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Power system expansion in Ecuador: A stakeholder driven sustainability assessment of generation technologies

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ABSTRACT

Ecuador experienced severe power shortages in 2024, with blackouts lasting up to 14 h a day, exposing the vulnerability of an electricity system that relies heavily on hydroelectric plants, is affected by drought, and has seen limited investment in new capacity since 2018. In this context, the central government has begun promoting nuclear energy as a medium- and long-term option, despite the country's lack of experience with this technology and the Electricity Master Plan's identification of substantial renewable potential. This study provides a sustainability assessment of eight generation technologies for Ecuador's future energy mix: PV-US, geothermal, onshore wind, biomass, combined-cycle gas turbines, mini hydropower, small modular nuclear reactors, and conventional nuclear fission. The analysis is supported by Multi-Criteria Decision Analysis methods using ELECTRE III and HELDA (Helmholtz MCDA Tool), based on a performance matrix with 15 static baseline sustainability criteria grouped into environmental, technical, economic, and social categories, and weightings derived from a 35-stakeholder survey across the public, private, and academic sectors. Results show that stakeholders rank the availability of domestic resources as the most important criterion, followed by the leveled cost of electricity, risk to human health, and investment costs. When technologies are ranked using these weighted criteria, four renewable options (mini hydropower, onshore wind, PV-US, and geothermal) are preferred, followed by combined-cycle gas turbines and biomass, while both nuclear options are consistently ranked at the bottom. These results recommend that energy policy decisions in Ecuador should be based on transparent, stakeholder-driven assessments of technological options, rather than unilateral decisions detached from stakeholder preferences and system realities.

1. Introduction

Power outages have emerged as a central symptom of Ecuador's growing vulnerability in the electricity sector. In 2024, the country faced nationwide blackouts lasting roughly three months, with interruptions reaching almost 14 h per day at their worst [1–3]. According to the Central Bank of Ecuador, the resulting economic losses totaled US\$ 1916 million, equivalent to a 1.4% reduction in gross domestic product. Commerce (US\$ 763.1 million in losses), manufacturing (US\$ 380.2 million), and services (US\$ 374.1 million) were the most affected sectors [4]. These interruptions reflected systemic issues driven by (a) an electricity matrix heavily concentrated in hydropower, (b) a

prolonged regional drought intensified by climate variability, and (c) a decline in investment in new generation capacity since 2018.

(a) In 2025, hydropower dominated Ecuador's electricity matrix, contributing 73.61% to total generation. Fossil fuel-based thermal generation contributed 24.72%, while biomass, wind, solar photovoltaic (PV), and biogas accounted for 0.97%, 0.49%, 0.10%, and 0.11% respectively, resulting in total electricity production of 38.21 TWh [5]. Therefore, renewable technologies other than hydropower accounted for just 1.67% of total generation, underscoring Ecuador's significant reliance on hydropower. This reliance has traditionally supported a low-carbon electricity mix. However, the 2024 energy crisis exposed its vulnerability. The limited diversification of the generation portfolio

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constrained the availability of alternative electricity sources during severe droughts [5].

(b) Hydropower generation fell from 25.3 TWh in 2023 to 22.6 TWh in 2024, a reduction of 2.7 TWh [6]. This decrease resulted from the severe drought that sharply lowered reservoir levels. Climate projections for the Andes have indicated more frequent and more intense extreme droughts, driven by large-scale climate variability [7]. For Ecuador, projected climate scenarios have suggested possible reductions of up to 25% in future hydropower generation [8]. At the same time, other studies have projected higher annual precipitation, especially in the wet season, which could benefit hydropower [9]. The divergence among these projections suggests uncertainty about future water availability, raising concerns about the long-term reliability of hydropower despite its continued cost competitiveness. Climate variability and potentially more frequent or severe droughts could alter river flow, affecting hydropower generation and the financial viability of hydropower projects.

(c) According to annual electricity statistics, installed capacity increased from 6.0 GW in 2015 to 8.6 GW in 2018, a 2.6 GW increase over three years. However, over the following six years, from 2018 to 2024, capacity expansion slowed markedly. Only 0.6 GW was added, bringing the total installed capacity to 9.2 GW by 2024 [5]. Meanwhile, electricity demand grew by 28.33% between 2015 and 2024 [10]. This imbalance, characterized by strong growth in demand and minimal new capacity, has increased Ecuador's dependence on electricity imports from Colombia and Peru, with Colombia serving as the primary supplier. In 2024, Colombia exported 1266.60 GWh to Ecuador, compared to 106.07 GWh in 2018, which is more than a tenfold increase. During this period, payments for imports increased from US\$ 4.63 million to US\$ 334.5 million [5]. These rising costs are funds that could have otherwise supported domestic investment in new generation capacity and reduced the risk of future blackouts.

Taken together, dependence on hydropower, Ecuador's exposure to drought, and limited capacity expansion make it a particularly relevant case for examining how vulnerable electricity systems can diversify their generation mix. A key priority is to diversify and expand electricity generation to reduce climate-related hydrological risks and meet growing demand. Diversification must take into account Ecuador's renewable energy potential, see Fig. 1. The country benefits from high solar irradiation in coastal and Andean regions [11,12], significant geothermal reservoirs along the volcanic arc [13], suitable wind resources in the highlands [14,15], and residual biomass potential [16]. Despite this, solar, wind, geothermal, and biomass still make only marginal contributions to electricity generation. Solar PV capacity is growing but remains a small share of total output; wind farms are limited to a few projects; and geothermal energy, despite decades of exploration, has not been developed at scale, mainly due to political and regulatory constraints. A detailed examination of these institutional barriers lies beyond the scope of this work, but it is an important topic for future research. Natural gas is also underused: although Ecuador's reserves are modest and mainly associated with oil fields [17], it is a cleaner and more efficient fossil fuel and could play a transitional role in power generation.

Beyond these options, political and technical debate in Ecuador has recently begun to consider nuclear energy as a prospective alternative [19]. Although the country has no nuclear infrastructure and lacks a specific regulatory framework, growing interest in small modular reactors (SMRs) among government authorities has revived discussion about the feasibility of nuclear power [20]. According to the International Atomic Energy Agency (IAEA), there are more than 80 SMR designs and concepts worldwide, which are at different stages of development. However, only a few are close to deployment. Four SMRs are currently under advanced construction in Argentina, China, and Russia [21], indicating that global SMR deployment remains limited and entails long development and construction periods. While Colombia and Peru, Ecuador's main electricity suppliers, do not yet include

nuclear power in their generation mixes, their planning agencies have begun exploratory assessments for possible future deployment [22,23]. In contrast, Ecuador's power sector roadmap, the Master Electricity Plan 2023–2032, foresees the addition of around 7100 MW of new capacity by 2032. This includes 3700 MW of hydropower, 585 MW of onshore wind, 1000 MW of solar PV, 1700 MW of thermal power plants, 30 MW of biomass power, and 50 MW of geothermal power. Notably, there is no mention of nuclear power [18].

In Ecuador, government institutions primarily lead energy-sector planning. The Ministry of Environment and Energy formulates policies and plans, and the Electricity Regulation and Control Agency (ARCONEL), the National Energy Control Center (CENACE), and the Institute for Geological and Energy Research (IIGE) play key roles in administering the sector. However, energy planning processes have often provided limited opportunities for affected communities and other non-governmental actors to participate. In a country characterized by substantial biodiversity and cultural diversity, this limited inclusion has contributed to social discontent over the expansion of hydropower, the country's main source of electricity. This opposition extends beyond indigenous peoples and directly affects local communities and a broader range of social groups. However, hydropower must be properly understood. Most of the country's installed hydroelectric capacity, and many of the social and environmental conflicts, are associated with hydroelectric plants that include reservoirs. Such projects can involve the flooding of land, the displacement of people, changes in river flow regimes, the loss of biodiversity, and conflicts over access to water and the distribution of benefits. A detailed discussion of socio-environmental conflicts associated with hydropower development in Ecuador can be found in Godoy et al. [24]. In contrast, the small-scale hydropower option evaluated in this study represents a configuration without a reservoir. As it does not require water storage, it is less exposed to reservoir-related vulnerabilities. However, small scale hydropower is not assumed to be impact free; its assessment considers environmental and social effects relevant to the local context.

This situation exemplifies a broader challenge in sustainable energy transitions: reconciling the preferences and priorities of stakeholders, including government agencies, industry, consumers, local communities, and environmental organizations, whose interests, objectives, and evaluation criteria often differ significantly. Participatory approaches are therefore necessary to identify and take into account these perspectives in decision-making processes. Policymakers must not only collect stakeholder views but also integrate them transparently into the design and implementation of the energy transition [25,26]. Participatory multi-criteria approaches can make these trade-offs explicit by assessing alternative energy pathways against economic, environmental, social, technical, and institutional criteria.

Ecuador is a particularly relevant case for addressing this challenge. Its power sector planning would benefit from a more participatory, multi-criteria approach that moves beyond purely techno-economic considerations and systematically engages stakeholders throughout the decision-making process. Building on this premise, the study is guided by two research questions and pursues two analytical objectives and one policy-oriented objective, which are presented below:

Research Questions:

1. Which sustainability criteria do different stakeholders see as most relevant for guiding technology choices in Ecuador's future electricity system?
2. How does a new option for Ecuador, such as nuclear power plants, compare with existing technologies like hydropower plants, onshore wind farms, solar PV power plants, thermal power plants based on residual biomass and natural gas, and geothermal, when evaluated through a stakeholder-driven multi-criteria sustainability assessment?

Objectives:

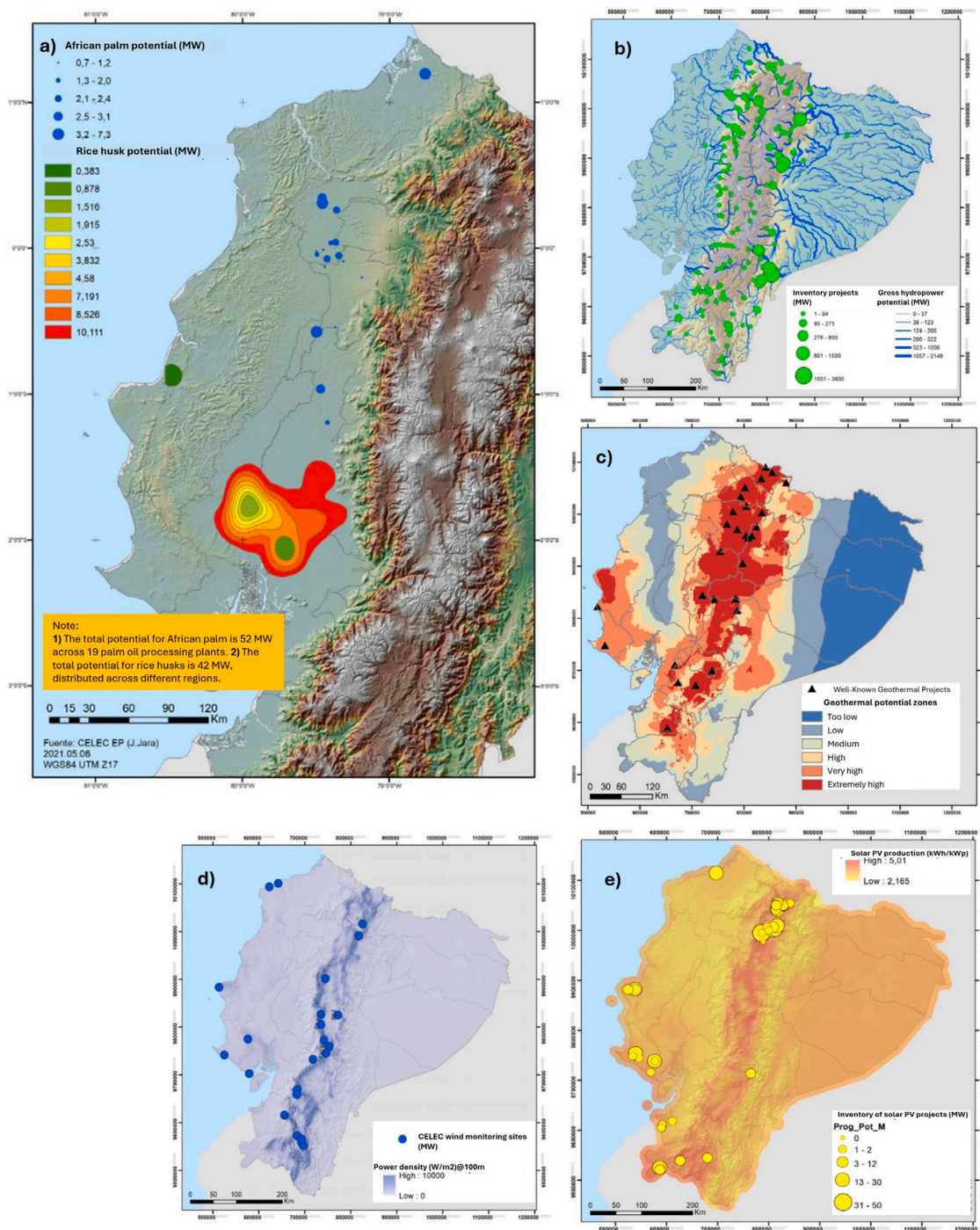


Fig. 1. Maps of renewable energy resource potential in Ecuador. (a) Bioenergy potential of African palm and rice husks, (b) Gross linear hydropower potential and hydropower projects; (c) geothermal potential and geothermal prospects; (d) wind-energy potential and wind projects; and (e) photovoltaic solar potential. Source: Taken from [13,18].

1. To identify and describe the sustainability criteria that experts consider most relevant for assessing power-generation technologies in Ecuador.
2. To examine how experts' preferences and relative weighting of these criteria influence the ranking of alternative power-generation technologies, and to evaluate the sustainability performance of these alternatives.
3. To provide a structured basis for policy advice on the sustainable expansion of Ecuador's electricity sector, particularly in a

context where nuclear energy is gaining prominence and non-hydropower renewable technologies remain underdeveloped.

To address these objectives, this study conducts a sustainability assessment of eight power generation technologies in Ecuador: small hydropower plants without reservoirs (up to 5 MW), utility-scale solar PV plants (PV-US), onshore wind farms, geothermal power plants, biomass-fired power plants, combined-cycle natural gas power plants, small modular nuclear reactors, and conventional nuclear fission power

plants. These technologies are evaluated against fifteen sustainability criteria organized into four categories: technical, economic, environmental, and social. The assessment uses Multi-Criteria Decision Analysis (MCDA) with the Helmholtz MCDA Tool (HELDA) [27,28]. The assessment incorporates the perspectives of three stakeholder groups, academia, the public sector, and the private sector, at different stages of the MCDA process, resulting in a stakeholder-driven assessment.

As the study is based primarily on secondary data and stakeholder judgments, the study is best understood as a strategic comparison that complements the Electricity Master Plan by informing the near- and medium-term prioritization of established renewable options and the longer-term evaluation of emerging alternatives such as nuclear energy, rather than as a tool for approving or rejecting specific projects.

This study's novelty lies in its empirical approach, which involves collecting and analyzing data on how different stakeholder groups assess the sustainability of future power-generation options in Ecuador. It brings together the perspectives of academia, the public sector, and the private sector, identifying the criteria and trade-offs that are important to these groups but which may not be fully reflected in conventional planning processes. The study provides a framework for incorporating these views into future electricity planning in Ecuador. This framework can inform decisions on diversifying the electricity mix and mitigating the risks associated with heavy reliance on hydropower. This approach could also be relevant to other countries facing similar drought-related risks that need to plan for a more reliable and sustainable electricity system.

To guide the reader through the study and its main findings, the article is organized as follows. Section 2 presents the conceptual foundations, reviews methodologies applied in previous studies, and identifies the research gaps addressed in other work. Section 3 describes the methodology used in the study. Section 4 presents and discusses the results, including the sensitivity analysis and policy implications. Section 5 discusses the limitations of the study and identifies directions for future research. Finally, Section 6 presents the main conclusions.

2. Conceptual foundations

The sustainable energy transition is a major challenge for society, science, and industry. It involves not only moving toward a more efficient energy system, but also managing environmental and social costs, risks, and benefits in line with sustainable development [29]. The following sections briefly introduce the concept of sustainability, the main methods used for sustainability assessment, and their application in the Ecuadorian energy context.

