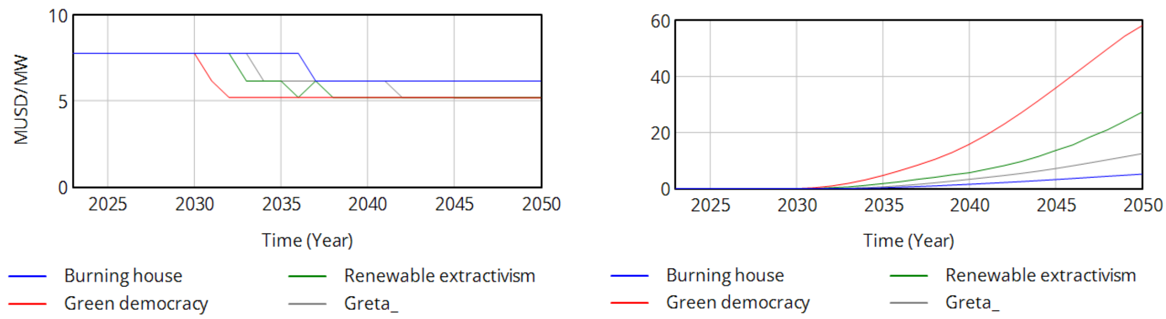
(a) (b)

Figure 2. Projections of (a) planned geothermal capacity and (b) capacity under construction by 2050 for the 4 scenarios



(a) (b)

Figure 3. Projections of (a) installed geothermal power and (b) technological development by 2050 for the 4 scenarios



(a) (b)

Figure 4. Projections of (a) installed MW and (b) tons of CO_2/MWh avoided by 2050 for the 4 scenarios

The findings suggest that without significant policy and investment shifts, geothermal energy in Colombia may continue to lag behind, potentially compromising the country's ability to meet its 2050 energy transition goals. However, if Colombia adopts a more proactive approach, including the implementation of favorable policies, increased investment in geological surveys, and the reuse of existing oil and gas infrastructure for geothermal purposes, the country could unlock substantial geothermal potential. This would not only diversify Colombia's energy mix but also enhance energy security and reduce greenhouse gas emissions.

In the future, the development of geothermal technology in Colombia could serve as a blueprint for other Latin American countries with similar geothermal potential [35]. Additionally, the integration of advanced modeling techniques, such as machine learning and artificial intelligence, could refine system dynamics models, providing even more accurate predictions and helping to optimize geothermal development strategies. As Colombia progresses toward its 2050 energy goals, continuous monitoring, evaluation, and adaptation of these strategies will be crucial to overcoming challenges and maximizing the benefits of geothermal energy.

4. CONCLUSION

To achieve an installed capacity of 793 MW from geothermal energy by 2050 in the best possible scenario, it is essential to promote the development of geothermal resources in the country. However, it is important to acknowledge the uncertainties on this path towards the "Green democracy." Deep adjustments in the regulatory framework are required, but the effective implementation of policies that encourage investment and sustainability faces challenges and unexpected changes.

Modifying the regulatory framework to simplify permitting and licensing processes is a goal, but the certainty regarding the acceptance and application of these changes is variable. Establishing clear and specific regulations for geothermal energy is a fundamental step, but adaptability to future uncertain circumstances is crucial. Promoting transparency in regulatory procedures can create a conducive environment, although political and social developments might affect these efforts.

Introducing government policies that offer specific tax incentives for geothermal projects and preferential rates is a strategy. But their continuity and effectiveness depend on variable political and economic factors. Setting clear goals and objectives in national energy policies is fundamental. Although implementation can be affected by changes in administration and public opinion.

In the social sphere, considering the impact on local communities is essential, but public response and participation can be unpredictable. Implementing policies that encourage citizen participation and consultation is an objective, but social dynamics can change over time. Investing in education and outreach programs for local communities is valuable, but receptivity to these efforts may vary.

