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Multi-criteria analysis for energy planning in Ecuador: Enhancing decision-making through comprehensive evaluation

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ABSTRACT

The growing demand for electricity and the need to mitigate climate change drive the development of renewable energy projects. In some cases, their implementation has led to socio-environmental conflicts. The planning of power plants generally prioritizes technical and economic criteria, while socio-environmental aspects and the involvement of local stakeholders remain limited. In Ecuador, the construction of hydroelectric plants has increased generation capacity but has also triggered conflicts in nearby areas. This study aimed to integrate diverse criteria and stakeholders into Ecuador's energy infrastructure planning process. A multi-criteria decision analysis (MCDA) was conducted on a portfolio of 101 renewable energy projects planned for the coming years, including 91 hydroelectric, 2 solar photovoltaic, 3 wind, and 5 geothermal projects, with a total capacity of 12,532.45 MW. Nine criteria were analyzed and organized into social, environmental, and technical categories. Social criteria included project perception, job creation, and relocation; environmental criteria covered deforestation, risks to wildlife, and proximity to natural reserves; and technical criteria included plant size, accessibility, and distance to transmission lines. The analysis involved four stakeholder groups—academia, public sector, private sector, and civil society—who expressed their preferences across criteria to ultimately rank the projects from best to worst using the PROMETHEE method. Results showed that energy project planning prioritizes social and environmental criteria over technical ones. Thus, 55 projects (49 hydroelectric, one geothermal, two solar photovoltaic, and three wind) were selected for future construction. In comparison, 42 hydroelectric and four geothermal projects were excluded due to potential impacts on wildlife and forests near protected areas. The methodology suggests that decision-makers should incorporate a multidisciplinary, inclusive, and participatory approach when planning energy infrastructure to ensure it is environmentally sustainable and socially acceptable.

1. Introduction

The energy transition refers to the global shift in energy production and consumption from conventional sources, such as fossil fuels, to cleaner, renewable sources. This shift is essential for addressing climate change, as it significantly reduces greenhouse gas emissions that drive global warming and extreme weather events. Within this framework, Ecuador has committed to the energy transition through the "Energy Matrix Change" project, initiated in 2008. The project aims to have an electricity generation mix based on renewable sources, primarily focused on hydropower, to reduce dependence on fossil fuels.

Fig. 1. illustrates the evolution of Ecuador's electricity generation installed capacity over the past 24 years. Historically, thermal power from fossil fuels and hydropower have been the primary sources of electricity. However, in 2016, due to the Energy Matrix Change initiative, installed hydropower capacity surpassed thermal capacity, driven by major hydroelectric plants like the 1500 MW Coca Codo Sinclair and the 486 MW Sopladora facilities. Since then, hydropower has become Ecuador's main electricity source, while growth in installed capacity has stagnated since 2018.

In 2023, total electricity generation plus imported electricity reached 36,683 GWh. As shown in Fig. 2, hydropower accounted

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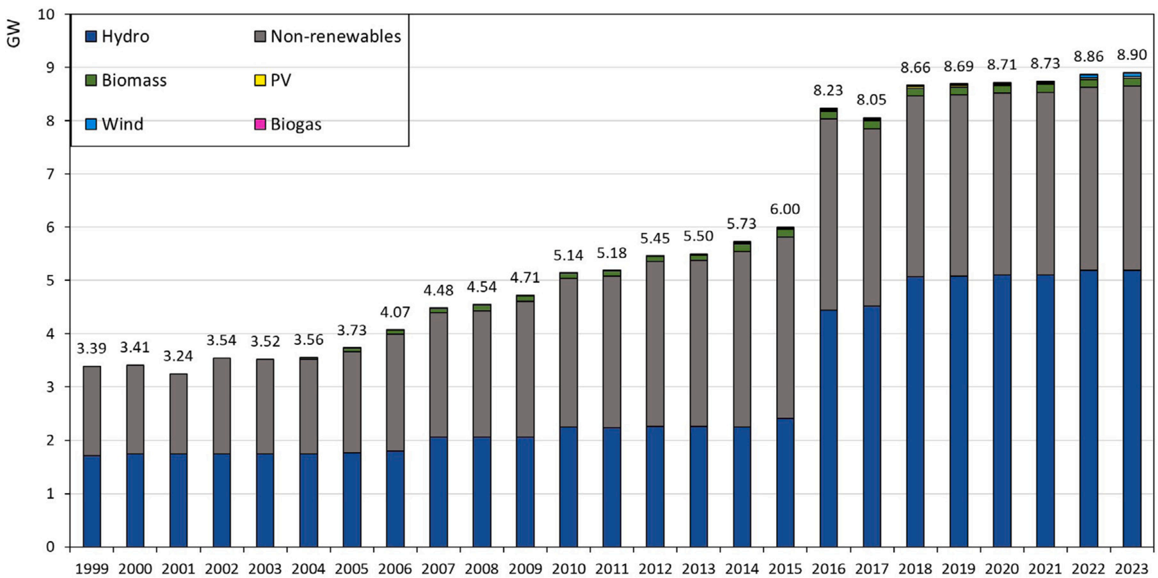


Fig. 1. Evolution of installed capacity for electricity generation from 1999 to 2023.

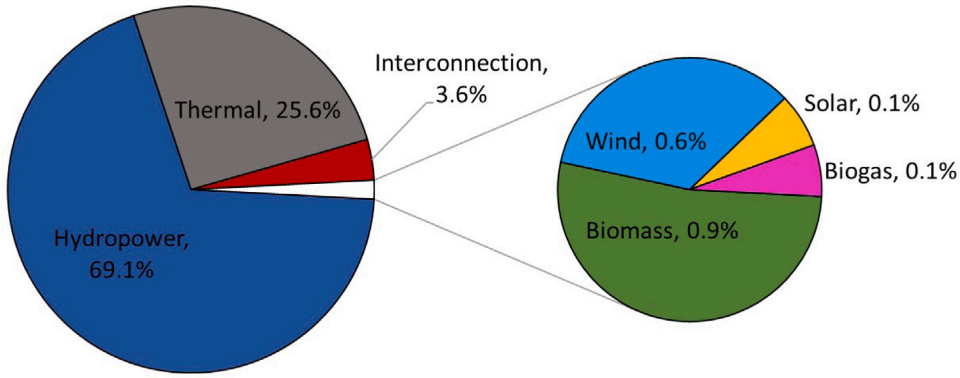


Fig. 2. Electricity generation share in 2023.

for 69.1% of the total, followed by thermal power at 25.6%, with other renewable sources, including solar, wind, biomass, and biogas, collectively contributing 1.7%, and 3.6% corresponding to imported electricity [1–4]. This energy mix reflects Ecuador's high dependence on hydroelectric power, which is further affected by the limited investment in electricity infrastructure in the last five years and added to the severe droughts this year, which have caused power outages of up to 14 h a day in the last months of 2024. This situation highlights the vulnerability of the Ecuadorian electricity system, which lacks diversification and relies heavily on a single resource.

Despite the dependency on hydropower, Ecuador's Electrification Master Plan (PME) prioritizes expanding hydropower capacity through 91 projects with a total capacity of 11,282.45 MW. The PME's extension outlines a four-year initiative to add 1440 MW from solar, wind, biomass, and small hydro sources [5–8]. However, this ambitious hydropower expansion faces challenges, including potential climate change impacts on water resources and social opposition to hydroelectric plants.

Documentation on socio-environmental conflicts related to hydroelectric power plants in Ecuador remains limited. However, the following section presents identified conflicts based on interviews conducted since 2014, supplemented by data from news articles, academic theses, and online platforms documenting resident protests in affected areas.

1.1. Socio-environmental conflicts arising from hydroelectric power plants in Ecuador

Jaime Roldós Aguilera project, located at the confluence of the Daule and Peripa rivers in Ecuador, is a multipurpose infrastructure development that includes a 130 MW hydroelectric power plant, along with water supply, irrigation, and flood control systems. The project has generated controversy due to significant environmental and social impacts, particularly the flooding of 27,000 hectares of protected forests and farmland. This led to the displacement of approximately 15,000 people and the isolation of an additional 100,000, who now live in poverty along the reservoir's fringes. In response, affected communities organized in 2004 to seek compensation from the Ecuadorian government for these impacts [9].

San José del Tambo hydroelectric power plant, an 8 MW run-of-river project in the Dulcepamba River basin, has faced opposition from local communities. Protests erupted between 2006 and 2007, involving confrontations between approximately 300 soldiers and residents of 72 communities, leading to 22 legal cases and the arrest of 14 community leaders on charges of rebellion. The nearby San Pablo de Amalícommunity claims that the project depletes the Dulcepamba River's water, affecting availability for consumption, agriculture, and ecosystem sustainability. The community also attributes recent floods and landslides, including a deadly 2015 flood that claimed three lives and destroyed 12 homes, to the project. A 2020 study by Ikiam University researchers found that human activities, not natural causes, had altered the riverbed over nearly 3 kilometers, disrupting fish migration from the coast to the Andes. While Hidrotambo maintains it follows environmental regulations and asserts support from some local groups, it claims that accusations against the project are unsubstantiated and emphasizes its national importance for power generation [9,10].

Baba multipurpose project includes a 42 MW hydroelectric plant and a 1100-hectare reservoir with four dikes and a spillway. Over 30 communities have opposed the project, reporting that the reservoir has caused crop damage and the displacement of approximately 1500 residents. Locals assert that the dam construction altered the Baba River's course, significantly reducing fish stocks, which previously provided food and income. Remaining residents face limited access to clean water; a company-installed well provides only cloudy water, which has been unsatisfactory. Despite these unresolved issues, the Baba hydropower plant continues to operate [9,11,12].

Hidroabanico, a 37.5 MW run-of-river hydroelectric plant in southeastern Ecuador, was constructed in two phases. The initial phase altered the flow of the Balaquepe and Jurumbaino Rivers, affecting local water availability, as reported by the Jimbotono community. Opposition intensified in 2006 when a mining company proposed using Hidroabanico to power its nearby mining projects. This led to a five-day strike in August, violent confrontations in October, and the occupation of mining camps in November. After 75 days of protests, the Ecuadorian government initiated dialogue with local communities and organizations, though the project's second phase was ultimately completed, and Hidroabanico remains operational [9,13,14].

Agoyán, San Francisco, and Topo hydroelectric plants (156 MW, 230 MW, and 29.2 MW) are located close to each other in Baños Canton. Agoyán has a reservoir of 1.8 million cubic meters, and its discharged water is captured by San Francisco, which also collects water from nearby springs. Baños residents report these plants' construction and operation have diminished local water resources, impacting tourism—a key economic sector. Environmental assessments indicate multiple adverse effects: loss of the Agoyán waterfall, a 1 km reduction in the Pastaza River, and water quality deterioration in the reservoir, which has introduced foul odors, insect infestations, and recurrent health issues. Soil erosion and geological instability in nearby areas have also been documented, alongside air pollution and altered local climate and ecosystems. Despite community objections, the Topo plant near Baños was licensed in 2005. However, the Tungurahua Provincial Tourism Chamber filed a constitutional lawsuit in 2006, citing flaws in the Environmental Impact Assessment, including risks to endemic species and local biodiversity. As a result, the Ministry of the Environment temporarily suspended Topo's license pending further environmental studies and citizen input. Although these impacts persist, the plants remain operational at present [15,16].

