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The Multi-Criteria Analysis as a tool for energy modeling: case study of Ecuador

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Abstract

This thesis explores the integration of energy governance and democracy into energy planning using Multi-Criteria Analysis as a practical tool in the context of the Ecuadorian power sector. By assessing a portfolio of power generation projects, including hydropower, solar, wind, and geothermal, through MCA and subsequent optimization in the *urbs* model, the study aims to enhance participatory decision-making, transparency, and inclusivity in energy planning. The results highlight the importance of considering diverse criteria, such as environmental, social, and technical aspects, and reveal that socio-environmental conflicts associated with hydropower projects in Ecuador can be mitigated through the application of MCA. The scenarios generated, including Policies, MCA, and High demand with CO_2 restrictions, provide insights into the potential transition to renewable energy in Ecuador, emphasizing the role of energy governance in achieving a sustainable and democratic energy future.

Zusammenfassung

Diese Arbeit untersucht die Integration von Energie-Governance und Demokratie in die Energieplanung unter Verwendung der Multikriterienanalyse als praktisches Instrument im Kontext des ecuadorianischen Stromsektors. Durch die Bewertung eines Portfolios von Stromerzeugungsprojekten, einschließlich Wasserkraft, Solarenergie, Windkraft und Geothermie, mittels MCA und anschließender Optimierung im *urbs*-Modell, zielt die Studie darauf ab, die partizipative Entscheidungsfindung, Transparenz und Inklusivität in der Energieplanung zu verbessern. Die Ergebnisse verdeutlichen, wie wichtig es ist, verschiedene Kriterien wie ökologische, soziale und technische Aspekte zu berücksichtigen, und zeigen, dass sozio-ökologische Konflikte im Zusammenhang mit Wasserkraftprojekten in Ecuador durch die Anwendung von MCA entschärft werden können. Die erstellten Szenarien, darunter Politik, MCA und hohe Nachfrage mit CO_2-Beschränkungen, bieten Einblicke in den potenziellen Übergang zu erneuerbaren Energien in Ecuador und unterstreichen die Rolle der Energiepolitik bei der Verwirklichung einer nachhaltigen und demokratischen Energiezukunft.

Acknowledgements

In the journey of a typical researcher, the path involves identifying a problem, exploring potential solutions, and ultimately presenting findings. Mine was a bit more challenging, marred by a condition I now affectionately refer to as "la tontera." It is through this bewildering experience that I found myself heavily reliant on the support of many individuals, without whom I would not be here today, let alone composing this thesis.

First and foremost, I extend my deepest gratitude to my husband, César, whose unwavering support has been invaluable. I thank him for the countless sacrifices he made to stand by my side, providing crucial support, especially during the most challenging years.

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Introduction

1.1 Problem Statement

The main objective of an energy model is to replicate and scrutinize the behavior of energy systems in diverse scenarios and conditions. Energy models are employed by policy makers, energy planners, and investors to forecast the potential impacts of policy decisions and technology options, and to inform energy planning and investment resolutions. By providing a quantitative basis for decision-making, energy models enable the identification of the most effective and efficient strategies for accomplishing energy and climate objectives, while minimizing costs and other repercussions [99], [50], [125]. However, it is important to highlight that most models do not assign equal importance to social and environmental criteria compared to technical and economic criteria. This disparity can impede the social acceptance of these models, acting as a constraint in achieving ambitious government targets for increasing the proportion of renewable energy [167].

Energy modeling has been used for decades to help decision-makers better understand the energy system and make informed decisions about energy policy and planning. The earliest forms of energy modeling were simple mathematical models used to estimate energy demand and supply. However, with the development of computers, energy modeling has become much more sophisticated, and today it involves complex computer simulations and data analysis techniques [102]. [125] provides a concise yet comprehensive overview of the development of energy systems models. In line with their study, this section will follow their framework and offer a succinct summary of their findings.
The evolution of energy systems modeling has been driven by the pursuit of insight rather than mere numerical outputs, as emphasized by [94]. The need for long-term strategic energy planning became apparent in the aftermath of the oil crisis in the 1970s, prompting industry and policymakers to recognize the significance of energy policy. Governments and international organizations started using energy models to explore different scenarios for energy supply and demand and to evaluate the potential impacts of different energy policies. To tackle the complex interactions and multi-layered aspects of energy in a modern economy, early energy systems models utilized linear programming methods that had been employed for large-scale planning since World War II. The International Energy Agency (IEA), initiated the Energy Technology Systems Analysis Program (ETSAP) in 1976 with the aim of creating an energy systems model.

Similarly, the International Institute for Applied Systems Analysis (IIASA), founded in 1972 embarked on the development of an energy systems model shortly after its establishment. The created models [37], [23], originally designed for use in developed economies, have now been applied in diverse contexts ranging from small off-grid systems in developing countries to continent-wide analyses in developed nations.

The development of energy systems models also coincided with the growing prominence of scenario planning throughout the twentieth century. In response to the lessons learned from the oil crisis in the seventies, scenario planning gained renewed focus as a means to understand and anticipate the future evolution of the energy sector. These models not only facilitated the creation of scenarios but also formalized fragmented knowledge about complex energy interactions, providing a structured framework to analyze the implications of changes within the system. Most significantly, they enabled policymakers to express their perspectives on the desired direction for the energy sector, aligning it with specific policy objectives. In the twenty-first century, energy systems modeling has gained further importance due to a convergence of critical challenges and opportunities. These include ensuring energy security, affordability, and resilience, as well as addressing environmental concerns such as pollution, climate change, and global sustainability. Climate change policy has particularly influenced energy systems studies, with a focus on achieving substantial greenhouse gas emission reductions as prescribed by climate science. Various global, regional, and national-scale studies have presented mitigation scenarios emphasizing the significant role of renewable energy sources, notably wind and solar power, in low-carbon electricity systems. However, emerging issues such as flexible demand driven by new technologies, the significance of electrification and intermittent supply, and the paradigm of distributed energy with varying renewable resource potential pose challenges to traditional energy systems modeling approaches. These emerging concerns highlight the limitations of conventional energy systems models in assessing competing claims and addressing feasibility issues in the transition towards renewable energy systems. While large-scale models can offer cost estimates and decarbonization targets, they often fall short in providing detailed insights into the configuration of a practical renewables-based energy system and identifying potential obstacles. Consequently, recent modeling efforts have aimed to enhance spatial and temporal resolution to effectively address these questions and contribute to the ongoing discourse surrounding the viability of renewable energy sources and the challenges involved in their implementation.

In their study, [125] examines four model groups, each with its own characteristics: (1) energy systems optimization models such MARKAL, TIMES, MESSAGE, OSeMOSYS, (2) energy systems simulation models such LEAP, NEMS, PRIMES, (3) power systems and electricity market models such WASP, PLEXOS, ELMOD, EMCAS, and (4) qualitative and mixed-methods scenarios such DECC 2050 pathways, Stabilization wedges. The challenges associated with these models are then presented.

One significant challenge in energy systems modeling is finding the right balance between model resolution, data availability, and computational feasibility. While coarse spatial and temporal resolutions may be suitable for fossil fuel or nuclear-based systems, they fall short when dealing with renewable energy and actively managed energy demand. Renewables' variability and location-dependency require detailed spatial representation, and addressing renewable intermittency necessitates accurate temporal resolution. High temporal resolution becomes particularly critical when modeling electricity markets to capture nuanced effects. Therefore, precise analysis of the energy system demands resolving temporal and spatial details.

Another challenge lies in addressing uncertainty and ensuring transparency in energy systems modeling. Two types of uncertainty are identified: epistemic uncertainty, which can be reduced through better data or models, and aleatory uncertainty, which cannot be further reduced. While handling epistemic uncertainty remains challenging, formal methods are available for managing aleatory uncertainty. Deterministic approaches, like Monte Carlo simulations, can analyze the effects of varying input data, while stochastic methods explicitly incorporate uncertainty by specifying parameter distributions. However, stochastic models often leave room for unforeseen uncertainties by varying only a subset of parameters. As energy systems models are not physically verifiable, transparency and accessibility are crucial. Releasing data and models for independent review enhances credibility, but it poses challenges in terms of resource allocation and documentation. Therefore, maintaining quality in both the modeling process and outcome is essential.

Complexity and optimization across scales present another challenge in energy systems modeling. Energy systems are complex, and compact representations may overlook important aspects or rely on simplified assumptions. Over-optimized complex systems may experience diminishing returns and increased vulnerability to unexpected shocks. The growing complexity of energy systems calls for a transdisciplinary approach to power grid science. Integrating information across different scales remains computationally demanding. Interdisciplinary complexity science offers promising approaches by specifying simple formulations for individual system parts (agents) and their interactions. Agent-based models, such as EMCAS, allow for capturing complex interactions effectively and are gaining traction in power systems modeling.

Lastly, capturing the human dimension is a challenge often overlooked in energy system models. Technical and economic factors receive significant attention, while human behavior, social acceptance, and non-financial barriers are neglected. This lack of understanding and representation contributes to high uncertainty in energy system models. Addressing energy demand, rather than just supply, is crucial for transitioning to a low-carbon energy system. However, achieving lasting changes in energy use behavior and integrating bottom-up research into system models remain difficult. Integrating studies on the acceptance or rejection of renewable technologies into energy system models holds promise, yet it necessitates further refinement and development. Alternative approaches, such as scenario building focused on non-technical factors and considering the role of actors in transitions, show promise but need to be effectively integrated into quantitative energy scenarios.

This research work significantly prioritizes addressing the fourth challenge, which highlights the critical need to incorporate social and environmental criteria alongside technical and economic criteria in national-scale energy system modeling. To illustrate the significance of this integration, several examples are provided that demonstrate conflicts arising from the absence of social acceptance towards energy facilities.

[147] makes a comprehensive analysis of 649 cases of resistance movements against both fossil fuel and low carbon energy projects, revealing that place-based resistance movements have been successful in impeding a significant portion of such projects. The study underscores that conflicts surrounding low carbon and renewable energy projects are comparable to

those associated with fossil fuel projects, disproportionately affecting vulnerable groups. It emphasizes the prevalence of repression and violence in these conflicts, with hydropower projects being particularly contentious.

Several countries have faced socio-environmental problems related to power plants, particularly when they are built in or near communities, or within sensitive ecosystems. The specific problems that arise can vary depending on factors such as the type of power plant, the location of the plant, and the level of community participation in the planning and decision-making processes. In countries like Guatemala, Bolivia and Panamá the construction of hydroelectric power plants has resulted in conflicts with indigenous communities. These communities have expressed concerns regarding the impact of the plants on their land, culture, and traditional practices, leading to widespread protests and legal challenges [60]. In China, the Three Gorges Dam, the world's largest dam, resulted in the displacement of millions of people and the loss of their livelihoods. In addition, the dam's severe environmental impacts, including threats of fish species extinction and geological instability, drew international criticism from environmental and human rights organizations such as Human Rights Watch and International Probe [97], [87]. The Tucuruí hydroelectric plant is the first large-scale dam in the Brazilian Amazon. The construction of the dam resulted in the flooding of a vast area and the displacement of approximately 32,000 people, including Quilombolas (afro-descendants), indigenous communities, peasants, and traditional riverside dwellers. These affected groups have been engaged in a long-standing struggle for their territorial rights, highlighting the interconnection between infrastructural megaprojects, economic growth, modernization, and the agrarian and landless conflicts in Brazil [13],[105].

Solar and wind energies are generally considered to have lower impacts and risks compared to other energy sources. However, the large-scale deployment and surface occupation of renewable energy projects in countries like Spain have led to the emergence of rejection movements. These movements, operating under the slogan "Renewable yes, but not like this," have gained sympathy in certain circles due to the romanticized image of rural communities fighting against corporate-driven environmental changes [83]. The case study of Himmelhausen (Germany) highlights a conflict over the installation of wind turbines. Initially, a motivated group supported wind energy, but a citizens' initiative against it emerged, led by influential individuals. Distrust was fueled by accusations of fraud, economic viability, and concern for nature conservation. The Himmelhausen conflict demonstrates the destructive nature of conflict, its impact on social relations, and the importance of trust in local disputes [80]. Additional examples similar to the aforementioned instances can be accessed via the Environmental Justice Atlas (EJAtlas), which systematically documents and analyzes environmental conflicts and social movements worldwide [13].

The conflicts cited before show that the decarbonization of the economy is by no means inherently environmentally friendly or socially inclusive. Climate and energy policymakers need to pay closer attention to the demands and preferences of the collective movements pointing to transformative pathways to decarbonization.

1.2 Motivation

The urgent need to revamp and improve energy system models for more effective and sustainable transitions is crystal clear. While these models play a crucial role, they often miss the mark by not fully embracing social and environmental criteria beyond just reducing CO_2 emissions, alongside the usual technical and economic considerations. This study recognizes this big gap and stresses how important it is to start weaving social and environmental aspects into national-scale energy system modeling.

Achieving a successful energy transition requires a profound integration of social and environmental considerations into energy models. This involves prioritizing equity in energy access, recognizing and addressing the needs and rights of marginalized communities, and ensuring inclusive decision-making processes where everyone's voice is heard. Simultaneously, on the environmental front, the emphasis lies on curbing carbon emissions, safeguarding biodiversity, and promoting sustainable resource use. This approach goes beyond merely reducing inequality; it aligns with the broader objectives of sustainable development.

The push to address this new perspective of energy system modeling isn't just coming from academics. International agreements, like the "Just Transition for All" event, are making it clear that we need a quick and fair move to renewable energy. This means we can't stick to the perspectives of energy experts alone – we need to tap into the knowledge and experiences of different communities [103]. By placing the needs and preferences of individuals and communities at the forefront, inclusive and participatory decision-making becomes the cornerstone for building trust and paving the way toward a genuinely fair and just energy future. And let's not forget the importance of learning from each other. Looking at experiences from different countries, sectors, and past transitions is key to shaping successful energy moves. When we bring social and environmental considerations into the mix with the technical and economic stuff, we're setting the stage for a more inclusive, people-friendly, and sustainable energy transition.

This study does not just change a few things but proposes a new way of thinking about energy planning. By incorporating social and environmental criteria on a national scale, we aim to bridge the gap between technical and financial aspects and the tangible realities of people and the environment. The goal? To create energy system models that are not only technically sound, but also take into account what people need and want, thus paving the way for a just and sustainable energy future.

1.3 Research Questions

This study aims to address three research questions specified below and their implementation in the particular case of the power sector in Ecuador

1. How to reduce socio-environmental conflicts surrounding power generation projects?

2. What is the influence of integrating environmental and social factors, alongside technical and economical aspects in the modeling of national energy systems?

3. Can a national energy model be developed that effectively integrates economic optimization, social and environmental criteria and stakeholder needs to achieve a sustainable energy system that ensures electricity demand coverage?

To answer the first research question, this study undertook an examination of historical and contemporary socio-environmental conflicts associated with energy generation projects in Ecuador. Through interviews with residents of areas affected by energy facilities, the study sought to discern the possible causes of conflicts, their implications for daily life, and community responses. In addition, the expectations of the central government to prevent future conflicts were explored. The subsequent research questions were addressed through a multi-criteria analysis (MCA) and an optimization model. The MCA included interviews with stakeholders from Ecuador's public, private, civil society and academic sectors who assigned degrees of importance to selected social, environmental, and technical criteria. With these results, a list of existing power generation projects was ranked from best to worst. Subsequently, the results of the MCA served as the basis for the development of a long-term optimization model for the Ecuadorian electricity sector using *urbs* software. This methodology made it possible to evaluate how the participation of various stakeholders and the consideration of various criteria can influence the results of an electricity system model in Ecuador.