2.1. Sustainability assessment of energy technologies

Sustainability is generally understood as meeting present needs without compromising the ability of future generations to meet their own [30–32]. This idea is commonly operationalized through the environmental, economic, and social dimensions of the Triple Bottom Line [33,34]. It is especially relevant to energy technologies, whose benefits in terms of electricity supply or lower emissions may also involve long-term environmental, social, or economic consequences. The United Nations Sustainable Development Goals (SDGs) provide a widely used framework for applying these principles. Their 17 goals link environmental protection, social well-being, and economic development, including objectives related to health, clean energy, decent work, and responsible consumption [35]. In this way, the SDGs help broaden the assessment of energy technologies beyond electricity output and greenhouse gas emissions. A sustainability assessment must therefore consider more than technical and economic performance. Different energy technologies can affect land and material use, biodiversity, human health, water resources, infrastructure, and local living conditions [36–38]. Translating these effects into clearly defined, transparent criteria enables consistent comparison of alternatives and identification of the main trade-offs involved [39].

2.2. Stakeholders integration in sustainability assessment

Sustainability assessments of energy technologies need to consider multiple, often conflicting, technical, economic, environmental, and social criteria. In this context, various assessment approaches have been developed to support energy-sector decision-making, including methods that address uncertainty, stakeholder preferences, and interactions among criteria [40–42]. However, the value of a sustainability assessment depends not only on the method applied but also on the meaningful involvement of stakeholders throughout the process. Stakeholders may include decision-makers from industry and government, policymakers, citizens, and non-governmental organizations (NGOs). They can contribute to the selection of alternatives, the definition of criteria and indicators, and the weighting of sustainability criteria [43]. This involvement is important because sustainability assessments reflect societal values, priorities, and trade-offs, as well as technical evidence. Several studies have integrated stakeholder perspectives in a structured manner. For example, Schär and Geldermann [44] applied Multiactor Multicriteria Analysis (MAMCA), combined with PROMETHEE, to evaluate energy-transition pathways in Germany, demonstrating how different stakeholder objectives can be incorporated into the assessment. John et al. [45] combined Life Cycle Assessment (LCA) with the Analytic Hierarchy Process (AHP) to assess renewable-energy options in rural Malaysia, integrating environmental information with stakeholder-informed criteria weights. Nevertheless, methodological reviews identify persistent gaps in stakeholder integration in sustainability assessments. Wulf et al. [43] found that many applications involve experts, whereas civil-society actors are included less frequently. Stakeholders are most commonly involved in weighting criteria, while their participation in selecting criteria and alternatives, or in discussing results, is less common. Other studies have identified challenges related to inappropriate weighting methods, mismatches between assessment methods and decision contexts, and limited stakeholder participation [46,47]. Sensitivity and robustness analyses can help examine how changes in stakeholder-defined weights affect assessment results [48].

2.3. Methodologies for sustainability assessment

A range of methods is used to assess the sustainability of energy technologies, each addressing different dimensions. Life Cycle Assessment quantifies environmental impacts across a technology's life cycle, including greenhouse-gas emissions, land use, water consumption, air pollution, and resource depletion [49,50]. However, it does not directly capture economic feasibility, social acceptance, or system-reliability considerations. Life Cycle Costing (LCC) and Techno-Economic Analysis (TEA) assess economic and technical performance through indicators such as levelized cost of energy, capital and operating expenditures, net present value, and fuel costs [51,52]. Although these approaches are important for examining financial viability, they generally exclude social effects and environmental externalities unless these are monetized [53]. Life Cycle Sustainability Assessment (LCSA) combines LCA, LCC, and Social Life Cycle Assessment to address environmental, economic, and social dimensions [54,55]. Its application, however, is constrained by limited data for social indicators and difficulties in integrating quantitative and qualitative information.

While the methods described above are widely used in sustainability assessment, they often focus on specific dimensions and may not directly compare alternatives across all relevant criteria. Multi-Criteria Decision Analysis (MCDA) can complement these methods by integrating diverse indicators and supporting transparent comparisons among alternatives [56,57]. MCDA can combine quantitative and qualitative criteria within a single assessment framework. It helps organize available information, aggregate criteria, and incorporate the preferences of experts and stakeholders in a transparent and traceable way. In assessments of solar PV, wind, geothermal, biomass, natural-gas, and nuclear technologies, MCDA has been used to integrate environmental indicators derived from LCA [51], economic metrics from TEA [52], and social criteria obtained through surveys or expert judgment [58].

2.4. MCDA for sustainability assessment in the Ecuadorian context

Although the literature on the sustainability assessment of energy technologies in Ecuador is limited, some studies have emerged that focus mainly on sustainability assessment and spatial planning for renewable energy projects. These applications are often combined with geographic information systems (GIS) to identify suitable locations for different energy projects, taking into account technical, environmental, and infrastructure-related conditions. Most studies focus on the suitability of specific sites for particular technologies rather than comparing alternative electricity generation technologies. Several studies have analyzed the deployment of solar energy. Quinteros et al. [59] applied a multi-criteria approach based on the Analytical Hierarchy Process (AHP) to identify suitable locations for large-scale photovoltaic projects in Azuay, finding that only a limited number of areas met the required conditions. Zambrano-Asanza et al. [60] developed an MCDA–GIS framework that included electricity load distribution, demonstrating the importance of considering demand-side information when selecting photovoltaic sites. At a national level, Villacreses et al. [61] compared seven MCDA methods for assessing photovoltaic site suitability, identifying areas with high potential for solar development and finding a high degree of consistency among the methods. MCDA–GIS approaches have also been used to evaluate other renewable resources. Villacreses et al. [62] conducted a nationwide assessment of suitable locations for onshore wind farms and identified areas of high potential in the Andean region. Salinas-León and Ochoa-Correa [63] used MCDA to identify suitable locations for hydrokinetic turbines, taking hydrological and environmental criteria into account. Godoy et al. [24] go one step further and present a nationwide assessment that incorporates stakeholder preferences. Using PROMETHEE, they ranked 101 renewable energy projects and demonstrated that priorities can vary among different stakeholder groups. However, this study focused on site-specific renewable energy projects and did not compare renewable, fossil fuel, and nuclear technologies within a common sustainability framework. Although the aforementioned studies use MCDA to evaluate certain energy technologies, their scope and limited stakeholder engagement restrict their applicability to a comprehensive assessment of the sustainability of energy technologies in Ecuador. These gaps are discussed in the following section.

2.5. Identified research gaps

- **Lack of comprehensive cross-technology sustainability assessments.** Existing national studies mainly focus on spatial suitability analyses for individual renewable technologies. They do not use a common multi-criteria framework to compare renewable, fossil-fuel, and nuclear electricity-generation technologies. As a result, the available evidence provides limited support for decisions on energy security, diversification, and planning.
- **Limited integration of stakeholder perspectives in technology-level assessments.** Although stakeholder participation has been incorporated in some studies, it has seldom been used to compare alternative electricity-generation technologies. Consequently, there is limited understanding of how sustainability priorities and technology preferences differ among academic, public-sector, and private-sector stakeholders.
- **Weak linkage between sustainability assessment and generation-expansion planning.** Existing Ecuadorian studies provide limited evidence on the sustainability trade-offs involved in diversifying a hydropower-dominated electricity system under hydrological uncertainty, rising electricity demand, delays in bringing new capacity online, and reliance on electricity imports during supply shortages. This limits the stakeholder-informed evidence available to evaluate alternative technology pathways for future generation expansion.

These research gaps have motivated the development of a stakeholder-driven sustainability assessment framework to inform the future expansion of Ecuador's electric power system. This framework's strength lies in its evaluation of energy technologies across multiple criteria, rather than solely on economic performance. These criteria are adapted to Ecuador's specific context and encompass technical feasibility, economic performance, social, and environmental impacts. Furthermore, the framework enables an evidence-based comparison of established renewable and fossil fuel technologies with emerging nuclear options, such as small modular reactors. This comparison has not been made before. The sustainability assessment framework is intended to complement, rather than replace, generation expansion models. By incorporating stakeholder preferences and context-specific sustainability criteria, it serves as a preliminary technology-screening and prioritization step to identify socially and environmentally suitable options for further evaluation.

3. Methodological approach

3.1. MCDA framework

This work adopts Multi-Criteria Decision Analysis as a general framework for assessing the sustainability of energy technologies. Fig. 2 presents the MCDA framework as adapted for this case study. It comprises nine main steps, four of which involve stakeholder participation.

3.1.1. Objective definition

As explained in Section 1, this study has two analytical objectives that guide the application of Multi-Criteria Decision Analysis.

- To identify and describe the sustainability criteria that experts consider most relevant for assessing power-generation technologies in Ecuador.
- To examine how experts' preferences and relative weighting of these criteria influence the ranking of alternative power-generation technologies, and to evaluate the sustainability performance of these alternatives.

3.1.2. Identification of stakeholder groups

As discussed in Section 2.2, stakeholder integration is a central element of MCDA for sustainability assessment. Although stakeholders may ideally participate throughout the process, their involvement is often limited to assigning indicator weights through surveys, interviews, or workshops [64]. In this study, stakeholder participation was extended beyond the weighting stage, with stakeholders contributing to the selection of sustainability criteria and alternatives, the development of the performance matrix, and the weighting of the sustainability criteria. Stakeholders from the public sector, private sector (industry), and academia were selected based on their expertise in Ecuador's electricity sector. Participants were identified through their current or previous professional roles and work experience in the institutions listed in Table 1, which provided evidence of their relevant sectoral expertise. Table 1 summarizes the participating institutions, the participants' roles within those institutions, and their respective stakeholder groups. These groups were included because they offer complementary perspectives on power-system development: public-sector participants contribute knowledge of regulation, policy, and planning; private-sector participants provide experience in investment, project development, and implementation; and academic participants contribute multidisciplinary scientific expertise. Potential experts were identified primarily through the professional networks of the Ecuadorian co-authors, complemented by contacts from institutions involved directly or indirectly in the investment, planning, design, and implementation stages of electricity-generation projects. Civil-society representatives were not included because the assessment focuses on

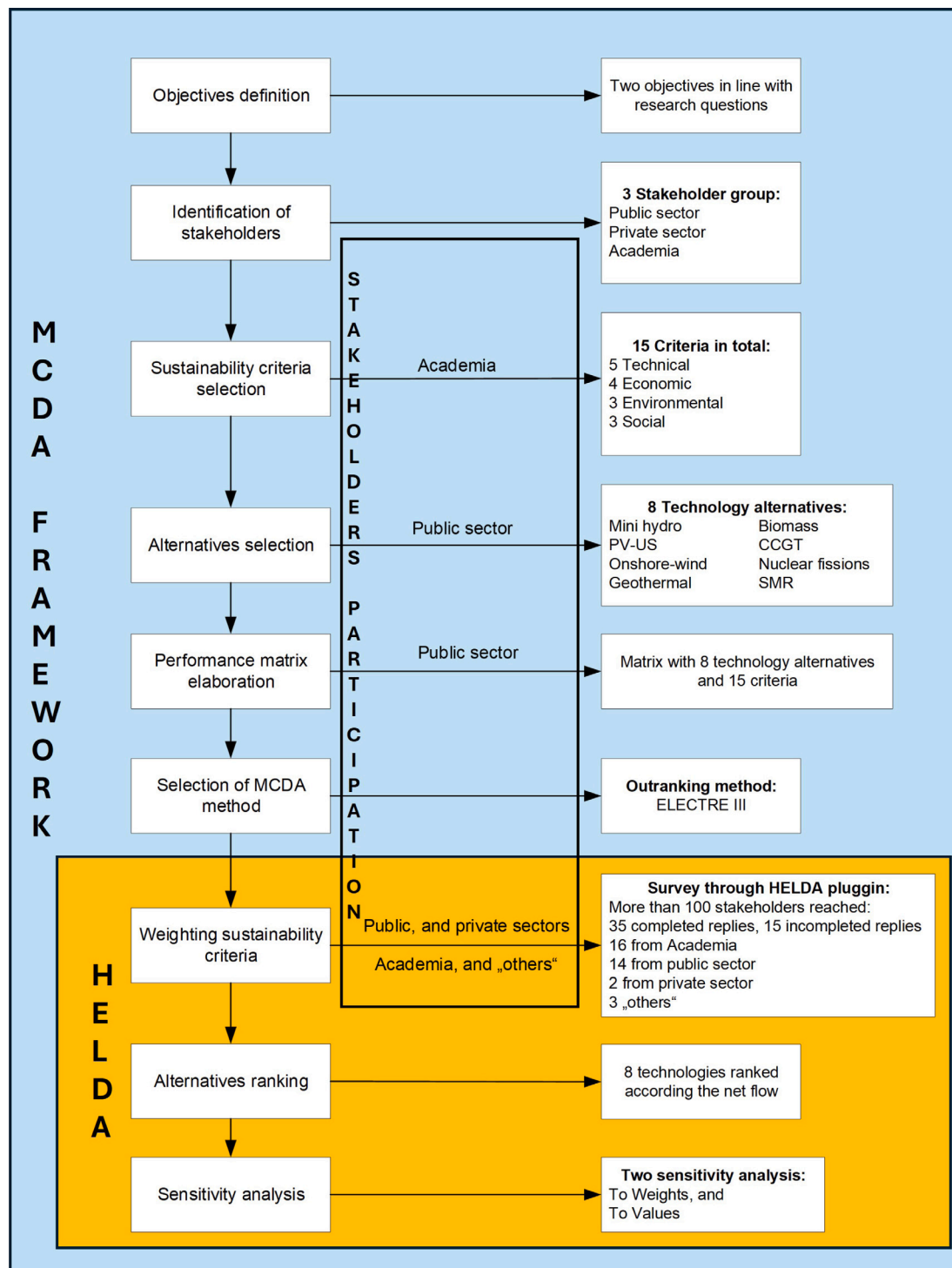


Fig. 2. MCDA framework based on [24,43].

stakeholders with specialized expertise in the electricity sector. Nevertheless, future research should incorporate civil society perspectives to support a more inclusive assessment of technological alternatives for electricity sector expansion.

For the *sustainability criteria selection*, four academics from ESPOL University reviewed the initial set of criteria identified in the literature and adapted it to the Ecuadorian context. They examined potential overlaps, redundancies, and omissions, and refined the final set of criteria for the assessment. The methodology followed for this review

is described in Section 3.1.3. For the *selection of alternatives* and the *development of the performance matrix*, a public-sector expert from CELEC EP was consulted. The expert had more than six years of experience in the institution's Prospective Department, which conducts studies on the future expansion of electricity-generation technologies. The expert reviewed the proposed alternatives and validated their relevance to Ecuador's generation-expansion planning. In addition, the expert examined the initial performance matrix and adjusted the values to reflect Ecuador-specific data and operating conditions. These procedures

Table 1
Identified stakeholders across sectors.

Institution name	Stakeholder's activities	Stakeholder group
Ministry of Environment and Energy	High-level decision-makers and technical staff responsible for electricity infrastructure expansion and the elaboration of the Ecuadorian Master Electricity Plan.	Public sector
Corporación Eléctrica del Ecuador (CELEC EP)	Decision-makers and technicians who worked at the public utility responsible for around 90% of electricity generation in Ecuador, which was the main developer of power generation projects in the country between 2009 and 2018.	Public sector
Elecaustro	High-level authorities and technical staff responsible for power generation in southern Ecuador.	Public sector
University of Cuenca	Researchers specializing in electrical engineering and renewable energy integration.	Academia
University of Azuay	Researchers specializing in renewable energy potential assessment and small hydropower.	Academia
Escuela Superior Politécnica del Litoral (ESPOL)	Researchers focused on developing and innovating products that promote sustainable energy systems, grounded in social responsibility and respect for the environment.	Academia
Central University (UCE)	Researchers focused on reducing environmental impacts and resource use by improving efficiency and integrating new energy sources into the energy and production mix.	Academia
Project developers and investors	Private investors on renewable energy.	Private sector

are described in Sections 3.1.4 and 3.1.5. Finally, during the *sustainability criteria weighting* phase, participants from the public, private, and academic sectors assigned weights to the selected criteria. Their preferences were collected through the structured procedure described in Section 3.1.7.

3.1.3. Sustainability criteria selection

A targeted literature search was conducted to identify sustainability criteria used to assess electricity-generation technologies. Elicit, an AI-based scientific search assistant, was used to identify relevant academic publications. The following question guided the search:

What key performance indicators and sustainability criteria have been used to assess renewable and non-renewable energy technologies between 2015 and 2025?