The 30 MW *Piatúa* hydroelectric plant, located on the Piatúa River between Pastaza and Napo provinces, faces significant opposition from the local Kichwa indigenous community and environmental experts. The project lies in an ecologically critical corridor linking Llanganates and Sangay National Parks, home to endemic species and serving as a key biodiversity zone between the Andes and the Amazon. Since 2014, the Kichwa have raised concerns over environmental damage, cultural impact, and economic loss. The Ministry of Environment, however, approved the Environmental Impact Assessment (EIA) submitted by the construction company, despite Kichwa's claims of inadequate consultation and insufficient disclosure on the project's scale. Experts reviewing the EIA found deficiencies in areas including amphibian impact, environmental management, and geological risk, with an elevated threat of alluvial instability at the planned diversion site. In 2019, the Kichwa filed a legal petition to halt construction, presenting multidisciplinary technical reports. Initially denied, a second judge later validated their claims of socio-environmental risks and suspended the project. Construction remains halted while the construction company maintains compliance with regulations and disputes the Kichwa's objections [17–19].

Downstream communities near the 1500 MW *Coca Codo Sinclair* hydropower plant have reported a marked decline in fish populations in the Tigre River since the plant began operating in 2016, impacting their traditional reliance on local fish for food. The 22 MW *Yanuncay* hydroelectric project has faced opposition since 2022 from residents and activists who argue that the project threatens the upper Yanuncay River basin and lacks prior community consultation. Elecaustro, the company overseeing the Yanuncay project, disputes these claims and is seeking government support to proceed, though construction remains suspended [20–24].

Hydropower development in Ecuador has led to numerous socio-environmental conflicts, mainly due to insufficient consultation with nearby communities, misinformation, and a limited understanding of stakeholder needs. These challenges highlight the need for a holistic approach to power plant planning. Sustainable and equitable energy planning must consider multiple criteria and involve diverse stakeholders in decision-making. This study aims to explore two research questions within the context of Ecuador's power sector:

1. What criteria are most relevant in planning electricity generation projects to diversify the energy generation matrix while minimizing socio-environmental conflicts?

2. How does active stakeholder participation influence integrating environmental, technical, and social factors in electricity generation project planning?

To address these two questions, this project addressed a multi-criteria decision analysis on 101 proposed electricity generation projects, including 91 hydropower plants, two solar, three wind, and five geothermal projects. This analysis incorporated the participation of four stakeholder groups, who evaluated nine criteria across social, environmental, and technical[1] dimensions in the planning of power plants in Ecuador.

The following section presents studies integrating MCDA into energy planning and case studies involving Ecuador. The research gap in these studies was identified, highlighting the innovative aspects of the current work.

2. Related work

The application of Multi-Criteria Decision Analysis in energy planning has gained substantial attention, effectively addressing challenges and integrating diverse stakeholder perspectives across various scales. In Pakistan, [25] utilized the Analytic Hierarchy Process (AHP) methodology of Multi-Criteria Decision-Making (MCDM) to assess the sustainability of different energy scenarios, contributing valuable insights to long-term electricity planning. Similarly, [26] employed MCDA in Iran to assess existing power plants, emphasizing energy assurance and electricity supply. The study demonstrated the reliability of the VIKOR method in ranking alternatives based on environmental, technological, and economic criteria. In rural African communities, [27] proposed a hybrid model integrating AHP-VIKOR with the Plan-Do-Check-Act (PDCA) cycle for renewable energy installation planning, considering health effects, greenhouse gas emissions, and cost efficiency. In the context of electric supply planning for rural areas, [28] explored MCDA methods, employing a combination of AHP and VIKOR to evaluate different electric supply options comprehensively. [29] scrutinized the applicability of MCDA in assessing the sustainability of national-level

[1] This study does not include economic criteria in its analysis, as these are addressed in the second part to be published later, which presents an energy system model for Ecuador through 2050. This model will examine factors such as investment, maintenance, and fuel costs, in addition to incorporating the findings of this study.

renewable energy technologies, highlighting the need to address uncertainties. The study by [30] addressed the challenge of selecting optimal renewable energy alternatives for electricity generation in residential buildings using a fuzzy multi-criteria group decision-making method. This innovative approach integrated the Delphi method, a questionnaire, the Fuzzy Analytic Hierarchy Process, and the Fuzzy Preference Ranking Organization Method for Enrichment Evaluation for robust and reliable decision-making in residential energy planning. [31] investigated the opposition and protests faced by wind energy projects in European countries. The study utilized qualitative (Focus Group) and quantitative (Optimized-Analytic Hierarchy Process and Monte Carlo simulation) approaches to assess the social acceptance of wind energy, revealing critical attitudes and providing insights for regulatory strategies.

Additionally, [32] introduced an integrated assessment framework that merges dynamic systems modeling, sustainability indicators, and multi-criteria decision analysis with active stakeholder engagement. It evaluates various climate policy bundles aimed at decarbonizing Iceland's road transport sector, highlighting the importance of diverse sustainability themes in guiding effective energy transition decisions. Finally, the works proposed by Dash et al. [33] and Fotis et al. (FLEXITRANSTORE project [34]) lie in their unique approaches to addressing challenges in sustainable energy and smart grid innovation. Dash et al. [33] stand out by integrating Multiple-Criteria Decision-Making with Self-Organizing Maps (SOM) to create a comprehensive framework for evaluating power plants. This integration enables a novel visualization of performance patterns, enhancing decision-making for optimal plant selection. In contrast, the FLEXITRANSTORE project [34] focuses on the practical scalability and replicability of renewable energy technologies, emphasizing regulatory, economic, and stakeholder challenges for integrating Battery Energy Storage Systems (BESS) into smart grids. Compared to earlier studies leveraging MCDM methods such as AHP-VIKOR [25–30] or dynamic modeling [32], these works present advanced applications tailored to distinct aspects of energy transition, offering actionable insights for global energy policy and innovation. In the Ecuadorian case, [35] presents a GIS-based approach combined with Multi-criteria Evaluation through the Analytic Hierarchy Process to identify sites for photovoltaic solar power plants in Azuay Province. Additionally, the study integrates economic, technical, and environmental criteria through host capacity and impact models. However, the article needs to address potential limitations such as stakeholder bias, the dynamic nature of social and environmental impacts over time, or the integration of local community feedback, which could significantly influence the effectiveness and acceptance of renewable energy projects in Ecuador. In a different study, [36] addressed the aspect of optimal site selection for photovoltaic plants. The study emphasized the impact of electric demand requirements and spatial distribution on solar photovoltaic (PV) integration, utilizing a geographic information system and multi-criteria decision analysis. Nevertheless, this work does not address potential social and risk criteria, such as community displacement or cultural impacts, which are crucial in energy infrastructure planning. Additionally, it lacks a comprehensive stakeholder engagement process, potentially overlooking diverse perspectives and local knowledge in decision-making.

In a related investigation, [37] utilized MCDA to identify optimal wind farm locations in Ecuador, emphasizing the significance of Geographic Information System (GIS) and MCDA as tools for site selection. However, this study does not consider economic factors such as project financing, cost–benefit analysis, and long-term sustainability. Additionally, it does not address potential conflicts arising from stakeholder preferences or the dynamic nature of energy demand, which could impact the project's feasibility and prioritization. Finally, [38] proposes a multi-criteria decision analysis using GIS and the AHP technique to identify optimal locations for transfer stations in Azuay, Ecuador, enhancing Municipal Solid Waste management through holistic evaluation of technical, environmental, economic, and social factors. Also, this article does not address potential biases in stakeholder preferences. Additionally, it overlooks the impact of socio-political factors and community engagement in the planning process, which are crucial for success. This comparison highlights the importance of integrating diverse perspectives and adaptive strategies in similar studies.

The selection of the MCDA method must fit the characteristics of the decision problem at hand [39] e.g., problem statement, criteria structure, types of weights. In the context of sustainable energy planning, MCDA methods should have low compensation (good performance of an alternative in one criterion does not compensate for a lousy performance in another one), hierarchical criteria structure, handle qualitative and quantitative information, include preference information (weights and thresholds), involve stakeholders and manage uncertainty. Guiding principles in energy planning include understanding project objectives, identifying evaluation criteria, assessing data availability, involving stakeholders, reviewing the literature, seeking expert advice, evaluating transparency, considering available software and tools, balancing robustness and simplicity, and reflecting on available resources and timeline [40]. Adhering to these principles enables decision-makers to choose the most suitable MCDA method aligned with their objectives and stakeholder preferences while effectively addressing the complexities of energy planning.

This paper introduces a novel approach to energy planning in Ecuador by leveraging Multi-Criteria Decision Analysis to select optimal power generation plants from an existing portfolio. This work stands out from previous studies in Ecuador by addressing critical gaps identified in the literature, such as stakeholder bias, the dynamic nature of social and environmental impacts, and the lack of community engagement. Unlike conventional methods prioritizing technical and economic factors, this research integrates a broader range of social, environmental, and technical criteria into the decision-making process, involving four distinct stakeholder groups. This inclusive approach ensures a more balanced consideration of diverse perspectives, mitigating limitations often undermining planning processes.

This work contributes to advancing the current state of knowledge by providing a comprehensive framework that promotes sustainable and inclusive energy planning. This study addresses potential conflicts and promotes transparency in the decision-making process by emphasizing the equal importance of considering social and environmental dimensions and technical ones. Furthermore, the paper outlines actionable insights for Ecuadorian electricity sector authorities, drawing on lessons from previous experiences to enhance national energy strategies. This work bridges theoretical and practical gaps and establishes a replicable model for integrating diverse criteria and stakeholder inputs, thereby contributing to a more robust and socially responsible energy infrastructure planning paradigm.

3. Methodological approach

As this work aims to analyze a problem using multiple criteria and involving various stakeholders, the MCDA methodology is applied.

3.1. Multi-criteria decision analysis in the Ecuadorian case

Multi-Criteria Decision Analysis supports decision-making when multiple criteria must be considered. MCDA methods are widely used to address real-world challenges across various socio-economic areas, including water management, agriculture, tourism, energy, environmental protection, biodiversity conservation, and forestry [41]. The steps for implementing MCDA have been tailored to the Ecuadorian context and are illustrated in Fig. 3.

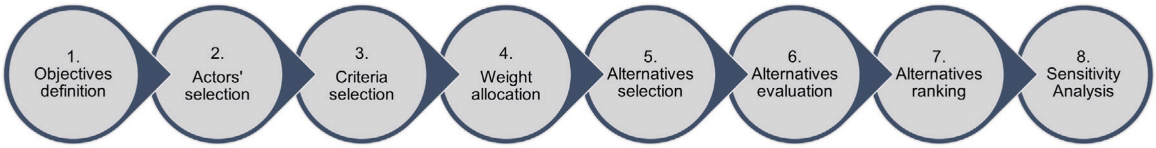


Fig. 3. Common steps for MCDA.

3.1.1. *Objectives definition*

The first step in the MCDA process is to define the study's objectives. The primary aim is to identify and promote strategies that enable the selection and planning of electricity generation projects that diversify Ecuador's energy matrix, minimize socio-environmental conflicts, and integrate environmental, technical, and social factors. The objective includes understanding methodologies to mitigate adverse environmental impacts and safeguarding the welfare of affected residents through inclusive stakeholder participation.

3.1.2. *Actors selection*

The second phase of the multi-criteria analysis involves the identification of actors and acknowledging their important role in the decision-making processes of energy planning. To select the actors who would participate in this MCDA, all relevant stakeholders (e.g., policymakers, private sector, Non-Governmental Organizations (NGOs), academia, and affected communities) were first identified based on the objectives of the study. Then, they were categorized by sectors or interests to ensure that all perspectives relevant to the decision context were included. Despite efforts to contact all identified actors, those from NGOs did not respond, and therefore, the analysis was conducted without their participation. In the end, four groups of actors were included, encompassing 40 individuals equally distributed across academia, civil society, the public sector, and the private sector.