1.4 Context of the case study of Ecuador

1.4.1 Planning the Ecuadorian Power Sector

To investigate the impact of energy transition towards renewable energies at the national level, a case study of Ecuador was conducted. Ecuador, a South American country, was chosen for its position as the sixth largest oil producer in Latin America and the Caribbean, out of a total of 16 countries, in 2021 [19]. Historically, oil has been the primary energy source in Ecuador. The annual crude oil production has maintained an average of 190 million barrels of oil equivalent (BOE) from 2011 to 2021, with the highest production in 2014, reaching 203 million barrels. In 2021, the total primary energy production in Ecuador amounted to 201 million barrels of oil equivalent (BOE). Oil production accounted for the majority, reaching 172.46 million BOE, which represents approximately 85.8% of the total. Natural gas production contributed 8.84 million BOE, accounting for approximately 4.4% of the primary energy produced. The remaining 19.7 million BOE came from renewable energy sources such as hydroenergy, wood, cane products, wind energy, photovoltaics, and biogas, making up approximately 9.8% of the total primary energy production in the country [73]. The contribution of renewable energy sources to the primary energy production has been lower compared to oil. Nevertheless, the production of renewable energy experienced significant growth during the period from 2011 to 2021. This growth was primarily attributed to the expansion of hydroelectric generation that will be detailed later in this chapter.

In the same period of time, there was a noticeable increase in energy demand in Ecuador. The energy demand rose from 78.9 million BOE in 2011 to 93.5 million BOE in 2021. Throughout this ten-year period, the transportation sector consistently exhibited the highest energy demand, averaging at 40.5 million BOE. In 2021, the transportation sector accounted for

45.72 million BOE, which represented 48.9% of the overall energy demand in Ecuador. The industrial sector followed with a consumption of 16.27 million BOE, accounting for 17.4% of the total energy demand. The residential sector ranked third, consuming 12.99 million BOE, equivalent to 13.9% of the total energy demand. The remaining 19.7% of energy consumption was attributed to sectors such as commercial, agricultural, fishing, and mining, as well as own consumption and others. See Figure 1.1.

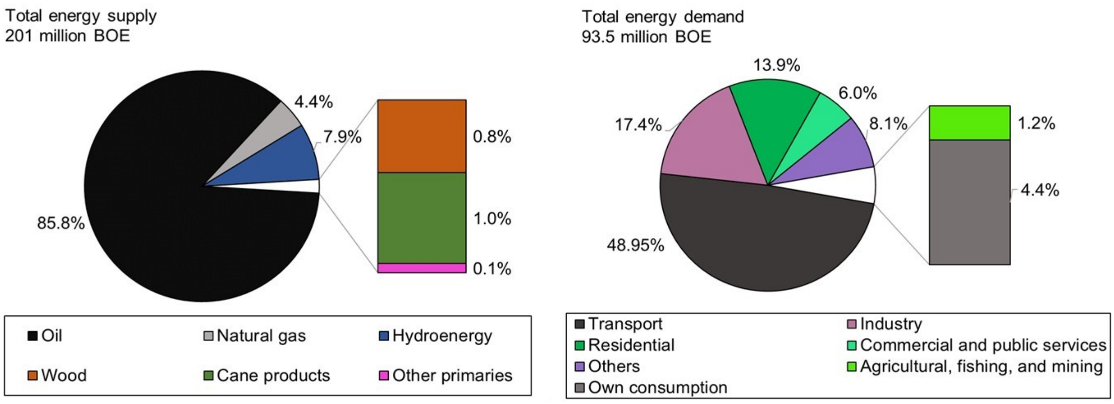


Figure 1.1: Primary Energy Supply and Demand [%] in 2021 in Ecuador

The electricity matrix in Ecuador has historically relied on thermal energy derived from fossil fuels and hydropower in nearly equal proportions. However, the ongoing project to shift the country's electricity matrix aims to decrease the reliance on fossil fuels and increase the share of renewable energy sources, primarily hydropower. Figure 1.2 illustrates the evolution of Ecuador's electricity matrix from 1999 to 2021, highlighting a significant increase in the share of hydropower. Notably, hydropower generation surpassed thermal generation in 2015, attributed mainly to the commissioning of hydroelectric plants, including Manduriacu (63.36 MW) and Baba (42.2 MW) in 2015, and Coca Codo Sinclair (1500 MW) and Sopladora (486 MW) in 2016. Despite some increase in other renewable energy sources, such as solar, wind, and biomass, which peaked in 2016 with 613 GWh, accounting for 2.2% of the country's total electricity generation, their contribution remains minimal. The shift in the electricity matrix has resulted in a reduction in CO_2eq emissions, decreasing from its peak of 8.58 million tons in 2014 to 4.66 million tons of CO_2eq in 2021 [71], [73], [34].

In 2021, the electricity generation in Ecuador was mainly derived from hydropower (79%), followed by thermal plants (19%) that use diesel, natural gas, and heavy oil, while solar, wind, and biomass resources only contributed 2%. The installed capacity of hydropower increased significantly from 2.2 GW in 2011 to 5.1 GW in 2021, while other renewable energy technologies only increased their installed capacity from 0.101 GW to 0.194 GW during the same period [74], [75].

As per the Electrification Master Plan (PME 2018-2027) of Ecuador, the primary focus for meeting future electricity demand will be the expansion of hydropower, which will be supported by the use of natural gas during dry seasons. However, the deployment of solar, wind, biomass, and geothermal energy will continue at low levels [70]. In August 2021, the Ministry of Energy and Non-Renewable Natural Resources approved an updated generation expansion plan of the PME until 2031. This plan is aimed at achieving the following objective:

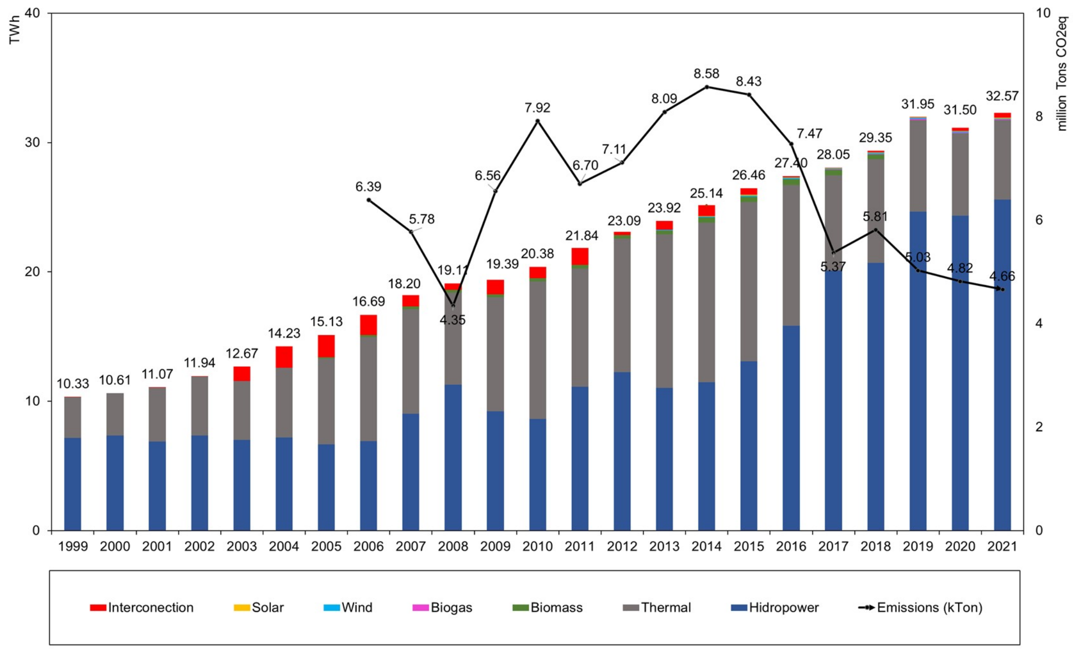


Figure 1.2: Evolution of electricity generation and CO_2eq emissions from 1999 to 2021 in Ecuador

> [...] to attract private investment of approximately USD 2,200 million in Non-Conventional Renewable Energies (NCRE), including photovoltaic, wind, geothermal, biomass, and other projects to ensure the country's electricity demand is met in the upcoming years, prioritizing the utilization of renewable resources. The plan is to incorporate around 1,440 MW of renewable energy into the National Interconnected System (SNI), in addition to the already planned projects.
>
> MERNNR, 2021 [6]

A 4-year deployment plan is set to install 1,440 MW of NCRE in Ecuador. The project will begin in 2024 with the installation of 500 MW, followed by another 500 MW in 2025, 120 MW in 2026, and 320 MW in 2028. Figure 1.3 shows the detailed breakdown of each project.

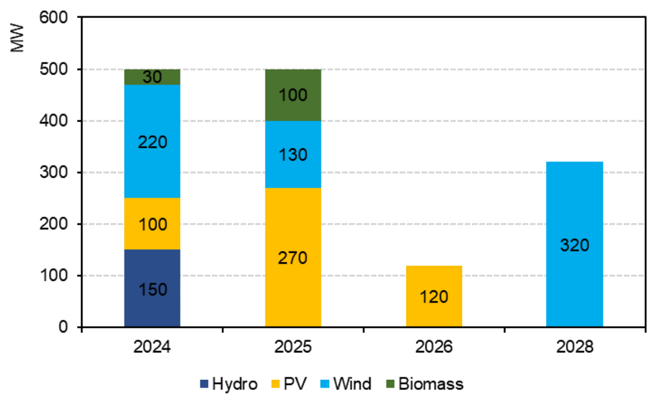


Figure 1.3: Deployment plan for 1,440 MW of installed capacity in Ecuador from 2024 to 2028

The aforementioned projects will supplement the existing hydroelectric portfolio comprising of 91 projects with a total capacity of 11,282.45 MW [70], [58]. Although the exact start-up dates are currently unknown, the country's hydroelectric expansion plan remains strong. However, this approach faces limitations since it fails to fully account for two critical factors, namely, the potential impacts of climate change, which could lead to variations in hydropower resource availability [59], [51], [84], [148],[137], and the lack of social acceptance of hydropower plants in the country, that will be detailed in the next subsection.

1.4.2 Socio-Environmental conflicts arising from hydroelectric power development in Ecuador

Currently, there is a lack of comprehensive documentation regarding socio-environmental conflicts arising from hydroelectric dams in Ecuador. Nevertheless, conflicts that will be explicated below have been gathered via interviews conducted since 2014, data derived from press articles, and web pages that highlight protests by residents from affected areas, such as the Environmental Justice Atlas [13]. To ensure the confidentiality and safety of the people who participated in the interviews in this study, it is important to maintain their anonymity. The use of anonymous references will be employed in situations where revealing the identity of participants may pose a risk to their safety or well-being. This precautionary measure is intended to protect the privacy of interviewees and to maintain ethical considerations throughout the research process.

Jaime Roldos Aguilera multi-purpose project (130 MW)

The Jaime Roldos Aguilera multi-purpose project is a large-scale infrastructure project situated at the confluence of the Daule and Peripa rivers in Ecuador, comprising a hydroelectric power plant, water supply, irrigation, and flood control systems. The project has been subject to controversy, with critics raising concerns regarding its potential environmental and social impacts. Specifically, the displacement of local communities, the impact on fish populations, and potential erosion and sedimentation in the river have been identified as potential issues. The flooding of the reservoir resulted in the submergence of one of the most fertile areas of the country, formerly dedicated to local market agricultural production, leading to the displacement of numerous communities. As a result, around 50,000 people were left isolated in the water fringes of the reservoir and continue to live in conditions of extreme poverty. These communities initiated an organization process in 2004 to demand redress for the damages suffered from the Ecuadorian government [13].

San José del Tambo hydropower plant (8 MW)

The San José del Tambo Hydroelectric Power Plant is a run-of-river type project located in the Dulcepamba river basin in the province of Bolívar, Chillanes canton, San José parish, which generates 8 MW of electrical energy without requiring a dam or reservoir. However, the Hidrotambo hydroelectric project has faced opposition from local groups and organizations, who have protested against the project and demanded compensation for the damage caused. In 2005, the Dulcepamba River Defense Committee was established by the communities to resist the implementation of the hydroelectric project, and to advocate for their rights. From 2006 to 2007, multiple confrontations occurred between the residents and the army, as approximately 300 soldiers were deployed to confront 72 communities. These incidents resulted in the opening of 22 legal proceedings, and the arrest of 14 leaders who were accused of engaging in rebellion activities. The community of San Pablo de Amalí, situated in the San José del Tambo parish, has claimed that the operation of the Hidrotambo hydroelectric plant is leading to the complete depletion of the Dulcepamba river's water, which threatens the river's availability for human consumption, agricultural use, and ecosystem preservation. Furthermore, they have accused the company of causing floods and landslides in 2015, 2017, and 2019, incidents that have drawn repeated criticism from the Ombudsman's Office. The 2015 flood, in particular, resulted in the loss of three lives and the destruction of 12 homes in the San Pablo de Amalí community. In late 2020, a team of water and aquatic resources researchers from Ikiam University conducted a study on the Dulcepamba River to measure the flow, collect information, and assess the capacity of the tributary to generate energy. The study revealed that human activities have caused modifications in the riverbed that have resulted in instability over a distance of almost 3 kilometers, as opposed to natural causes. The researchers concluded that this modification has negative effects on fish migration from the Ecuadorian coast to the Andes. The Hidrotambo company claims to comply with environmental regulations and that there are communities that support the plant. However, false accusations have been made against the project, and the company requested the principles of legal certainty to be complied with due to the national importance of the power generation plant's operation [10], [13].

Baba multi-purpose project (42 MW)

The Baba hydroelectric project is situated at kilometer 39 of the Quevedo-Santo Domingo highway, in the Buena Fe canton. The project commenced operations in 2013 with the aim of mitigating flooding during the winter season in crops located in the Buena Fe, Valencia and Quevedo cantons. Furthermore, the project aims to provide water during the dry season through the control of an ecological gate, and generate electricity. The project features a 1,100-hectare reservoir with four dikes and a duck-billed spillway. The construction and operation of the Baba hydropower plant have given rise to social and environmental conflicts in the surrounding areas. Over 30 communities, including Peripa del Baba, La Ceiba, and Corriente Grande, have opposed the Baba Multipurpose Project, arguing that the reservoir has resulted in a shortage of fish, damage to crops, and displacement of the local population. According to the villagers, the construction of the hydroelectric dam has altered the course of the Baba River, leading to a significant decrease in fish populations. Prior to the construction of the dam, fishing was a common practice among the villagers, who relied on it for their daily meals and income. However, with the introduction of the dam, fish stocks have declined substantially, causing significant harm to the local communities. The exact number of individuals who had to evacuate their homes due to the flooding caused by the construction of the Baba hydropower plant is currently unknown. However, reports from community leaders suggest that approximately 50 people per community, or a total of around 1,500 inhabitants, were forced to migrate. The remaining residents have faced challenges in accessing clean water for human consumption. In an attempt to address this issue, one of the companies responsible for the construction of the plant drilled a water well for the community. However, the quality of the water extracted from the well has been inadequate, with residents reporting that the water is cloudy and does not meet their expectations. This has added to the difficulties faced by the community, as the construction of the dam has significantly restricted the flow of the river, which was previously a primary source of water for the population. As of February 2023, the Baba hydropower plant remains operational and is generating electricity, despite the outstanding issues outlined above which have yet to be resolved [12], [32], [13].

Hidroabanico power plant (37.5 MW)

The Abanico hydroelectric project, known as Hidroabanico, is a run-of-river hydroelectric power plant situated in the southeastern region of Ecuador. It is located approximately 15 kilometers from Macas, the capital of Morona Santiago province, in a remote area without significant population centers. Hidroabanico does not have a reservoir, and its excess flow is controlled through spillways and bottom drains. The project was built in two stages, with no displacement of people or landowners reported, and land was acquired through purchase and signed easement documents.

The construction of the first stage of Hidroabanico potentially affected the water availability in the area and altered the flow of the Balaquepe and Jurumbaino Rivers, according to residents of the Jimbotono community located in close proximity to Macas. In May 2006, social organizations opposing the construction of the second phase of Hidroabanico began mobilizing after the mining company Corriente Recursos announced a letter of intent to supply energy to its Mirador mining project through Hidroabanico. The affected communities claim that the hydropower plants will provide electricity to mega copper and gold mining projects in the southern part of the region. A five-day strike started on August 30, 2006, and extended throughout the province. Violent confrontations between Jimbotono residents, guards, and Hidroabanico workers occurred on October 3, 2006. Subsequently, on November 7, a new strike began in the province, leading to the takeover of two mining camps on November 8. After 75 days of protests, the government of then-president of Ecuador, Dr. Alfredo Palacio, sent the Minister of Labor as his delegate to sign an agreement with the Committee on November 12, 2006. Dialogue tables were established with the participation of organizations, communities, local authorities, and institutions of the province, who committed to defend life and nature. Despite these commitments, the second phase of the project was built, and Hidroabanico continues to operate and generate electricity [13], [28], [152], [38].