Using this query, Elicit performed a semantic search of academic publications and retrieved 497 studies for abstract-level screening. Studies were retained if they met the following eligibility criteria: (i) Does the study address renewable energy technologies, such as solar, wind, hydropower, geothermal, biomass, or other renewable sources? (ii) Does the study address non-renewable energy technologies, such as coal, oil, natural gas, nuclear energy, or other fossil-fuel-based energy systems? (iii) Does the study identify, propose, or apply specific key performance indicators or sustainability criteria that can be measured? (iv) Does the study address at least one of the following performance dimensions: environmental, social, technical, or economic? (v) Was the study published between 2015 and 2025? (vi) Was the study published as a peer-reviewed journal article or conference proceeding? (vii) Can sustainability criteria be clearly identified and extracted from the study? The abstract-level screening yielded 42 sources published

between 2015 and 2025. The authors subsequently reviewed these studies and excluded five that did not match the scope of this work. Specifically, [65] addresses biodiesel production rather than electricity generation; [66] examines hydrogen production unrelated to electricity generation; [67] evaluates battery technologies not considered in this assessment; [68] does not specify concrete sustainability criteria; and [69] focuses on energy-storage systems, which are also outside the scope of this study. The final sample comprised 37 studies, including seven review articles and 30 research articles shown in Table A.9 in Appendix A with their respective references. Table A.10 summarizes the sustainability criteria extracted from these studies. Indicators with equivalent meanings were consolidated under a single label; for example, “land use” and “land requirement” were grouped as “land use”.

The selected criteria reflect the search strategy and eligibility criteria applied in this study. Different search parameters or inclusion criteria could have produced a different set of indicators. Because this study does not aim to provide an exhaustive systematic review of all sustainability criteria reported in the literature, but rather to identify a relevant set of indicators for assessing electricity-generation technologies in Ecuador, the targeted approach was considered appropriate.

Table A.10 was subsequently reviewed by four Ecuadorian academics with experience in assessing electricity-generation technologies in the country. The online consultation was conducted via Zoom and focused on evaluating the relevance of the 49 criteria identified in the literature for Ecuador's context. The consultation followed a structured process. First, one author introduced the study objectives and explained how the initial list of criteria had been compiled. Second, Table A.10 was shared on screen, allowing participants to ask questions about the study and the intended use of the criteria. Third, the academics reviewed each criterion and indicated whether it should be retained. Where appropriate, they explained why an indicator would be difficult to apply in Ecuador, for example, because of data limitations or institutional constraints. The discussion lasted approximately three hours and continued until consensus was reached among all four participants. Based on this consensus, the initial set of 49 sustainability criteria was reduced to 15 indicators for use in this study. These indicators and their definitions are presented in Table 2. The units of measurement and direction of preference for each sustainability criterion are reported in Table 4, while the corresponding data sources are listed in Table B.11.

According to the academics, as this study provides a comparative assessment of electricity-generation technologies rather than an assessment of individual projects, some indicators were considered outside its scope. The excluded criteria are: energy efficiency, energy yield, distance to transmission lines, infrastructure accessibility, reliability, maintenance requirements, technical risk, payback time, revenue, profitability, ecosystem impacts, community displacement, visual impacts, noise, and contributions to rural development.

For the technical dimension, the academics selected to keep criteria relevant to Ecuador's long-term electricity planning that can be assessed using reliable information. Capacity factor, resource availability, service life, and technology maturity were retained to reflect operational performance, domestic resource security, and technological development. Average construction time was also included, given the importance of bringing new capacity online within a reasonable timeframe and Ecuador's experience with delayed energy projects.

For the economic dimension, LCOE, CAPEX, and OPEX were retained because they capture complementary aspects of economic performance. CAPEX represents the initial investment required to build a plant; OPEX reflects recurring operations and maintenance costs; and LCOE estimates the average cost of electricity over the plant's lifetime. Fuel costs were also included because Ecuador's dependence on imported fuels affects electricity prices and energy security.

For the environmental dimension, detailed life-cycle impact categories, including acidification, eutrophication, ozone depletion, photochemical ozone formation, and ecotoxicity, were excluded because

Table 2
Sustainability criteria for the Ecuadorian study case.

Number	Cluster	Sustainability criteria	Description
1	Technical	Technology Readiness Level (TRL) ^b	Maturity and state of development of an energy technology, from initial research to commercial implementation.
2	Technical	Capacity factor ^a	The ratio between the actual electrical energy generated by a power plant and the maximum theoretical electricity it could have produced if it had operated at full capacity for a given period, usually one year.
3	Technical	Resource availability ^a	Amount of resources (both renewable and non-renewable) that a country has available to produce electricity
4	Technical	Service life ^b	Expected useful life, or acceptable period of service use for an energy technology.
5	Technical	Average construction time ^b	Average time it takes to build a power plant, from the start of construction until it is ready to operate, not including the time required to obtain operating permits.
6	Economic	Capital Expenditure (CAPEX) ^a	The upfront costs to build renewable energy projects
7	Economic	Operational Expenditure (OPEX) ^a	The recurring, day-to-day costs of running renewable energy projects,
8	Economic	Levelized Cost of Electricity (LCOE) ^a	The average cost of generating electricity over the lifetime of a power plant.
9	Economic	Fuel cost ^a	Direct expenses arising from the purchase of fuel to generate electricity
10	Environmental	Land use intensity ^a	Land area required to produce one unit of electrical energy
11	Environmental	Lifecycle CO ₂ e emissions ^a	A metric that quantifies total greenhouse gas emissions per unit of energy produced, covering the entire life cycle, from raw material extraction to final disposal.
12	Environmental	Blue water consumption ^a	Surface or groundwater consumed through the life cycle of the power plant to produce one unit of power
13	Social	Risk for human health ^a	Health risks associated with hazardous substances throughout the life cycle of these technologies.
14	Social	Local employment factor ^a	Number of jobs created during the construction phase of the power plant
15	Social	Trained professionals ^a	Number of undergraduate and graduate programs specializing in energy technologies offered by higher education institutions in the country.

Notes:

^a Criteria kept from the literature search.

^b Criteria added by the academics.

their assessment would require a technology-specific life-cycle assessment. Life-cycle CO₂e emissions were retained as a practical indicator of climate impacts. Land use and water consumption were also included because they are relevant to Ecuadorian power-sector planning and potential social-environmental conflicts. Waste generation and critical raw material use were excluded because they are more appropriately addressed through project-specific Environmental Impact Assessments and supply chain analysis, respectively.

For the social dimension, social acceptance, public engagement, gender impacts, and occupational health were not retained because their assessment would require broader social consultation or project-level analysis. Local employment during construction and the training of professionals were included because they are particularly relevant in Ecuador, where employment opportunities are limited and skilled professionals often migrate. Training was considered especially important because it can support local participation in long-term operation and maintenance activities.

3.1.4. Technology alternatives selection

In 2025, Ecuador had an installed electricity-generation capacity of 8879.39 MW. Hydropower accounted for the largest share, at 5387.42 MW (60.67%), followed by internal-combustion-engine (ICE) thermal plants at 1980.08 MW (22.30%). Other fossil-fuel-based capacity consisted of gas turbines (808.05 MW) and steam turbines (446 MW). Non-conventional renewable sources accounted for only 2.90% of total installed capacity: biomass plants, mainly fueled by bagasse, provided 148.50 MW; wind farms, 71.13 MW; solar photovoltaic plants, 28.24 MW; and biogas plants based on organic waste, 11.12 MW [70].

Given the country's realities, the technological alternatives considered in this sustainability assessment were selected in line with Ecuador's Electricity Master Plan (PME), which guides the long-term development of the electricity sector. Hydropower was included because it is Ecuador's dominant generation technology and is expected

to remain central to the national electricity system. The country has accumulated substantial experience in hydropower development and operation since the installation of its first hydraulic turbines in 1897 [71]. Under normal hydrological conditions, hydropower supplies approximately 80% of annual electricity demand in the National Inter-connected System. The PME further identifies considerable untapped hydroelectric potential; a 2020 CELEC EP assessment estimated that projects larger than 5 MW could provide up to 24,896 MW of additional capacity [18]. The PME also identifies opportunities to expand other renewable technologies. It estimates approximately 500 MW of onshore wind potential, concentrated mainly in the Andean highlands, and highlights the substantial photovoltaic potential available throughout the country, particularly in the inter-Andean corridor. In addition, the national Bioenergy Atlas identifies nearly 1000 MW of gross potential from agricultural, livestock, and forestry residues. However, further analysis is required to determine the technically and economically feasible capacity. The PME also identifies more than 20 prospective geothermal sites, with an estimated combined potential exceeding 900 MW [18]. In addition to renewable technologies, the PME considers expanding natural-gas-fired generation to reduce dependence on more polluting thermal fuels, particularly diesel and fuel oil [18].

Other studies suggest that Ecuador's resource potential may exceed the estimates reported in the PME. For example, a GIS-based assessment estimated photovoltaic potential at 15 GW [72]; other studies reported 1.67 GW of onshore wind potential [15] and geothermal potential exceeding 1 GW [13]. The U.S. Energy Information Administration estimates Ecuador's proven natural-gas reserves at 385 billion cubic feet [73].

Nuclear power was included as an emerging, prospective alternative. Although Ecuador does not currently operate nuclear power plants and no national estimate of nuclear-resource potential is available, the government has announced plans to develop a 300 MW small modular reactor in the medium term and a 1000 MW nuclear power plant in the longer term [74].

Table 3
Technology alternatives included in this analysis.

Resource	Technology alternative	Name used on this work
Water	Hydro power plants with an installed capacity up to 5 MW	Mini hydro (without reservoir)
Solar radiation	Utility scale solar PV power plants	Photovoltaic Utility Scale (PV-US)
Wind	Onshore wind farms	Onshore-wind
Geothermal heat	Geothermal power plants	Geothermal
Agricultural, livestock, and forestry waste	Biomass power plant: Steam Rankine Cycle	Biomass SRC
Natural gas	Combined cycle gas turbine	CCGT
Uranium	Fission nuclear power plants	Nuclear fission
Uranium	Small modular reactors	SMR

This preliminary list of technology alternatives was reviewed in a brief online consultation with a power-sector planning expert from CELEC EP. The expert emphasized the importance of assessing small rather than large hydropower, given the potential role of smaller projects in Ecuador's future electricity expansion. Drawing on experience in feasibility studies for projects below 5 MW, the expert noted that small hydropower can have shorter construction periods than large reservoir-based plants, generally lower environmental impacts, and greater potential to supply remote areas by using local rivers and streams. Depending on site conditions and proximity to existing electricity infrastructure, these plants can operate either as grid-connected generation or as off-grid systems for isolated communities.

Based on the resource potential identified in the PME, supporting literature, the expert consultation, and Ecuador's current policy context, this study evaluates eight representative electricity-generation technologies: mini-hydropower, solar photovoltaic, onshore wind, biomass, geothermal energy, natural-gas-fired generation, and nuclear power, including small modular reactors. These alternatives are presented in Table 3.

3.1.5. Performance matrix elaboration

To develop the performance matrix, a consistent evaluation framework and clearly defined system boundaries are required [36]. The assessment uses 2024 as the base year; therefore, all cost data and underlying assumptions refer to this period. Mainland Ecuador constitutes the spatial boundary of the analysis. The system boundary encompasses the eight electricity-generation alternatives listed in Table 3, along with their relevant upstream and downstream processes. Energy storage, demand-side management, energy efficiency, regional electricity trade, transmission expansion, and hybrid renewable-energy systems are not included. These options concern flexibility, demand-side measures, cross-border exchange, network development, or integrated-system configurations rather than stand-alone generation technologies. Their assessment would require different alternatives, criteria, and modeling approaches.

The performance matrix evaluates each technology alternative against the sustainability criteria presented in Table 2. It compiles the performance value of every alternative for each criterion, thereby enabling a consistent comparison across technologies. The direction of preference is reported as “max.” or “min.” where “max.” indicates that higher values are preferred, whereas “min.” indicates that lower values are preferred.

The initial values were derived from secondary data, technical reports, peer-reviewed literature, and national statistics. Their sources, assumptions, units, and initial values are provided in Table B.11 in Appendix B. Where several sources provided comparable values, the most recent values were used. When the available sources reported different values, the average of the most recent estimates was applied.

All economic values are expressed in 2024 US dollars; values from earlier years were adjusted for inflation. For fuel-cost estimates, hydropower, wind, and solar photovoltaic technologies were assumed to have no fuel costs because their primary energy resources (water, wind,

and solar radiation) are available without direct purchase. For biomass, fuel costs include the collection, transport, and storage of agricultural, livestock, and forestry residues, but not the cost of the residues themselves. The Electricity Master Plan provides detailed maps of Ecuador's hydropower, wind, solar photovoltaic, and geothermal potential [18], while the Bioenergy Atlas presents the geographical distribution of biomass resources [16]. Because these resource assessments and maps are already comprehensively documented in those sources, reproducing them is beyond the scope of this study.

For technologies not yet deployed in Ecuador, specifically nuclear fission and small modular reactors, the assessment relies on international evidence. In the absence of national operating experience and locally validated data, these values are not country-specific and are subject to greater uncertainty. To clarify potential relationships between criteria, Roy (2016) notes that criteria within an MCDA framework do not necessarily need to be independent, as the concept of independence is complex. However, the criteria family should remain non-redundant [75]. For example, the “Resource Availability” criterion refers to the domestic availability of primary energy resources. For nuclear energy, this criterion was assigned a value of zero because no domestic uranium resources were considered available in Ecuador for this assessment. This criterion differs from the “Fuel Cost” criterion, which evaluates the economic and strategic conditions associated with fuel procurement. Although both criteria are affected by the need to import uranium, they address distinct concerns: resource sovereignty and the cost of external fuel supply.

Several criteria could not be expressed as precise quantitative values because of limited data availability. Average construction time, risk for human health, employment factor, and trained professionals were therefore assessed using ordered categories of low, medium, and high, based on documented evidence and expert judgment. For average construction time, “low” refers to less than two years, “medium” to two to four years, and “high” to more than four years. The qualitative risk scale for human health reflects the inherent hazards and typical exposure pathways associated with each technology. For solar photovoltaic and wind technologies, potentially hazardous materials, including lead, cadmium, epoxy resins, and styrene, are generally encapsulated or used in limited quantities; under appropriate design and operation, typical exposure is low [76,77]. Geothermal facilities handle mineralized fluids, but effective containment and reinjection can limit environmental and human exposure [78]. Natural-gas generation entails risks associated with methane leakage and combustion emissions. In contrast, biomass generation may expose workers and nearby communities to organic dust and bioaerosols during fuel handling and storage [79,80]. These technologies were therefore assigned an intermediate risk level. Nuclear fission, including SMRs, was assigned a high-risk level because radiological hazards and the need for long-term radioactive-waste management remain inherent to the nuclear fuel cycle. However, Generation III+ and Generation IV SMR concepts can incorporate inherent and passive safety features that reduce reliance on active systems and operator intervention and may reduce the likelihood and consequences of accidental releases [81]. The high-risk classification therefore does

Table 4
Performance matrix for analyzed energy technologies adjusted to the Ecuadorian case.

Sustainability criteria	Unit	Preference	Mini Hydro	Nuclear fission	CCGT	SMR	PV-US	Onshore-wind	Geothermal	Biomass SRC
TRL	–	max.	9	9	9	6	9	9	9	9
Capacity factor	%	max.	90	83	59.7	85	20	50	90	85
Resource availability	GWh	max.	47,304	0	5,774,134	0	26,280	7314	7884	7446
Service life	years	max.	100	60	30	50	25	25	25	25
Average construction time	–	min.	High	High	Medium	Medium	Low	Low	High	Low
CAPEX	\$/kW	min.	3000	11,901	1463	6900	800	1041	4015	3242
OPEX	\$/kW/year	min.	90	357.03	43.89	207	24	31.23	120.45	97.26
LCOE	\$/kWh	min.	0.055	0.065	0.09	0.08	0.055	0.034	0.06	0.097
Fuel cost	\$/MWh	min.	0	8.66	47.22	8.66	0	0	0	42.47
Land use intensity	m ² /GWh/year	min.	4000	71	800	75	20,000	120,000	404	1300
Lifecycle CO ₂ e emissions	gCO ₂ e/kWh	min.	3	13	486	13	43	13	37	52
Blue water consumption	l/MWh	min.	330	2290	598	1891	330	43	1022	1360
Risk for human health	–	min.	Low	High	Medium	High	Low	Low	Low	Medium
Employment factor	–	max.	Medium	High	Low	High	Low	Low	Medium	Medium
Trained professionals	–	max.	High	Low	High	Low	High	High	High	High

not imply high routine exposure during normal operation; rather, it reflects the potentially severe consequences of radiological releases and the long-term responsibility for radioactive-waste management, even under modern safety provisions [82].