Academia: The researchers selected for the MCDA comprise researchers from leading Ecuadorian universities who have academic experience and expertise in various aspects of the energy sector. Their work includes research on decarbonization in Latin America [42], energy modeling [43], renewable energy use [44–46], and lifecycle analysis [47], among other energy related topics. They are affiliated with university research groups, including CIENER, SCINERGY, and the Energy and Materials Institute. Through these networks, the academic stakeholders contribute scientific knowledge and perspectives to the MCDA process.

Civil society: Civil society actors include union leaders and representatives of indigenous communities from regions significantly affected by social and environmental impacts of hydropower plants, such as Baños, Pastaza, Napo, Coca, Santo Domingo de los Tsáchilas, and Macas. They provide local knowledge and experiential insights grounded in real-life encounters. Their advocacy for the rights and welfare of the community adds an ethical dimension to the MCDA process.

Public sector: Public sector actors representing key state institutions that make the decisions in the energy sector, such as The Ministry of Energy, CELEC E.P (Electric Corporation of Ecuador), and IGE (Institute for Geological and Energy Research), bring their expertise in energy policy, project management, and energy research-oriented perspectives.

Private sector: Private sector actors from 5 different private companies that build power plants in Ecuador bring practical experience in renewable energy projects, offering insights into technical, economic, and operational aspects.

3.1.3. *Criteria selection*

The criteria selection process for the multi-criteria analysis involved a literature review and expert interviews to identify relevant factors for energy planning in Ecuador. From global studies, criteria such as proximity to populations, transmission lines, capacity, and environmental considerations were considered. Interviews with experts in energy, social, and environmental fields refined the criteria, identifying four major groups: social, environmental, technical, and economic. Economic criteria were excluded from this MCDA, as they will be addressed in the optimization model stage, which is not part of this article. The chosen criteria were organized into three main groups, each with three sub-criteria, detailed in Table 1.

3.1.4. *Weight allocation*

The Analytic Hierarchy Process (AHP) was developed by Dr. Thomas L. Saaty [48] as a structured decision-making method designed to address complex problems involving multiple criteria and alternatives. AHP was chosen for this work because it allows stakeholders to express their preferences through pairwise comparisons, facilitating dialogue and supporting consensus-building on priorities and trade-offs, which can be measured by the tool, using a consensus indicator ranging from 0% (no consensus among decision-makers) to 100% (complete consensus among decision-makers). This method is widely used to determine relative weights for indicators in the energy sector [49,50] and to assess the sustainability of renewable energy systems based on multiple criteria [51].

Employing Saaty's scale [52], a numerical scale ranging from 1 to 9, the four groups of actors assigned scores indicating the relative importance of each criterion. This pairwise comparison process underwent a consistency check to ensure accuracy, and the obtained scores were used to calculate priority weights for each element. This study conducted a data collection process through online and on-site interviews with the 40 identified actors. Structured interviews conducted in 2020 and 2021, lasting 40 to 60 min, included briefing participants on the project's objectives, their role, expected outcomes, and a detailed explanation of each criterion. The two-part question format facilitated comparisons, asking stakeholders to assess the importance of one criterion over another and quantify the extent of the difference. The two-part question format is as follows:

According to your knowledge and expertise, which criterion is more important to consider when choosing between power generation projects, criterion A or criterion B? and to what extent is criterion A/B more important than criterion A/B.

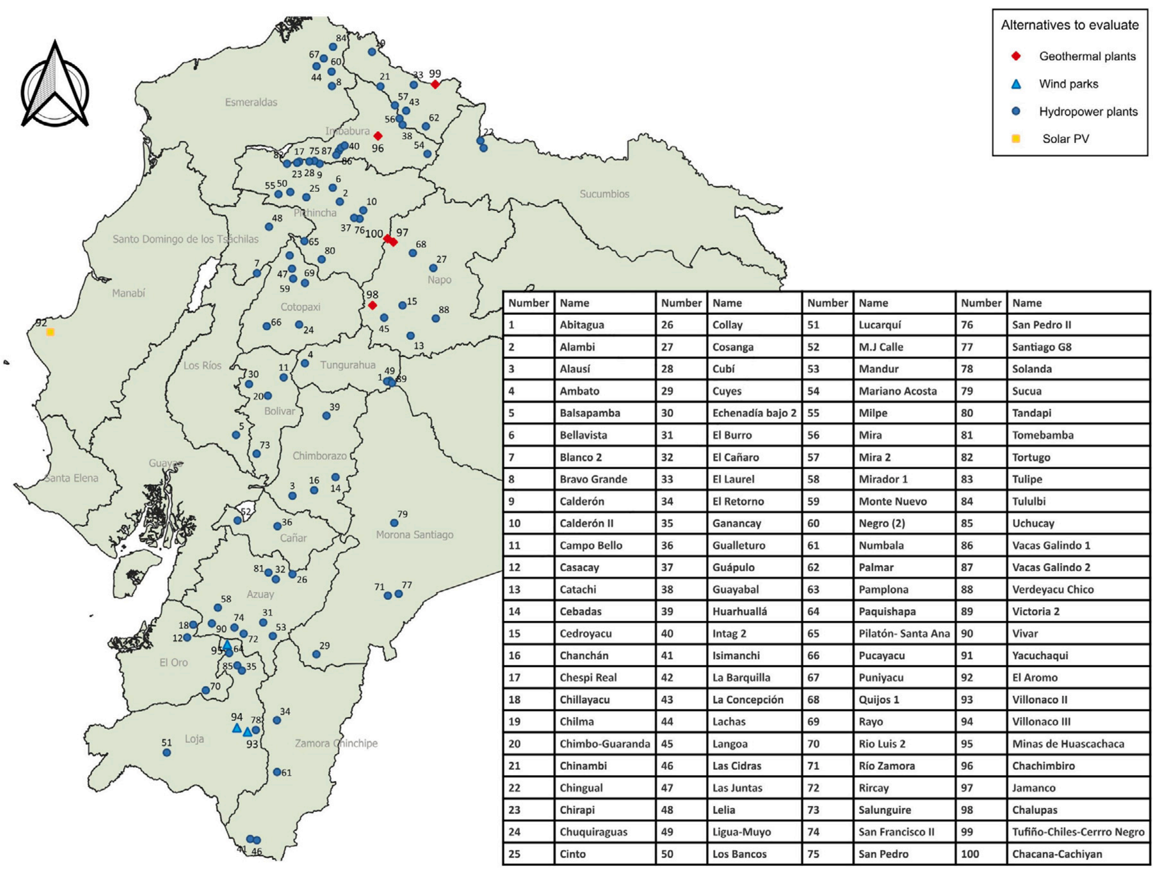
This study used a specialized AHP worksheet by Goepel (2018) to maintain consistency and minimize bias, available through [53]. This Excel-based tool streamlined the comparison process, providing a structured approach to capturing stakeholder preferences. The pairwise comparison procedure was applied consistently across all nine preselected sub-criteria to achieve a consistency ratio of at least 10%. The tool automatically calculates the consistency ratio, and in cases of inconsistency, responses were revisited and clarified during interviews to ensure harmonization and alignment of stakeholder inputs.

3.1.5. *Alternatives selection*

This step involves identifying future power generation projects in Ecuador. During the data collection for this study, renewable energy projects from the Master Electrification Plan of Ecuador [5], the country's official energy planning document, were considered. Additionally, this information was complemented by studies on Ecuador's hydropower potential, such as the one presented by [6]. It is worth noting that none of these sources included solar photovoltaic systems for residential rooftops in their analyses. For this reason, a pilot project of this type with a capacity of 3 kW was included.

Table 1
Selected criteria for MCDA in the context of Ecuador.

Criteria	Sub-criteria	Description
Social	Project perception	Visual, auditory and olfactory impact
	Job creation	Employability of the workforce
	Displacement or relocation of people	Change of location of settlements, communities, towns due to the construction and operation of power plants
Environmental	Deforestation	Tree removal from protected forest
	Proximity to Natural Reserves	How close is any power plant to Natural Parks, and Biosphere reserves
	Threat to fauna and wildlife	The power plant invades the natural habitat or migratory routes of the animals
Technical	Size	Installed capacity of the power plant
	Accessibility	Easy access to the power plant location
	Distance to transmission lines	Power plant proximity to transmission lines



Number	Name	Number	Name	Number	Name	Number	Name
1	Abitagua	26	Collay	51	Lucarquí	76	San Pedro II
2	Alambi	27	Cosanga	52	M.J Calle	77	Santiago G8
3	Alausí	28	Cubí	53	Mandur	78	Solanda
4	Ambato	29	Cuyes	54	Mariano Acosta	79	Sucua
5	Balsapamba	30	Echenadía bajo 2	55	Milpe	80	Tandapi
6	Bellavista	31	El Burro	56	Mira	81	Tomebamba
7	Blanco 2	32	El Cañaro	57	Mira 2	82	Tortugo
8	Bravo Grande	33	El Laurel	58	Mirador 1	83	Tulipe
9	Calderón	34	El Retorno	59	Monte Nuevo	84	Tululbi
10	Calderón II	35	Ganancay	60	Negro (2)	85	Uchucay
11	Campo Bello	36	Gualleturo	61	Numbala	86	Vacas Galindo 1
12	Casacay	37	Guápulo	62	Palmar	87	Vacas Galindo 2
13	Catachi	38	Guayabal	63	Pamplona	88	Verdeyacu Chico
14	Cebadas	39	Huarhuallá	64	Paquishapa	89	Victoria 2
15	Cedroyacu	40	Intag 2	65	Pilatón- Santa Ana	90	Vivar
16	Chanchán	41	Isimanchi	66	Pucayacu	91	Yacuchaqui
17	Chespi Real	42	La Barquilla	67	Puniyacu	92	El Aromo
18	Chillayacu	43	La Concepción	68	Quijos 1	93	Villonaco II
19	Chilma	44	Lachas	69	Rayo	94	Villonaco III
20	Chimbo-Guaranda	45	Langoa	70	Rio Luis 2	95	Minas de Huascachaca
21	Chinambi	46	Las Cidras	71	Río Zamora	96	Chachimbiro
22	Chingual	47	Las Juntas	72	Rircay	97	Jamanco
23	Chirapi	48	Lelia	73	Salunguire	98	Chalupas
24	Chuquiraguas	49	Ligua-Muyo	74	San Francisco II	99	Tufiño-Chiles-Cerrro Negro
25	Cinto	50	Los Bancos	75	San Pedro	100	Chacana-Cachiyan

Fig. 4. Geographic distribution of power plants portfolio.

The portfolio considered includes 91 hydroelectric projects (11,282.45 MW), five geothermal projects (900 MW), three wind projects (150 MW), and one solar photovoltaic project (200 MW), totaling an installed capacity of 12,532 MW, as shown in Fig. 4. In 2021, Ecuador updated this portfolio by adding 150 MW of hydroelectric projects, 670 MW of wind energy, 490 MW of solar, and 130 MW of biomass-based projects. However, these new projects' technical specifications and exact locations are unavailable, making them unsuitable for inclusion in this analysis. Therefore, the analysis conducted in this study covers 89.7% of the planned installed capacity in the country. The remaining 10.3% could not be evaluated for the reasons mentioned above.