Agoyán, San Francisco, and Topo power plants (156 MW, 230 MW, 29.2 MW)

The Agoyán Power Plant is a hydroelectric facility located in the Tungurahua province, approximately 180 km southeast of Quito, designed to harness the flow of the Pastaza River. It is situated in the Agoyán region, which lies 5 km east of Baños on the main road leading to the Ecuadorian Amazon sector. The plant comprises a reservoir with a total storage capacity of 1.8 million cubic meters. The water discharged through the tunnels of the facility is collected directly by the San Francisco power plant as it cascades down as a waterfall.

The canton of Baños, Ecuador, has faced significant challenges concerning its hydroelectric plants, particularly the Agoyán and San Francisco power plants, which have been problematic for the local residents. This is a pressing issue for a town that heavily relies on tourism, which is boosted by its diverse biodiversity and favorable climate.

According to interviews conducted to some Baños inhabitants:

> [. . .] the construction of the Agoyán hydroelectric plant from 1982 to 1987 and Odebrech's construction of the San Francisco power plant from 2004 to 2007 had a significant impact on the natural water resources of the area, which are crucial for the economic and social well-being of the local community that relies on tourism as a key source of income. The construction of these plants caused the waterfall after which Agoyán was named to dry up, and the San Francisco plant not only collected turbine water from Agoyán but also from other springs along the way, resulting in the disappearance of the San Jorge river. These changes had a significant impact on the area's natural water resources, affecting the economic and social well-being of the local community.

The Municipality of Baños has also identified multiple environmental impacts resulting from the operation of two hydroelectric plants, including the loss of "La Cascada de Agoyán," the deterioration of water quality in the reservoir, which negatively affects the health of the population, and the disappearance of 1 km of the Pastaza River in the Agoyán sector. Additionally, the operation of these plants has caused erosion on the left and right banks of the dam and geological failures in the soil of Barrio La Ciénega. The decomposition of solid and liquid waste in the dam has resulted in the emission of foul odors, proliferation of insects such as mosquitoes and gnats, and permanent epidemics of infectious and skin diseases for 25 years. The operation of these plants has also caused air pollution, and during reservoir cleaning operations, all decomposing material is transported downstream. Furthermore, the flooding caused by these plants alters climatic conditions in the long term, modifying local ecosystems and affecting the water supply for human consumption [159].

Despite the opposition expressed by the inhabitants and authorities of Baños canton regarding the two hydroelectric plants already in operation, an environmental license was granted in 2005 for the construction of the Topo hydroelectric plant, also located within Baños canton. However, in July 2006, the Tungurahua Provincial Chamber of Tourism filed a constitutional protection lawsuit, asserting various irregularities, such as essential omissions in the Environmental Impact Study that concealed information regarding the expected environmental impacts from the construction and operation of the Topo Hydroelectric Project. These impacts included the imminent danger of extinction of several endemic species of flora and fauna, endangering the preservation of nature, the conservation of ecosystems, and the integrity of Ecuador's genetic heritage. Consequently, the Ministry of the Environment temporarily withdrew the environmental license for El Topo until the observations made in the constitutional appeal and by the citizens of Baños and the areas of influence of Proyecto Topo were considered. Three additional environmental impact studies were carried out to address errors identified in the previous version, with the ultimate objective of gaining community approval.

Currently, the hydroelectric plants in Baños, Agoyán, San Francisco, and Topo are still operational, despite the opposition and evidence of their negative impacts [159], [88].

Piatúa power plant (30 MW)

The Piatúa hydroelectric plant, owned by Generación Eléctrica San Francisco (Genefran), is located on the Piatúa River, which marks the boundary between the Pastaza and Napo provinces. The project is causing concern among members of the Kichwa indigenous community and settlers residing in Santa Clara canton in Pastaza province. Environmental experts have raised red flags about the site of the Piatúa hydroelectric project, which falls within the ecological corridor connecting the Llanganates National Park and the Sangay National Park. This region is home to several endemic species and is crucial for wildlife conservation. Additionally, the area sits at the transition between the tropical Andes and the Amazon plain, making it ecologically significant.

Starting in 2014, the Kichwa indigenous community has actively opposed the development of the Piatúa hydroelectric plant, citing concerns over environmental degradation, cultural disruption, and economic losses. Despite significant opposition from the Kichwa people, the Ecuadorian Ministry of Environment approved the Environmental Impact Assessment (EIA) submitted by Genefran. The Kichwa indigenous community contends that there was no Free, Prior and Informed Consultation about the project, and that the Genefran company did not provide explicit information about the proposal to build a hydroelectric plant. According to the Kichwa's leader, Christian Aguinda interviewed in November 2022, the Kichwa community regarded the engagement as an exchange of information rather than a decision-making process and did not approve a project that would extract more than 90% of the river's water.

The objections to the hydroelectric project on the Piatúa River extend beyond cultural and ancestral issues, and experts from various scientific disciplines express concerns about the environmental impact of the project and deficiencies identified in Genefran's submitted environmental impact study. The Pontificia Universidad Católica del Ecuador evaluated the amphibian component of the study and environmental management plan for the Piatúa hydroelectric project, and the assessment revealed inadequacies in assessing the project's impact. Additionally, geological studies for the Piatúa project are under scrutiny because they identify a significant risk of alluvium at the proposed location of the diversion structure, and an adequate level of geological risk assessment is lacking.

In May 2019, the Kichwa indigenous community filed a protective action in Ecuadorian courts seeking protective action and precautionary measures for their people against the proposed Piatúa hydroelectric project. To support their case, the Kichwa presented technical reports from experts in various fields, including geology, anthropology, archaeology, and biology, outlining the potential impact on nature and collective rights. However, the Criminal Judicial Unit - Constitutional B of Pastaza denied the protection action on the grounds that there was no violation of constitutional rights. This ruling was later investigated for corruption. In the second instance, a different judge agreed with the Kichwa about the socio-environmental deficiencies in the Piatúa hydroelectric project and halted construction activities. Meanwhile, the Genefran company claimed that its studies met all the necessary requirements and accused Kichwa leader Christian Aguinda of intimidation, a charge that he denied. As a result, the construction of the Piatúa hydroelectric plant is on hold until February 2023, and the Kichwa community continues to fight against it [25], [9], [40].

Coca Codo Sinclair (1,500 MW) and Yanuncay (22 MW) power plants

The Coca Codo Sinclair (CCS) hydroelectric project, with a capacity of 1500 MW, and the Yanuncay hydroelectric project, with a capacity of 22 MW, have also faced social conflicts and generated negative impacts. Communities living downstream of the CCS hydroelectric plant have reported a significant decrease in the amount of fish in the Tigre River since the start of the plant's operation in 2016. The residents are now forced to purchase other sources of food, whereas they previously had access to free fish for consumption. In the case of the Yanuncay hydroelectric dam, the residents of the areas of influence rejected the project in 2022 and prevented the passage of machinery for the construction of the project's first phase. A group of residents from the Soldados community, supported by activists from the Yasunidos collective, argue that the project will cause environmental damage in the upper Yanuncay river basin, where it is located, and that there was a lack of prior consultation. However, Elecaustro, the company responsible for the project, has rejected the accusations of the residents, stating that their protests are unfounded, and seeks the Ministry of Energy's support to continue with the project's construction [7], [26], [33], [30], [5].

The hydropower projects in Ecuador have been associated with numerous socio environmental conflicts, as described in this subsection. These conflicts underscore the challenges involved in hydropower construction and emphasize the significance of assessing the impacts on local communities and ecosystems during energy sector planning. Such projects serve as an example of the importance of considering the potential impacts of energy development on the environment and human communities and the need for stakeholders to work collaboratively to address these concerns. The present work advocates for the integration of energy governance within the energy planning process to ensure that sustainable, equitable, and democratic energy development is achieved, while taking into account the interests of all relevant stakeholders.

1.5 Thesis Outline

This thesis is structured into five distinct chapters, each serving a well-defined purpose. Chapter 1 serves as the introductory foundation of this work. Within this chapter, the research problem that motivates this study is presented. It meticulously formulates four research questions that guide the subsequent investigation. Moreover, this chapter immerses the reader in the specific context of this study, providing a comprehensive overview of the case study, which centers on the electrical sector in Ecuador. Chapter 2 is dedicated to elucidating the theoretical underpinnings of this work and the practical application of these theories through the use of Multi-Criteria Analysis. This chapter offers a comprehensive literature review that sets the stage for the subsequent analytical exploration. In Chapter 3, the research methodology is detailed in a structured manner. This chapter is divided into two sections. The first section meticulously outlines the specific steps involved in the Multi-Criteria Analysis process. The second section shifts focus to the *urbs* model, shedding light on its structure and its critical role in modeling the Ecuadorian electrical system. This modeling process combines existing data with the outcomes of the preceding methodology section. Chapter 4 is the heart of the thesis, where the research findings are presented in a structured manner. It is subdivided into two distinctive sections. The first section unveils the results of the Multi-Criteria Analysis, encompassing the crucial elements of weight assignment and the ultimate ranking of alternatives. In the second section, the chapter delves into the outcomes of modeling the Ecuadorian electrical system under three distinct scenarios, offering a comprehensive analysis of these scenarios. Finally, in Chapter 5, we explore the broader implications of employing Multi-Criteria Analysis in the modeling of energy systems. This exploration is grounded in the context of Ecuador, providing a practical perspective on the relevance of the methodology. Additionally, this chapter critically examines the limitations of the tool and offers the final conclusions and insights derived from the extensive research conducted throughout the thesis.

Chapter 2

Literature Review

This chapter undertakes a systematic literature review to provide a comprehensive understanding of energy planning and the tools employed for its enhancement. Section 2.1 enlightens the concepts of energy governance and energy democracy as they relate to energy planning, establishing a foundational background. Moving forward, Section 2.2 presents a critical review of Multi-Criteria Decision Making (MCDM) as a robust methodology capable of accommodating multiple criteria and diverse stakeholder perspectives within the decision-making process inherent to energy planning. Subsequently, Section 2.3 conducts a thorough examination of the various MCDM techniques employed for modeling energy systems across different scales. Finally, the chapter concludes with a concise summary in Section 2.4, highlighting the alignment of the research questions addressed in this PhD thesis with the identified gaps in the existing literature.

2.1 Energy governance and energy democracy as fundamental pillars of the energy planning paradigm

> The primary structural driver of socio-environmental conflicts due to energy transition stems from the fragmented nature of public policy discourse, characterized by distinct realms: the legislative arena dominated by corporate and local interests, the executive sphere marked by authoritarianism and bureaucratic tendencies, and the informal domain of public opinion capturing societal demands but lacking universal legitimacy. Fontaine, 2010 [82]

By incorporating energy governance and energy democracy as essential pillars of energy planning, our aim is to offer a potential solution, or at the very least, a substantial reduction, to the socio-environmental conflicts that arise from the transition to renewable energies, as discussed in Section 1.2 and Sub-section 1.4.2. The integration of these concepts will enable inclusive decision-making processes that consider the interests of diverse stakeholders, ranging from local communities to industry representatives and environmental advocates. This approach seeks to foster sustainable and equitable energy development, ensuring that the benefits and burdens of the transition are distributed fairly and that social, economic, and environmental considerations are appropriately addressed. By promoting transparency, participatory mechanisms, and accountability, energy governance and energy democracy contribute to the creation of a more resilient and socially just energy system, capable of addressing the complex challenges of the energy transition.

The concept of energy governance is contingent upon contextual factors and typically encompasses attributes pertaining to policies, such as international interactions, coordinated and interactive arrangements, institutionalized rules, and a diverse array of stakeholder groups [45]. Its objective is to establish functional relationships among various actors involved in the decision-making, implementation, and evaluation processes pertaining to energy-related matters [117], [127]. On the other hand, the term of energy democracy has gained significant popularity, particularly in the context of low-carbon transitions that aim for broader socio-economic and political transformation. This rise of energy democracy aligns with a broader trend in research and practice, emphasizing the significance of political dynamics. While related concepts such as energy justice and energy citizenship have been extensively explored in academia, energy democracy has predominantly emerged from social movements. It embodies aspirations for greater democratic control and community involvement in energy decision-making processes [155]. This thesis handles the term energy democracy used by grassroots activists in the United States and parts of Europe who call for and justify the integration of policies linking social justice and economic equity with the transition to renewable energy. It is not the purpose of this work to delve into what is and is not democratic about energy democracy [54].

According to [145] and [81], energy governance and energy democracy are closely intertwined and complementary in achieving effective and inclusive energy systems. Energy governance refers to the structures, processes, and institutions involved in making decisions and implementing policies related to energy. It encompasses both public and private actors, as well as formal and informal mechanisms. On the other hand, energy democracy emphasizes the importance of democratic principles, such as participation, transparency, and accountability, in shaping energy systems. It advocates for the inclusion of diverse stakeholders in decision-making processes and aims to ensure that the benefits and costs of energy policies are distributed equitably. Both terms share the goal of enhancing citizen involvement and promoting sustainable energy practices. Energy governance provides the framework for decision-making processes, while energy democracy provides the values and principles that guide those processes. By integrating democratic principles into energy governance frameworks, such as inclusive stakeholder engagement, access to information, and mechanisms for public participation, energy systems can become more responsive to societal needs and aspirations. Moreover, energy governance and energy democracy mutually reinforce each other. Effective energy governance requires democratic legitimacy and active citizen participation to ensure that decisions are accountable and aligned with societal interests. Conversely, energy democracy relies on robust governance structures to translate democratic ideals into practical policy implementation and systemic change.

Energy governance and energy democracy offer substantial potential for improving the energy planning process through a number of key mechanisms. First, these concepts facilitate inclusive decision-making by involving diverse stakeholders, including local communities and marginalized groups, allowing for a more comprehensive consideration of perspectives, local knowledge and innovative ideas within energy planning [162]. Second, transparency and accountability are prioritized, ensuring the availability of clear and accessible information on energy policies and projects, thereby building public trust and enabling informed participation. At the same time, oversight mechanisms and control systems contribute to the impartiality, objectivity and accountability of energy planning decisions [134]. Third, energy governance and energy democracy emphasize the integration of the principles of sustainability and resilience, promoting long-term planning that incorporates environmental and social considerations, prioritizes renewable energy sources, and adopts energy efficiency measures. This integration accelerates the transition to cleaner and more sustainable energy systems, reducing greenhouse gas emissions and mitigating the risks of climate change. Furthermore, these concepts emphasize the equitable distribution of benefits and costs, addressing socioeconomic disparities and safeguarding the rights of vulnerable groups. By prioritizing equitable access to energy services and taking into account the impact on marginalized communities, energy planning can mitigate energy poverty and contribute to social welfare. Finally, energy governance and energy democracy facilitate conflict resolution and consensus building among various stakeholders by providing platforms for dialogue, negotiation and mediation [133]. These mechanisms foster social cohesion and build support for energy planning decisions, thus facilitating smoother implementation and greater public acceptance. Overall, energy governance and energy democracy hold immense potential for promoting inclusive, transparent, sustainable, equitable and conflict-resolving energy planning processes.

The integration of energy governance and energy democracy terms into energy planning has garnered considerable attention in academic research and practical applications. Researchers have explored the implications of these concepts in shaping inclusive, sustainable, just, and equitable energy planning processes. This literature review synthesizes key studies and provides an overview of the cases where energy governance and energy democracy have been applied in the context of energy planning.