The initial matrix was reviewed and refined through an individual online interview with the CELEC EP planning expert, who had also contributed to the selection of alternatives. The Microsoft Teams interview lasted approximately 90 min and followed a structured procedure. The authors first presented the initial matrix in Table B.11, including its data sources, assumptions, and units. The expert then assessed the entries for each technology based on experience in national electricity system planning and generation expansion studies. The review resulted in updates to capacity factor, resource availability, CAPEX, and LCOE, as well as revisions to selected criteria definitions and measurement units. Following the recommendation of the expert, the resource availability criterion expressed in GW in Table B.11 was changed to GWh in Table 4. Renewable resource availability was estimated as annual electricity-generation potential using technical potential (GW), technology-specific capacity factors, and 8760 h per year. In contrast, the CCGT value represents the cumulative electricity-generation potential associated with the available natural-gas reserve, calculated using the assumed CCGT conversion efficiency. Within this technology-level assessment, the CCGT value was used as a static indicator of the finite resource base rather than as an estimate of annual CCGT generation. Future generation expansion modeling should annualize gas availability and explicitly represent reserve depletion over the planning horizon.

The performance matrix was revised following this consultation, and the final version is presented in Table 4.

3.1.6. Selection of the MCDA method

The selection of an MCDA method depends on the characteristics of the decision problem, the type and availability of data, and the sustainability concept adopted [83]. This study adopts a sustainability perspective and integrates quantitative and qualitative data. In energy planning and technology assessment, Multi-Attribute Decision-Making methods are frequently used because they allow a finite set of alternatives to be evaluated against multiple criteria. Among these methods, outranking approaches such as ELECTRE are particularly suitable when poor performance in one criterion should not be fully offset by good performance in others. This feature is consistent with a sustainability perspective, in which certain trade-offs may be unacceptable, and criterion weights represent relative importance rather than unrestricted compensation rates [83,84]. Thus, ELECTRE III was selected to rank the technology alternatives.

The method establishes an outranking relation for each pair of alternatives by combining concordance and discordance information. It incorporates an indifference threshold (q), a preference threshold (p), and, where appropriate, a veto threshold (v) for each criterion

Table 5
Threshold values used in this study.

Sustainability criteria	min.value	q (5% of min.value)	p (10% of min.value)
TRL	–	0	1
Capacity factor	20	1	2
Resource availability	7314.6	365.73	731.46
Service life	25	1.25	2.5
Average construction time	–	0	1
CAPEX	800	40	80
OPEX	24	1.2	2.4
LCOE	0.034	0.0017	0.0034
Fuel cost	8.65	0.4325	0.865
Land use intensity	71	3.55	7.1
Lifecycle CO ₂ e emissions	3	0.15	0.3
Blue water consumption	43	2.15	4.3
Risk for human health	–	0	1
Employment factor	–	0	1
Trained professionals	–	0	1

[85]. These thresholds account for uncertainty and imprecision in performance values and prevent small differences from being interpreted as meaningful preferences. Accordingly, ELECTRE III represents each criterion through a pseudo-criterion model [86]. The ELECTRE III exploitation method used in this study is the Net Flow value, whose algorithm consists of six steps: (1) outranking degree, (2) concordance index, (3) discordance index, (4) reliability index, (5) concordance and discordance credibility degrees, and (6) net credibility degree. The final ELECTRE III ranking is obtained by ordering alternatives according to decreasing net flow values [85].

ELECTRE III has been applied in energy planning and environmental decision-making, including the assessment of renewable energy alternatives and resource management strategies [68,87,88]. It is therefore an appropriate method for the sustainability-oriented screening of electricity-generation technologies conducted in this study. Specifying the indifference and preference thresholds involves judgment and depends on the decision context. To establish transparent and consistent values without undertaking a separate threshold-elicitation study, this analysis applies simple rules of thumb. For quantitative criteria, the indifference threshold was set to 5% of the minimum criterion value and the preference threshold to 10% of that value. These thresholds reduce the likelihood that small relative differences between alternatives are treated as decisive [89]. For qualitative criteria, q was set to 0 and p to 1. No veto thresholds were specified because no criterion was considered sufficient, on its own, to rule out an alternative regardless of its performance on all other criteria. The thresholds applied are reported in Table 5.

3.1.7. Weighting of criteria/indicators

Stakeholder preferences were collected via an online survey administered using the HELDA online survey plug-in [28]. The plug-in

employs an n-point scale (up to 10) to assign relative weights to the criteria, generating weights that serve as importance coefficients suitable for outranking methods. Participants first selected their stakeholder category from a predefined list. Then the participants assign relative importance scores to the sustainability criteria on a scale from 1 to 10. In this study, a score of 1 represented the least important criterion and a score of 10 the most important criterion, according to each participant's preferences. The plug-in then aggregates individual responses within each stakeholder group, normalizes the average weights to range from 0 to 1, and finally generates a weighting set for each group.

The survey was initially distributed by text message to 46 experts working in Ecuador's electricity sector, primarily from the institutions listed in Table 1. These initial contacts were invited to share the survey with colleagues in their professional networks who had comparable expertise in the sector. In some cases, public-sector participants also visited institutions in person to encourage colleagues to participate. Because the survey was distributed through professional networks, the exact number of individuals who received the invitation cannot be determined. It is estimated that approximately 100 professionals were reached, including staff from the institutions listed in Table 1 and other organizations.

The survey was open from 15 December 2025 to 20 March 2026. Respondents self-identified as belonging to academia, the public sector, or industry. Respondents who selected none of these categories were assigned to the "Others" group. A total of 50 responses were received. Fifteen incomplete questionnaires were excluded, resulting in 35 complete responses included in the analysis. Of these, 16 respondents represented academia, 14 the public sector, two industry, and three the "Others" group. The distribution of respondents was skewed toward perspectives from academia and the public sector, while the private sector was significantly underrepresented. This imbalance may have influenced the weightings of the criteria, which could have given greater importance to the priorities associated with respondents from academia and the public sector, including public interest objectives and state sovereignty. In contrast, the limited participation of actors from the private sector may have reduced the influence of industry perspectives on the final weighting of the criteria, particularly with regard to economic or technical considerations. The sample should not be interpreted as statistically representative of all stakeholder groups in Ecuador's electricity sector, given the limited number of participants. Instead, it provides expert-based stakeholder perspectives for the comparative assessment. A broader and more representative stakeholder engagement process would ideally be led by the public institutions responsible for electricity sector planning.

The last two steps of the MCDA, the alternatives ranking and sensitivity analysis, are presented in the next section.

4. Results, discussion, and policy implications

This section presents stakeholder-informed results from 35 complete survey responses collected from experts in Ecuador's electricity sector. The findings should therefore be interpreted as expert perspectives rather than as nationally representative stakeholder preferences. The section is organized into three main subsections: Results, Discussion, and Policy Implications. Section 4.1 shows all the results obtained in the weighing part and the ranking alternatives. Section 4.2 interprets these stakeholder-informed findings and discusses their implications for Ecuador's electricity-sector strategy. Finally, Section 4.3 outlines the policy implications of the assessment.

4.1. Results

This Subsection is divided into four subsections. Section 4.1.1 reports the direct criterion-importance ratings provided by the 35 survey participants. Section 4.1.2 presents the normalized resulting weights for each sustainability criterion, both by stakeholder group and for the full sample. Section 4.1.3 reports the ranking of the eight technology alternatives based on the weighted criteria, while Section 4.1.4 examines how the ranking changes under alternative weighting assumptions.

4.1.1. Distribution of stakeholder-assigned importance scores for sustainability criteria

Table 6 presents the distribution of importance scores assigned by the 35 survey participants to each sustainability criterion, using a scale from 1 (least important) to 10 (most important). The results illustrate both areas of convergence and differences in stakeholder preferences.

Among the technical criteria, resource availability received consistently high ratings: 30 participants assigned scores between 8 and 10, including 12 ratings of 9, 11 of 10, and 7 of 8. Only one participant assigned the lowest score of 1, while four assigned a score of 5. Technology readiness level (TRL) also received relatively high importance ratings, with 19 participants assigning scores between 8 and 10. However, preferences for TRL were more dispersed than for resource availability: 10 participants assigned medium scores between 4 and 7, and six assigned low scores between 1 and 3.

Within the economic dimension, CAPEX and OPEX received no ratings of 1 or 2, whereas LCOE received one rating of 1. CAPEX showed the greatest variation in preferences, with eight participants assigning a score of 5 and another eight assigning the maximum score of 10. LCOE was rated 9 or 10 by 18 participants, indicating that it was highly important for approximately half of the sample. Fuel costs also received high ratings, with 20 participants assigning scores between 8 and 10, reflecting the perceived relevance of fuel expenditures for electricity costs and energy security.

Environmental preferences were more heterogeneous. Land-use intensity received low scores (1–3) from 12 participants, medium scores (4–7) from 16, and high scores (8–10) from seven, indicating a concentration around medium to low importance. Ratings for lifecycle CO₂e emissions were evenly distributed, with 11 low, 13 medium, and 11 high ratings. This distribution indicates substantial variation in how participants prioritized life-cycle climate impacts. Blue-water consumption received comparatively higher ratings: 7 participants assigned low scores, 14 assigned medium scores, and 14 assigned high scores. Water consumption was therefore given greater importance overall than land-use intensity and lifecycle CO₂e emissions.

Among the social criteria, risk to human health received the strongest support, with 21 participants assigning high scores between 8 and 10, compared with 11 medium and three low ratings. The employment factor also received high ratings from 17 participants, although 11 participants assigned low ratings, indicating divergent views regarding its importance. Training of professionals received high scores from 14 participants and low scores from 11 participants, making it the most polarizing social criterion.

4.1.2. The importance of criteria among stakeholder groups

Fig. 3 presents the stakeholder-group weighting sets as a cobweb chart, while Table 7 reports the corresponding normalized weights. Together, these results show how the stakeholder groups prioritized the sustainability criteria used to rank the technology alternatives.

The **public sector** group assigned the highest weights to resource availability and LCOE (8.5% each), followed by CAPEX (7.6%), capacity factor (7.5%), OPEX and risk to human health (7.4% each), and fuel costs (7.3%). This pattern indicates a strong emphasis on resource adequacy, economic performance, and health considerations. By contrast, employment factor (5.6%) and the availability of trained professionals (6.1%) received lower weights. Among the environmental criteria, blue water consumption was assigned moderate importance (6.5%), whereas lifecycle CO₂e emissions (5.3%) and land-use intensity (3.5%) received lower weights. Land use intensity was the least important criterion for this group.

The **academic** group showed a more even distribution of weights across the criteria. Resource availability received the highest weight (8.2%), followed by TRL (7.4%), risk to human health (7.1%), service life (7.0%), capacity factor and CAPEX (6.8% each), OPEX (6.8%), and LCOE (6.7%). All remaining criteria received weights above 5%, including land use intensity (6.7%). This distribution suggests that

Table 6

Distribution of responses based on the importance assigned to sustainability criteria by the 35 stakeholders who completed the survey.

Sustainability criteria	Scale of importance										Total responses
	1	2	3	4	5	6	7	8	9	10	
TRL	5	0	1	3	2	2	3	4	2	13	35
Capacity factor	1	2	0	1	4	2	10	4	3	8	35
Resource availability	1	0	0	0	4	0	0	7	12	11	35
Service life	2	1	2	0	3	9	4	11	0	3	35
Average construction time	4	2	1	2	3	4	7	7	1	4	35
CAPEX	0	0	3	0	8	2	4	6	4	8	35
OPEX	0	0	2	3	5	2	7	5	9	2	35
LCOE	1	0	2	0	3	4	3	4	7	11	35
Fuel cost	2	3	3	1	2	3	1	8	8	4	35
Land use intensity	8	1	3	2	5	5	4	1	4	2	35
Lifecycle CO ₂ e emissions	7	1	3	3	5	2	3	8	0	3	35
Blue water consumption	3	1	3	2	5	4	3	6	4	4	35
Risk for human health	1	1	1	4	4	1	2	7	4	10	35
Employment factor	5	1	5	1	3	0	3	8	5	4	35
Trained professionals	6	1	4	0	1	4	5	4	5	5	35

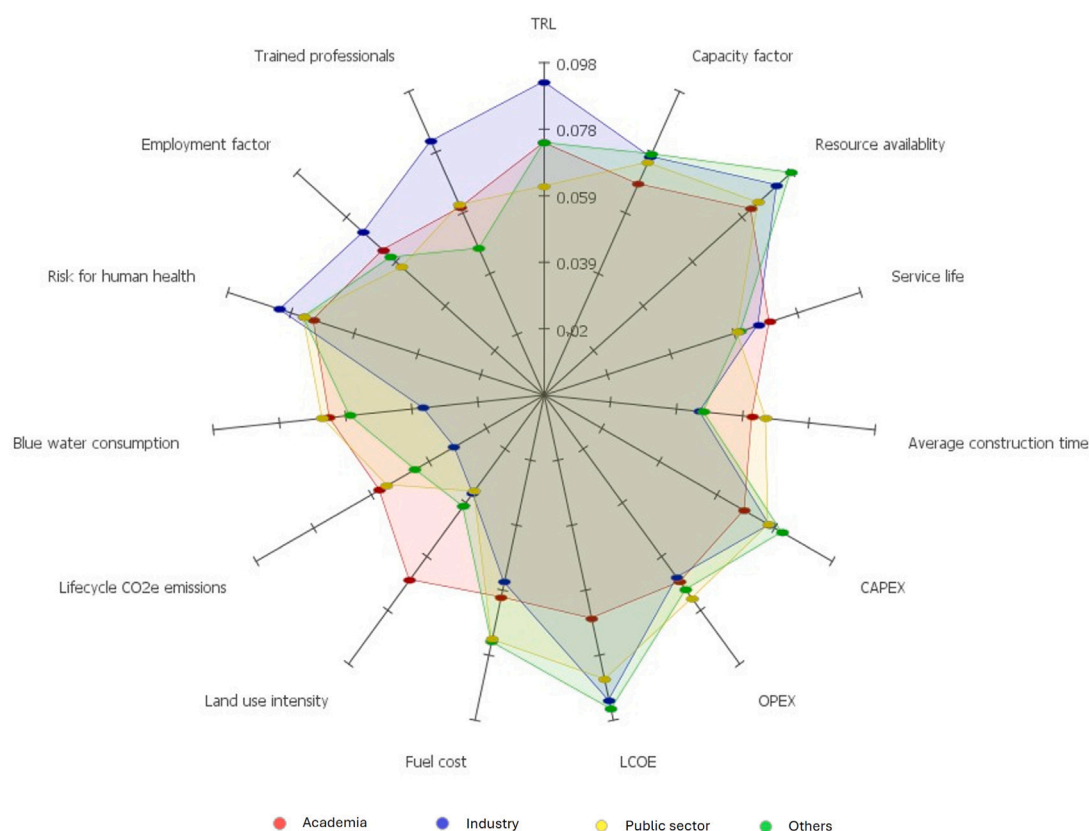


Fig. 3. Cobweb chart of weight sets from academia, industry, public sector and “Others”.

academic participants considered technical, economic, environmental, and social dimensions more evenly than the other stakeholder groups.

The **industry** group gave the greatest priority to technology readiness level, resource availability, and LCOE (9.2% each). Capacity factor (7.7%), risk to human health (8.2%), and the availability of trained professionals (8.2%) also received relatively high weights. In contrast, land use intensity (3.6%), lifecycle CO₂e emissions (3.1%), and blue-water consumption (3.6%) received the lowest weights. Given the small number of industry respondents, these results should be interpreted as the preferences of the participating industry experts rather than as representative of Ecuador’s private sector as a whole. Nevertheless, the relatively low weighting of land use contrasts with

the relevance of land-related impacts in some Ecuadorian hydropower projects, including Baba and Daule Peripa [90,91].

The **“Others”** group assigned the highest weights to resource availability (9.8%) and LCOE (9.4%), followed by CAPEX (8.1%) and capacity factor (7.7%). This pattern likewise emphasizes technical and economic performance. The risk to human health received a weight of 7.4%. The lowest weights were assigned to land use intensity (4.0%), lifecycle CO₂e emissions (4.4%), average construction time (4.7%), and the availability of trained professionals (4.7%).