Most of Ecuador's hydroelectric projects are concentrated in the Sierra region, with some in the Amazon due to the high water potential of the Amazon and Pacific basins. The three proposed wind projects are located in the southern part of the country, specifically in Azuay and Loja, where conditions are optimal for wind resource utilization. The only planned solar photovoltaic project is situated in an area with moderate solar potential on land previously prepared for constructing the Pacific Refinery. This project was ultimately not carried out. Although solar photovoltaic resources show high viability in several regions of the country, particularly in the Andes mountain range and the Insular region (notably in the provinces of Loja, Pichincha, and Galapagos), their development has not been included in the

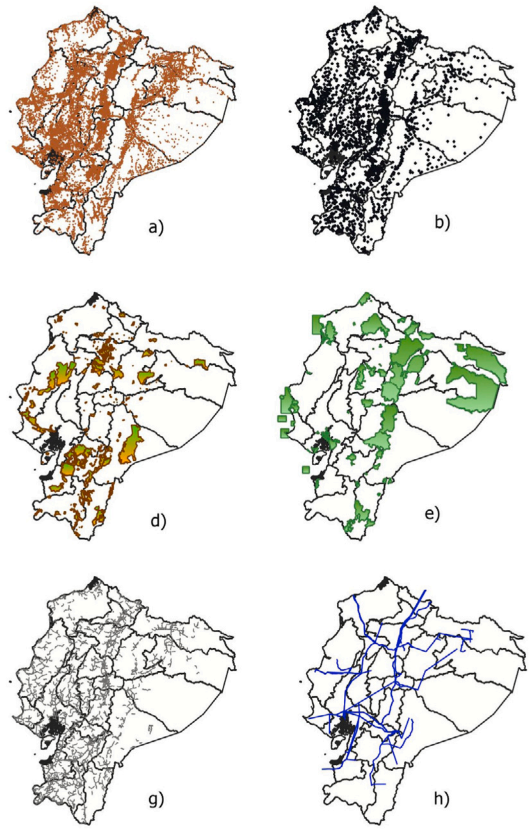


Fig. 5. Used layers for the Ecuadorian MCDA: (a) Urban areas, (b) Hospital infrastructure, (c) Existing schools, (d) Protected forest and vegetation, (e) National system of protected areas (SNAP), (f) Biosphere reserves, (g) Existing roads, (h) National transmission system.

PME [54]. The most favorable areas for geothermal development in Ecuador are in the northern part of the country, leading to the proposal of five geothermal projects in the PME. However, the southern Andes and the southwestern coast appear to have unexplored potential that could contribute to the country's total theoretical geothermal energy capacity [46].

3.1.6. Alternatives evaluation

The association of each criterion with the 101 projects in the portfolio was conducted using the Open Source Geographic Information System (QGIS). Geospatial analysis layers were used to match specific criteria to each project, with social, environmental, and technical factors assessed based on spatial data. This data included the distribution of urban areas, the location of existing hospitals and schools, protected forests and vegetation areas, the national protected areas system (SNAP), biosphere reserves zones, existing roads, and the national transmission grid, as sourced from [55–57]. Fig. 5 visually represents these geographic elements. This phase of the MCDA was particularly demanding in terms of time and, at times, the availability of information. Official online sources were consulted to gather the necessary data, and publicly accessible feasibility studies were provided by consulting firms. In some cases, technical experts from the public sector with direct knowledge of this information were also approached.

Each evaluated sub-criterion was categorized within one of the three criteria clusters, whose structure and evaluation methodology are outlined below.

Social cluster

Concerning the evaluation of *Project Perception*, the impact on people's perceptions was analyzed based on observable, olfactory, and auditory influences. The assessment considered a 1 km distance between power generation projects and urban, school, or hospital areas, considering the project's size (refer to Table 2). Fig. 5(a), (b), and (c) visually present the pertinent geographic information for the analysis of these criteria.

Table 2
Guideline for the evaluation of project perception criterion.

Criterion name	Project type	Good perception	Average perception	Bad perception
Project perception	All	>1 km and Any size	≤1 km and ≤10 MW	≤1 km and >10 MW

In this context, a project, regardless of its capacity, planned for construction at a distance greater than 1 km from the nearest urban area, school, or hospital, is perceived positively due to the low risk of directly impacting the population in terms of visual, olfactory, and auditory impacts. In contrast, a project with an installed capacity greater than 10 MW, located less than 1 km from urban areas, schools, and hospitals, will be perceived negatively due to the higher probability of direct impact on the population associated with its proximity. Finally, the perception may be neutral when a project has an installed capacity of less than 10 MW but is located less than 1 km from the nearest urban areas, as it is assumed that, being small in size, it does not generate significant impacts in terms of odors, visibility, or noise. The *Job Creation* criterion was examined to quantify direct job opportunities resulting from various alternatives. Employment Factors (EFs) served as metrics, measuring jobs created per unit of physical output in electricity supply, expressed in megawatts (MW) or megawatt-hours (MWh) [58]. It is important to note that EFs are context-dependent and subject to local regulations. However, prevailing research suggests identifiable trends in these values [59,60]. The calculation excluded the manufacturing stage due to the absence of Ecuadorian labor involvement, given the non-domestic origin of materials. Refer to Table 3 for detailed EFs.

The assessment scale for the *Displacement or Relocation of People* criterion is categorized risk levels as high or low. The risk level is

Table 3
Employment factors for quantifying direct job creation.

Project type	Manufacturing Jobs/MW	Construction Installation Jobs-years/MW	Operation and Maintenance Jobs/MW
Hydro-large	1.5	6	0.3
Hydro-small	5.5	15	2.4
Wind onshore	6.1	2.5	0.2
Solar PV	6.9	11	0.3
Geothermal	3.9	6.8	0.4

Table 4
Guideline for the evaluation of displacement or relocation of people criterion.

Criterion name	Project type	High risk	Low risk
Displacement relocation of people	Hydropower plants	With reservoir	Run-of-river
	Wind parks Solar PV Geothermal plants	≤500 m from urban areas	>500 m from urban areas
	PV rooftops	n/a	All

Table 5
Guideline for the evaluation of deforestation criterion.

Criterion name	Project type	High risk	Low risk
Deforestation	All	Located ≤500 m from protected forest and vegetation	Located >500 m from protected forest and vegetation

influenced by project type and location, detailed in Table 4, and its evaluation is based on the geographic information represented in Fig. 5(a), (b), and (c). For example, a wind project, regardless of its size, located less than 500 meters from an urban area is represented as having a high risk of requiring the relocation of the population, while if the distance is greater, it is indicated as having a lower risk. In the case of hydroelectric plants, those with reservoirs are classified as high risk in terms of population relocation, while run-of-river plants are considered low risk. However, it is important to note that the risk of relocation is not absent in the latter but is significantly lower.

Environmental cluster

Forests in Ecuador have been affected by activities from different sectors, such as agriculture, livestock farming, oil extraction, and mining. Between 1990 and 2010, the country recorded the highest deforestation rates in South America, with annual rates ranging from −1.5% to −1.8% and an accumulated loss of 21,340 km^2 between 1990 and 2020 [61]. To prevent the electricity sector from becoming a new threat to the country's forests, this study includes the *Deforestation* criterion, which considers the protection of forested areas designated as protected zones when selecting the location of electricity generation projects. These protected areas, officially recognized by the Ministry of Environment and Ecological Transition, are illustrated in Fig. 5(d).

The evaluation of this criterion is conducted by calculating the distance between the proposed projects and the protected forests, using a 500-meter buffer zone, as detailed in Table 5. For instance, if a power generation project is located less than 500 meters from a protected forest, its construction poses a high risk of deforestation in that area. Conversely, if the distance exceeds 500 m, the risk of deforestation associated with the protected forest is classified as low.

Various ecosystems, including tropical forests, Andean paramos, and marine ecosystems, support Ecuador's environmental heritage. This heritage is primarily protected through the National System of Protected Areas (SNAP), which consists of 50 areas distributed throughout the national territory. These areas include national parks, biological and ecological reserves, geobotanical areas, wildlife production zones, marine areas, wildlife refuges, and recreational areas [62], as shown in Fig. 5(e). Additionally, Ecuador is home to Biosphere Reserves, internationally recognized by UNESCO, which promote sustainable coexistence between human activities and nature [63], represented in Fig. 5(f). This study incorporates SNAP areas and Biosphere Reserves into the criterion of *Proximity to natural reserves*. This approach aims to assess the impacts of installing electricity generation projects in areas of high environmental sensitivity. To evaluate the impact of projects on natural areas, the parameters of installed capacity and distance to these zones are considered, as detailed in Table 6. For example, an electricity generation project is classified as having a high impact if planned within the SNAP or Biosphere Reserve areas or has an installed capacity greater than 10 MW and is located less than 10 km from these zones. The impact is classified as medium for projects with an installed capacity of less than 10 MW located less than 10 km from SNAP areas or Biosphere Reserves. Finally, a project is considered to have a low impact if it is located more than 10 km from these protected areas, regardless of its installed capacity.

The *Threat to Fauna and Wildlife* criterion evaluates the potential risk of a project to the natural habitat of wildlife and the disruption of migratory routes within its designated site. Due to the lack of specific data for Ecuador on how electricity generation projects affect wildlife, this analysis relies on conclusions from existing literature and factors such as project type, installed capacity, and location, as detailed in Table 7. For instance, a hydropower plant of any size located within SNAP areas, Biosphere Reserves, or protected forests, or a reservoir-based hydropower plant located anywhere in Ecuador is classified as high risk for fauna. Regardless of location, run-of-river hydropower projects with an installed capacity greater than 10 MW are considered medium risk. In comparison, those with a capacity below 10 MW are classified as low risk. In the case of wind energy projects, those located within SNAP areas, Biosphere Reserves, or protected forests are considered high risk for fauna. Projects situated less than 1200 meters from these protected areas are classified as medium risk, while those located more than 1200 meters away are considered low risk for fauna.

Technical cluster

Technical criteria are essential in planning the site selection for a power plant. The technical cluster includes three main criteria: size, accessibility, and distance to transmission lines. Figs. 5(g) and (h) present the geographic information used to analyze these criteria.

The *Size* of a project, defined by its installed capacity in megawatts (MW), depends on the technical specifications of the infrastructure and impacts costs, timelines, resource requirements, and regulatory demands. Larger projects require more investment, land, and time and may sometimes face stricter regulatory and environmental demands. The distance to transmission lines and roads also influences construction. Proximity to transmission lines reduces costs and energy losses, while closeness to roads facilitates transportation, maintenance access, and operations. Greater distances increase costs and project complexity. For the evaluation of these criteria, the distance values were based on references from previous studies, such as [71,72].

The *Accessibility* criterion evaluates the ease of access to the project's location based on the distance to the existing road network in Ecuador. This criterion is evaluated using a five-point scale applicable to all types of power plants. The specific details of this scale are provided in Table 8. For instance, a project less than 1.5 km from the nearest road is categorized as having very good accessibility. In contrast, a distance between 4.5 km and 7.5 km indicates average accessibility, whereas a project situated more than 10 km from a road is classified as having very poor accessibility.

Finally, the criterion *Distance to Transmission Lines* considers the project's proximity to the electrical transmission lines. Greater distances imply increased technical complexity and higher investment requirements. Similar to the accessibility criterion, the measurement scale adheres to a five-point system, outlined in Table 9, and is interpreted as follows: a project located less than 1 km from the transmission line network is categorized as having very good proximity to the grid. In comparison, a project more than 10 km away is classified as having very bad proximity to the grid.

Table 6
Guideline for the evaluation of proximity to Natural Reserves criterion.