[81] highlights the increasing interdependence of energy systems across borders and the growing need for effective governance mechanisms to address global energy challenges. The study emphasizes the need for improved international cooperation, enhanced regulatory frameworks, and inclusive decision-making processes to navigate the complexities of global energy governance. It calls for a more holistic and integrated approach that considers environmental, social, and economic dimensions to ensure sustainable and equitable energy systems in the face of emerging challenges. [46] examines the discourses surrounding climate governance and highlight the role of energy democracy in shaping post-Copenhagen climate negotiations. They emphasize the importance of participatory decision-making and inclusive processes in achieving effective energy planning outcomes. [54] focuses on the concept of energy democracy and its implications for sociotechnical transitions in the energy sector. The authors argue that energy democracy goes beyond the conventional understanding of renewable energy deployment and emphasizes broader democratic values and participation in decision-making processes. [98] examines the relationship between energy democracy and social movements in driving sustainability transitions. It explores how diverse coalitions of actors and social movements play a crucial role in advancing energy democracy agendas. The paper highlights the importance of collective action, grassroots mobilization, and collaboration across different sectors to promote democratic decision-making, social justice, and equitable energy systems. [157] analyzes the governance of the energy transition at the national and

international levels, highlighting challenges and opportunities in implementing effective energy policies. [53] revisit the urban politics of climate change and emphasize the significance of local governance and community participation in shaping energy planning initiatives at the city level. [96] explores the concept of energy justice and its application in the context of the energy transition. It emphasizes the importance of addressing social and environmental inequities throughout the transition to a more sustainable energy system. Also, highlights the need for policies and practices that ensure fair distribution of benefits and burdens, promote inclusive decision-making processes, and prioritize the needs of vulnerable and marginalized communities.

Case-specific studies offer valuable insights into the practical implementation of energy governance and energy democracy in energy planning. [123] examines the challenges and conflicts surrounding wind energy landscapes, highlighting the importance of addressing community concerns and ensuring participatory decision-making processes. By conducting case studies in diverse countries such as Australia, the Netherlands, Kenya, New Zealand, Greece, and Cyprus, among others [114] enlightens a comprehensive analysis of renewable energy governance. The study primarily emphasizes the intricate landscape of renewable energy governance, encompassing various facets such as institutions, plans, policies, and stakeholders involved in its implementation. Moreover, investigates both successful and unsuccessful instances, shedding light on the complexities and challenges associated with the governance of renewable energy. The findings contribute valuable insights into the multifaceted nature of renewable energy governance and its implications for sustainable energy transitions.

The literature also addresses broader issues such as climate governance, justice, and global responses to climate change. [100] explores climate governance at the crossroads, emphasizing the need for innovative governance structures to address the challenges of climate change. [165] emphasizes the importance of incorporating principles of justice, such as fairness, equality, and inclusivity, into the planning and implementation of energy transition policies and practices.

In summary, the benefits of energy governance and energy democracy lie in fostering global cooperation, participatory decision-making, and addressing social inequities. Their strengths include shaping democratic values, driving sustainability transitions, and emphasizing local governance. Challenges encompass navigating complexities, achieving inclusive decision-making, and managing conflicts. Collectively, these aspects contribute to the overarching objectives of effective and equitable energy planning.

In this thesis, the integration of energy governance and energy democracy into energy planning is approached through the utilization of Multi-Criteria Analysis (MCA) as a practical tool, which will be broadly defined in Section 2.2, and Section 2.3. The aim is to enhance the participatory nature, information base, and alignment with democratic decision-making principles and inclusive governance within energy planning processes. By employing MCA, the decision-making framework becomes more robust, accommodating multiple criteria and stakeholder perspectives, thus fostering a more comprehensive and inclusive approach to energy planning. The application of MCA enables the systematic evaluation and comparison of various criteria, facilitating the consideration of diverse dimensions such as social, economic, technical, and environmental aspects. Consequently, this approach contributes to a more informed, transparent, and participatory energy planning process, promoting the integration of energy governance and energy democracy principles into practical decision-making contexts.

2.2 The Multi Criteria Analysis (MCA)

Multi-criteria analysis serves as both an approach and a set of techniques aimed at providing a holistic ordering of options, ranging from the most preferred to the least preferred. The options being evaluated can vary in their ability to achieve multiple objectives, and it is rare for a single option to excel in all objectives. Often, a conflict or trade-off exists among the objectives, where options that yield greater benefits also tend to incur higher costs. Moreover, short-term benefits may clash with long-term ones, and certain options, despite being more beneficial overall, may entail greater risks. MCA offers a systematic way to tackle complex problems characterized by a mix of monetary and non-monetary objectives. It breaks down the problem into manageable components, allowing data and judgments to be applied to each part. Subsequently, the pieces are reassembled to provide a coherent overall view to decision-makers [79].

The primary goal of utilizing Multiple Criteria Analysis is to make rational and efficient choices that ensure the representation of public values in decision-making processes [44]. Energy planning has become increasingly intricate due to the inclusion of diverse factors such as technical, social, economic, and environmental benchmarks. Consequently, decision analysis assumes a critical role in designing energy systems by incorporating multiple criteria and objectives. MCA, a branch of operational research, addresses the identification of optimal outcomes in complex scenarios characterized by conflicting objectives, diverse indicators, and criteria. MCA has gained popularity as a valuable tool in energy planning due to its inherent flexibility, empowering decision-makers to consider and weigh all criteria and objectives simultaneously [111, 107].

MCA serves as an evaluative framework that tackles the complexities arising from environmental, socio-economic, technical, and institutional challenges in energy planning. It provides a structured approach for systematically considering and analyzing multiple criteria and decision-making factors in energy planning processes. By employing MCA methodologies, decision-makers can assess trade-offs, prioritize objectives, and navigate the intricate relationships among different dimensions, facilitating informed and comprehensive energy planning decisions [151]. For [44] is important to realize that since there will be conflicting viewpoints and different hypothetical solutions, the best choice resulting from applying MCA methods would be the best negotiated solution and not the explicit optimum one.

Given that the energy sector, particularly energy planning, directly impacts the interests and resources of various stakeholders, it is socially unacceptable to propose policy alternatives without considering the preferences and interests of these stakeholders [156]. Neglecting the perspectives and concerns of affected actors can undermine the legitimacy and acceptance of proposed policies, disregarding the diverse range of stakeholders who are directly influenced by energy decisions. In this context, the participation of diverse actors in MCA within the energy sector holds crucial significance. Firstly, it incorporates a broader range of interests, concerns, and preferences, resulting in more comprehensive and inclusive decision-making outcomes. Secondly, involving actors with diverse backgrounds ensures a comprehensive understanding of the technical, economic, environmental, and social dimensions of energy decisions. Furthermore, it fosters transparency, accountability, and legitimacy while reducing conflicts and promoting trust among stakeholders. The participation of different actors also facilitates knowledge sharing and promotes evidence-based decision-making, fostering innovation and adaptive responses to emerging energy issues [164, 132].

Multi-criteria analysis involves the utilization of a model to optimize a set of objective functions, whether they are quantitative or qualitative, while considering the applicable constraints. MCA extends beyond being a standalone model and encompasses a comprehensive methodology. This study adheres to the six components illustrated in Figure 2.1 [107], [79], which will be expounded upon in the subsequent paragraphs.

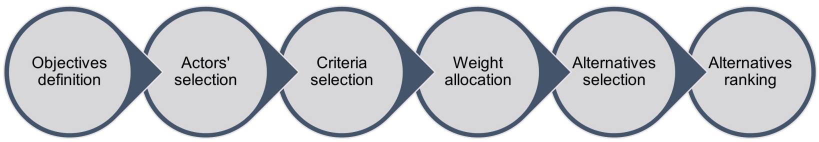


Figure 2.1: Common steps for MCA

Objectives definition and actor's selection

This step involves identifying the system in which the decision problem exists and specifying the goals, constraints, and stakeholders involved. It is crucial to establish a shared understanding of the decision context, encompassing administrative, political, and social structures surrounding the decision-making process. To begin, the decision problem itself should be clearly defined, ensuring a comprehensive understanding of the issues at hand. This includes identifying the specific objectives and constraints that will guide the evaluation of alternatives. By clearly defining objectives, decision-makers can ensure that the alternatives are assessed based on relevant criteria, leading to more effective decision-making outcomes. In the MCA framework, it is important to recognize that conflicting objectives are inherent. Trade-offs are inevitable when multiple objectives are involved. However, to facilitate the analysis, it is necessary to identify a single high-level objective that captures the overall ambition the decision aims to contribute to. This high-level objective is typically supported by sub-objectives that further clarify the desired outcomes. These objectives provide a framework for evaluating the alternatives and comparing their performance against the established criteria. The objectives pursued in multi-criteria analysis (MCA) can vary depending on the specific context and focus of each study. For instance, in the study by [92], the objective was to conduct a comprehensive evaluation of alternative options for the development of a new energy system. The aim was to assess and compare various alternatives based on multiple criteria to inform decision-making in the energy sector. Similarly, in [101], the objective was to apply multi-criteria decision analysis in optimizing the dispatch of distributed generation systems. The study aimed to identify the most efficient and effective strategies for coordinating the operation of distributed generation sources based on multiple criteria. In the research conducted by [86], the objective was to develop a decision support system for the exploitation of renewable energy sources. The focus was on creating a tool that could aid in decision-making regarding the design and implementation of renewable energy projects. These examples demonstrate the diverse range of objectives that can drive the use of MCA, highlighting its versatility in addressing various decision problems in different domains.

In multi-criteria analysis, along with defining clear objectives, the identification of relevant actors or stakeholders plays a crucial role. Stakeholders are individuals or groups who have a vested interest, whether financial or otherwise, in the outcomes of the decision-making process. The inclusion of stakeholders ensures that diverse perspectives and interests are taken into account, promoting transparency and inclusivity. Identifying stakeholders involves considering those directly and indirectly affected by the decision and seeking their input. While there are no rigid guidelines for stakeholder selection, it is important to ensure that all actors who could be impacted or have the potential to influence the decision are included in the stakeholder list. Even if certain groups are unable to organize themselves or provide input on criteria weights, their inclusion is ethically important to avoid exclusion from the analysis [109]. In the context of sustainable energy planning in Crete Island, as described in [151], stakeholders involved in the process included local authorities, potential investors, local communities, academic institutions, environmental groups, and government and European Union representatives. By engaging a wide range of stakeholders, MCA enables a more comprehensive and representative decision-making process, considering the perspectives and interests of all relevant actors involved.

Criteria selection

In this step, the relevant criteria for evaluating the alternatives are identified. These criteria can be quantitative, such as cost or energy efficiency, or qualitative, such as social acceptance or environmental impact. The selected criteria should be measurable, meaningful, and directly relevant to the decision problem at hand. Involving stakeholders in the criteria selection process is important to ensure that their preferences and perspectives are taken into account. To initiate the criteria identification process, it is beneficial to recapitulate the earlier steps and then engage in brainstorming. By asking the question, "What would distinguish between a good choice and a bad one in this decision problem?" and encouraging uncritical responses, a range of potential criteria can be generated. These responses can be noted down, perhaps on whiteboards in a group setting, to capture a comprehensive set of criteria options. Considering the perspective of interest groups is also crucial in criteria selection. According to [79], involving affected parties directly in the MCA process is one approach. Alternatively, examining policy statements and secondary information sources from various interest groups can help derive criteria that reflect their concerns. Another option, if suitable expertise exists within the decision-making team, is to assign one or more team members to roleplay the position of key interest groups. This ensures that the perspectives of these groups are adequately considered during the criteria derivation stage. While determining the number of criteria, it is advisable to strike a balance between comprehensiveness and manageability. There is no definitive rule for this judgment, and it may vary depending on the specific application. Complex decisions with significant financial or technical implications, such as selecting a location for a nuclear waste facility, may involve a larger number of criteria, potentially exceeding a hundred. However, a typical range is between six to twenty criteria. Grouping criteria into sets that relate to distinct components of the overall decision objective can be helpful, particularly when there are a relatively large number of criteria. Grouping criteria serves several purposes, including assessing the appropriateness of the selected criteria for the problem, facilitating the calculation of criteria weights in large MCA applications, and enabling a higher-level understanding of how the options achieve trade-offs between key objectives.

The selection of criteria in multi-criteria analysis (MCA) is dependent on the specific objectives and scope of the analysis. Different studies consider a range of criteria based on the nature of the problem at hand. For instance, in the study conducted by [128], the focus was on rural electrification systems in Nepal, where economic and environmental criteria were analyzed. The study aimed to assess the viability of various options by considering factors such as cost-effectiveness and environmental impact. On the other hand, in the research presented by [66], the criteria selection encompassed a broader perspective. The study aimed to identify a portfolio of biomass conversion technologies suitable for Central America, considering technical, economic, environmental, and socio-political aspects. This comprehensive set of criteria enabled a thorough assessment of the suitability of different biomass conversion technologies in the regional context. The selection of criteria in MCA is driven by the specific research objectives and the need to consider relevant factors that impact the decision-making process. By carefully choosing and analyzing appropriate criteria, researchers can gain valuable insights and make informed decisions within the context of the studied problem or scenario.

Weight allocation

This step involves eliciting the preferences of decision-makers and assigning relative importance to the criteria. Various methods have been developed to determine criteria weights in MCA. In the literature, a wide range of weighting methods have been proposed and utilized to address diverse multiple criteria decision-making problems. These methods include goal programming, Analytic Hierarchy Process (AHP), weighted score method, VIKOR, TOPSIS, and many others. Each of these methods offers a distinct approach to assigning weights and determining the relative importance of criteria in the decision-making process [118]. [106] proposed a value trade-off approach where decision-makers compare pairs of alternatives based on each pair of criteria, making adjustments until an indifference value is achieved. [138] introduced a pairwise comparison approach based on a hierarchical structure, where decision-makers construct a reciprocal pairwise comparison matrix using a subjective scale. [146] extended Saaty's approach to consider decision-makers' uncertainty about the estimates in the matrix, while [47] analyzed the properties of acceptable solutions. Fuzzy set theory is further employed in works by [154], [104], [52] to accommodate subjectiveness and imprecision in pairwise comparisons. [124] proposed a direct ranking and rating approach where decision-makers rank criteria by importance and assign estimated numerical values. [168] developed a technique where a fuzzy knowledge bases and IF-THEN rules captures decision-makers' imprecise judgments of criteria weights. These methods enable decision-makers to interact with the uncertain decision-making environment and facilitate more informed and robust decision-making processes.

Alternatives selection

This step involves identifying and listing the set of alternatives to be considered in addressing problems, exploiting opportunities, and achieving desired outcomes. The alternatives should be feasible and relevant to the decision problem. Initially, this step may require multiple iterations, especially when there is a scarcity of acceptable alternatives. Subsequent stages of MCA can reveal the inadequacies of the initially proposed options, prompting the need for fresh ideas and creative thinking. The MCA framework guides this process by encouraging the exploration of new options that combine the strengths of different existing alternatives in various areas [79]. In practical planning and policy scenarios, options are often predefined as potential solutions put forward by project promoters and relevant stakeholders before the formal appraisal exercise begins. Typically, pre-defined multi-criteria frameworks, as outlined in government guidance and guidelines, are employed to assess and compare these options [78]. Different objectives may require the proposal of different kind of alternative sets. For example, in the context of electric supply planning in rural and remote areas, [136] presented a group of thirteen discrete alternatives. Six of these alternatives pertained to optimal multi-objective solutions related to dispersed decentralized generation, another six focused on compact decentralized generation (CDG), and the final alternative involved extending the public electric grid. In [86], six different scenarios representing varying degrees of renewable energy source penetration in the power system in Greece were presented as alternatives. Similarly, an analysis of achieving a sustainable energy supply in Crete [151] examined four policy alternatives: (1) installation of only wind farms, (2) wind farms and PV systems, (3) wind farms, PV systems, and 4 olive kernel units, and (4) installation of wind farms, PV systems, and oilstone biomass. Furthermore, a study in Spain [141] presented thirteen alternatives for an electric generation project aimed at achieving a target of 12% of primary energy from renewable sources by 2010. By considering a diverse range of alternatives and their specific characteristics, MCA enables decision-makers to comprehensively evaluate and compare options based on multiple criteria, facilitating informed and robust decision-making processes.