To reflect the combined preferences of the participating stakeholder groups, the final ranking of alternatives in Section 4.1.3 uses the average weights derived from the 35 complete survey responses rather than the weighting set of any single group. Fig. 4 presents these average

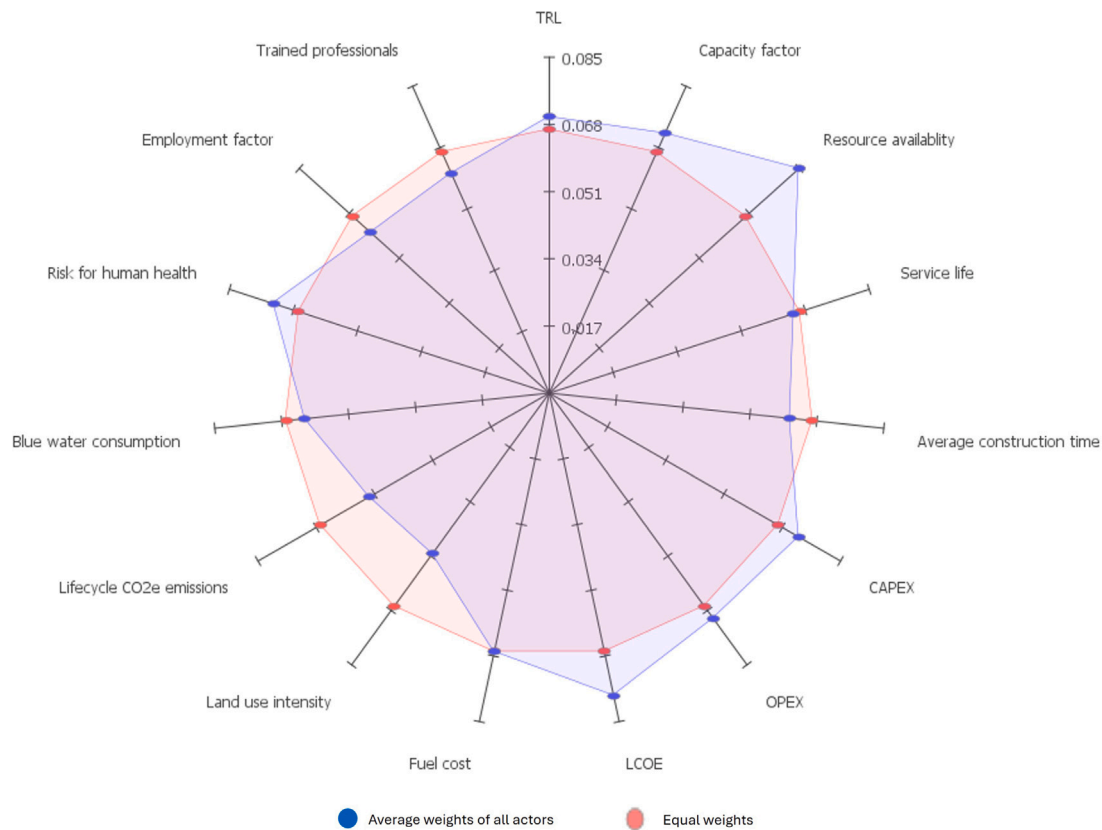


Fig. 4. Cobweb chart of criteria weights based on the average values across all stakeholder groups.

Table 7
Normalized weights for the four stakeholder groups.

KPIs	Academia	Industry	Public sector	Others
TRL	0.074	0.092	0.061	0.074
Capacity factor	0.068	0.077	0.075	0.077
Resource availability	0.082	0.092	0.085	0.098
Service life	0.070	0.066	0.060	0.061
Average construction time	0.062	0.046	0.065	0.047
CAPEX	0.068	0.077	0.076	0.081
OPEX	0.068	0.066	0.074	0.071
LCOE	0.067	0.092	0.085	0.094
Fuel cost	0.061	0.056	0.073	0.074
Land use intensity	0.067	0.036	0.035	0.040
Lifecycle CO ₂ e emissions	0.056	0.031	0.053	0.044
Blue water consumption	0.063	0.036	0.065	0.057
Risk for human health	0.071	0.082	0.074	0.074
Employment factor	0.063	0.071	0.056	0.061
Trained professionals	0.060	0.082	0.061	0.047

weights and, for comparison, shows a scenario in which all 15 criteria receive equal importance.

Resource availability received the highest average weight (8.5%), followed by LCOE (7.8%). Risk to human health and CAPEX each received a weight of 7.3%, followed by capacity factor (7.2%), OPEX (7.1%), technology readiness level (TRL; 6.9%), fuel costs (6.7%), and service life (6.5%). Blue water consumption was the highest-ranked environmental criterion, with an average weight of 6.2%. Average construction time, employment factor, and the availability of trained professionals each received 6.1%. Lifecycle CO₂e emissions (5.2%) and land use intensity (5.0%) received the lowest average weights.

These results answer the first research question of this work: stakeholder groups considered resource availability the most relevant criterion for guiding technology choices in Ecuador's future electricity system. They also placed strong emphasis on electricity costs, investment requirements, and risks to human health. Although land-use intensity

and lifecycle CO₂e emissions received comparatively lower importance, blue-water consumption remained relatively relevant among the environmental criteria. Employment and the availability of trained professionals also received moderate importance; however, these priorities may differ if civil society representatives are included in future assessments.

4.1.3. Alternatives ranking

Fig. 5 presents the ranking of the eight technology alternatives based on the average weights derived from the stakeholder preferences. The vertical axis shows the net-flow score, with higher values indicating a more preferred alternative. Four technologies obtained positive net-flow values: mini-hydropower plants of up to 5 MW ranked first (2.74), followed by onshore wind farms (1.51), utility-scale photovoltaics (PV-US; 1.40), and geothermal power plants (0.34). These results indicate that, under the average stakeholder weighting set, mini-hydropower, wind, solar PV, and geothermal energy are the most preferred technology alternatives. Biomass SRC was the only renewable alternative with a negative net-flow score.

The remaining technologies received negative net-flow values: combined-cycle gas turbines (CCGT) ranked fifth (−0.50), followed by biomass SRC (−1.33), small modular reactors (SMR; −2.04), and nuclear fission power plants (−2.12). Thus, the two nuclear alternatives occupied the lowest positions in the stakeholder-informed ranking.

Table 8 presents the ELECTRE III pairwise outranking matrix for the eight technology alternatives. *P+* shows that the row alternative performs better than the column alternative, while *P-* shows that the row alternative performs worse than the column alternative. For example, in the PV-US row, *P+* appears under nuclear fission, CCGT, SMR, geothermal, and biomass SRC, meaning utility-scale photovoltaics perform better than these five technologies, while *P-* appears under onshore wind and mini-hydro, indicating worse performance than those two options. Mini-hydropower displays *P+* in all pairwise comparisons,

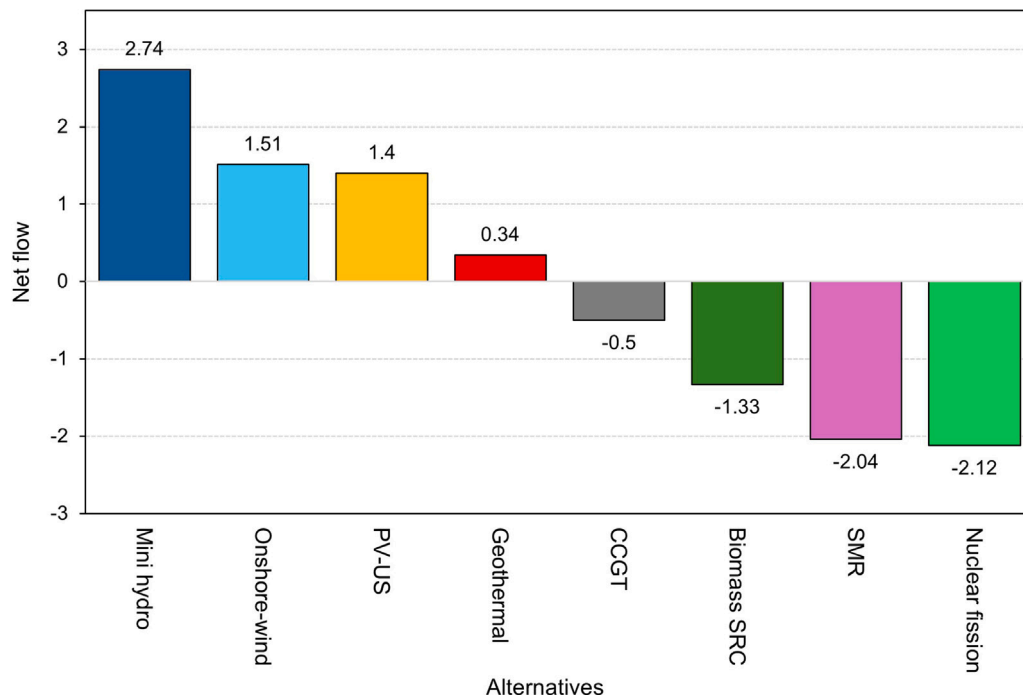


Fig. 5. Bar chart of alternatives ranking.

Table 8

Outranking matrix - ELECTRE III.

	Nuclear fission	CCGT	SMR	PV-US	Onshore-wind	Geother.	Biomass SRC	Mini hydro
Nuclear fission	–	P–	P–	P–	P–	P–	P–	P–
CCGT	P+	–	P+	P–	P–	P–	P+	P–
SMR	P+	P–	–	P–	P–	P–	P–	P–
PV-US	P+	P+	P+	–	P–	P+	P+	P–
Onshore-wind	P+	P+	P+	P+	–	P+	P+	P–
Geother.	P+	P+	P+	P–	P–	–	P+	P–
Biomass SRC	P+	P–	P+	P–	P–	P–	–	P–
Mini hydro	P+	P+	P+	P+	P+	P+	P+	–

Notes:

P+ the row alternative performs better than the column alternative.

P– the row alternative performs worse than the column alternative.

confirming its first-place position in the final ranking. Nuclear fission, in contrast, shows *P–* in most comparisons, consistent with its position as the lowest-ranked alternative.

These results help explain why mini-hydropower is the most preferred electricity-generation alternative. Under the average stakeholder weighting set, mini-hydropower outranks all other technologies, supported by its strong performance on the most highly weighted criteria: resource availability, LCOE, CAPEX, and risk to human health. In particular, it combines high resource availability with comparatively low electricity and investment costs and a low risk-to-human-health score.

Onshore wind and utility-scale photovoltaics show similar overall performance. Both technologies combine strengths and weaknesses across the most highly weighted criteria; consequently, their relative positions may change when performance values vary. Appendix C examines these potential changes in some of the alternatives through a sensitivity analysis of the criterion values. At baseline values, onshore wind ranks above PV-US partly due to its lower LCOE. If wind LCOE increases while the values for PV-US and geothermal remain unchanged, its ranking performance declines (Fig. C.8). Similarly, if the capacity factor of PV-US exceeds its baseline value and approaches or

surpasses that of onshore wind, PV-US improves its position (Fig. C.10). PV-US and onshore wind also have higher life-cycle CO₂e emissions than geothermal power; therefore, a reduction in PV-US emissions improves its relative performance (Fig. C.9). Their comparable performance across the 15 criteria explains their close ranking and their potential to exchange positions. Both, therefore, represent viable complementary options for expanding Ecuador's electricity system alongside mini-hydropower, according to the stakeholder-informed assessment.

Among the technologies with negative net-flow values, combined-cycle gas turbines rank highest, followed by biomass SRC. CCGT has a slightly lower LCOE than biomass SRC; however, a reduction in the LCOE of biomass SRC would improve its relative position (Fig. C.11). CCGT also has higher resource availability than biomass SRC, for which the assessment considers residues from selected agricultural, livestock, and forestry activities. If a broader estimate of biomass resources were used, the assessed resource availability and relative performance of biomass SRC would increase (Fig. C.12).

CCGT ranks fifth primarily because its LCOE exceeds that of the four higher-ranked renewable technologies: mini-hydropower, onshore wind, PV-US, and geothermal energy. If the LCOE of CCGT declined to

values comparable to those of onshore wind, its net-flow score would improve and could become positive (Fig. C.13).

Small modular reactors and nuclear fission plants occupy the final positions. Their lower ranking reflects relatively weak performance on several highly weighted criteria. Both options have no identified domestic uranium resource base in Ecuador and would therefore depend on imported fuel. They also involve comparatively high capital costs. The sensitivity analysis indicates that nuclear fission would require CAPEX comparable to that of SMRs to improve its performance relative to the SMR alternative (Fig. C.14).

These results answer the second research question: within the stakeholder-driven sustainability assessment, nuclear power, both SMRs and nuclear fission plants, ranked below all other assessed alternatives. Compared with technologies already deployed or considered for expansion in Ecuador, nuclear options performed less favorably, primarily because Ecuador has no identified domestic uranium resource base, implying dependence on imported fuel, and because of their high capital costs and higher risk to human health. This conclusion is conditional on the Ecuador-specific data, selected criteria, and stakeholder-derived weighting set used in this assessment, rather than representing a universal assessment of nuclear technology.

To assess whether the results remain consistent under different stakeholder preferences and criteria-weighting assumptions, Appendix D presents a robustness analysis of the alternative rankings. This analysis helps determine whether the identified preferences are stable or sensitive to changes in the weighting structure. Fig. D.15 presents the rankings of the eight alternatives for each stakeholder group, while Table D.12 and Fig. D.16 report the criteria weights and resulting rankings under three importance scenarios. Finally, Appendix E examines the stability of the rankings under variations in the preference (p) and indifference (q) thresholds. Figs. E.17 and E.18 show that the rankings remain stable for most criteria under the tested threshold variations. This stability indicates that the outranking relations are not sensitive to the tested changes in p and q, as the performance differences among alternatives and the resulting aggregated concordance are sufficiently robust to preserve their relative positions. The only exception is the land use intensity criterion, for which the PV-US and onshore-wind alternatives switch positions when the preference threshold p is increased.

4.1.4. Sensitivity analysis of criteria weights

A weight sensitivity analysis was conducted to examine whether the ranking of alternatives changes when the normalized weight assigned to an individual criterion is changed. The analysis identifies the criteria for which changes in relative importance can alter the net flows and relative positions of the alternatives. Using HELDA, the weight of a single criterion is varied while the resulting net flows for the eight alternatives are displayed. Figs. 6 and 7 present these results. In each plot, the horizontal axis represents the normalized weight of the criterion under examination, the vertical axis represents the net flow, and the vertical black line indicates the criterion's weight in the evaluation matrix.

Fig. 6 presents the results for technical and economic criteria. PV-US and onshore wind show the greatest sensitivity to changes in criterion weights because their baseline net flows are close. For geothermal, increasing the weight of the capacity factor improves its net flow, whereas increasing the weights of average construction time, CAPEX, or OPEX reduces it. Varying the weight of LCOE does not change the ranking of any alternative. Increasing the weight of TRL causes conventional nuclear fission to rank above SMR; for the remaining criteria, increasing their weights retains SMR above conventional nuclear fission.

Fig. 7 presents the results for environmental and social criteria. Increasing the weight of land use intensity shifts the relative positions of PV-US and onshore wind. Under higher weights for this criterion, geothermal approaches their net flow levels. Increasing the weight of life-cycle CO₂e emissions gives onshore wind an advantage over PV-US. By contrast, changing the weights assigned to the risks to human

health and to trained professionals does not alter the relative positions of PV-US and onshore wind. Across the tested weight variations, mini-hydropower remains ranked first, and biomass SRC remains sixth. The relative positions of geothermal, CCGT, and the two nuclear alternatives are also largely stable, except for the exchange between SMR and conventional nuclear fission under changes in the TRL weight and, for some reduced weights, average construction time or capacity factor. PV-US and onshore wind are the most weight-sensitive alternatives, but their changes occur primarily relative to one another. Thus, within this one-way weight sensitivity analysis, the main ordering of the alternatives is largely maintained. In contrast, the relative ranking of closely performing alternatives depends on the importance assigned to particular criteria.

4.2. Discussion

4.2.1. Interpretation of the assessment

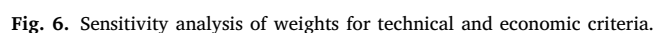
This sustainability assessment examines electricity-generation alternatives for Ecuador, a country whose electricity system is highly dependent on hydropower and therefore exposed to hydrological variability. By combining multiple sustainability criteria with the preferences of different stakeholder groups, the assessment indicates that, using the selected Ecuador-specific data and stakeholder-derived weights, a diversified portfolio of established renewable technologies performs more favorably than new nuclear projects. This emphasis on diversification is consistent with previous research on electricity systems with high dependence on hydropower [92].