Criterion name	High impact	Medium impact	Low impact
Proximity to Natural Reserves	Inside the SNAP or Biosphere Reserve, or ≤10 km from the limits of SNAP or Biosphere Reserve and installed capacity > 10 MW	≤10 km from the limits of SNAP or Biosphere Reserve, and installed capacity ≤ 10 MW	>10 km from the limits of SNAP or Biosphere Reserve

Table 7
Guideline for the evaluation of threat to fauna and wildlife criterion.

Criterion name	Project type	High risk	Medium risk	Low risk
Threat to Fauna and Wildlife	Hydropower plants	Any size located inside the SNAP, Biosphere Reserve, or protected forest; or hydro with reservoir located anywhere [64–66].	ROR > 10 MW located anywhere	ROR ≤ 10 MW located anywhere [67]
	Solar PV		Large scale projects [68].	PV rooftop
	Geothermal plants	Located inside the SNAP, Biosphere Reserve, or protected forest	Located ≤ 1 km from rivers or water bodies [68].	Located >1 km from rivers or water bodies
	Wind parks		Located ≤1200 m from the SNAP, Biosphere Reserve, or protected forest	Located >1200 m from the SNAP, Biosphere Reserve, or protected forest [69,70].

Table 8
Guideline for the evaluation of accessibility criterion.

Criterion name	Very good	Good	Average	Bad	Very bad
Accessibility	≤1.5 km	>1.5 km and ≤4.5 km	>4.5 km and ≤7.5 km	>7.5 km and ≤10 km	>10 km

Table 9
Guideline for the evaluation of distance to transmission lines criterion.

Criterion name	Very good	Good	Average	Bad	Very bad
Distance to the Grid	≤1 km	> 1 km and ≤4 km	> 4 km and ≤7 km	> 7 km and ≤10 km	>10 km

3.1.7. Alternatives ranking

The next step in the MCDA involves ranking alternatives. The methodology employed for this purpose is the PROMETHEE method (Preference Ranking Organization Method for Enrichment Evaluations), developed by Brans et al. [73] and Brans and Vincke [74]. This method belongs to the outranking family and is used to establish a ranking of alternatives, referred to as "actions" in the method's terminology, based on preference degrees [75]. Specifically, this study employs PROMETHEE II due to its systematic approach, which integrates quantitative and qualitative factors, considers low compensation between criteria, and handles preference-based information [41]. The software tool used for this analysis is Visual PROMETHEE, recognized for its robust implementation of the PROMETHEE multi-criteria decision analysis method [76].

In the PROMETHEE II method, the net outranking flow (ϕ) represents the overall preference of an alternative compared to others. When ϕ is positive, the project performs well relative to other alternatives, meeting the evaluation criteria favorably. Conversely, when ϕ is negative, the project scores poorly compared to others, failing to meet key criteria [77].

To rank the alternatives, it is necessary to define whether each criterion should be maximized or minimized, as shown in Table 10. In this study, two social criteria—project perception and job creation—are set to be maximized to ensure that nearby communities better accept projects and generate more employment opportunities. Similarly, two technical criteria—accessibility and distance to transmission lines—are also maximized to ensure that projects are closer to access roads and the national transmission system. Regarding environmental criteria, the aim is to minimize impacts and risks to fauna and flora and the risk of population displacement. Finally, this study considered that the project size criterion should be minimized, meaning that smaller projects were prioritized. This decision was based on interviews with key stakeholders, who indicated that smaller projects are perceived to generate less impact. Besides, the Usual preference function was used to reduce the complexity of the analysis.

3.1.8. Sensitivity analysis

Sensitivity analysis is a method used to evaluate the robustness and reliability of results in decision-making processes. It provides insight into how variations can affect the evaluated alternatives' desirability. As described by [78], most studies focus on assessing the robustness of decision models by examining how changes in the weights of criteria—used as input parameters—impact the outcomes. This approach helps identify how variations in the importance of decision parameters influence the ranking of the alternatives.

This study's sensitivity analysis involves modifying the weights assigned to the criteria to observe how these changes affect the selected alternatives. Five cases were evaluated, and the different criteria weights were adjusted. Case 1 uses the weights assigned by the interviewed stakeholders, which serve as the base case for this study. In Case 2, equal weights were assigned to all criteria. In Case 3, social criteria were given greater weight than environmental and technical criteria. In Case 4, the emphasis shifted to environmental criteria as the top priority. Meanwhile, in Case 5, technical criteria were prioritized over environmental and social considerations. Table 11 shows the used weights for each criterion on each case.

4. Results

For clarity, the results section is structured into three distinct subsections. The first one presents findings from interviews conducted with four stakeholder groups, outlining their criteria preferences. In

Table 10
Criteria settings for the visual PROMETHEE.

Criteria	Type	Scale	Values/Units	Preference
Project perception	Qualitative	Perception	Good, Average, Bad	Maximize
Job creation	Quantitative	Numerical	Jobs/MW	Maximize
Displacement of people	Qualitative	Risk	High, Low	Minimize
Deforestation	Qualitative	Risk	High, Low	Minimize
Proximity to natural reserves	Qualitative	Impact	High, Medium, Low	Minimize
Threat to fauna and wildlife	Qualitative	Risk	High, Medium, Low	Minimize
Size	Quantitative	Numerical	MW	Minimize
Accessibility	Qualitative	5-point	Very good, Good, Average, Bad, Very bad	Maximize
Distance to transmission lines	Qualitative	5-point	Very good, Good, Average, Bad, Very bad	Maximize

Table 11
Criteria weights across study cases.

Cluster	Criteria	Case 1	Case 2	Case 3	Case 4	Case 5
Social	Project perception	6.35%	11.11%	16.66%	8.33%	8.33%
	Job creation	9.00%	11.11%	16.66%	8.33%	8.33%
	Displacement of people	20.38%	11.11%	16.66%	8.33%	8.33%
Environmental	Threat to fauna	21.04%	11.11%	8.33%	16.66%	8.33%
	Deforestation	16.01%	11.11%	8.33%	16.66%	8.33%
	Proximity to natural reserves	8.70%	11.11%	8.33%	16.66%	8.33%
Technical	Size	8.66%	11.11%	8.33%	8.33%	16.66%
	Accessibility	5.66%	11.11%	8.33%	8.33%	16.66%
	Distance to transmission lines	4.18%	11.11%	8.33%	8.33%	16.66%

the second subsection, the focus shifts to the outcomes of the alternative ranking process that involves delineating projects that performed better than the other. The final subsection presents the results of the sensitivity analysis, illustrating how changes in criteria weights affect the ranking of alternatives.

4.1. Weight allocation for criteria by different stakeholders

Fig. 6 illustrates preference results and group consensus among diverse stakeholders. The public sector participants showed a 65.6% consensus. This percentage reflects the degree of alignment or shared understanding among the participants in their decision-making process. Notably, the displacement of people criterion was the highest priority at 27.48%, followed by environmental concerns—threat to fauna and wildlife (17.13%) and deforestation (13.20%). Significant weights were also assigned to proximity to natural reserves, job creation, and project size. Within the technical domain, accessibility held a notable share at 6.37%, emphasizing the importance of easy project site access. The project perception criterion (6.05%) underscored the significance of public perception, while the distance to transmission lines received a weight of 3.82%.

The civil society group demonstrated a 74.9% consensus, the highest among all groups of actors. They emphasized the importance of environmental aspects in evaluating electricity generation projects. Their top priority was the threat to fauna and wildlife (29.07%), reflecting a strong commitment to biodiversity protection. Deforestation (25.50%) and proximity to natural reserves (11.06%) also received substantial weight, demonstrating concern for conserving vital ecological areas. Social criteria such as displacement of people (10.99%) revealed their commitment to protecting the homes of the communities; however, project perception (8.09%) and job creation criteria (2.53%) have lower valuation despite their direct connection to community well-being. The project size (7.19%) showed concern about the negative impacts that large-scale projects may cause. While the other technical criteria of accessibility and distance to transmission lines obtained 3.15% and 2.43%, respectively.

The private sector had diverse opinions or preferences regarding the priorities in decision-making. Their level of agreement, measured as consensus, was 50.3%, suggesting moderate alignment but significant variation in viewpoints. This lower consensus than other groups highlights differing priorities or perspectives among the private sector stakeholders. Their main concerns in selecting power generation projects are the impact on wildlife (20.70%), displacement of communities (18.91%), and deforestation (13.85%), as violations of these criteria could lead to social opposition and disruptions that may ultimately halt the project. Technical criteria also received relatively high ratings, highlighting their importance for the private sector in power generation project development.

For academic stakeholders, social criteria—such as displacement of people and job creation—are prioritized above environmental criteria, which come second. Technical criteria hold the third level of importance. Notably, the project perception criterion, a social measure, was given only a 4.78% importance rating. Despite its relevance to residents near the project areas, this criterion is generally considered a low priority among all stakeholders. Interviewees indicated that other social criteria, like displacement, carry more weight due to their immediate impact during power plant planning, while project perception mainly affects those in the surrounding areas.

As shown in Fig. 7, the overall agreement among the four stakeholder groups in their decision-making process was 55.1%, reflecting a moderate level of alignment. This percentage highlights the challenge of reconciling diverse preferences, priorities, and perspectives across

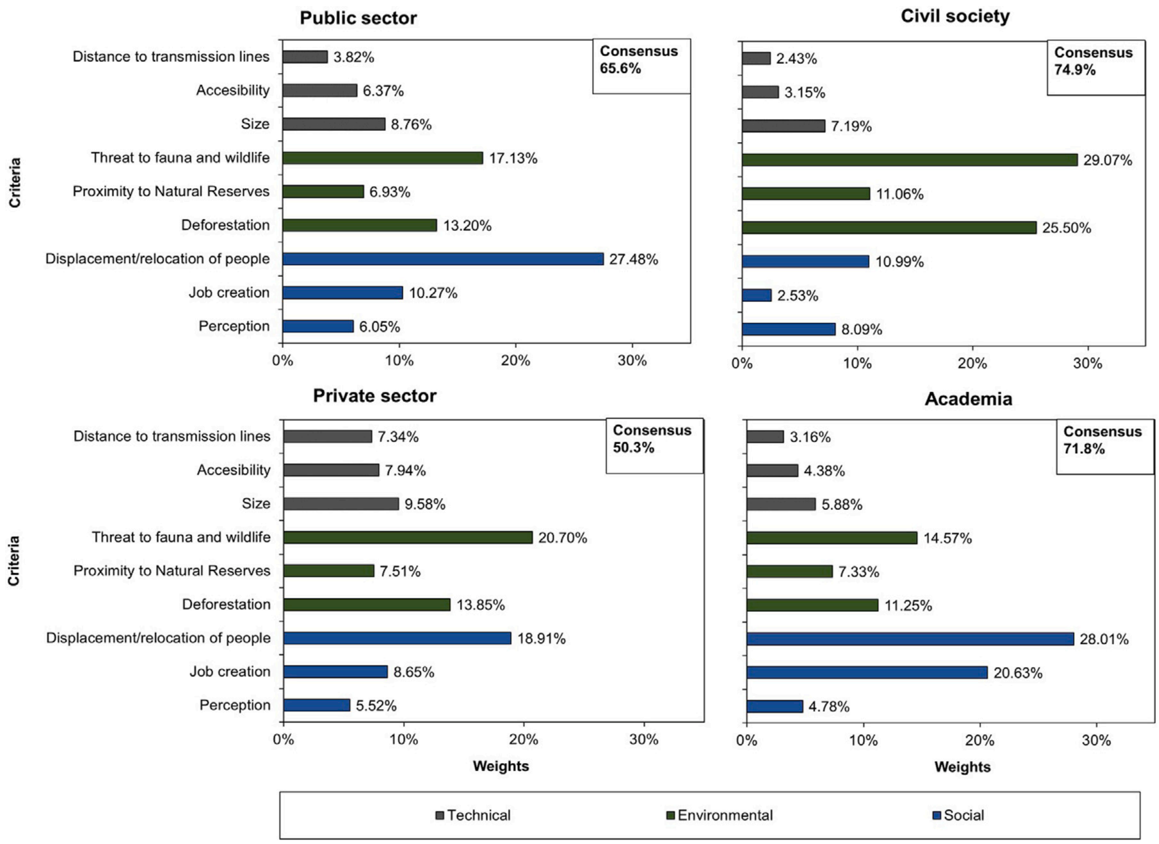


Fig. 6. Different actors' weights after the AHP.