Alternatives ranking

This step involves a comprehensive assessment and comparison of different alternatives based on the predetermined criteria. Its objective is to gain a thorough understanding of how each alternative performs in relation to the decision objectives and constraints. During this step, a suitable evaluation method is selected and applied to assess the performance of the alternatives against the identified criteria. It is essential to choose a method that is appropriate for the specific decision problem and the available data. For instance, in the field of energy planning, outranking methods such as PROMETHEE and ELECTRE, as highlighted in [107], are frequently employed. These methods are favored by decision-makers due to their ability to provide a comprehensive view of the problem, accommodating various concerns and uncertainties. In the evaluation process, both quantitative and qualitative data are collected and analyzed to generate a comparative analysis of the alternatives. Performance measurements are conducted for each alternative based on the identified criteria. This assessment can involve assigning scores or ratings to each alternative for each criterion or performing pairwise comparisons to establish relative rankings among the alternatives. The weights assigned to the criteria, determined in earlier steps, are often utilized to aggregate the individual evaluations into an overall assessment for each alternative. The outcome of the alternative's evaluation step is a comprehensive comparative analysis that provides decision-makers with valuable insights into the strengths and weaknesses of each option. This analysis enables the identification of the most promising alternatives that align closely with the decision objectives and constraints.

By considering the performance of the alternatives across multiple criteria, decision-makers can make informed choices and prioritize the alternatives effectively. Ultimately, this step supports the implementation of more robust and rational decision-making processes in MCA.

2.3 MCA techniques applied to energy systems modeling

According to [169], [110], and [111] Multi-Criteria Analysis can be classified into two categories: Multi-Attribute Decision Making (MADM) and Multi-Objective Decision Making (MODM), based on the number of alternatives being considered. MADM is suitable for evaluating discrete decision spaces with predetermined alternatives. These alternatives represent different choices available to the decision-maker, and their number is typically assumed to be finite. MADM methods involve screening, prioritizing, and ultimately ranking or sorting the alternatives based on the specified decision criteria or goals. On the other hand, MODM is particularly suited for continuous decision problems where alternatives are not predetermined. Instead, the focus is on optimizing a set of objective functions while considering various constraints, see Figure 2.2 obtained from [85].

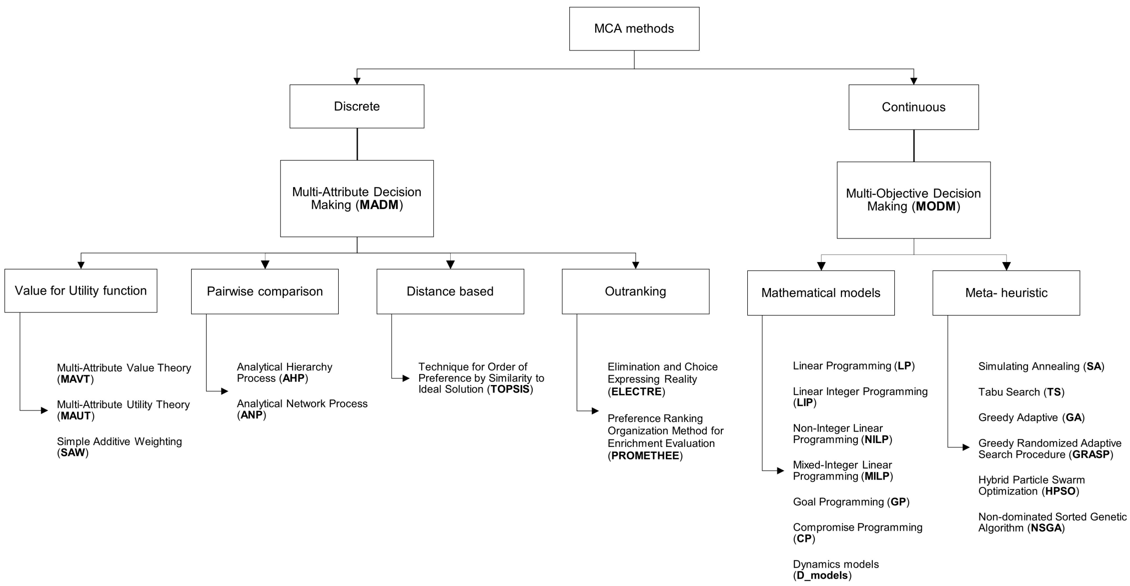


Figure 2.2: Classification of MCA

A diverse range of methods for multi-criteria analysis provides various opportunities for different applications. Extensive literature reviews, such as those conducted in [107] and [44], have comprehensively examined these methods in the context of sustainable energy development.

One prominent group of MCA methods is Multi-Attribute Decision Making (MADM), which encompasses several techniques with distinct characteristics. Among these methods, the Analytical Hierarchy Process (AHP) is widely used. AHP involves constructing a hierarchical structure that breaks down the decision problem into goal, criteria, sub-criteria, and alternative levels. Expert input is obtained through pair-wise comparisons, and the best alternative is determined based on the highest rank. AHP has found utility in energy planning, resource management, public policy, and logistic transportation engineering.

Another notable method is ELECTRE, which is capable of handling both quantitative and qualitative criteria. ELECTRE focuses on identifying dominance relations between alternatives and provides a complete ordering of the alternatives. It employs pair-wise comparisons and is applied in the domains of energy, business, financial management, and logistic transportation engineering. PROMETHEE, another member of the outranking methods, offers a simpler approach while utilizing the outranking principle for alternative ranking. This method is commonly employed in energy planning, risk and structural analysis, and mining engineering.

The TOPSIS method selects the alternative that performs best across all criteria, following the idea of maximizing positive attributes and minimizing negative ones. It has found application in logistics, water resource management, energy management, and chemical engineering. The Multi-Attribute Utility Theory (MAUT) is a popular MCA method that incorporates decision makers' preferences through utility functions defined over attributes. MAUT is typically used in city planning, economic policy, and government policy.

Additional methods such as VIKOR have been applied in mechanical and manufacturing engineering, energy policy, business management, and healthcare. [85] highlighted that decision-making applications do not exhibit a clear trend pattern across methods. However, AHP, Linear Programming, and Simulated Annealing rank among the most widely used decision-making methods, particularly in land allocation problems. AHP's prominence can be attributed to its suitability for comparative analysis of finite allocation problems in land use planning.

The wide array of MCA methods provides decision-makers with flexibility and adaptability to address different decision-making scenarios. Each method exhibits unique strengths and is suitable for specific domains, enabling decision-makers to select the most appropriate approach based on the problem's nature and desired outcomes.

In the domain of energy planning, a subset of MCA methods has found particular application. Noteworthy methodologies include the Simple Additive Weighting (SAW), Analytical Hierarchy Process (AHP), Elimination and Choice Translating Reality (ELECTRE), Preference Ranking Organization Method (PROMETHEE), Multi Attribute Utility Theory (MAUT), and various combinations thereof [107],[163].

By leveraging these methodologies, decision-makers in the field of energy planning can effectively assess and compare alternatives based on multiple criteria, facilitating informed decision-making processes. The diversity of available methods empowers decision-makers to tailor their approach to the specific context and requirements of their energy planning initiatives, ultimately enhancing the quality and accuracy of the decision outcomes.

The selection of an appropriate Multi-Criteria Analysis (MCA) method for energy planning involves considering various guiding principles. [129] suggests several factors to be taken into account, including sustainability issues, decision maker preferences, technical characteristics, treatment of uncertainty, and practical considerations. Sustainability issues are paramount in energy planning as they involve finding a balance between economic, social, environmental, and resource dimensions. Different MCA methods such as SAW, MAUT, and AHP allow for trade-offs between criteria, enabling moderate performance in one criterion to compensate for poorer performance in others. On the other hand, outranking methods like ELECTRE and PROMETHEE adopt a more stringent sustainability perspective, particularly when veto thresholds need to be considered. MCA methods incorporate decision maker preferences through value-measurement models and utility-based models. Value-measurement models assign numerical values to criteria, quantifying their importance from the decision maker's perspective. Utility-based models use utility functions to align with decision maker preferences, ensuring a fair and unbiased evaluation of options. Outranking approaches employ relative weights to indicate the significance of criteria within the decision system. The technical characteristics of the chosen MCA method, such as comprehensibility and input capabilities, are crucial in selecting an appropriate method. A smooth interaction between the method and decision makers, without parameters lacking concrete meanings, is essential for successful implementation. In the context of energy planning, the method's ability to accommodate both quantitative and qualitative data is of utmost importance. The treatment of uncertainty is another factor to consider. Utility-based methods handle uncertainty effectively by incorporating probability distributions, making them suitable for scenarios characterized by weak uncertainty and high predictability. However, these methods may be less applicable to environmental issues. Outranking methods address inaccuracies in criteria values through the use of indifference and preference limits, requiring meticulous assessments of each threshold value.

In the field of energy planning, MCA has emerged as a valuable tool for addressing key challenges and incorporating the perspectives of diverse stakeholders and multiple criteria. Researchers have applied MCA methods at various scales, offering promising solutions and insights. For example, [151] presents a case study of applying MCA to sustainable energy planning in the island of Crete, Greece. The study identified the most appropriate mix of renewable energy sources and energy storage technologies for the island of Crete while considering economic, social, and environmental criteria. The study presented in [116] focuses on the regional level, specifically the case of Thassos, Greece. The framework aims to determine the optimal mix of renewable energy sources, including wind, solar, biomass, geothermal, and small hydro, to meet the increasing power demands while ensuring environmental sustainability. [158] integrates spatial data and various criteria, including wind speed, land use, proximity to infrastructure, and environmental factors, to identify optimal sites for wind farm development. The research highlights the significance of GIS and MCA as effective tools for evaluating and selecting suitable locations for wind farms, providing valuable insights for renewable energy planning in Ecuador. For this work, a group of five MCA methods were used by the authors. [136] explores the use of multicriteria analysis methods in the context of electric supply planning for rural and remote areas. By considering multiple criteria such as cost, reliability, environmental impact, and social aspects, MCA methods enable a comprehensive evaluation of different electric supply options. In this analysis a combination of AHP and VIKOR methods are used. [150] examines the applicability of multi-criteria analysis in evaluating the sustainability of renewable energy technologies on a national level. The study assesses the suitability of this approach and investigates the uncertainties associated with its implementation. When selecting an MCA method for energy planning, it is important to understand the objectives of the project, identify evaluation criteria, assess data availability and computational requirements, consider stakeholder involvement, review existing literature and case studies, seek expert advice, evaluate transparency and interpretability, consider available software and tools, balance robustness and simplicity, and reflect on available resources and timeline. By considering the guiding principles, decision makers can choose the most appropriate MCA method that aligns with their objectives, incorporates stakeholder preferences, and effectively addresses the complexities of energy planning.

2.4 Chapter Summary

This chapter has examined two fundamental concepts, energy governance and energy democracy, that underpin energy planning. Their significance lies in their ability to ensure inclusiveness, equity, transparency, accountability, adaptability, and democratic decision-making. By involving diverse stakeholders, energy planning becomes more representative and legitimate, leading to effective and sustainable outcomes. These principles address social justice concerns by promoting a fair distribution of benefits and burdens, while transparent and accountable processes build trust and ensure decisions are made in the public interest. Energy plans that consider diverse perspectives become more adaptable and resilient, capable of responding to changing needs and circumstances. Emphasizing democratic decision-making empowers communities and fosters socially acceptable and sustainable energy systems.

The current way of energy modeling faces challenges such as limited stakeholder engagement and underrepresentation of social and environmental factors. Addressing these challenges requires advancements in modeling methodologies, greater data quality and availability, enhanced stakeholder engagement, and broader consideration of social and environmental dimensions. Open and transparent modeling practices can lead to more robust and inclusive energy models. MCA, with its consideration of multiple criteria and actors in the planning process, aligns with the objectives of energy governance and energy democracy.

This research aims to assess the efficacy of Multi-Criteria Analysis and its potential integration with other energy modeling tools. The objective is to examine whether it is feasible to incorporate the principles of governance and energy democracy in a manner compatible with traditional mathematical models. This entails minimizing the dominance of technocratic considerations, ensuring that socio-environmental factors wield equivalent influence as economic costs in determining diverse technological options. The ultimate goal is to foster a more balanced and accelerated energy transition, where considerations beyond mere economic parameters play a significant role in decision-making.

Chapter 3

Methodology

This chapter presents a comprehensive analysis of the Ecuadorian electricity sector model, employing a range of tools and methodologies. Figure 3.1 illustrates the overall approach adopted in this study. In Section 3.1, a meticulous multi-criteria analysis is detailed, specifically tailored to the context of Ecuador. This involved the implementation of the Analytic Hierarchy Process (AHP) to assign weights to the criteria, along with conducting interviews with four distinct stakeholder groups. Furthermore, the PROMETHEE method was employed to establish a final ranking of alternative electricity generation projects, resulting in the development of a comprehensive portfolio. Section 3.2 delves into the utilization of the urbs tool to optimize the Ecuadorian electricity sector model, utilizing the aforementioned portfolio and referencing the outcomes from the previous section. The base year for this optimization is 2019, and the model's inputs are adjusted accordingly. Additionally, the validation of the model for the base year is presented, where its performance is compared against the actual outcomes observed in 2019. In Section 3.3, the process of creating different scenarios for the electricity sector model until the year 2050 is elaborated. Each scenario encompasses a distinct set of assumptions that underpin their formulation. These scenarios aim to explore and project the potential trajectory of the Ecuadorian electricity sector, considering diverse future circumstances and developments.

3.1 The MCA in the Ecuadorian case

The methodology employed in this study, as depicted in Figure 2.1 of Chapter 2, involves a six-step Multi-Criteria Analysis (MCA) process. These steps were rigorously adhered to during the case study conducted in Ecuador, and they are outlined in detail below:

3.1.1 Objectives definition

The main objective of our MCA is to answer the first and second research questions shown in Section 1.3. The first focuses on the reduction of socio-environmental conflicts associated with power generation projects. We aim to identify strategies and approaches that can reduce conflicts arising from such projects. The second research question concerns understanding the influence of the integration of economic, environmental, technical, and social factors in the modeling of national energy systems. We intend to explore the impact and importance of taking

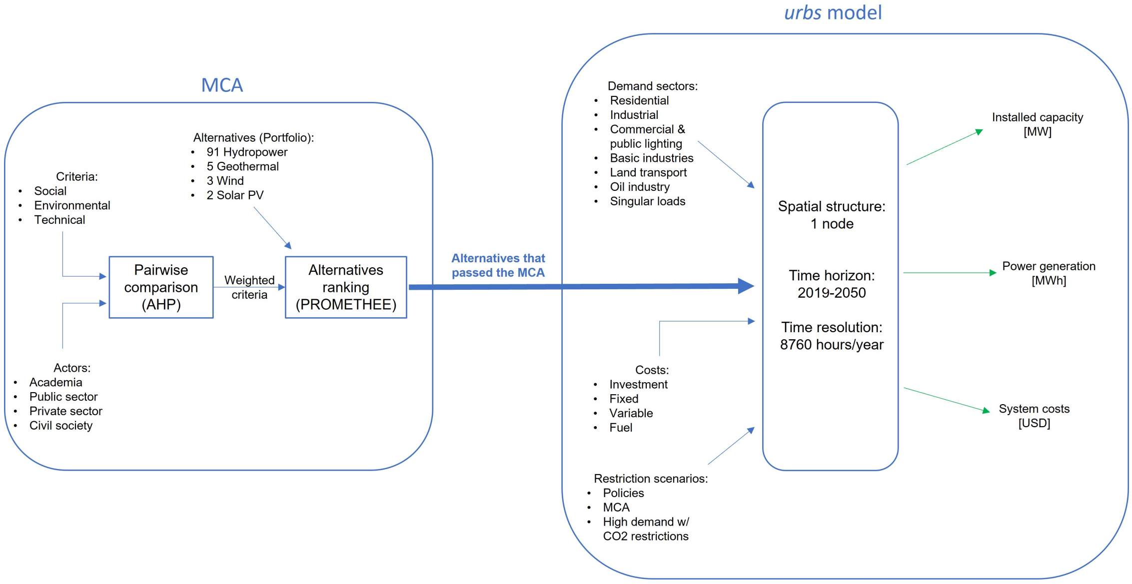


Figure 3.1: Overview of the MCA and optimization model methodology

these various factors into account when analyzing and designing energy systems on a national scale. In light of these research questions, our objective is to conduct a multi-criteria analysis to select renewable energy projects in Ecuador. This analysis will involve evaluating and comparing different projects based on multiple criteria and perspectives. Specifically, we will consider the viewpoints of four distinct stakeholder groups that are affected by the decision-making process. By incorporating these perspectives, we aim to ensure a comprehensive evaluation of the projects. Furthermore, our objective is to minimize negative impacts associated with the selected renewable energy projects. These negative impacts include environmental damage, adverse effects on the quality of life of residents in the areas surrounding the project sites, and harm to the local flora and fauna. By considering these aspects and incorporating them into the decision-making process, we aim to select projects that not only contribute to diversifying the electricity generation matrix but also minimize the negative consequences on the environment and affected communities.