These findings should be interpreted as the outcome of a strategic sustainability assessment, rather than as an implementation sequence or evidence that the highest-ranked technology can be readily deployed. Although the selected criteria capture some implementation-related considerations, the feasibility of individual projects also depends on financing, regulation, permitting, supply chains, land availability, social acceptance, and institutional readiness. These aspects require project-specific analysis.

The stakeholder-informed design is central to this interpretation. It extends the assessment beyond technical feasibility alone by incorporating the priorities, knowledge, and concerns of actors involved in, or affected by, energy-system planning. This includes perceptions of human-health risks, the availability of qualified professionals, and employment opportunities. The ranking should therefore be understood as identifying alternatives that perform relatively well under the selected technical, economic, environmental, and social criteria, rather than as prescribing which technologies should be implemented. Within this framework, the higher ranking of mini-hydropower, onshore wind, utility-scale PV, and geothermal energy reflects the importance assigned by stakeholder groups to domestic availability of renewable resources, the leveled cost of electricity, and perceived risks to human health. Technologies that use domestic resources, with comparatively favorable costs and lower perceived risks, tended to rank higher. In contrast, alternatives that were dependent on imports, required high upfront investment, or were associated with higher perceived risks tended to rank lower. These preferences are particularly relevant in the context of Ecuador's recent electricity crisis and the vulnerability of a hydropower-dominated system.

4.2.2. Implications for renewable diversification

The 2024 electricity crisis provides important context for interpreting the relative performance of the renewable alternatives. According to CENACE, electricity rationing in 2024 resulted in 1922.69 GWh of energy not supplied, occurring between 16 and 30 April and between 22 September and 19 December [93]. The prolonged drought and reduced river inflows exposed the vulnerability of an electricity system heavily reliant on hydropower plants, despite the high availability of hydropower resources estimated under average conditions. Although most interviewed stakeholders assigned substantial importance to this



supply during hydrological extremes. This distinction is particularly relevant for mini-hydropower, which ranked first in the assessment. Its high estimated capacity factor and relatively short construction

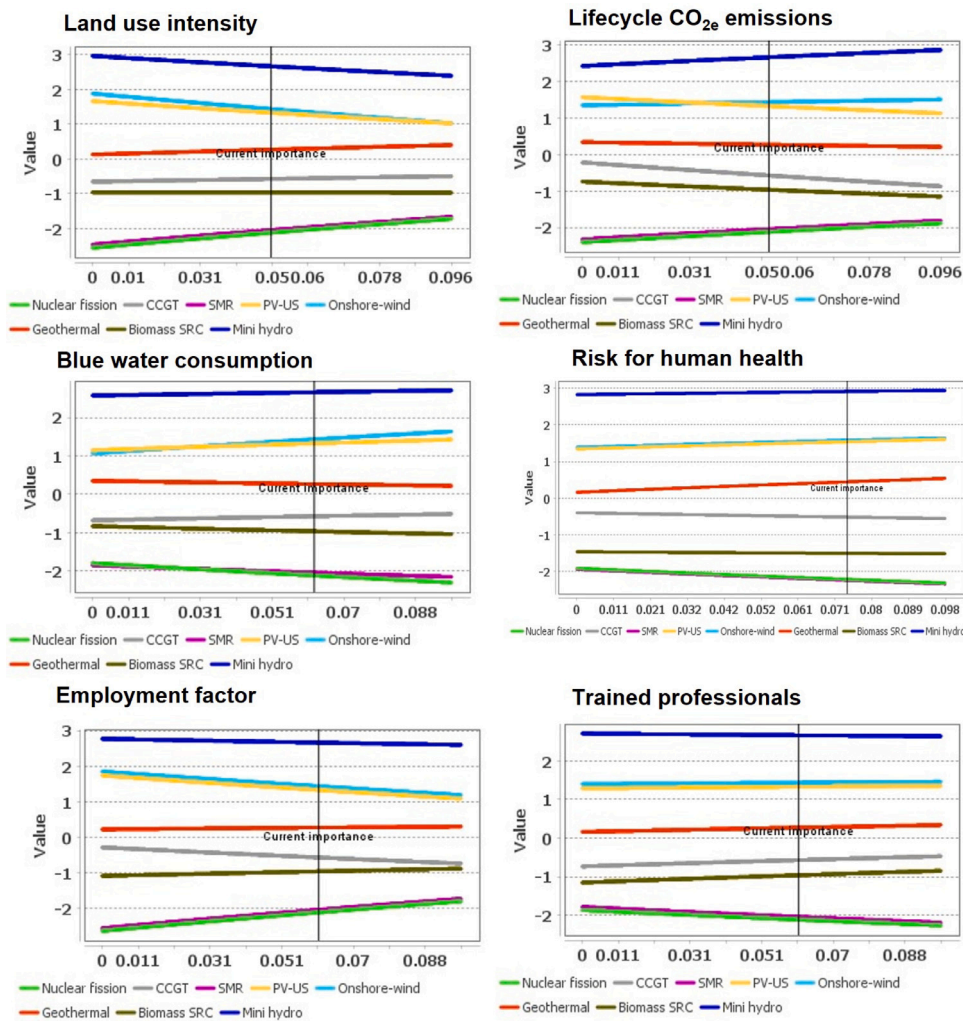


Fig. 7. Sensitivity analysis of weights for environmental and social criteria.

period support its potential contribution to supply, where suitable sites and permitting conditions exist. However, because mini-hydropower generation also depends on hydrological conditions, it cannot by itself eliminate Ecuador's exposure to climate variability. Its role is therefore best understood as part of a diversified electricity mix that combines technologies with complementary resource profiles.

The second- and third-ranked alternatives, onshore wind and PV-US, offer a distinct resource complement to hydropower. Both benefit from abundant domestic resources and comparatively short construction periods [18,72,94]. Although their capacity factors are lower than that of mini-hydropower and their output is variable, their generation profiles may be valuable when hydropower availability is reduced. PV generation, in particular, may contribute during the dry season, subject to site-specific resource conditions, grid capacity, and the ability to integrate variable generation. In contrast to wind and solar, geothermal energy could provide dispatchable generation that is not weather-dependent. Its high estimated capacity factor and resource potential make it relevant to a longer-term diversification strategy. However, resource exploration, confirmation, and project development are necessary before its commercial role can be established [13]. Biomass SRC may also complement hydropower by providing dispatchable generation, particularly when resource supply coincides with dry-season needs. Its lower ranking mainly reflects uncertainty and limitations in the available resource data, rather than an inherent lack of sustainability. More detailed assessment of biomass volumes, logistics, prices,

competing land uses, regional variation, and nutrient and carbon-cycle effects is therefore needed [95,96].

Considered together, the results point to the value of combining technologies with different resource profiles and development timeframes rather than relying on a single alternative. PV-US and, where appropriate, distributed PV could provide relatively near-term additions, although distributed generation was not directly evaluated in this MCDA and would require separate analysis. Onshore wind may contribute as resource assessment, project development experience, and grid integration capacity expand. Over longer development horizons, geothermal and sustainably sourced biomass could provide dispatchable renewable generation. This portfolio interpretation should be seen as a recommendation; it does not constitute a generation-expansion plan. The present assessment does not include system-level integration costs or grid-integration requirements. Therefore, the appropriate scale, timing, location, and integration requirements for each technology should be assessed in subsequent generation-expansion and power-system optimization models, including costs related to energy storage, grid reinforcement, and ancillary services. At high shares of variable renewable energy, these requirements may increase system costs in a non-linear manner and should be explicitly represented in such models.

4.2.3. Role of CCGT and nuclear energy

The relative positions of CCGT and the nuclear alternatives reflect different trade-offs. CCGT illustrates that the ranking is determined by the combined performance of each alternative across all selected

criteria, rather than by performance on a single criterion. Although natural gas resource availability was evaluated favorably, CCGT received comparatively lower scores for LCOE and risk to human health, thereby reducing its overall net flow under the stakeholder-derived weights. Its relatively low ranking should therefore not be attributed solely to resource availability, but to the balance of its advantages and disadvantages across the economic, environmental, and social dimensions considered in the assessment. At the same time, CCGT can provide operational flexibility, a potential benefit not fully captured by the selected criteria or the net-flow ranking. It should therefore not be interpreted as having no possible role in Ecuador's electricity system. Instead, CCGT may warrant separate consideration as a transitional or backup option during hydropower shortages, including assessment of fuel supply, emissions, infrastructure, operational requirements, and its potential contribution to system adequacy.

Nuclear fission and small modular reactors ranked at the bottom of the assessed alternatives. Their lower performance is primarily due to the lack of identified domestic uranium resources, high capital costs, and stakeholder concerns about human health risks. This finding is consistent with Guerrero et al. (2025), who identify potential low-carbon benefits of nuclear power in Ecuador but also emphasize challenges related to governance, social acceptance, radioactive-waste management, and technical and institutional capacity [97].

Accordingly, the inclusion of nuclear fission and SMRs in the MCDA should be understood as an *ex ante* strategic assessment, not evidence of deployment readiness or an endorsement of implementation. Any future nuclear pathway would require a separate analysis of independent regulation and safety governance, waste management, licensing and construction schedules, financing, institutional and workforce capacity, supply chain development, and sustained public engagement. The results, therefore, do not establish that nuclear technologies should be excluded from future consideration; rather, they indicate that they perform less favorably than the assessed alternatives under the present Ecuador-specific framework.

4.2.4. Value of stakeholder participation

These results also demonstrate why stakeholder participation matters for evaluating alternatives in Ecuador's electricity sector. Participation and transparency do not eliminate disagreements, but they make different perspectives explicit, including potential differences between government proposals and the preferences expressed by informed stakeholders. In this study, stakeholder input revealed how priorities related to resource security, cost, health risks, and domestic capacity shape the comparative performance of the assessed alternatives. The study provides a participatory and context-specific basis for comparing technologies before policy or investment decisions are made. This is particularly relevant where technologies successful in other settings may not be equally suitable for Ecuador's resources, institutional conditions, or social priorities.

The principal contribution of this research is its empirical demonstration of how a stakeholder-informed, multi-criteria, and multi-technology assessment can support sustainable power-system planning in Ecuador. Although the numerical rankings are conditional on Ecuador's resource availability, institutional conditions, selected performance data, and stakeholder preferences, the methodological approach can be adapted to other countries with high hydropower dependence, exposure to drought-related electricity risks, and a need to diversify their power supply.

4.3. Policy implications

The results provide a stakeholder-based perspective that can complement future revisions of Ecuador's Electricity Master Plan. Rather than focusing future expansion on large hydropower plants, planners could use this assessment to consider a more diversified renewable energy portfolio that includes small hydroelectric plants, utility-scale

solar photovoltaic power, onshore wind power, and geothermal energy. Such diversification would help address Ecuador's exposure to hydrological variability while recognizing that each technology has distinct requirements for development and integration. The framework for identifying energy technologies should more systematically involve stakeholders in strategic energy planning.

The discrepancy between the government's interest in nuclear energy and stakeholders' preferences establishes that technology decisions involve more than just technical and economic considerations. Before allocating public resources to long-term infrastructure, expert panels, public consultations, and multisectoral advisory councils could help bring greater visibility to underlying assumptions, trade-offs, and social concerns. In this context, the stakeholder-driven multi-criteria decision analysis framework can serve as a useful complement to conventional electricity system planning. It offers a structured way to compare technical, economic, environmental, social, and institutional considerations that might otherwise receive less attention in modeling exercises. When used in conjunction with generation expansion models, power grid studies, and project-level feasibility assessments, it can support more transparent and context-specific decisions, particularly for technologies with which Ecuador has little experience.

The priorities identified in the assessment can also guide support policies. In the case of geothermal and biomass energy, this could involve improving resource information, supporting early-stage exploration and project preparation, and reducing financing risks once environmental safeguards and sustainable resource management are in place. For solar photovoltaic and onshore wind power, the focus could be on clear procurement and permitting procedures, grid connection processes, and planning for transmission needs and system flexibility. Combined-cycle gas turbine power plants could be evaluated as a potential transition or backup option, taking into account fuel costs, emissions, infrastructure requirements, and Ecuador's long-term decarbonization goals. More generally, the results suggest that Ecuador should evaluate technologies in relation to its own resources, institutions, and social priorities, rather than adopting options simply because they have been implemented elsewhere. A transparent and participatory planning process can help align decisions on electricity grid expansion with the country's energy security and sustainability goals.

5. Limitations and future research work

This study provides a stakeholder-informed comparison of electricity-generation technologies for Ecuador. Its results should therefore be interpreted in relation to the selected alternatives, criteria, data, and stakeholder-derived weights. The following limitations also identify priorities for further research.

- First, the performance matrix is based on technical and cost data obtained from published literature and reports. Future CAPEX, OPEX, and LCOE values remain uncertain, and changes in these inputs could affect the relative ranking of alternatives, particularly when net flows are close. Future studies could update the matrix as additional Ecuador-specific data become available and examine alternative cost trajectories.
- Second, the future availability of hydropower resources is uncertain under changing climatic conditions. Although mini-hydropower was evaluated using a high capacity factor based on minimum river flows, future precipitation patterns, landslides, and other natural hazards may affect its performance. Future research could use climate scenarios to assess the implications for resource availability and capacity factors.
- Third, the number of survey responses may have limited the diversity of perspectives represented in the stakeholder-weighting exercise. Preferences may also evolve in response to energy crises, political developments, technological advances, changes

in technology costs, and policy debates. Future studies could broaden participation through structured workshops that engage government, industry, academia, civil society, local communities, and environmental organizations. Coordination with Ecuador's energy-sector regulator could support a more inclusive and institutionally relevant process.

- Finally, this multi-criteria decision analysis is a sustainability assessment rather than a model for generation, expansion, or dispatch. It does not explicitly take into account future demand, detailed grid and operational constraints, or site-specific conditions. A next step for this research would be to use the current results to inform a subsequent multi-objective generation expansion model. Technology rankings derived from stakeholders preferences could be used to select, prioritize, or limit the technological options considered in the expansion model. The model could then evaluate the timing, scale, location, and composition of capacity additions under demand, resource, transmission, operational, and dispatch constraints. In particular, severe drought scenarios could be represented by reduced hydropower availability and water-related operational constraints, in order to assess the reliability and resilience of alternative expansion pathways. Combining MCDA based on stakeholder input with system-level optimization could improve electricity planning in Ecuador by linking socially and environmentally preferred technologies with viable, reliable, and cost-effective expansion pathways, thereby supporting a more diversified and drought-resilient electric system.

6. Conclusions

Ecuador's 2024 electricity crisis underlined the vulnerability of a power system heavily dependent on hydropower during prolonged droughts. In this context, this study conducted a stakeholder-driven sustainability assessment of eight electricity-generation technologies for Ecuador's future electricity mix. The alternatives included five technologies based on locally available renewable resources: mini-hydropower, utility-scale solar PV, onshore wind, geothermal energy, and biomass from agricultural, livestock, and forestry residues, as well as combined-cycle gas turbines and two nuclear options. Using the selected performance data, sustainability criteria, and stakeholder-derived weights, mini-hydropower, onshore wind, utility-scale solar PV, and geothermal energy ranked more favorably than CCGT, biomass SRC, and the nuclear alternatives.

The results indicate that technologies that combine domestic resource availability, comparatively moderate capital requirements, favorable electricity costs, and lower perceived risks to human health performed best within the assessment framework. At the same time, the 2024 crisis illustrates that high hydropower potential alone does not guarantee resource security. Reducing exposure to hydrological variability requires a more diversified electricity mix with complementary resource profiles.

The results support consideration of technologies across different development horizons. Utility-scale solar PV and mini-hydropower may be relevant for relatively near-term additions where project, site, and grid conditions are favorable. Onshore wind may play a larger role as resource assessment, project development experience, and grid integration capacity develop. Geothermal energy could provide dispatchable renewable capacity over a longer horizon, subject to resource confirmation and project development. These findings should be interpreted as decision-support guidance, not as a prescribed implementation schedule or a generation-expansion pathway.

The assessment also shows that technology rankings reflect the combined effect of multiple criteria and stakeholder preferences, rather than technical performance or resource availability alone. The relatively low ranking of CCGT, despite favorable resource availability, illustrates the importance of considering cost, health, environmental, and social priorities alongside technical characteristics. The lower

ranking of nuclear alternatives further reflects their performance under the Ecuador-specific criteria and stakeholder weights used in this study. The difference between the stakeholder preferences in this study and the government's renewed interest in nuclear energy further accentuates the value of transparent and participatory processes before long-lived infrastructure commitments are made.