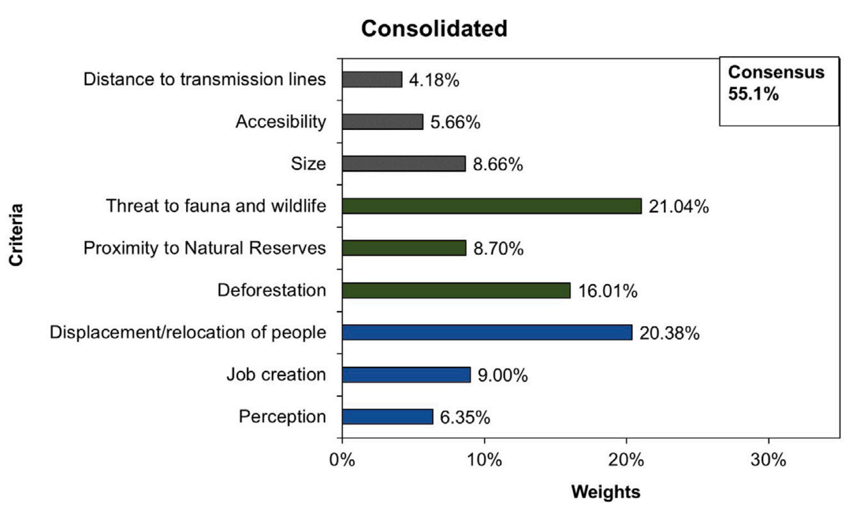


Fig. 7. Consolidated weights for all actors.

different groups, indicating that achieving a higher level of consensus is difficult when stakeholders have varying interests and objectives. The most important criterion is the threat to fauna and wildlife, holding 21.04% of the total weight, closely followed by the displacement of people at 20.38%, and in third place is deforestation, with 16.01% weight. The top three criteria fall within the environmental and social clusters, emphasizing their importance among all the actors. Criteria with the lowest weights include distance to transmission lines at 4.18% and accessibility to the project construction at 5.66%. The project size criterion registers a weight of 8.66%, while proximity to natural reserves and job creation hold comparable weights of 8.70% and 9%, respectively.

4.2. Comparative outranking analysis of analyzed power plants

This subsection presents the results of ranking power plant projects based on stakeholder preferences. Fig. 8 indicates the 101 analyzed projects with a positive or negative net preference flow (Phi). Projects above the zero axis have a positive Phi value, suggesting that, relative to the other evaluated projects, they performed better in meeting the criteria. In the PROMETHEE method, this positive performance signifies that these projects are more favorable than others and should be prioritized for future implementation. Conversely, projects below the zero axis have a negative Phi value, indicating they performed worse than other projects and face more significant challenges in feasibility,

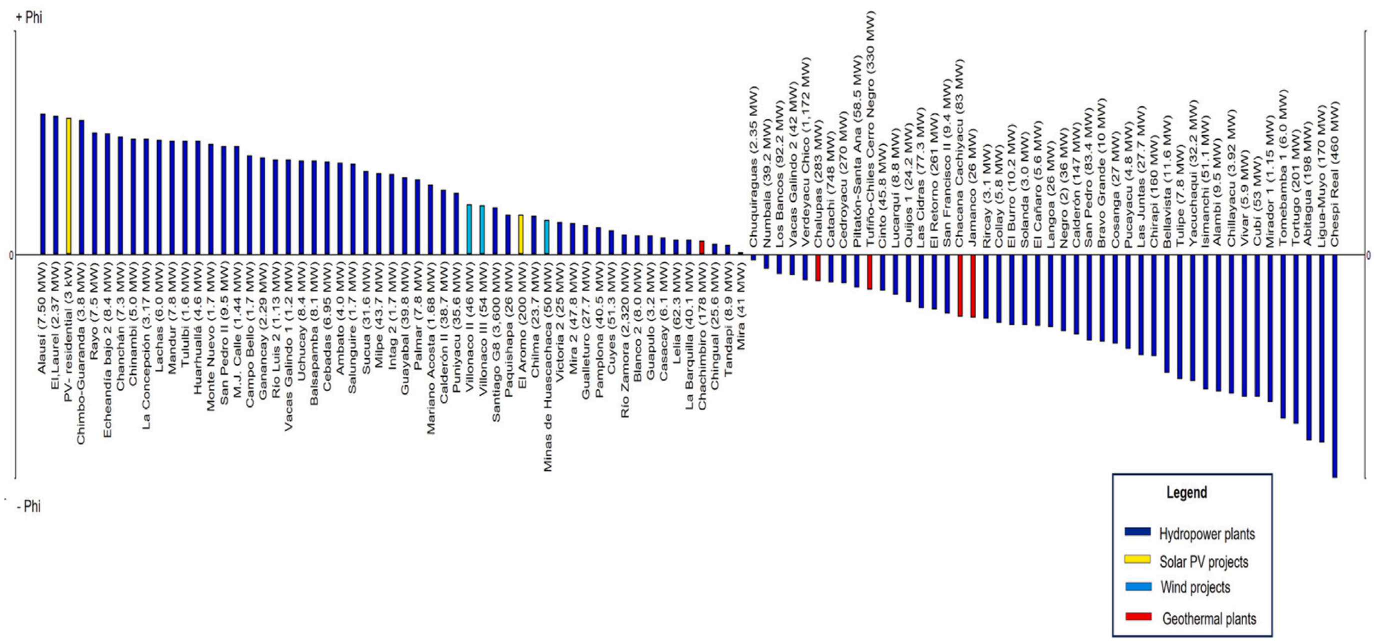


Fig. 8. Alternatives ranked from the best to worst after the PROMETHEE analysis.

Table 12
Results of MCDA by project type.

Type	Passed MCDA			Failed MCDA		
	Quantity	Capacity [MW]	[%]	Quantity	Capacity [MW]	[%]
Hydro	49	6670.93	53.8%	42	4611.52	46.2%
Solar PV	2	200.003	100%	0	0	0%
Wind	3	150	100%	0	0	0%
Geothermal	1	178	20%	4	722	80%
Total	**55**	**7198.93**	–	**46**	**5333.52**	–

acceptance, or alignment with desired goals, making them less suitable for implementation. Table 12 shows the summarized results.

Fifty-five projects with an installed capacity of 7198.93 MW were classified as satisfactory according to stakeholder preferences, as they achieved positive Phi results. Among these projects, 49 are hydroelectric plants: 31 with an installed capacity of less than 10 MW, 14 between 10 and 50 MW, and 4 exceeding 50 MW. It is important to note that none of these hydroelectric plants have reservoirs; they are all run-of-river plants. Additionally, the pilot solar PV rooftop project scored third highest, emphasizing the need to address affordability barriers. With a combined capacity of 150 MW, wind projects achieved positive Phi values, while only one geothermal project of 178 MW was evaluated positively.

On the other hand, 46 projects resulted in negative Phi values. Of these, 42 are hydroelectric plants: 15 have a capacity of less than 10 MW, 11 are between 10 and 50 MW, 12 are over 50 MW, and four hydroelectric plants have reservoirs. Similarly, four geothermal projects, with a total of 722 MW, were rated negatively for not meeting the criteria specified by the stakeholders.

Below are the results of six projects, including their Phi values and geographical locations, analyzed in greater detail. Fig. 9 highlights two specific projects: El Aromo photovoltaic solar project, with a capacity of 200 MW, and the Villonaco II wind project, with a capacity of 46 MW. Both projects obtained positive Net Preference Flow values of 0.0830 and 0.1044, respectively. These values ranked Villonaco II in 35th place and El Aromo in 38th out of 101 evaluated projects.

The El Aromo project met 7 out of the nine analyzed criteria. Its favorable evaluation is primarily due to its location, far from urban and SNAP areas and more than 3 km away from the nearest protected forest, which minimizes risks to the population, flora, and fauna. However, the project did not meet criteria related to size and accessibility. Its capacity, above the average of existing projects, combined with its remote location far from main roads, makes site access challenging, though it is considered feasible. By comparison, the Villonaco II wind project received positive evaluations for 6 out of the nine analyzed criteria. However, it failed to meet job creation and project size criteria. While smaller projects are usually preferred due to their reduced environmental impact, this preference limits their potential for generating local employment. Furthermore, Villonaco II did not meet the criterion regarding proximity to natural reserves, as it is located near the Podocarpus-El Cóndor Biosphere Reserve. This proximity categorizes it as a medium-risk project for the reserve's ecosystem, requiring special attention during construction due to the area's environmental sensitivity. In general, both projects align with the criteria most valued by the stakeholders, as they do not pose significant risks or threats in critical aspects. However, it is essential to address the identified limitations to ensure their feasibility and sustainability.

Fig. 10 presents the analysis of the Jamanco geothermal project, with a capacity of 26 MW, and the Mirador 1 hydroelectric plant, with a capacity of 1.15 MW. Both projects obtained negative Phi values of −0.1339 and −0.3115, respectively, reflecting insufficient performance according to the criteria evaluated by the interviewed stakeholders. These ratings placed the Jamanco project in position 73 and the Mirador 1 project in position 96 out of the total ranking of 101 projects evaluated.

The geothermal project failed to meet the criteria related to job creation, proximity to natural reserves, and risk to wildlife. Its location near the Cayambe Coca National Park represents a significant risk to local fauna, considered the most heavily weighted criterion in the evaluation. Despite meeting other aspects, its potential negative impact on

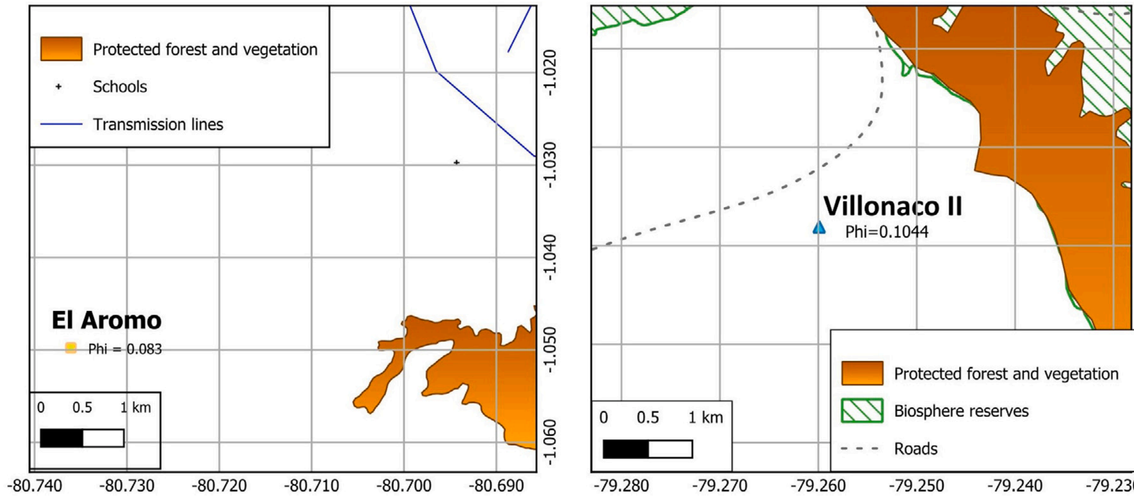


Fig. 9. El Aromo and Villonaco II power plants geographical location and Phi results.