The inherent stability of geothermal energy is a strong point, but geological conditions may present unforeseen challenges. Staff training should focus not only on technical skills but also on social and regulatory aspects, although the rapid evolution of these dimensions can pose challenges. The findings of this research underscore the untapped potential of geothermal energy in Colombia and the critical role it can play in the country's energy transition by 2050. Through the system dynamics model, it becomes evident that while Colombia possesses significant geothermal resources, the current regulatory framework and lack of targeted government policies are major barriers to its development. The research suggests that revising these frameworks and introducing more robust incentives are essential steps to unlocking this potential. Moreover, proper social and environmental management, with active local community involvement, is crucial for the success of geothermal projects. These findings have broad implications for the field, highlighting the need for integrated approaches that consider technical, economic, regulatory, and social factors in energy planning. For the community, this research provides a pathway for achieving a more sustainable and diversified energy future. Future work should explore the scalability of these findings and apply the model to other regions with similar geothermal characteristics, potentially extending Colombia's experience to the broader Latin American context.

ACKNOWLEDGEMENTS

This work was supported by Universidad de Bogotá Jorge Tadeo Lozano.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Diego Alberto Carreño	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Isaac Dyner		✓				✓		✓	✓	✓	✓	✓		✓
Enrique Ángel Sanint	✓		✓	✓			✓			✓	✓		✓	
Andrés Julián Aristizábal	✓	✓			✓				✓	✓	✓	✓		

C	: **C**onceptualization	I	: **I**nvestigation	Vi	: **Vi**sualization
M	: **M**ethodology	R	: **R**esources	Su	: **Su**pervision
So	: **So**ftware	D	: **D**ata Curation	P	: **P**roject administration
Va	: **Va**lidation	O	: Writing - **O**riginal Draft	Fu	: **Fu**nding acquisition
Fo	: **Fo**rmal analysis	E	: Writing - Review & **E**diting		

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, AJA. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to certain restrictions.

REFERENCES

[1] S. I. Evangeline and S. Darwin, "The role of carbon dioxide in enhancing geothermal energy: A review of current developments and future potential," *Renewable and Sustainable Energy Reviews*, vol. 214, p. 115525, May 2025, doi: 10.1016/j.rser.2025.115525.

[2] M. D. Kumar, D. Himabindu, Y. N. V. Kumar, T. Mohana, R. Shashank, and B. V. Rajanna, "Efficiency enhancement in hybrid renewable energy system using polycrystalline silicon cell," *International Journal of Applied Power Engineering*, vol. 13, no. 3, pp. 679–686, Sep. 2024, doi: 10.11591/ijape.v13.i3.pp679-686.

[3] H. Chang, G. Kong, and H. Liu, "Estimation of the technical geothermal potential through energy piles at a small regional scale: A campus case study," *Energy*, vol. 320, p. 135290, Apr. 2025, doi: 10.1016/j.energy.2025.135290.

[4] J. W. Lund, G. W. Huttrer, and A. N. Toth, "Characteristics and trends in geothermal development and use, 1995 to 2020," *Geothermics*, vol. 105, p. 102522, Nov. 2022, doi: 10.1016/j.geothermics.2022.102522.

[5] A. C. Avci, O. Kaygusuz, and K. Kaygusuz, "Geothermal energy for sustainable development," *Journal of Engineering Research and Applied Science*, vol. 9, no. 1, pp. 1414–1426, 2020.

[6] J. Lewandowska - Śmierzchalska and B. Uliasz - Misiak, "Assessment of potential sites for simultaneous exploitation of geothermal energy and CO2 storage in aquifers: Multi-criteria approach," *Renewable Energy*, vol. 226, p. 120449, May 2024, doi: 10.1016/j.renene.2024.120449.