3.1.2 Actor's selection

The second step of the multi-criteria analysis involves the selection of stakeholders, recognizing their indispensable role in shaping energy planning decisions. For this study, four distinct stakeholder groups were thoughtfully chosen, consisting of a total of 40 stakeholders equally distributed among academia, civil society, the public sector, and the private sector. These stakeholders represent a diverse range of perspectives, expertise, and interests, ensuring a comprehensive and well-rounded analysis.

Academia

The academic group brings together researchers in the field of energy from a number of public and private universities in Ecuador. These leading institutions include the Escuela

Politécnica Nacional, Universidad San Francisco de Quito, Universidad Central del Ecuador and Universidad del Azuay. The researchers selected to participate in the MCA process are recognized for their academic achievements and expertise in various aspects of the energy sector. Their research experience covers the topics of decarbonization in Latin America [48], [63], energy modeling [59], [56], use of renewable energies [143], [62], [65], lifecycle analysis [64], among others [130], [119]. Moreover, the strengths of the academic group lies in their affiliation with research groups within their respective universities (CIENER, SCINERGY, Energy and Materials Institute). These research groups act as knowledge clearinghouses, fostering interdisciplinary collaboration and the integration of cutting-edge methodologies. By leveraging these research networks, academic stakeholders bring a collective pool of expertise, thereby enriching the MCA process with a diverse range of perspectives and solutions. The contributions of the academic group go beyond their scholarly achievements and institutional affiliations. Their participation also signifies a commitment to real-world energy challenges, seeking practical and workable solutions that align with the principles of sustainable development.

Civil society

Civil society actors constitute an indispensable and influential group within the MCA process, bringing to the table a wealth of experiential insights that go beyond mere data and statistics. At the core of this group are union leaders who stand as defenders of their communities, persistently advocating for their rights and well-being in the face of energy generation projects, particularly hydroelectric power plants. These leaders hail from regions directly affected by such projects, including Baños, Pastaza, Napo, Coca, Santo Domingo de los Tsáchilas, and Macas, where the social and environmental impacts of these initiatives are profoundly felt. The experiences shared by these civil society actors are grounded in real-life encounters, offering a perspective that cannot be gleaned from technical reports alone. Their frontline involvement has equipped them with a profound understanding of the human dimensions of energy planning decisions. By engaging with these stakeholders, decision-makers can gain deeper insights into the potential social implications, community concerns, and sustainable development considerations related to energy projects. Moreover, the inclusion of representatives from environmental rights organizations was diligently sought, recognizing their vital role in safeguarding community rights and advocating for environmentally sustainable policies. While securing their direct participation for interviews proved challenging, the potential influence of these organizations remains a critical aspect to consider. Their dedication to preserving the environment and ensuring a balanced approach to energy development adds an ethical dimension to the MCA process, reinforcing the importance of environmental stewardship and community well-being.

Public sector

The public sector actors form a critical cohort of individuals who hold key positions within state institutions entrusted with shaping energy planning policies and strategies in Ecuador. Their participation in this MCA process brings expertise and experience, honed through years of service to the nation's energy sector. The institutions to which the interviewed actors belong are The Ministry of Energy and Non-Renewable Natural Resources, Corporación Eléctrica del Ecuador (CELEC E.P), and Instituto de Investigación Geológico y Energético (IGE).

The Ministry of Energy and Non-Renewable Natural Resources serves as the central authority responsible for formulating and implementing energy policies that align with sustainable development goals and national interests. Within the Ministry, decision-makers and experts work to analyze energy trends, assess resource availability, and design robust frameworks for energy security and efficiency. The Corporación Eléctrica del Ecuador is the entity responsible for overseeing the development and operation of major electricity generation projects in the country. CELEC E.P plays the role in managing hydropower plants, thermal power plants, and other renewable energy facilities, ensuring the steady supply of electricity to meet the nation's growing demands. With an acute understanding of the technical and logistical intricacies involved in energy generation, CELEC E.P experts contribute valuable insights to the MCA process, shedding light on the potential implications of various energy planning decisions. The Instituto de Investigación Geológico y Energético adds a research-oriented perspective to the public sector's involvement in the MCA. This institution specializes in energy research, aiming to unlock Ecuador's vast potential for renewable energy sources and natural resources. The IGE researchers bring their knowledge of renewable energy technologies, and environmental impact assessments to the table, facilitating a comprehensive analysis of energy alternatives.

Private sector

The private sector actors also play a role in the MCA process, bringing with them expertise and practical experience in spearheading power generation projects that harness renewable energy sources. Among these companies are Ibertek [17], Tratural Cía. Ltda. [39], J3M [18], AdvicENERGY [3], and EnerPro Cía.Ltda. Their presence in the renewable energy sector underscores the private sector's commitment to sustainable development and its active participation in shaping Ecuador's energy landscape. These companies possess an understanding of the technical, economic, and operational aspects of renewable energy projects, making their insights invaluable in the evaluation and selection of alternatives during the MCA. Their experience in implementing and managing such initiatives contributes to a pragmatic perspective that considers the feasibility and viability of renewable energy options. Furthermore, the inclusion of private sector actors ensures a well-rounded representation of diverse interests within the energy sector. Their involvement is rooted in the pursuit of business opportunities aligned with sustainable energy development, highlighting the symbiotic relationship between environmental stewardship and economic growth. By actively engaging with these industry actors, the MCA process gains insights into market trends, innovation potential, and emerging technologies that can further advance Ecuador's renewable energy.

The private sector's presence also underscores the significance of public-private partnerships in driving energy transitions and sustainable development. Collaborating with these companies fosters a sense of shared responsibility in creating a sustainable and resilient energy future. As the private sector plays an instrumental role in the implementation of energy projects, their perspectives and interests are vital for establishing a coherent and robust energy policy framework.

The diverse selection of these stakeholder groups ensures the comprehensive inclusion of multidisciplinary knowledge, expertise, and viewpoints in the energy planning process. Each group's participation enriches the study, providing a holistic understanding of the multifaceted challenges and opportunities that lie ahead.

3.1.3 Criteria selection

The third step of the multi-criteria analysis involves the task of selecting the alternatives to be considered for the energy planning process. To ensure a comprehensive evaluation, an exhaustive literature review was conducted, focusing on the most significant criteria relevant to energy planning. The review encompassed diverse studies that employed MCA for different energy projects worldwide. For instance, in a study examining the location of a hydroelectric power plant in Andalusia, Spain [93], criteria such as proximity to populations, distance to transmission lines, capacity, proximity to protected areas, and amount of annual precipitation were utilized to conduct the MCA. Similarly, in Turkey, researchers studying the optimal location of solar plants incorporated criteria like land use, distance to residential areas, roads, and transmission lines [153]. Another study focusing on power generation plants utilized two major groups of criteria, namely technical and sustainable, which were further divided into eight sub-criteria, including efficiency, availability, capacity, reserves, capital costs, fixed and variable costs, and fuel costs [61]. These criteria enabled a comprehensive evaluation using the Analytical Hierarchy Process (AHP). Beyond the literature review, interviews were conducted with expert researchers in the energy, social, and environmental fields, further refining the identification of criteria for the multi-criteria analysis tailored to the case of Ecuador. Ultimately, four major groups of criteria emerged: social, environmental, technical, and economic. However, the economic criteria were not included in the MCA, as the urbs model's optimization stage already considers investment costs, fixed and variable costs, and fuel costs for electric power generation projects. The selected criteria were further organized into three main groups, each comprising three sub-criteria essential to the energy planning process in Ecuador. These sub-criteria are detailed in Table 3.1, capturing the diverse dimensions of energy planning and ensuring a comprehensive evaluation of the available alternatives.

By meticulously selecting these criteria, the multi-criteria analysis can accurately assess each alternative's impact on social welfare, environmental sustainability, and technical feasibility, fostering a well-informed decision-making process that aligns with Ecuador's unique energy needs and aspirations. This careful selection of criteria enables decision-makers to navigate complex trade-offs and prioritize alternatives that best align with the country's sustainable energy goals.

3.1.4 Weight allocation

The Analytic Hierarchy Process (AHP) is a structured decision-making methodology, developed by Dr. Thomas L. Saaty in the 1970s, designed to handle complex decision problems involving multiple criteria and alternatives. This versatile approach finds applications in various fields, including business, engineering, social sciences, and environmental management. The process involves breaking down a complex problem into a hierarchical structure of criteria and sub-criteria, enabling decision-makers to systematically evaluate and compare different elements

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

Table 3.1: Selected Criteria for MCA in the context of Ecuador

Intensity of importance	Definition	Explanation
1	Same importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over the other
5	Strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is strongly favored over another, its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

Table 3.2: Fundamental scale of AHP

based on their relative importance or preference. To conduct the pairwise comparisons of elements, decision-makers use a numerical scale to assign scores that indicate their relative importance. To facilitate the comparison process, the Saaty scale shown in Table 3.2 allowed stakeholders to express their relative preferences or priorities on a numerical scale ranging from 1 (equal importance) to 9 (extremely more important).

A consistency check is included in the AHP to ensure accurate comparisons, and the pairwise scores are used to calculate priority weights for each element. These weights represent the relative importance of each element concerning the overall goal. Consequently, the priority weights aid in ranking and prioritizing the alternatives based on their performance against the established criteria. The AHP's systematic approach offers transparency, consistency, and valuable insights into the trade-offs and preferences involved in complex decision-making processes [140], [139].

In the context of the Ecuador case study, a data collection process was undertaken to elicit insights from the identified stakeholders (as discussed in Subsection 3.1.2). The data collection involved both online and on-site interviews with the 40 stakeholders, aiming to discern their preferences and judgments concerning the nine pre-selected sub-criteria (as outlined in Subsection 3.1.3). Each interview lasted approximately 40 to 60 minutes and followed a structured approach. Initially, the interviewees were briefed on the project's objectives, their role in the study, the expected outcomes, as well as a comprehensive explanation of each criterion under consideration and the methodology to be employed. Once the stakeholders grasped the procedures, they were presented with questions to compare two criteria, with the two-part question format as follows:

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

To facilitate the analysis and ensure consistency in stakeholder responses, a specialized AHP worksheet developed by Goepel in 2018 was utilized [90]. This Excel-based tool streamlined the comparison process, minimized potential bias, and guaranteed a consistent and methodical approach to stakeholder preferences. The tool was made available through [24].

An illustrative example of the Excel-based AHP tool and its application for a civil society stakeholder is presented in Table 3.3. The table exhibits the stakeholder's pairwise comparisons for selected criteria. According to the stakeholder's assessment, the criterion of job creation (B) holds moderate importance (3) compared to the project perception criterion (A) in the first row. In the second comparison, the same stakeholder considers the criterion of displacement/relocation of people (B) to be equally important (1) as the project perception criterion (A). However, the third row indicates that the deforestation criterion (B) significantly outweighs (with a value of 9) the importance of the project perception criterion (A). Moving on, the stakeholder perceives the project perception criterion (A) to be moderately more important (3) than the proximity to nature reserves (B). Additionally, the wildlife threat criterion (B) is strongly emphasized (5) over the project perception criterion (A) in the subsequent comparison. Moreover, the stakeholder's belief that the project perception criterion (A) is strongly more significant (5) than the project size criterion (B). The penultimate comparison highlights the conviction that the project perception criterion (A) strongly holds importance (5) than the criterion of accessibility to the project site. Finally, the last comparison demonstrates again the stakeholder's strong conviction that the project perception criterion (A) has a strong importance over the criterion of distance to transmission lines. Such comprehensive pairwise comparisons conducted with stakeholders during the interviews formed an essential part of the AHP methodology, capturing valuable insights into their preferences and enabling the subsequent ranking of power generation projects.

Throughout the interview process, the same pairwise comparison procedure was followed for the remaining eight criteria. It was essential to ensure a consistency ratio of at least 10% in the stakeholders' answers. In cases where consistency was not achieved, the answers were revisited and clarified during the interview, resulting in a harmonization of the responses.

Criterion A	Criterion B	more important? (A or B)	Scale (1-9)
Project perception	Job creation	B	3
	Displacement/relocation of people	B	1
	Deforestation	B	9
	Proximity to natural reserves	A	3
	Threat to fauna and wildlife	B	5
	Size	A	5
	Accessibility	A	5
Job creation	Displacement/relocation of people	A	3
	Deforestation	B	5
	Proximity to natural reserves	A	3
	Threat to fauna and wildlife	B	3
	Size	A	7
	Accessibility	A	7
Displacement/ relocation of people	Deforestation	B	7
	Proximity to natural reserves	B	5
	Threat to fauna and wildlife	B	5
	Size	A	3
	Accessibility	A	3
Deforestation	Proximity to natural reserves	A	7
	Threat to fauna and wildlife	A	1
	Size	A	9
	Accessibility	A	7
Proximity to natural reserves	Threat to fauna and wildlife	B	7
	Size	A	3
	Accessibility	A	3
Threat to fauna and wildlife	Size	A	7
	Accessibility	A	7
Size	Accessibility	B	3
Project perception	Distance to transmission lines	A	5
Job creation	Distance to transmission lines	A	7
Displacement/ relocation of people	Distance to transmission lines	A	3
Deforestation	Distance to transmission lines	A	7
Proximity to natural reserves	Distance to transmission lines	A	5
Threat to fauna and wildlife	Distance to transmission lines	A	7
Size	Distance to transmission lines	B	3
Accessibility	Distance to transmission lines	B	1

Table 3.3: Illustrative pairwise comparison conducted with a Civil Society actor

This systematic approach to data collection, utilizing the specialized AHP worksheet, ensured that the stakeholders' preferences were captured in a robust and consistent manner, setting the foundation for a comprehensive multi-criteria analysis of the power generation projects in Ecuador.

3.1.5 Alternatives selection

The selection of alternatives in the multi-criteria analysis entails choosing the power generation projects that will be subject to evaluation. In the case study of Ecuador, an existing portfolio of 101 electricity generation projects was considered, encompassing various renewable energy sources [70], [58]. Specifically, the selected alternatives comprised 91 hydroelectric projects with a cumulative installed capacity of 11,282.45 MW, 5 geothermal projects with a total capacity of 900 MW, 3 wind projects with a combined capacity of 150 MW, and 2 solar photovoltaic projects. Among the solar projects, one featured a substantial capacity of 200 MW, while the other was a 3 kW residential photovoltaic pilot project. Overall, the analysis encompassed 12,532 MW of installed capacity distributed across 101 electricity generation projects. A detailed description of each project is provided in Table 3.4.