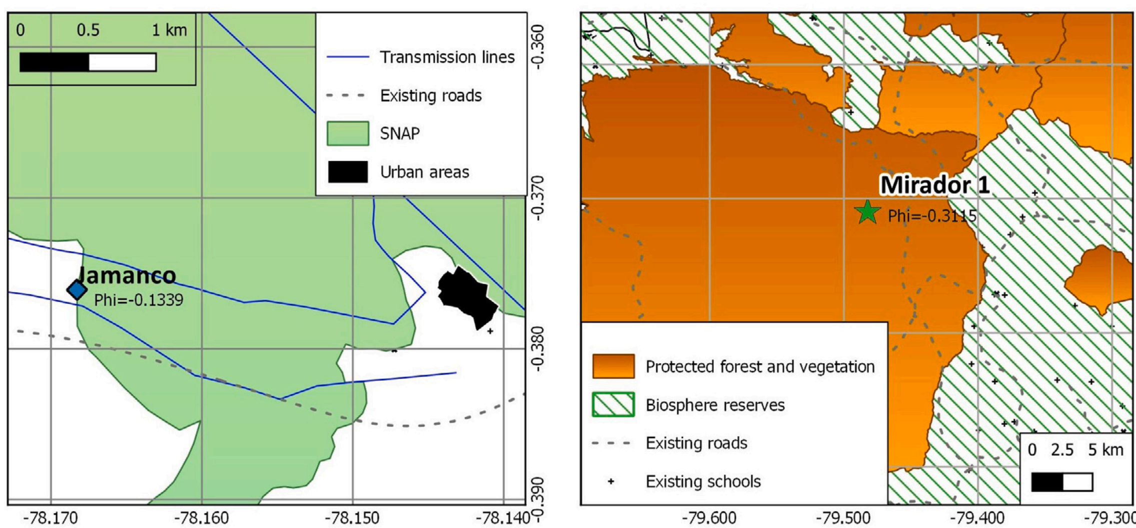


Fig. 10. Jamanco and Mirador 1 power plants geographical location and Phi results.

wildlife renders it unfeasible for construction due to the high environmental risk in the area. In addition, the Mirador 1 hydroelectric plant, despite its small capacity of 1.15 MW, received an unfavorable evaluation as it failed to meet five of the nine criteria analyzed. Its location, close to protected forests and the Macizo del Cajas Biosphere Reserve, significantly increases environmental risks, outweighing the positive ratings related to its small size and low population displacement risk. This case challenges the assumption that smaller projects inherently have lower impacts, highlighting the importance of considering both size and location in the final project outcomes. Finally, Fig. 11 presents two large-scale hydroelectric plants: Santiago G8, with a capacity of 3600 MW and a Phi value of 0.0996, and Verdeyacu Chico, with a capacity of 1172 MW and a Phi value of −0.0547. Despite being large projects, their specific characteristics result in significant differences in their performance, reflected in their ranking positions, with Santiago G8 ranked 36th and Verdeyacu Chico ranked 60th.

From a geographical perspective, Santiago G8 stands out for not being located near SNAP zones, urban areas, and biosphere reserves and for maintaining a safe distance from the Kutukú-Shaimi protected forest. This allows it to meet 7 out of the nine evaluated criteria. However, it falls short in two technical criteria: project size, due to its large capacity, and distance to transmission lines, as it is located far from the existing transmission system. In contrast, the Verdeyacu Chico project, although smaller in size compared to Santiago G8, fails to meet expectations in all three technical criteria: its large capacity, its remoteness from existing roads, and the transmission system. Additionally, its location near the Colonso Chalupas Biological Reserve and the Sumaco Biosphere Reserve classifies it as a high-risk project for local fauna. This negative environmental impact and its technical limitations render it unfeasible for implementation.

After analyzing these six projects, it becomes evident how stakeholder preferences influence project viability beyond their technical characteristics. Projects whose locations involve significant risks are more likely to be deemed unfeasible for construction. Stakeholders placed high importance on environmental and social criteria related to population displacement. Consequently, if a project is classified as high-risk in any of these aspects, it is highly likely to lack public support during its implementation.

This finding is important, as avoiding the construction of projects that do not meet the criteria valued by stakeholders and prioritizing those that adhere to these considerations significantly increases their social acceptance. Furthermore, this approach considerably reduces the risk of social conflicts surrounding construction sites, thereby promoting the harmonious development of energy initiatives.

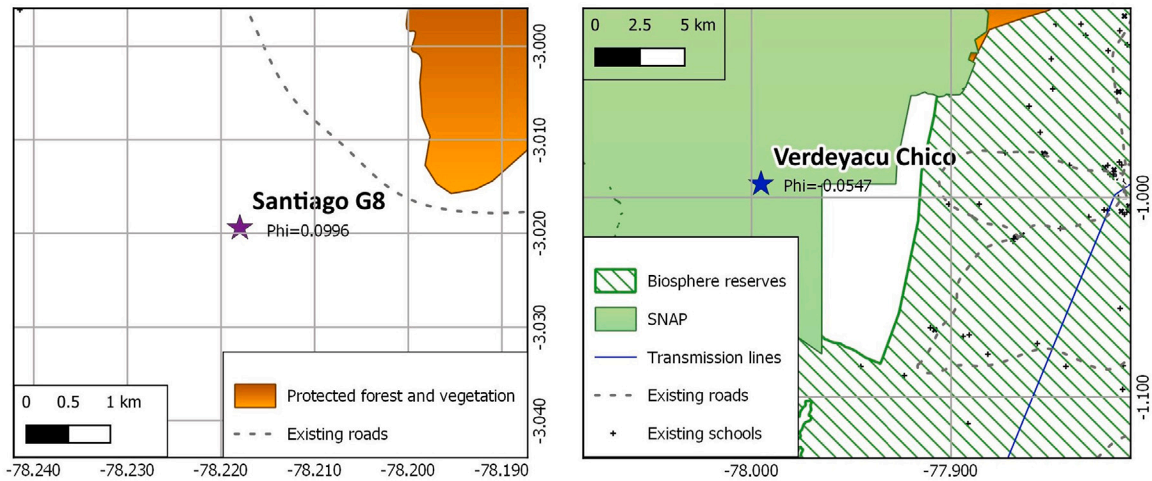


Fig. 11. Santiago G8 and Verdeyacu Chico power plants geographical location and Phi results.

Table 13
Comparison of case percentages across projects.

Project Type	Case 1	Case 2	Case 3	Case 4	Case 5
Hydro Passed (%)	53.8	52.7	51.6	49.5	50.5
Hydro Failed (%)	46.2	47.3	48.4	50.5	49.5
Solar Passed (%)	100	100	100	100	50
Solar Failed (%)	0	0	0	0	50
Wind Passed (%)	100	67	67	100	67
Wind Failed (%)	0.0	33	33	0	33
Geothermal Passed (%)	20	20	60	20	40
Geothermal Failed (%)	80	80	40	80	60

4.3. Sensitivity analysis

Table 13 shows the percentages of projects that passed and failed the MCDA for Hydro, Solar, Wind, and Geothermal across all five cases detailed in Section 3.1.8.

Hydropower projects exhibit high sensitivity to both environmental (Case 4) and technical criteria (Case 5). The lowest performance for hydropower projects occurs when environmental criteria are given greater weight (Case 4), resulting in a higher failure rate in the MCDA. This outcome is primarily due to the location of many hydropower projects in environmentally sensitive areas, where their impacts on forests and fauna are considered high risk. Additionally, poor results are observed when technical criteria dominate (Case 5), with nearly half of the projects failing the MCDA. This is mainly attributable to the projects' remote locations, which lead to challenges in accessibility and distance from the electrical grid. In contrast, hydropower projects achieve their highest passing rates when criteria weights are balanced (Case 2), reflect stakeholder-derived preferences (Case 1), or prioritize social criteria (Case 3). However, although Case 3 has high passing rates, it also exhibits higher failure rates than the base case (Case 1). This suggests that when hydropower projects involve significant displacement of people, low job creation, or negative perceptions from local inhabitants, there is an increased risk of projects failing the MCDA.

Solar projects perform consistently well across most cases due to their low environmental and social impacts. However, in Case 5, they face challenges in remote areas with inadequate infrastructure, emphasizing the importance of grid connectivity and accessibility. Addressing these issues through infrastructure improvements could enhance their feasibility under technical criteria. The pilot rooftop solar PV project achieved perfect results in all cases, making it the most reliable and practical option for future projects.

Wind projects display variability in their outcomes, performing perfectly under Case 1 and Case 4 focused weightings but facing challenges when prioritizing technical and social criteria. Among the three analyzed projects, one fails primarily due to its location. Its remote position, far from the grid and existing roads, results in significant penalties under technical criteria. However, its distance from protected areas allows it to score favorably on environmental criteria. In the base case, this project was on the threshold of passing the MCDA, making it highly sensitive to slight changes in weightings, which determine whether it passes or fails.

Geothermal projects perform best under social preference schemes, as their locations away from urban areas contribute to positive public perception, and their construction stage presents a high potential for job creation. However, these projects fail in most cases due to their proximity to protected areas, which poses significant risks to forests and fauna. These environmental factors were prioritized by stakeholders and given substantial weight in Case 4, leading to poor outcomes for geothermal projects in these two cases.

Summarizing, the performance of projects is directly influenced by the weighting of criteria, requiring decision-makers to select a portfolio that aligns with the country's priorities. A portfolio emphasizing environmental criteria would favor low-impact projects such as solar and wind but limit the deployment of hydropower plants and geothermal projects due to their environmental impacts. Alternatively, prioritizing social criteria could focus on job creation and promoting geothermal projects despite their locations in natural reserve areas while supporting hydropower, solar PV, and wind projects. A third option is a portfolio driven by technical criteria, favoring projects near existing roads and transmission lines while penalizing those in remote areas with grid connectivity challenges. Beyond these focused approaches, decision-makers may also consider a balanced portfolio that integrates stakeholder preferences or evenly weights technical, social, and environmental criteria. Such an approach ensures that no single criterion dominates, enabling a more inclusive and equitable selection of projects.

Based on the presented results, the following section provides a discussion of their implications.

5. Discussion

The discussion section has been divided into four subsections to enhance the clarity of the study. These subsections include a discussion on stakeholder preferences, the prioritized projects, and an analysis of why specific projects performed better than others. Additionally, the challenges of incorporating MCDA into energy planning in Ecuador are addressed, followed by recommendations for its implementation.