Overall, this study provides a context-specific, stakeholder-informed basis for comparing electricity-generation alternatives in Ecuador. Its main contribution is not to select a single technology, but to show how a multi-criteria comparison can make the trade-offs underlying electricity-planning decisions explicit. This approach can complement conventional energy planning by supporting more transparent and inclusive decisions for a diversified and resilient electricity system.

Declaration of competing interest

The authors 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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Appendix A. Sustainability criteria

See [Tables A.9](#) and [A.10](#).

Appendix B. Performance matrix

See [Table B.11](#).

Appendix C. Sensitivity analysis of the criteria values

See [Figs. C.8–C.14](#).

Appendix D. Robustness analysis of the alternative rankings

In [Fig. D.15](#), the ranking of the eight alternatives for each stakeholder group is presented. Academia and public sector stakeholders produce the same ordering of technologies, although with different net flow values. In the private sector and "other" groups, the two nuclear options change relative positions, with SMRs ranking below conventional nuclear fission. Overall, the rankings remain largely consistent across stakeholder groups; the only change among the leading renewable technologies is the reversal of PV-US and onshore wind in private-sector preferences.

[Table D.12](#) shows the weights for three different importance weighting scenarios, alongside their respective rankings in [Fig. D.16](#). The equal-importance scenario, in which all 15 criteria receive identical weights, reproduces the baseline ordering, although the net flow values differ. The two economic scenarios place the greatest emphasis on either CAPEX or LCOE. When CAPEX is assigned the highest weight, PV-US ranks first, followed by onshore wind, CCGT, and mini-hydropower; geothermal and both nuclear options have negative net flows. When LCOE receives the highest weight, onshore wind ranks first, followed closely by PV-US and mini-hydropower. Nuclear technologies still have negative net flows but rank above CCGT and biomass SRC, indicating comparatively stronger performance under an LCOE-focused weighting structure. Their investment costs nevertheless constrain their overall ranking.

Appendix E. Thresholds analysis

See [Figs. E.17](#) and [E.18](#).

Table A.9
Sustainability criteria from the literature search with their respective references.

Number	References	Technologies assessed	Type of study	Sustainability criteria
1	[98]	Wind, solar PV, geothermal, hydropower	Research article	Lifecycle CO ₂ e emissions Conversion efficiency Capacity factor Land use requirements Water consumption Social impacts
2	[99]	Solar PV	Research article	Energy yield LCOE Land use Critical materials Recycling potential
3	[100]	Hybrid decentralized system (solar PV, diesel generator, wind, biomass)	Research article	Efficiency LCOE Fuel consumption CO ₂ e emissions Land requirement Job creation
4	[101]	Fossil (oil, gas), hydropower, wind, solar, nuclear options	Research article	CO ₂ e emissions Land use Water use O&M cost LCOE Efficiency Capacity factor Reliability Employment Acceptance
6	[102]	Fossil and renewable technologies (coal, gas, biomass, wind, PV)	Research article	CO ₂ e emissions LCOE Fuel costs Investment costs Efficiency Land use
7	[103]	Hydrogen produced from wind power for mobility	Research article	GHG emissions Water consumption Production costs Investment costs Efficiency Reliability Acceptance.
8	[37]	German energy system transformation pathways (whole power mix)	Research article	System cost LCOE Land use Import dependency Acceptance GHG emissions.
9	[36]	Biomass, wind	Research article	Global warming potential Acidification Eutrophication Photochemical ozone formation Land occupation Water use Critical raw materials CAPEX OPEX LCOE Safety issues Occupational health
12	[104]	Solar PV, natural gas	Research article	GHG emissions Water use Air pollutants Production costs CAPEX OPEX Efficiency Land use

(continued on next page)

Table A.9 (continued).

Number	References	Technologies assessed	Type of study	Sustainability criteria
13	[105]	Solar PV, wind, diesel	Research article	LCOE Reliability GHG emissions Fuel consumption Land use Employment Contribution to rural development
14	[106]	Geothermal	Research article	Efficiency Reliability GHG emissions Water use LCOE O&M cost
15	[107]	Oil and gas	Research article	GHG emissions Water use Waste generation Safety Efficiency Return on assets Net profits Cost reduction Revenue growth
16	[108]	Oil and gas	Research article	Revenue GHG emissions Efficiency Investment Staff training Safety performance
18	[109]	Solar PV	Research article	Annual yield Payback period Investment costs O&M cost LCOE GHG emissions Land use Acidification Eutrophication
19	[110]	Biomass	Research article	GHG emissions Air pollutants Land use Water consumption Investment cost Employment Efficiency
21	[111]	Biomass, nuclear, solar PV, wind, hydropower, geothermal	Research article	Water use Land use GHG emissions LCOE
23	[112]	Solar PV	Research article	Global warming potential Ozone depletion Acidification Eutrophication Human toxicity Ecotoxicity Land occupation Water consumption Resource depletion Resource availability
24	[113]	Spanish electricity system (renewable and non-renewable technologies)	Research article	Fossil depletion Ozone layer depletion Terrestrial acidification Human toxicity LCOE Direct employment

(continued on next page)

Table A.9 (continued).

Number	References	Technologies assessed	Type of study	Sustainability criteria
25	[114]	Solar PV, wind, small hydropower, biomass	Research article	CAPEX LCOE GHG emissions Land use Water use Resource availability Reliability Capacity factor Employment
27	[115]	Solar PV	Research article	Reliability Efficiency Payback Tariff levels Cost recovery Affordability GHG emissions Land use Electricity access Gender impacts
28	[116]	Spanish electricity system (renewable and non-renewable technologies)	Research article	Employment Affordability Health indicator Air pollutants Land use Water consumption LCOE
29	[117]	Solar PV	Research article	Electricity yield GHG emissions Resource use Land use Investment cost O&M cost Payback period
30	[118]	Wind	Research article	Capacity factor Reliability Maintenance OPEX LCOE Safety
31	[119]	Biomass	Research article	GHG emissions Carbon neutrality Land use Water use Impacts on ecosystems Efficiency CAPEX Employment
32	[88]	Geothermal	Research article	GHG emissions Local pollutants Land use Water requirements CAPEX LCOE Social acceptance Technical risks
33	[120]	Power technologies in general	Research article	GHG emissions Air pollutants Land occupation Water consumption Reliability Affordability LCOE Employment
34	[121]	Hydropower	Research article	GHG emissions Land use Water flow regime Biodiversity effects CAPEX LCOE Resettlement Acceptance

(continued on next page)

Table A.9 (continued).

Number	References	Technologies assessed	Type of study	Sustainability criteria
35	[24]	Hydropower, solar PV, wind, geothermal, biomass	Research article	Job creation Resettlement Biodiversity effects Accessibility Distance to transmission lines Perception
36	[122]	Wind	Research article	Employment Public participation Social acceptance Visual impacts Noise
37	[87]	Hydropower, wind, geothermal, solar, biomass	Research article	CAPEX LCOE GHG emissions Land use Access to energy Poverty reduction

Table A.10

Summary of the sustainability criteria obtained from the literature search.

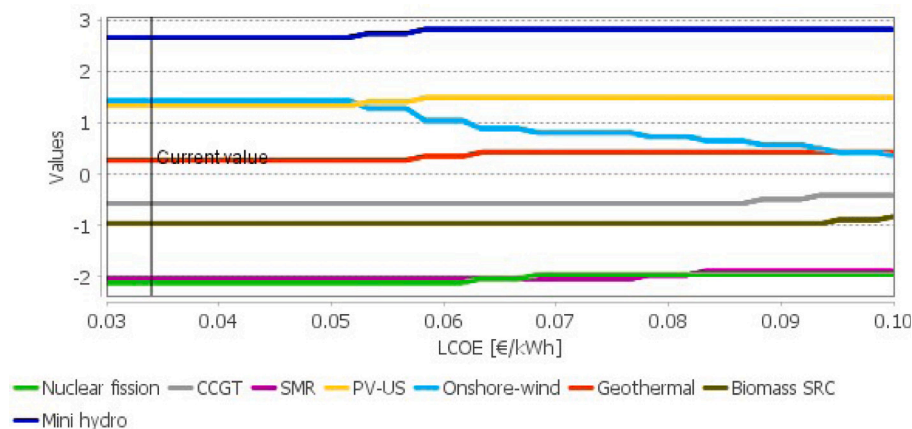
Clusters	Sustainability criteria
Technical	Efficiency (conversion/overall)
	Capacity factor
	Energy yield
	Reliability
	Maintenance requirements
	Technical risk
	Resource availability
	Distance to transmission lines
Economic	Accessibility (to infrastructure)
	Levelized cost of electricity (LCOE)
	Total system cost (incl. CAPEX, OPEX)
	Fuel consumption/fuel cost
	Investment cost (CAPEX)
	Operation and maintenance cost (O&M/OPEX)
	Tariff level
	Affordability
Environmental	Payback time
	Revenue
	Profitability (net profit, return on assets, cost reduction)
	GHG emissions (Lifecycle CO ₂ e emissions)
	Air pollutants (SO _x , NO _x , particulates, etc.)
	Global warming potential
	Acidification
	Eutrophication
	Photochemical ozone formation
	Ozone depletion
	Human toxicity
	Ecotoxicity
	Land use
	Water use/water consumption
Social	Waste generation
	Resource depletion
	Critical raw materials
	Fossil resource depletion
	Carbon neutrality
	Ecosystem impacts (incl. biodiversity effects)
	Employment/job creation
	Contribution to rural development
	Staff training and skills development
	Safety and occupational health
	Access to electricity
	Poverty reduction
	Gender impacts
	Social acceptance/perception
	Public participation
	Health impact
	Resettlement impacts
	Visual impacts
	Noise

Table B.11

Performance matrix for analyzed energy technologies based on literature.

Sustainability criteria	Unit	Preference	Mini Hydro	Nuclear fission	CCGT	SMR	PV-US	Onshore-wind	Geothermal	Biomass SRC
TRL	–	max.	9 [123]	9 [124]	9 [125]	6 [126]	9 [127]	9 [128]	9 [129]	9 [130]
Capacity factor	%	max.	52 [131]	83 [132]	59.7 [133]	85 [126]	17.4 [131]	34 [131]	80 [134]	55 [135]
Resource availability	GW	max.	12 [18]	No studies available	1104.1 [17]	No studies available	15 [72]	1.67 [15]	1 [13]	1 [16,18]
Service life	years	max.	75 [8]	60 [136]	30 [137]	50 [126]	30 [137]	25 [137]	25 [138]	25 [139]
Average construction time	–	min.	Medium [140]	High [141,142]	Medium [143]	Medium [144]	Low [143]	Low [143]	High [145]	Low [143]
CAPEX	\$/kW	min.	2067 [131]	11,901 [137]	1463 [146]	6900 [147]	691 [131]	1041 [131]	4015 [131]	3242 [131]
OPEX	\$/kW/year	min.	62.01 [131]	108 [137]	21.64 [137]	202.48 [147]	13.1 [131]	18 [131]	125 [131]	129.68 [131]
LCOE	\$/kWh	min.	0.05 [131]	0.065 [136]	0.085 [131]	0.09 [147]	0.043 [131]	0.034 [131]	0.06 [131]	0.097 [148]
Fuel cost	\$/MWh	min.	0	8.66 [137]	47.22 [137]	8.66 [137]	0	0	0	42.47 [149]
Land use intensity	m ² /GWh/year	min.	4000 [150]	71 [151,152]	800 ^a [153]	75 [154]	20,000 [151,152]	120,000 [152]	404 [155,156]	1300 [152]
Lifecycle CO ₂ e emission	gCO ₂ e/kWh	min.	3 [157]	13 [158]	486 [158]	13 [158]	43 [158]	13 [158]	37 [158]	52 [158]
Blue water consumption	l/MWh	min.	330 [159]	2290 [159]	598 [159]	1891 [160]	330 [159]	43 [159]	1022 [159]	1360 ^b [161]
Risk for human health	–	min.	Low	High	Medium	High	Low	Low	Low	Medium
Employment factor	–	max.	Medium [162]	High [163]	Low [164]	High [163]	Low [164]	Low [164]	Medium [162]	Medium [162]
Trained professionals	–	max.	High	Low	High	Low	High	High	High	High

Notes:

^a Ecuador's largest natural gas field is located offshore in Block 6 of the Gulf of Guayaquil; therefore, the land-use plan covers only the infrastructure for the thermal power plant.^b Only the water consumed at a thermal power plant with a single-pass cooling system is taken into account, since the biomass used consists of waste and no additional water is required for irrigation.**Fig. C.8.** Stability of the LCOE value in onshore wind technology.

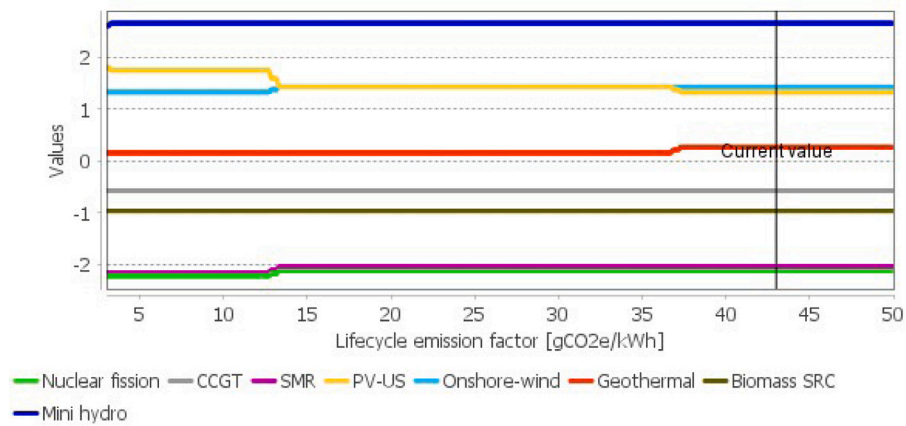


Fig. C.9. Stability of the Lifecycle CO₂e emissions value in PV-US technology.

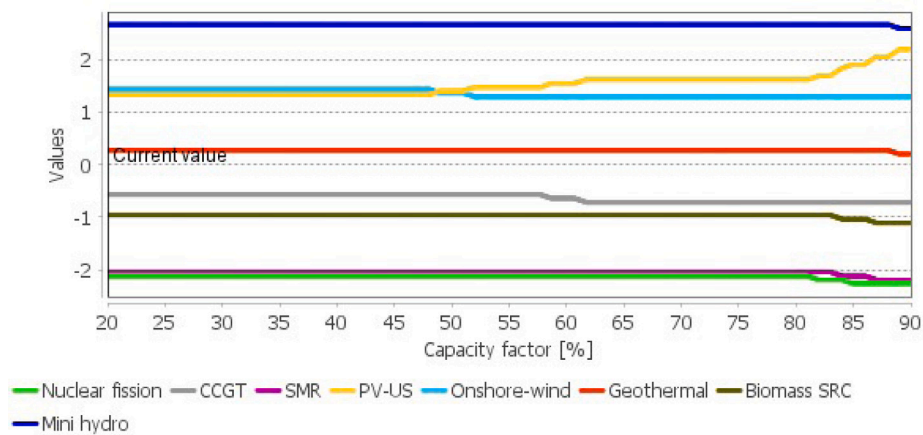


Fig. C.10. Stability of the capacity factor value in PV-US technology.

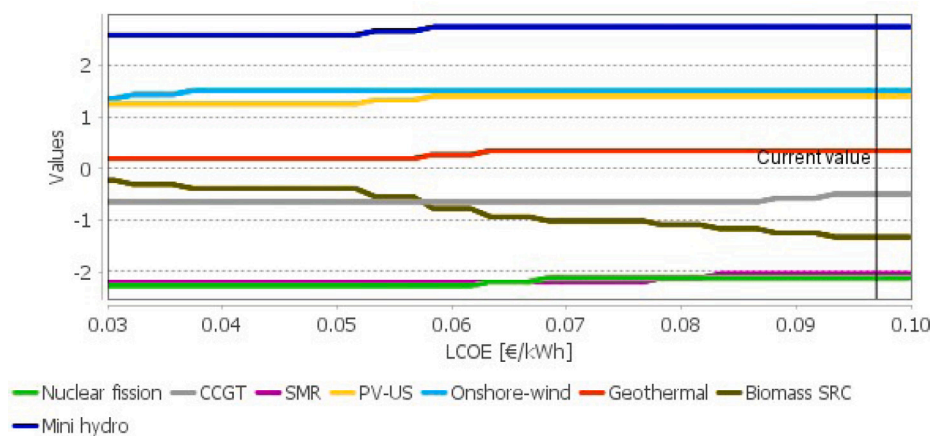


Fig. C.11. Stability of the LCOE value in biomass SRC technology.