No.	Name	Capacity [MW]	Type	Watershed
1	PV-residential	0.003	Solar	n/a
2	Río Luis 2	1.13	Hydro	Pacific
3	Mirador 1	1.15	Hydro	Pacific
4	Vacas Galindo 1	1.20	Hydro	Pacific
5	M.J. Calle	1.44	Hydro	Pacific
6	Tululbi	1.60	Hydro	Pacific
7	Mariano Acosta	1.68	Hydro	Pacific
8	Monte Nuevo	1.70	Hydro	Pacific
9	Campo Bello	1.70	Hydro	Pacific
10	Salunguire	1.70	Hydro	Pacific
11	Intag 2	1.70	Hydro	Pacific
12	Ganancay	2.29	Hydro	Pacific
13	Chuquiraguas	2.35	Hydro	Pacific
14	El Laurel	2.37	Hydro	Pacific
15	Solanda	3.00	Hydro	Pacific
16	Rircay	3.10	Hydro	Pacific
17	La Concepción	3.17	Hydro	Pacific
18	Guápulo	3.20	Hydro	Pacific
19	Chimbo-Guaranda	3.80	Hydro	Pacific
20	Chillayacu	3.92	Hydro	Pacific
21	Ambato	4.00	Hydro	Amazon
22	Huarhuallá	4.60	Hydro	Amazon
23	Pucayacu	4.80	Hydro	Pacific
24	Chinambi	5.00	Hydro	Pacific
25	El Cañaro	5.60	Hydro	Amazon

No.	Name	Capacity [MW]	Type	Watershed
26	Collay	5.80	Hydro	Amazon
27	Vivar	5.90	Hydro	Pacific
28	Lachas	6.00	Hydro	Pacific
29	Tomebamba	6.00	Hydro	Amazon
30	Casacay	6.10	Hydro	Pacific
31	Cebadas	6.95	Hydro	Amazon
32	Chanchán	7.30	Hydro	Pacific
33	Alausí	7.50	Hydro	Pacific
34	Rayo	7.50	Hydro	Pacific
35	Mandur	7.80	Hydro	Pacific
36	Palmar	7.80	Hydro	Pacific
37	Tulipe	7.80	Hydro	Pacific
38	Blanco 2	8.00	Hydro	Pacific
39	Balsapamba	8.10	Hydro	Pacific
40	Echeandía bajo 2	8.40	Hydro	Pacific
41	Uchucay	8.40	Hydro	Pacific
42	Lucarquí	8.80	Hydro	Pacific
43	Tandapi	8.90	Hydro	Pacific
44	San Francisco II	9.40	Hydro	Pacific
45	San Pedro II	9.50	Hydro	Pacific
46	Alambi	9.0	Hydro	Pacific
47	Bravo Grande	10.00	Hydro	Pacific
48	El Burro	10.20	Hydro	Pacific
49	Bellavista	11.60	Hydro	Pacific
50	Chilma	23.70	Hydro	Pacific
51	Quijos 1	24.20	Hydro	Amazon
52	Victoria 2	25.00	Hydro	Amazon
53	Chingual	25.60	Hydro	Amazon
54	Paquishapa	26.00	Hydro	Pacific
55	Jamanco	26.00	Geothermal	n/a
56	Langoa	26.00	Hydro	Amazon
57	Cosanga	27.00	Hydro	Amazon
58	Gualleturo	27.70	Hydro	Pacific
59	Las Juntas	27.70	Hydro	Pacific
60	Sucua	31.60	Hydro	Amazon
61	Yacuchaqui	32.20	Hydro	Pacific
62	Puniyacu	35.60	Hydro	Pacific
63	Negro (2)	36.00	Hydro	Pacific
64	Calderón II	38.70	Hydro	Pacific
65	Numbala	39.20	Hydro	Amazon
66	Guayabal	39.80	Hydro	Pacific
67	La Barquilla	40.10	Hydro	Amazon

No.	Name	Capacity [MW]	Type	Watershed
68	Pamplona	40.50	Hydro	Pacific
69	Mira	41.00	Hydro	Pacific
70	Vacas Galindo 2	42.00	Hydro	Pacific
71	Milpe	43.70	Hydro	Pacific
72	Cinto	45.80	Hydro	Pacific
73	Villonaco II	46.00	Wind	n/a
74	Mira 2	47.80	Hydro	Pacific
75	Minas de Huascachaca	50.00	Wind	n/a
76	Isimanchi	51.10	Hydro	Amazon
77	Cuyes	51.30	Hydro	Amazon
78	Cubí 2	53.00	Hydro	Pacific
79	Villonaco III	54.00	Wind	n/a
80	Pilatón-Santa Ana	58.50	Hydro	Pacific
81	Lelia	62.30	Hydro	Pacific
82	Las Cidras	77.30	Hydro	Amazon
83	Chacana-Cachiyacu	83.00	Geothermal	n/a
84	San Pedro	83.40	Hydro	Pacific
85	Los Bancos	92.20	Hydro	Pacific
86	Calderón	147.00	Hydro	Pacific
87	Chirapi	160.00	Hydro	Pacific
88	Ligua-Muyo	170.00	Hydro	Amazon
89	Chachimbiro	178.00	Geothermal	n/a
90	Abitagua	198.00	Hydro	Amazon
91	El Aromo	200.00	Solar PV	n/a
92	Tortugo	201.00	Hydro	Pacific
93	El Retorno	261.00	Hydro	Amazon
94	Cedroyacu	270.00	Hydro	Amazon
95	Chalupas	283.00	Geothermal	n/a
96	Tufiño-Chiles-Cerro Negro	330.00	Geothermal	n/a
97	Chespi Real	460.00	Hydro	Pacific
98	Catachi	748.00	Hydro	Amazon
99	Verdeyacu Chico	1,172	Hydro	Amazon
100	Río Zamora	2,320	Hydro	Amazon
101	Santiago G8	3,600	Hydro	Amazon
	Total [MW]	**12,532.45**		

Table 3.4: Alternatives/Portfolio of power generation projects for the MCA in the context of Ecuador

3.1.6 Alternatives ranking

The final step of the multi-criteria analysis involves the ranking of alternatives or projects based on stakeholders' expressed preferences regarding the identified criteria. To achieve this, the Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE) was utilized, initially developed by Brans in 1982 and later extended by Vincke and Brans in 1985. PROMETHEE II operates on the principle of pairwise comparisons of alternatives against recognized criteria, where some criteria require maximization and others minimization. In the study's context, the weighted criteria were obtained using the Analytic Hierarchy Process (AHP) in subsection 3.1.4. The preference function was employed to convert the differences in evaluations for two alternatives into preference degrees ranging from zero to one, facilitating a comprehensive comparison of alternatives. The implementation of PROMETHEE II involves several stages, including the determination of deviations based on pairwise comparisons, the utilization of relevant preference functions for each criterion, and the calculation of global preference indices. Subsequently, positive and negative outranking flows are computed for each alternative, resulting in partial rankings. Finally, the net outranking flow Phi ($\phi(a)$) is calculated, enabling the generation of a complete ranking of alternatives. The set of equations that describe the procedure is shown in Figure 3.2 and were obtained from [49].

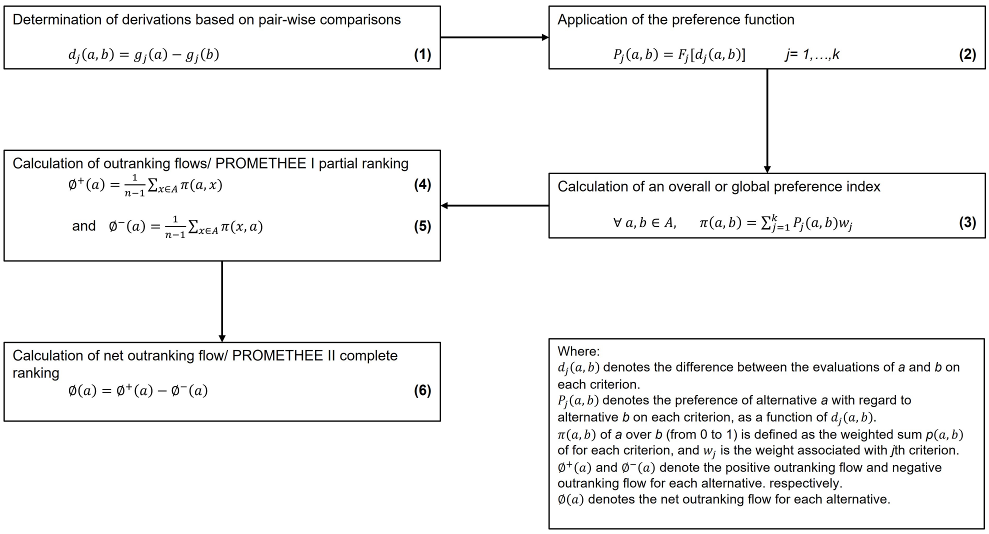


Figure 3.2: Stepwise procedure for PROMETHEE II

PROMETHEE II offers a systematic approach for ranking alternatives, considering both quantitative and qualitative factors. This method enables decision-makers to gain valuable insights into the overall preference of each alternative, helping identify the most promising options in accordance with stakeholders' preferences and established criteria. In this study, Visual PROMETHEE, a comprehensive software implementation of the PROMETHEE and GAIA multicriteria decision analysis methods, was employed. This tool was developed by VPSolutions under the guidance of Professor Bertrand Mareschal. Mareschal has been actively involved in the development and application of the PROMETHEE and GAIA methods for over three decades, working alongside Professor Jean-Pierre Brans, the father of this outranking method. This extensive experience and expertise have significantly contributed to the robustness and effectiveness of the Visual PROMETHEE software, making it a reliable choice for conducting advanced multicriteria decision analysis [43].

To facilitate the analysis within the framework of Visual PROMETHEE, a classification of criteria is imperative, distinguishing them as qualitative or quantitative in nature. In parallel, a selection of measurement scales, units of measurement, and decision-maker preferences is imperative. The latter aspect is instrumental in determining the optimization direction for each criterion, indicating whether it should be maximized or minimized to align with the overarching objectives of the decision-making process.

In this study, our focus is on maximize the public perception of power generation projects. We aim to garner positive acceptance from the community, and maximizing job creation as well. To address potential issues such as displacement, deforestation, and threats to wildlife and nature reserves, our goal is to minimize the risk and impact of power plants on protected flora, fauna, and local inhabitants. Concerning project size, our objective is to minimize it based on insights from stakeholder interviews and past socio-environmental conflicts associated with larger projects. However, it's important to note that this is not an absolute rule. Lastly, we aim to maximize proximity to transmission lines and access roads.

This rigorous approach to criterion identification, classification, and characterization is essential to uphold the analytical rigor and accuracy of the multi-criteria analysis results. Subsequently, the specific characteristics designated for this study in the context of the Ecuadorian case are elucidated in the Table 3.5.

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

Table 3.5: Criteria settings for the Visual PROMETHEE

Subsequent to the determination of measurement scales for the criteria, the intricate process of associating each criterion with the 101 distinct projects enumerated within the portfolio detailed in Table 3.4. To accomplish this task, the Open Source Geographic Information System (QGIS) software was used, taking advantage of its ability to manage spatial data and perform geospatial analysis. The multifaceted nature of the task was addressed through the use of different geographic layers, each of which encapsulated data relevant to our study. The foundational layers serving as the bedrock for all criteria measurements encompassed the geographical demarcation of Ecuador itself, complemented by the precise geospatial positions of each distinct power generation project within the region [70], [1],[31], [29], [15], [22], [35], [14], [2], [131], [58], [112], as shown in Figure 3.3. These layers served as the basis for aligning specific criteria with the respective projects examined. Figure 3.4 articulates the specific layers [4], [20], [21] used for the analyzed criteria, thus elucidating the coherent orchestration of data for this multidimensional assessment.

Once the geospatial analysis layers to be used had been identified, the next step was to assign values to each of the nine criteria examined, according to the stipulated scale illustrated in Table 3.5. These assigned numerical values were incorporated into the PROMETHEE Visual software, which was a major step towards the ultimate goal of ranking the 101 alternatives. The precise numerical values for each of the nine criteria examined are given below, thus underlining the methodical approach that governed the development of the framework.

Alternatives evaluation for social criteria

To assess the 101 alternatives concerning the social criteria, it necessitated geospatial data concerning the spatial arrangement of urban zones, hospital infrastructure, and school areas. This relevant geographic information is visually depicted in Figure 3.4 a), b), and c).

Regarding the *Project perception* criterion, the assessment was based on people's perceptions influenced by the extent of impact detected—what they observe, smell, or hear. This was gauged by considering a 1 km distance between power generation projects and urban, school, or hospital areas, coupled with the project's size. Consequently, if a power generation project, regardless of its size, is situated over 1 km away from the mentioned areas, it receives a positive perception value. Conversely, if a project with a capacity equal or below 10 MW is within 1 km, it gets an average perception rating. However, if a project surpassing 10 MW is located less than 1 km from urban, school, or hospital sites, it garners a negative perception score, due to its potential heightened impact. Further details on this approach are provided in Table 3.6.

Criterion	Type	Scale	Projects	Good	Average	Bad
Project perception	Qualitative	Perception	All	>1 km Any size	<=1 km <= 10 MW	<=1 km >10 MW

Table 3.6: Guideline for the evaluation of Project perception criterion

Within this context, the criterion under consideration is *Job creation*, a metric employed to assess the direct job opportunities engendered by the various alternatives. Specifically, employment factors (EFs) offer a quantification of jobs created per unit of physical output in the realm of electricity supply, such as in terms of megawatts (MW) or megawatt-hours (MWh) [113]. It's worth noting that there exists no universal set of EFs that universally fit all countries,

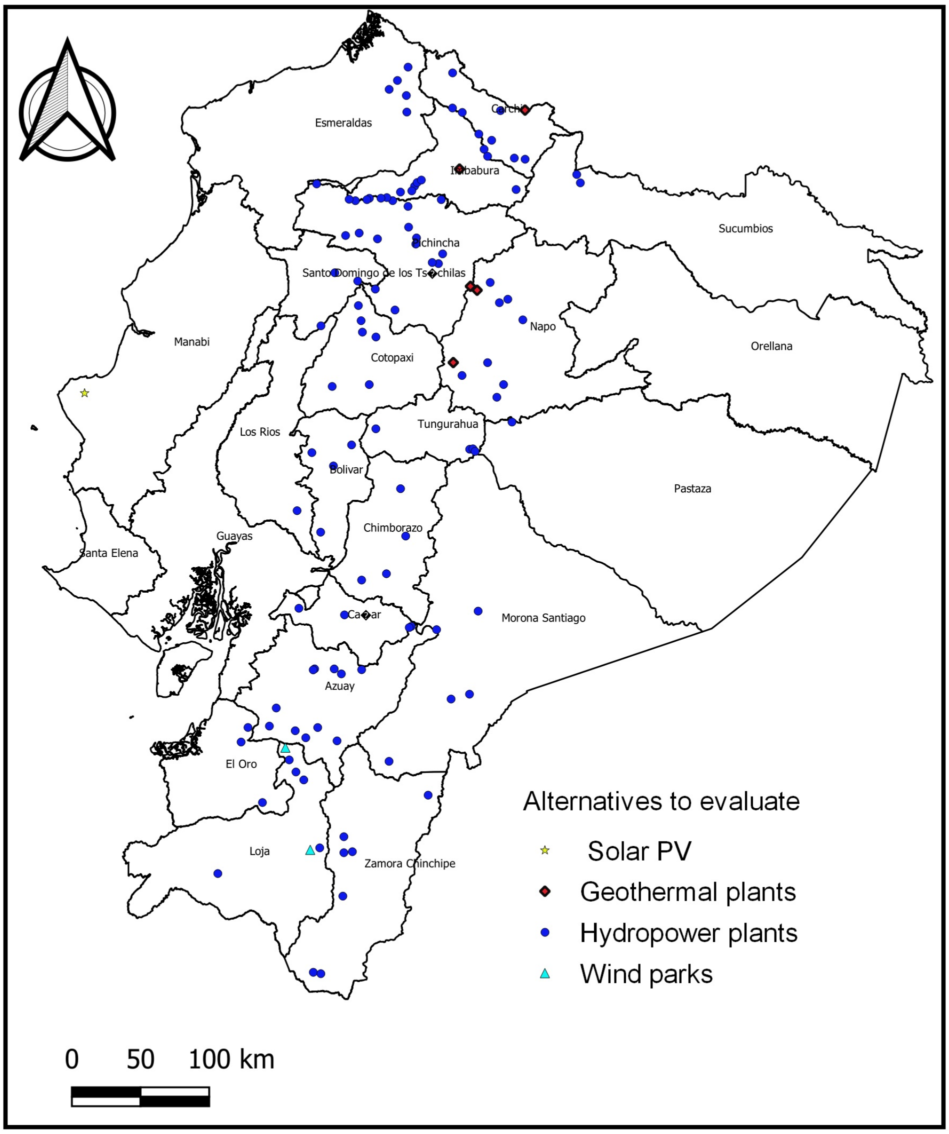


Figure 3.3: Ecuador base layer with the 101 power plants generation portfolio

as these values are contingent upon local regulations and policies. Nonetheless, existing research hints at a discernible trend in these values [55], [57], [120]. In this study, EFs for key stages—Manufacturing, Construction and Installation, and Operation and Maintenance—were sourced from [113]. The calculation exclusively factored in the construction and installation, and operation and maintenance phases, omitting the manufacturing stage. This omission stems from the fact that the manufacturing phase doesn't involve Ecuadorian labor due to the non-domestic origin of materials. Refer to Table 3.7 for a comprehensive depiction of the employed EFs.