5.1. Stakeholder priorities and decision-making drivers

The results of this study reveal significant differences in stakeholder priorities in terms of their interest in the criteria for electricity generation projects in Ecuador. Civil society prioritizes biodiversity protection, influenced by cultural values such as the Andean worldview, which generates a high level of consensus within this group. In contrast, academia, the public sector, and the private sector emphasize minimizing the displacement of people, focusing on avoiding social and economic conflicts during project implementation. The proximity criterion to protected areas receives less attention from most stakeholders, who trust Ecuadorian environmental legislation, except for civil society, which expresses distrust in its enforcement. Technical criteria, such as accessibility and proximity to transmission lines, are more relevant to the public and private sectors due to their impact on economic feasibility but are less of a priority for academia and civil society. Job creation also generates divided opinions: the public sector, private sector, and academia consider it essential for securing local acceptance, while civil society views it as irrelevant due to previous experiences with temporary jobs. These differences highlight a gap between the relevance of specific criteria and their limited integration into energy planning. The comparison with other countries using multi-criteria and multi-stakeholder analysis in energy planning shows similarities and differences relative to the Ecuadorian case. In Morocco and Tunisia, energy independence is a priority due to reliance on imported resources. At the same time, in Jordan, air pollution reduction is prioritized because of its impact on public health in densely populated urban areas [79]. In Germany, criteria are diverse and include climate change mitigation and the protection of ecosystems, such as forests, in wind energy projects [80,81]. In Ecuador, biodiversity protection, including flora and fauna, holds a central role for the actors. In contrast, criteria such as energy independence or greenhouse gas emissions reduction, which are prioritized in other countries, are not considered relevant. These differences reflect the particularities of the Ecuadorian context, such as its rich biodiversity, associated cultural values, and perceptions of environmental policy enforcement. These findings highlight the importance of approaches tailored to local realities in energy planning. While international experiences can offer valuable insights, their application must be carefully adjusted to ensure that national priorities are adequately represented. In Ecuador, this requires strengthening the integration of environmental and social criteria into energy planning processes, respecting the specific characteristics of the territory while incorporating international best practices to address common challenges in the transition to more sustainable energy systems.

5.2. Project prioritization and comparative analysis

The analysis of the MCDA results reveals that, despite the high scores achieved by wind and solar projects, these technologies remain underrepresented in Ecuador due to interconnected political and economic factors. The country's historical reliance on hydropower has created a bias toward this technology, perceived as the most reliable option to meet growing energy demand. Additionally, the absence of specific public policies, such as targeted subsidies, feed-in tariffs, or tax incentives, has hindered the growth of emerging renewable technologies, placing them at a disadvantage compared to established traditional options. Another significant factor is the low electricity prices for end consumers, driven by government subsidies, which discourage private investment in photovoltaic solar and wind energy technologies. Without an attractive market, these technologies struggle to compete with traditional options despite their long-term benefits in terms of sustainability and energy system decentralization. This situation is further compounded by misconceptions about these technologies' complexity and high costs, which have limited their adoption and perpetuated the preference for traditional systems. If these barriers are not addressed, Ecuador will continue to depend on hydropower, even though it is not always the most suitable option.

The heatmap analysis of the 46 projects that performed less favorably than the other 55 in meeting the MCDA criteria (Fig. 12) provides key insights into their poor performance. Hydropower plants like Abitagua and Tortugo, which failed the most significant number of criteria, stand out due to their low overall viability, suggesting shortcomings in the integrated planning of environmental, social, and technical aspects. Examining the evaluated criteria reveals recurring issues, such as deforestation, proximity to natural reserves, and threats to fauna, which show high non-compliance rates across multiple projects.

This underscores the need to strengthen mitigation strategies from the early stages of project design to address these challenges effectively. Although all the projects shown in the heat map failed to meet the MCDA criteria, some show relatively better performance in certain areas, reflected in a higher presence of blue cells in the heatmap. These partial strengths can serve as benchmarks for replicating good practices and improving future projects, reducing non-compliance rates in the most critical criteria. The fact that none of these 46 projects fully met the MCDA standards raises questions about the effectiveness of current approaches. This highlights the importance of adopting a more holistic perspective to identify, prioritize, and mitigate the most significant impacts. In particular, criteria with the highest non-compliance rates should receive focused attention through specific solutions to increase the likelihood of success in future evaluations.

5.3. Limitations of the tool and challenges for the MCDA application in Ecuador

In some instances, while using the Analytic Hierarchy Process method, challenges arose in achieving a consistency ratio below 10%, as it was often difficult to revisit the model with stakeholders to refine their inputs. The Deck of Cards Method (DCM) is recommended as a potential alternative for future applications. Like AHP, DCM allows stakeholders to express their preferences without considering the range or encoding of criteria scales [82]. The advantage of the DCM over AHP is that it could reduce the cognitive effort for stakeholders, avoiding pairwise comparisons and consistency checks. Additionally, DCM weights are applicable and compatible with the PROMETHEE method, complementing the strengths of AHP by further enhancing the reliability and usability of the analysis results [83].

Implementing MCDA-based decisions in Ecuador's energy sector could face significant political and economic challenges. On the political side, institutional resistance to transition from traditional techno-economic approaches and potential conflicts between stakeholders with different priorities, such as economic development versus environmental protection, pose considerable obstacles. Weak governance and inconsistent enforcement of environmental and social standards further complicate the adoption of MCDA outcomes. From an economic point of view, conducting comprehensive MCDA studies and involving various stakeholders require additional resources, burdening already limited budgets. To address these challenges, some recommendations are presented to incorporate MCDA in Ecuadorian energy planning successfully.

5.4. Policy recommendations

Based on the analysis conducted, the following recommendations are presented to strengthen the planning and implementation of energy projects in Ecuador, promoting their sustainability, social acceptance, and resilience to climate challenges:

Diversification and resilience of the energy matrix

Reduce reliance on hydropower by incorporating renewable technologies such as solar, wind, and geothermal energy. This is essential to ensure the country's energy security among uncertainties related to climate change impacts, which, according to Carvajal et al. could result in energy production increases of up to 7% in wet scenarios

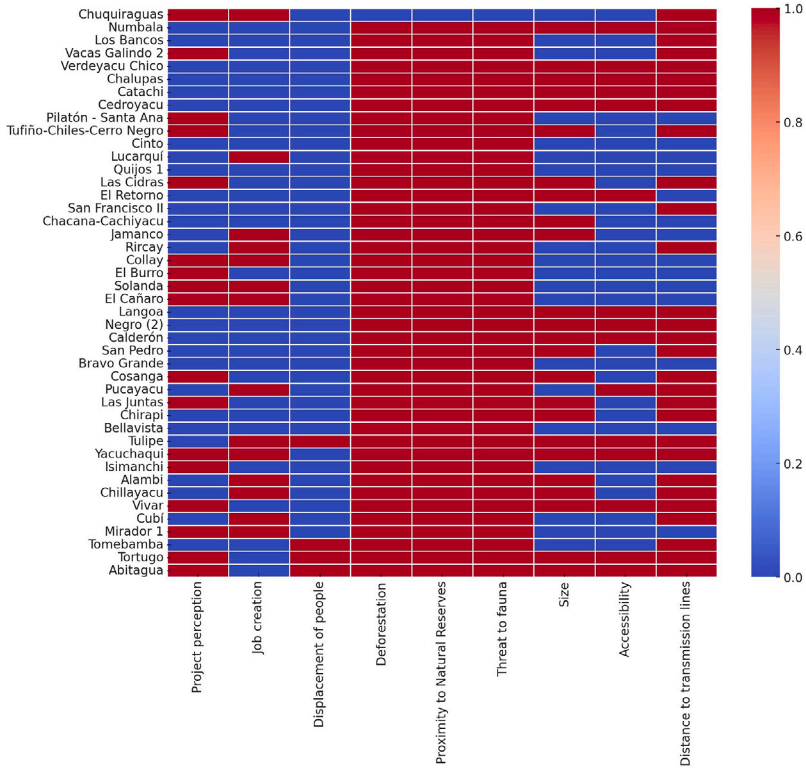


Fig. 12. Heatmap: Criteria compliance by project that failed MCDA.

and reductions of up to 25% in dry scenarios by 2050 [43]. Projects less vulnerable to climatic variations should be prioritized to ensure a reliable and sustainable electricity supply while mitigating risks associated with water resource scarcity.

Holistic methodology for energy system modeling

Incorporate a multi-criteria approach into energy planning to balance projects' technical and economic feasibility with environmental sustainability and social acceptance. This analysis should prioritize criteria relevant to the Ecuadorian context, such as biodiversity protection, mitigation of social impacts, and compliance with technical standards. The results of the MCDA should serve as a key input for long-term energy optimization models, ensuring that strategic decisions reflect not only techno-economic feasibility but also socio-environmental priorities.

Participatory, inclusive, and transparent planning

Actively involve various stakeholders (civil society, academia, public and private sectors) from the initial planning stages and ensure transparency throughout the process. This includes establishing clear communication channels, disclosing environmental and socio-economic impact studies, and continuously informing communities and other key stakeholders. This approach fosters consensus, reduces mistrust, prevents socio-environmental conflicts, and ensures that decisions reflect the needs and priorities of all parties involved.

Strengthening public policies and regulations

Ensure the effective enforcement of environmental and community protection laws, especially in sensitive areas. Additionally, policies should be developed to promote the adoption of emerging renewable technologies and ensure their competitiveness against traditional options. The constraints of an academic study limited the scope of this analysis; however, based on these recommendations, its implementation at the governmental level would provide the authority and scale necessary to guide energy planning effectively. This would facilitate the development of renewable energy projects aligned with the priorities of a just energy transition in Ecuador.

6. Conclusions

Ecuador's power sector faces significant challenges in balancing the growing demand for electricity with the need to mitigate socio-environmental conflicts arising from power plants. While the country relies heavily on hydropower, its expansion has often prioritized technical and economic factors, neglecting the social and environmental dimensions critical to sustainable energy planning. This study addresses these gaps by incorporating a Multi-Criteria Decision Analysis framework to evaluate 101 renewable energy projects, including hydroelectric, solar, wind, and geothermal options, from a comprehensive perspective. The primary objective was to identify strategies for selecting and planning electricity generation projects that diversify Ecuador's energy matrix, minimize socio-environmental conflicts, and integrate environmental, technical, and social factors while safeguarding residents' welfare through inclusive stakeholder participation. The methodology involved the participation of stakeholders from academia, civil society, the public sector, and the private sector, whose inputs were obtained through interviews and analyzed using the AHP and PROMETHEE methods. This participatory approach ensured the inclusion of diverse perspectives in assessing nine criteria grouped into three clusters. The results of this study highlight the prioritization of environmental and social criteria, such as biodiversity protection, deforestation avoidance, and displacement minimization, over purely technical considerations. Fifty-five projects, with a total installed capacity of 7198.93 MW, were deemed suitable for implementation based on their alignment with stakeholder priorities, while 46 projects, representing a combined capacity of 5333.52 MW, failed to meet the criteria due to environmental risks, proximity to protected areas, or technical challenges such as poor accessibility or long distance to transmission infrastructure. This work demonstrates the value of MCDA in achieving balanced and participatory decision-making in energy planning. By addressing the limitations of traditional approaches and emphasizing the integration of multiple criteria, the study provides a roadmap for sustainable and socially acceptable energy infrastructure development in Ecuador. Furthermore, the results underscore the importance of diversifying the electricity matrix by incorporating well-evaluated technologies such as solar and wind, which showed strong performance in the MCDA. Expanding these technologies can reduce dependence on hydropower, enhance energy system resilience, and better address environmental and social considerations. Incorporating MCDA into national energy policies and enhancing mitigation strategies for socio-environmental impacts will be essential for advancing Ecuador's energy transition while safeguarding its natural and social heritage.

CRediT authorship contribution statement

Janeth Carolina Godoy: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Ricardo Cajo:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Laura Mesa Estrada:** Writing – original draft, Methodology, Investigation, Data curation. **Thomas Hamacher:** Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Janeth Carolina Godoy reports financial support for her PhD studies was provided by National Secretary of Higher Education Science Technology and Innovation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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