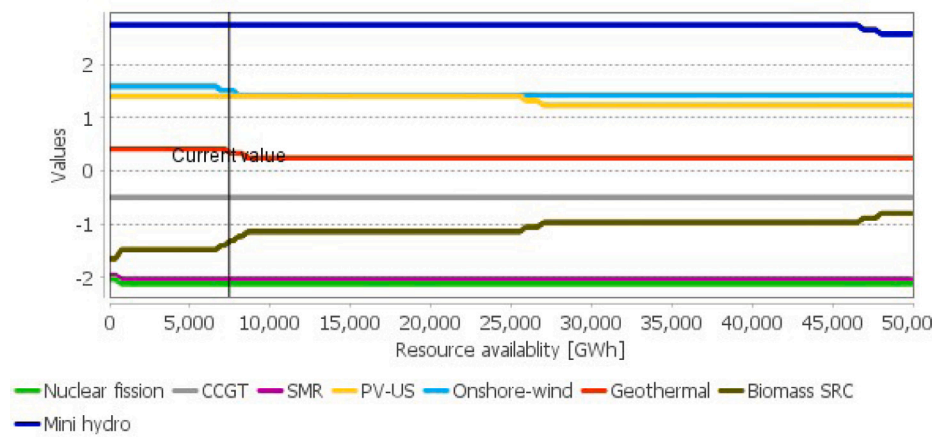


Fig. C.12. Stability of the resource availability value in biomass SRC technology.

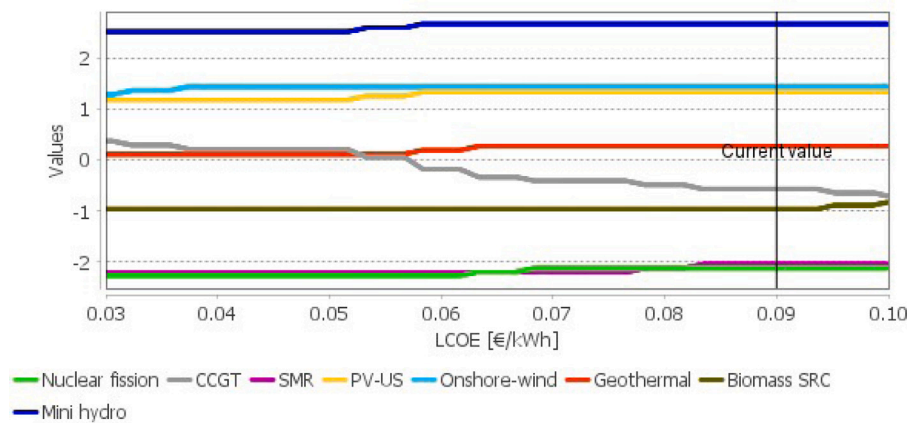


Fig. C.13. Stability of the LCOE value in CCGT technology.

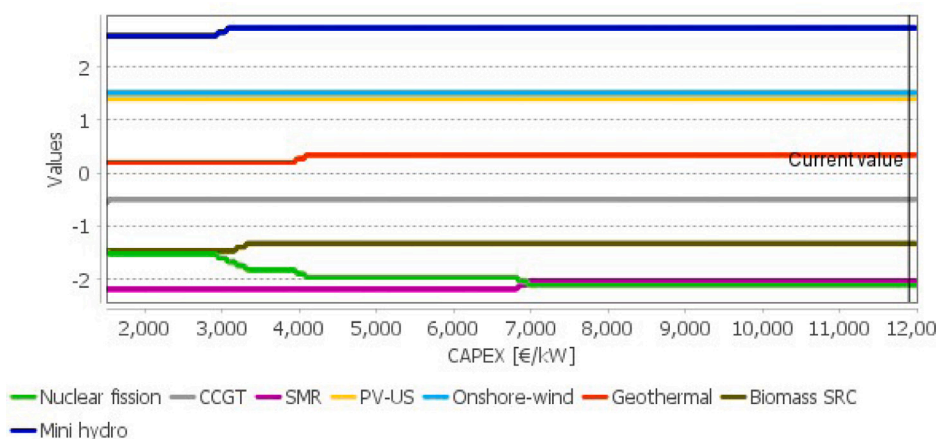


Fig. C.14. Stability of the CAPEX value in nuclear fission technology.

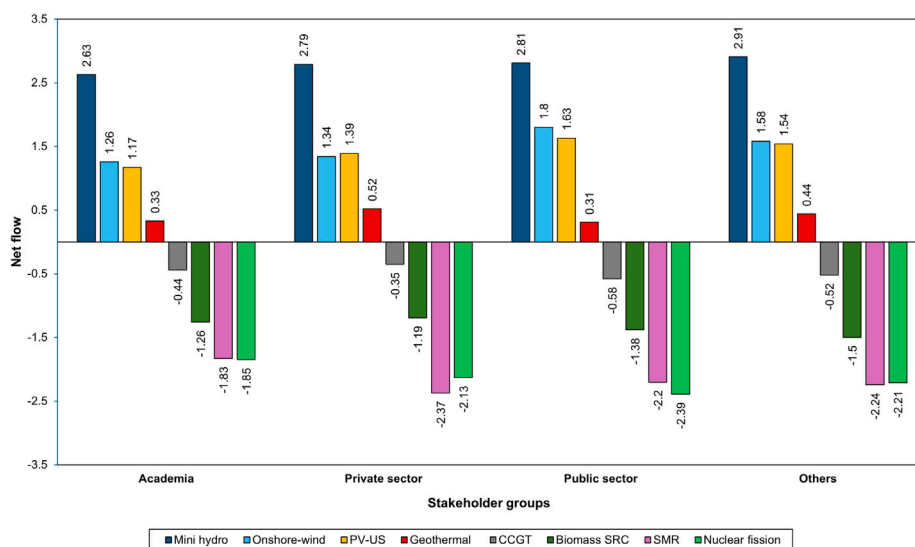


Fig. D.15. Ranking of alternatives for the four stakeholder groups.

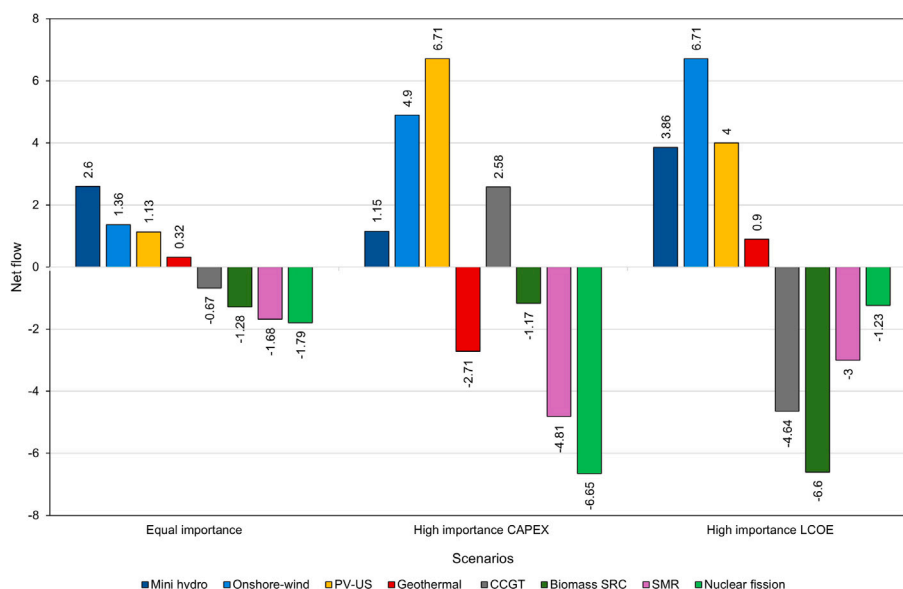


Fig. D.16. Ranking of alternatives for three different importance weighting scenarios.

Table D.12

Normalized weights for three different importance weighting scenarios.

	Equal importance	High importance CAPEX	High importance LCOE
TRL	0.067	0.002	0.002
Capacity factor	0.067	0.002	0.002
Resource availability	0.067	0.002	0.002
Service life	0.067	0.002	0.002
Average construction time	0.067	0.002	0.002
CAPEX	0.067	0.924	0.017
OPEX	0.067	0.017	0.017
LCOE	0.067	0.018	0.924
Fuel cost	0.067	0.018	0.017
Land use intensity	0.067	0.003	0.003
Lifecycle CO ₂ e emission	0.067	0.003	0.003
Blue water consumption	0.067	0.003	0.003
Risk for human health	0.067	0.003	0.003
Employment factor	0.067	0.003	0.003
Trained professionals	0.067	0.003	0.003

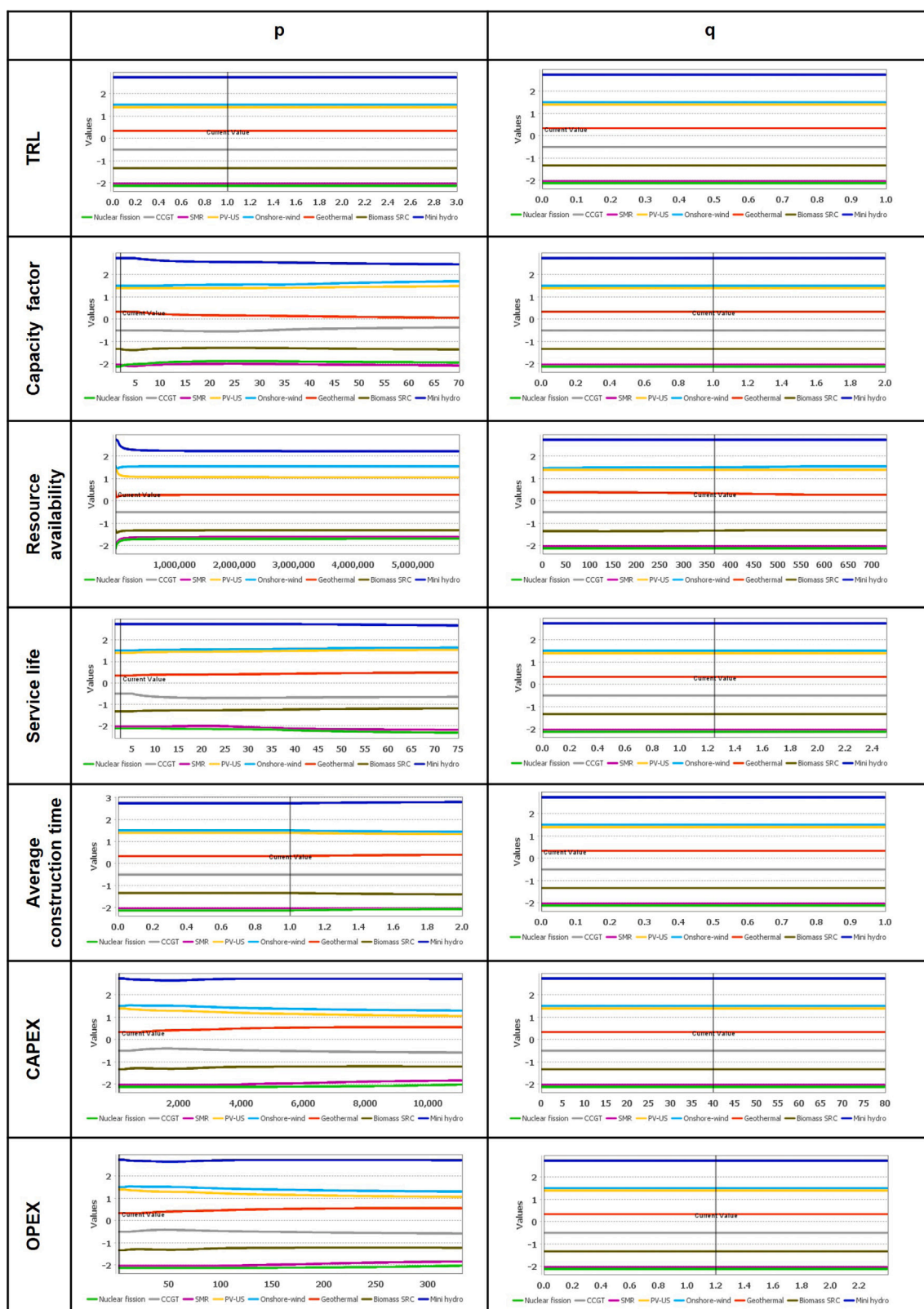


Fig. E.17. Stability of thresholds part 1.

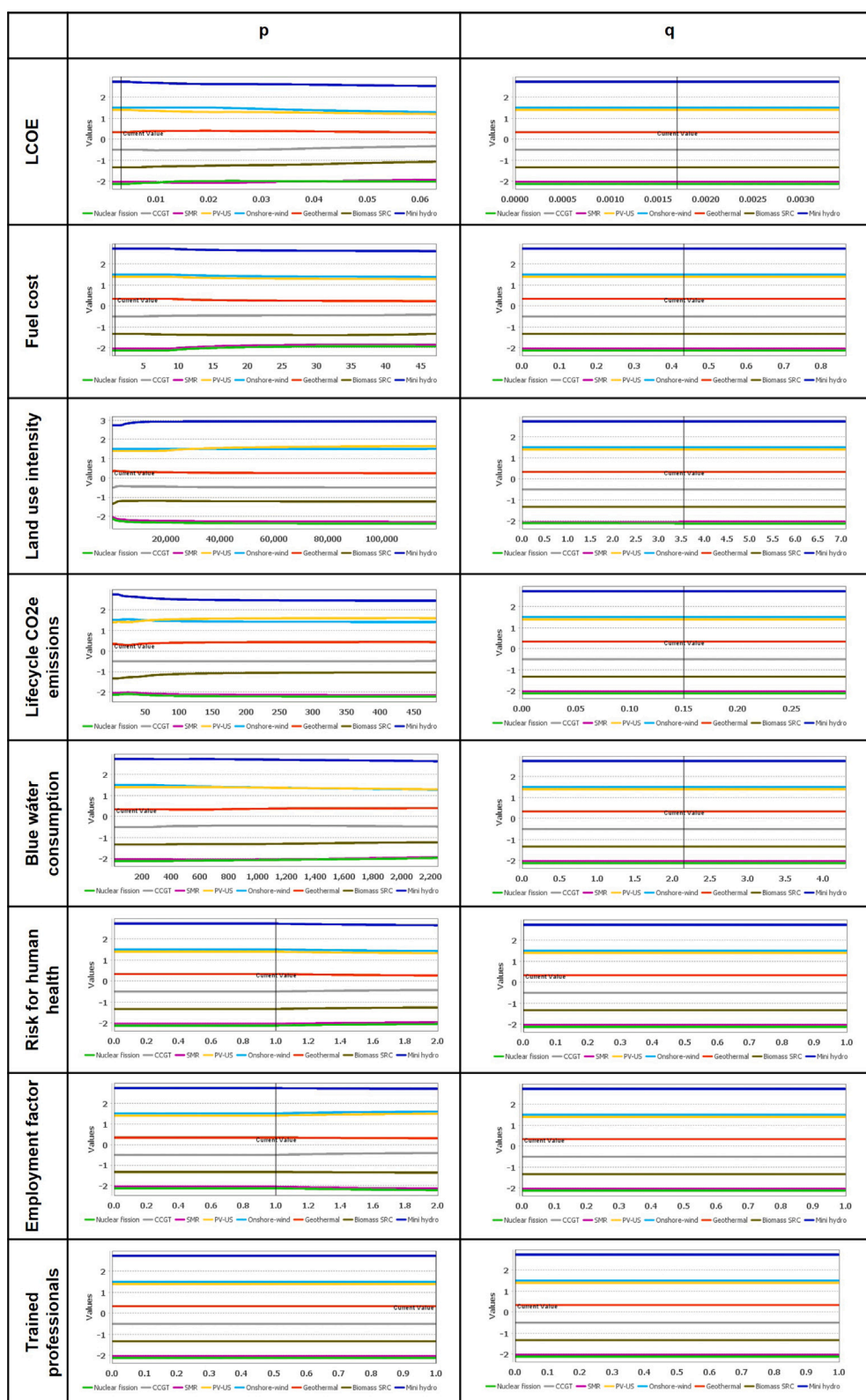


Fig. E.18. Stability of thresholds part 2.

Data availability

All data used on this article is cited.

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