[7] N. A. Pambudi and D. K. Ulfa, "The geothermal energy landscape in Indonesia: A comprehensive 2023 update on power generation, policies, risks, phase and the role of education," *Renewable and Sustainable Energy Reviews*, vol. 189, p. 114008, Jan. 2024, doi: 10.1016/j.rser.2023.114008.

[8] Y. Aryanfar, J. L. García Alcaraz, J. Blanco Fernandez, H. Köten, and M. M. Awad, "Comprehensive investigation on the geothermal energy sector in Mexico," *CTyF - Ciencia, Tecnologia y Futuro*, vol. 13, no. 1, pp. 43–55, Jun. 2023, doi: 10.29047/01225383.665.

[9] C. Granados, M. Castañeda, S. Zapata, F. Mesa, and A. J. Aristizábal, "Feasibility analysis for the integration of solar photovoltaic technology to the Colombian residential sector through system dynamics modeling," *Energy Reports*, vol. 8, pp. 2389–2400, Nov. 2022, doi: 10.1016/j.egyr.2022.01.154.

[10] G. Kılınç *et al.*, "Assessing Seferihisar-İzmir (Türkiye) geothermal energy prospects through marine seismic and field geology data modelling," *Geothermics*, vol. 129, p. 103295, Jun. 2025, doi: 10.1016/j.geothermics.2025.103295.

[11] M. Castaneda, S. Zapata, and A. Aristizabal, "Assessing the effect of incentive policies on residential PV investments in Colombia," *Energies*, vol. 11, no. 10, p. 2614, Oct. 2018, doi: 10.3390/en11102614.

[12] F. Taghizadeh-Hesary *et al.*, "Role of energy finance in geothermal power development in Japan," *International Review of Economics and Finance*, vol. 70, pp. 398–412, Nov. 2020, doi: 10.1016/j.iref.2020.06.011.

[13] Y. Komori, A. Kioka, and M. Nakagawa, "Predictive model for history matching of social acceptance in geothermal energy projects," *Renewable Energy Focus*, vol. 45, pp. 192–200, Jun. 2023, doi: 10.1016/j.ref.2023.04.003.

[14] J. M. R. Jones and T. G. Kretzschmar, "The Mexican Center of Innovation in Geothermal Energy, CeMIE-Geo: challenges and opportunities," *Procedia Earth and Planetary Science*, vol. 17, pp. 905–908, 2017, doi: 10.1016/j.proeps.2017.01.013.

[15] C. M. Nkinyam, C. O. Ujah, C. O. Asadu, and D. V. V Kallon, "Exploring geothermal energy as a sustainable source of energy: a systemic review," *Unconventional Resources*, p. 100149, Feb. 2025, doi: 10.1016/j.uncres.2025.100149.

[16] A. Roos, "Renewing the subterranean energy regime? How petroculture obscures the materiality of deep geothermal energy technology in Sweden," *Ecological Economics*, vol. 219, p. 108129, May 2024, doi: 10.1016/j.ecolecon.2024.108129.

[17] H. Oh, S. Akar, K. Beckers, E. Bonnema, C. Vivas, and S. Salehi, "Techno-economic feasibility of geothermal energy production using inactive oil and gas wells for district heating and cooling systems in Tuttle, Oklahoma," *Energy Conversion and Management*, vol. 308, p. 118390, May 2024, doi: 10.1016/j.enconman.2024.118390.

[18] R. Archer, "Geothermal energy," in *Future Energy: Improved, Sustainable and Clean Options for Our Planet*, Elsevier, 2020, pp. 431–445. doi: 10.1016/B978-0-08-102886-5.00020-7.

[19] R. Ashena, "Analysis of some case studies and a recommended idea for geothermal energy production from retrofitted abandoned oil and gas wells," *Geothermics*, vol. 108, p. 102634, Feb. 2023, doi: 10.1016/j.geothermics.2022.102634.

[20] L. Santos, A. Dahi Taleghani, and D. Elsworth, "Repurposing abandoned wells for geothermal energy: Current status and future prospects," *Renewable Energy*, vol. 194, pp. 1288–1302, Jul. 2022, doi: 10.1016/j.renene.2022.05.138.

[21] M. F. Bin Alam *et al.*, "Assessing the factors influencing the adoption of geothermal energy to support the national grid in emerging economies: Implications for sustainability," *Sustainable Operations and Computers*, vol. 5, pp. 167–180, 2024, doi: 10.1016/j.susoc.2024.03.001.

[22] K. Wang, J. Liu, and X. Wu, "Downhole geothermal power generation in oil and gas wells," *Geothermics*, vol. 76, pp. 141–148, Nov. 2018, doi: 10.1016/j.geothermics.2018.07.005.

[23] K. Nadkarni, L. M. Lefsrud, D. Schiffner, and J. Banks, "Converting oil wells to geothermal resources: Roadmaps and roadblocks for energy transformation," *Energy Policy*, vol. 161, p. 112705, Feb. 2022, doi: 10.1016/j.enpol.2021.112705.

[24] "Geothermal energy market size and share analysis - Industry research report - Growth trends," *Mordorintelligence*, 2023. Accessed: Aug. 21, 2024. [Online]. Available: https://www.mordorintelligence.com/es/industry-reports/geothermal-energy-market

[25] S. Toledo-Cortés, J. S. Lara, Á. Zambrano, F. A. G. Osorio, and J. R. García, "Characterization of electricity demand based on energy consumption data from Colombia," *International Journal of Electrical and Computer Engineering*, vol. 13, no. 5, pp. 4798–4809, Oct. 2023, doi: 10.11591/ijece.v13i5.pp4798-4809.

[26] S. Inac and A. Midilli, "On geothermal and wind energy integrated methanol production by using green hydrogen," *Energy*, vol. 318, p. 134712, Mar. 2025, doi: 10.1016/j.energy.2025.134712.

[27] R. Shortall, B. Davidsdottir, and G. Axelsson, "A sustainability assessment framework for geothermal energy projects: Development in Iceland, New Zealand and Kenya," *Renewable and Sustainable Energy Reviews*, vol. 50, pp. 372–407, Oct. 2015, doi: 10.1016/j.rser.2015.04.175.

[28] M. A. Raza, M. A. Al-Khasawneh, Y. Z. Alharthi, M. Faheem, R. Haider, and L. Kumar, "Power generation expansion planning with high penetration of geothermal energy – Potential, prospects and policy," *Environmental and Sustainability Indicators*, vol. 26, p. 100614, Jun. 2025, doi: 10.1016/j.indic.2025.100614.

[29] F. H. Ouerghi, M. Omri, K. S. Nisar, R. M. Abd El-Aziz, and A. I. Taloba, "Investigating the potential of geothermal energy as a sustainable replacement for fossil fuels in commercial buildings," *Alexandria Engineering Journal*, vol. 97, pp. 215–229, Jun. 2024, doi: 10.1016/j.aej.2024.03.094.

[30] G. M. Idroes, I. Hardi, I. S. Hilal, R. T. Utami, T. R. Noviandy, and R. Idroes, "Economic growth and environmental impact: Assessing the role of geothermal energy in developing and developed countries," *Innovation and Green Development*, vol. 3, no. 3, p. 100144, Sep. 2024, doi: 10.1016/j.igd.2024.100144.

[31] M. A. Kassem, A. Moscariello, and P. Hollmuller, "Navigating risk in geothermal energy projects: a systematic literature review," *Energy Reports*, vol. 13, pp. 696–712, Jun. 2025, doi: 10.1016/j.egyr.2024.12.052.

[32] C. Yilmaz and S. A. Korkmaz, "Life cycle cost assessment of geothermal energy assisted hydrogen liquefaction for sustainable and renewable energy applications: Case study and adaptation for Afyon geothermal power plant," *International Journal of Hydrogen Energy*, vol. 72, pp. 772–788, Jun. 2024, doi: 10.1016/j.ijhydene.2024.05.417.

[33] H. Duan, D. Ma, L. Zou, S. Xie, and Y. Liu, "Co-exploitation of coal and geothermal energy through water-conducting structures: Improving extraction efficiency of geothermal well," *Renewable Energy*, vol. 228, p. 120666, Jul. 2024, doi: 10.1016/j.renene.2024.120666.

[34] N. A. Pambudi and D. K. Ulfa, "The geothermal energy landscape in Indonesia: A comprehensive 2023 update on power generation, policies, risks, phase and the role of educationnn," *Renewable and Sustainable Energy Reviews*, vol. 189, p. 114008, Jan. 2024, doi: 10.1016/j.rser.2023.114008.

[35] A. S. Oyewo, A. Aghahosseini, M. M. Movsessian, and C. Breyer, "A novel geothermal-PV led energy system analysis on the case of the central American countries Guatemala, Honduras, and Costa Rica," *Renewable Energy*, vol. 221, p. 119859, Feb. 2024, doi: 10.1016/j.renene.2023.119859.

BIOGRAPHIES OF AUTHORS

Diego Alberto Carreño is an automation engineer and holds a master's degree in sustainable energy management engineering from Universidad Jorge Tadeo Lozano. His research areas include programming, power and circuits, automation, control systems, renewable energies, geothermal power, and modeling through system dynamics. He provides consultancy for major automation companies, manufacturers and other industry bodies in his field of expertise. He can be contacted at email: diegoa.carreñob@utadeo.edu.co.

Isaac Dyner Dean of the Faculty of Natural Sciences and Engineering at Universidad Jorge Tadeo Lozano (2013-2023), holds a Ph.D. in decision sciences from the University of London (LBS); with a master's degree in statistics and operational research and an undergraduate degree in mathematics. He has been a professor at the National University of Colombia in the areas of operational research, system dynamics, strategy, regulation, and energy. He was the director of the center for basic and applied interdisciplinary Studies in Complexity (CEIBA) and the Institutes of Energy and Decision Sciences at the National University of Colombia, whose groups have been accredited by Colciencias in the highest category. He was also the director of the postgraduate program in systems and the mathematics program; in addition to having served as the interim vice-rector of research and resources at the same university. His main research interest has focused on energy policy and regulation, energy markets, corporate strategy, emissions reduction policy, scenario planning, modeling, simulation, and the role of energy in development. He has over 175 publications, including international conference proceedings, books, and refereed journals such as the journal of the operational research society, system dynamics review, and energy policy, among others, in which he has presented his insights on energy and operational research. He can be contacted at email: isaac.dyner@utadeo.edu.co.

Enrique Ángel Sanint is a civil engineer and holds a master's degree in hydraulic resources management from the Universidad Nacional de Colombia. He also holds a master's degree in science from the University of California. He has served as director of Electrical Interconnection ISA in Medellin, Colombia (1994-1995; 2005-2013), director of Isagen in Medellin, Colombia (1995-1997), and as a professor at the National University of Colombia (1998-present). Currently, he is a professor of Environmental Engineering at EIA University, and leader of the Poleka Kasue Research Group, which focuses on understanding the impact of climate change in Colombia. His areas of interest include environmental management, wind energy, energy scenarios, climate change, quantitative methods, among others. He can be contacted at email: enrique.angel@eia.edu.co.

Andrés Julián Aristizábal received the Ph.D. degree in science – physics from Universidad Nacional de Colombia, Bogotá, Colombia, in 2008. He is currently the coordinator of the master in engineering - sustainable management of energy, at Universidad Jorge Tadeo Lozano, Bogotá, Colombia. He is the leader of the EADE research group. His areas of interest are photovoltaic solar energy, virtual instrumentation, power quality and sustainability. He can be contacted at email: andresj.aristizabalc@utadeo.edu.co.