In the context of the final criterion within the social category, pertaining to the potential *Displacement or relocation of people* due to the establishment of power generation projects, the assessment scale pertains to the level of risk, categorized as high or low. This indicates

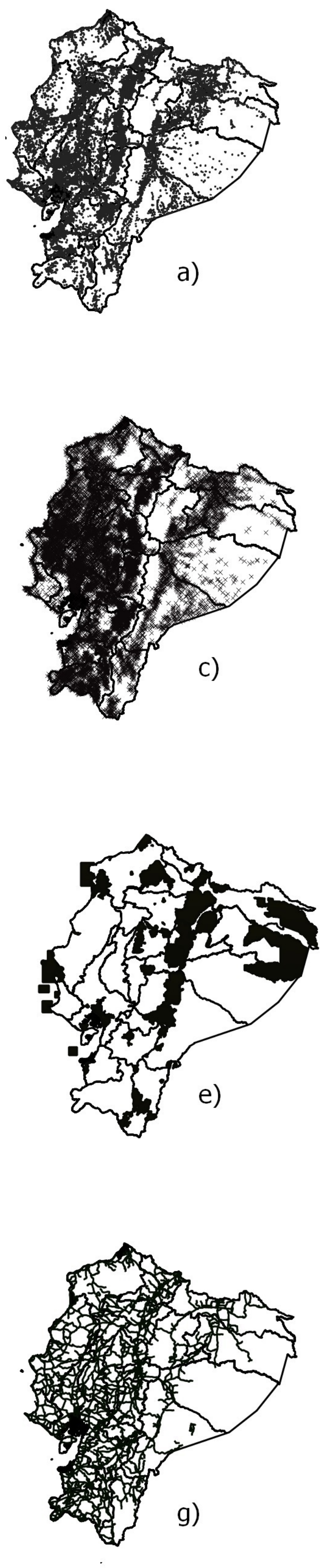


Figure 3.4: Used layers for the Ecuadorian MCA: a) Urban areas, b) Hospital infrastructure, c) Existing schools, d) Protected forest and vegetation, e) National system of protected areas, f) Biosphere reserves, g) Existing roads, h) National transmission system

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

Table 3.7: Employment factors

whether there is a considerable or minimal risk of people being displaced as a result of project construction. The degree of risk is contingent upon project type and location, as delineated in Table 3.8. The consequences of hydropower dam projects on population displacement, as delineated by the World Commission on Dams, are diverse and often substantial [76]. While dams are typically constructed for water provision, hydropower generation, irrigation, flood control, and other socioeconomic benefits, their implementation can also provoke the displacement of communities, commonly referred to as "resettlement" or "displacement-induced migration". Consequently, irrespective of location, projects involving a water reservoir are classified as high-risk in terms of potential displacement, while run-of-river projects are deemed low-risk. For wind, solar photovoltaic (except rooftop installations), and geothermal projects analyzed here, those planned for construction near to urban zones are designated high-risk concerning population displacement, whereas projects slated for development outside urban areas carry a low risk. Notably, photovoltaic rooftop projects are exclusively categorized as low-risk. It is imperative to note that even projects deemed low-risk in terms of population displacement or relocation do not imply a complete absence of risk; rather, they denote a significantly reduced level of risk.

Criterion	Type	Scale	Projects	High	Low
Displacement/ relocation of people	Qualitative	Risk	Hydropower plants	With reservoir	Run-of-river
			Wind parks PV farms Geothermal plants	Located <= 500 m from urban areas	Located > 500 m from urban areas
			PV rooftops	n/a	All

Table 3.8: Guideline for the evaluation of Displacement or relocation of people criterion

Alternatives evaluation for environmental criteria

The environmental cluster encompassed an evaluation of three distinct criteria: deforestation, proximity to nature reserves, and the threat to flora and fauna. The relevant geographic information for the analysis of these criteria is visually depicted in Figure 3.4 d), e) and f).

Forests hold profound significance as they serve as sources of water, biodiversity, habitat, and cultural traditions. Unfortunately, Ecuadorian forests have been progressively impacted by various industries, including agriculture, livestock, oil, and mining. Notably, Ecuador sustained the highest deforestation rates in South America between 1990 and 2010, with annual rates ranging from -1.5% to -1.8% and an overall deforestation of 21,340 km² during the period 1990 to 2020 [135]. For our analysis the *Deforestation* criterion pertains to the removal of trees and vegetation from areas demarcated as protected zones by the Ecuadorian Government through the Ministry of Environment and Ecology Transition. These designated areas contrast with the potential sites for electricity generation projects. This criterion's assessment involves calculating the distance between the proposed projects and the forest, using a 500-meter buffer zone. The specifics of this spatial parameter can be found in Table 3.9.

Criteria	**Type**	**Scale**	**Projects**	**High**	**Low**
Deforestation	Qualitative	Risk	All	Located <= 500 m from protected forest and vegetation	Located > 500 m from protected forest and vegetation

Table 3.9: Guideline for the evaluation of Deforestation criterion

Within the context of the criterion concerning *Proximity to natural reserves*, the scope extends beyond the National System of Protected Areas (SNAP) to encompass the consideration of Biosphere Reserves. Within the nation, the comprehensive SNAP encompasses a collection of 11 distinguished national parks, namely Cayambe Coca, Cotopaxi, Galapagos, Llanganates, Machalilla, Podocarpus, Sangay, Sumaco, Yasuni, Yacuri, and El Cajas. Additionally, this system embraces 7 vital biosphere reserves: Chocó Andino, Galapagos, Yasuni, Podocarpus, Sumaco Napo Galeras, and Cajas. While each holds distinct definitions, their shared emphasis on protection underscores their equal importance. Ecuador's commitment to safeguarding its natural heritage is evident in the Ministry of the Environment's disclosure of the nation's 19.1 million hectares of Protected Areas. This translates to roughly 19% of the country's landmass, encompassing 49 regions vigilantly conserved to ensure biodiversity preservation and the well-being of all life forms. Ecuador's environmental and cultural legacy is a tapestry of emotions woven by the tranquility of its jungles, the majestic presence of its páramos, and the resounding power of its oceans. This rich heritage finds expression within the SNAP, a network comprising National Parks, Biological, Ecological, Geobotanical, Fauna Production, Marine, Wildlife Refuges, and Recreation Areas thoughtfully distributed across Ecuador [36]. Given Ecuador's extraordinary biodiversity, it boasts 7 Biosphere Reserves. These reserves are internationally acknowledged zones situated within their respective countries, promoting harmonious coexistence between humanity and nature while preserving pivotal global ecosystems. Chosen for their scientific, ecological, biological, and cultural significance, these areas also serve as hubs for sustainable socioeconomic activities and conservation efforts by local inhabitants, thereby advancing sustainability [11]. Consequently, within this analysis, these reserves were accorded equivalent importance as Ecuador's national system of protected areas. The specifics of this spatial parameter can be found in Table 3.10 and are valid for all type of power plants.

Ecuador has taken significant measures to protect its natural ecosystems, as evident in the previous criteria involving the National System of Protected Areas, Biosphere Reserves, and forests. The designation of an area as a National Park entails meeting stringent criteria beyond geographical boundaries; it must encompass a spectrum of elements including diverse

Criteria	Type	Scale	High	Medium	Low
Proximity to Natural Reserves	Qualitative	Impact	Inside the SNAP or Biosphere Reserve, or <= 10 km from the limits of SNAP or Biosphere Reserve and installed capacity >10 MW	<= 10 km from the limits of the SNAP or Biosphere Reserve and installed capacity <= 10 MW	> 10 km from the limits of SNAP or Biosphere Reserve

Table 3.10: Guideline for the evaluation of Proximity to Natural Reserves criterion

flora and fauna species, geological characteristics, and habitats of scientific, educational, and recreational importance [8]. These areas serve as habitats for animal species that warrant utmost protection. Ecuador's national parks serve as remarkable repositories of animal and flora biodiversity. Among the prominent parks like Yasuní, Galápagos, Cotopaxi, Machalilla, Sangay, and Cajas, a plethora of species flourish. These ecosystems span from the lush Amazon rainforest to the high-altitude paramo landscapes, offering refuge to an array of creatures such as jaguars, giant tortoises, condors, howler monkeys, and marine species. These distinct habitats are pivotal in safeguarding these diverse species and contribute significantly to Ecuador's globally recognized efforts in conserving biodiversity.

The *Threat to fauna and wildlife* criterion addresses the potential for a project to disrupt fauna and wildlife migration routes within its designated site. The assessment incorporates factors such as the proximity to wildlife conservation areas and the potential impact on river ecosystems. However, due to limited data specific to Ecuador and the absence of information concerning local animal migration routes, a comprehensive analysis of the precise severity of this impact is currently hindered. Consequently, this study draws upon existing literature for insights and considerations regarding this aspect, underlining the need for further research to comprehensively evaluate this criterion's implications in the Ecuadorian context. The assessment scale of this criterion gauges the potential impact associated with the placement of different types of power plants. In this context, the extent of impact is quantified based on specific conditions outlined in Table 3.11. Owing to space limitations, the "Type" category will be excluded from the table; nevertheless, it is crucial to emphasize that this criterion is qualitative in nature. This criterion takes into consideration various types of power generation projects, including hydroelectric projects with or without reservoirs and differing capacities (greater or smaller than 10 MW), solar photovoltaic installations, wind farms, and geothermal facilities. Detailed specifications of these projects are cataloged in the existing project portfolio, as outlined in Table 3.4.

In this study, a distinction is made between reservoir and small run-of-river hydropower

Criteria	Scale	Project	High	Medium	Low
Threat to fauna and wildlife	Impact	Hydropower plants	Any size located inside the SNAP, Biosphere Reserve, or protected, forest; Or hydro with reservoir located anywhere [121], [166], [95].	ROR > 10 MW	ROR <= 10 MW [16]
		PV power plants	Located inside the SNAP, Biosphere Reserve, or protected forest	Large scale projects [108].	PV rooftop
		Geothermal plants		Located <= 1 km from rivers or water bodies [108].	Located > 1 km from rivers or water bodies
		Wind parks		Located <= 1.2 km from the SNAP, Biosphere Reserve, or protected forest [161], [142].	Located >1.2 km from SNAP, Biosphere Reserve, or protected forest

Table 3.11: Guideline for the evaluation of Threat to fauna and wildlife criterion

plants, emphasizing the greater environmental impact of the former. This distinction arises from a combination of both design and operational characteristics. The establishment of reservoirs for hydropower plants necessitates the inundation of vast areas, thereby contributing to habitat loss and the displacement of local communities. In contrast, run-of-river plants, with their smaller physical footprint, do not require such extensive reservoirs. The presence of reservoirs also disturbs the natural flow patterns of rivers, resulting in consequences for aquatic ecosystems, sediment transport, and downstream habitats. During reservoir construction, the potential for erosion and sediment buildup poses risks to water quality and aquatic habitats. Moreover, the accumulation of organic materials in reservoirs can lead to methane emissions, whereas run-of-river plants generally exhibit lower methane emissions. The impact of reservoir-based plants extends to the fragmentation of habitats, changes in water temperature, and long-term alterations in nutrient cycles. Often, these effects are accompanied by considerable land use transformations, such as deforestation. Overall, the collective impacts of reservoir-based hydropower plants tend to be more substantial and enduring, while run-of-river plants exert a more localized and less disruptive influence on the environment.

It’s important to note that our aim is not to vilify hydropower plants of any size. However, our assessment is rooted in the extensive literature review and numerous interviews conducted. The consensus from these sources is that hydropower plants with reservoirs generally entail higher environmental impacts when compared to run-of-river counterparts. To distinguish between the two types, we have also considered an installed capacity threshold of 10 MW for hydropower plants. While there is no definitive research that conclusively establishes that plants smaller than 10 MW have fewer negative impacts than those exceeding 10 MW, this threshold was chosen based on feedback from various stakeholders and serves the analytical purposes of this study.

Alternatives evaluation for technical criteria

The technical cluster encompassed an evaluation of three distinct criteria: size, accessibility, and distance to transmission lines. The relevant geographic information for the analysis of these criteria is visually depicted in Figure 3.4 g) and h). The *Size* criterion evaluates the project’s installed capacity in megawatts (MW), and its representation can be found in the third column of Table 3.4. Another crucial technical criterion is *Accessibility*, which pertains to the ease of reaching the project location. This aspect bears high significance during the construction, operation, and maintenance phases of the project. To assess accessibility, the distance of the alternatives from the road network is employed. This metric holds relevance across all types of power plants and adheres to a 5-point scale, as detailed in Table 3.12. Furthermore, the *Distance to Transmission Lines* criterion accounts for the proximity of power transmission and distribution lines, measured from the nearest point of the project in kilometers. Longer distances correspond to heightened technical complexities and increased investment requirements. Similar to the accessibility criterion, the distance to the road network is used for assessment across all power plant categories. The measurement scale also follows a 5-point scale, elucidated in Table 3.13. The determination of distances for these two criteria was informed by relevant research in the field, including sources like [122], [115], and [149]. The intention was to strike a harmonious balance by considering various authoritative references.

Criteria	**Type**	**Very good**	**Good**	**Average**	**Bad**	**Very bad**
Accessibility	Qualitative	<=1.5 km	>1.5 km and <=4.5 km	>4.5 km and <=7.5 km	>7.5 km and <= 10 km	>10 km

Table 3.12: Guideline for the evaluation of Accessibility criterion

Criteria	**Type**	**Very good**	**Good**	**Average**	**Bad**	**Very bad**
Distance to the Grid	Qualitative	<=1 km	>1 km and <=4 km	>4 km and <=7 km	>7 km and <= 10 km	>10 km

Table 3.13: Guideline for the evaluation of Distance to the grid criterion

This section delineated the phases undertaken in the multi-criteria analysis, with comprehensive details specific to this study. Appendix A displays the comprehensive PROMETHEE matrix, presenting compound information pertinent to the 101 projects based on the assessment of nine criteria.The outcomes derived from these steps are expounded upon in Chapter 4. Next, Section 3.2 outlines the attributes underpinning the model of Ecuador's electrical system within the urbs software.

3.2 *urbs* model for the Ecuadorian power sector

The Ecuadorian power system underwent a comprehensive analysis using *urbs*, an open-source linear optimization modeling framework developed by the Chair of Renewable and Sustainable Energy Systems at the Technical University of Munich (ENS-TUM). This tool was employed to minimize the annual energy system costs, which encompass not only investment costs but also consider their annualized depreciation, as well as operational and environmental expenses. *urbs* stands out for its versatility in handling multiple input and output commodities, enabling the creation of highly detailed representations of energy conversion processes.

One of the features of *urbs* is its temporal resolution, allowing for the visualization of the chronological behavior of supply and demand within the energy system, with a granularity of 8760 hours per year. This temporal granularity ensures that the required energy demand is consistently met by coordinating input commodities and various technological processes at each time step.

Moreover, *urbs* operates by independently expanding energy and power capacities, thus providing a comprehensive assessment of the system's growth potential. This approach facilitates an understanding of the intricate interplay between energy and power capacities, with a linear dependence thoughtfully integrated into the modeling framework. Through these capabilities, *urbs* emerges as a valuable resource in optimizing and planning the Ecuadorian power system, offering insights into efficient capacity expansion and unit commitment analyses while considering economic and environmental factors [41], [42].

3.2.1 Model structure

urbs comprises various model components, including commodities, processes, transmission, and storage. In this context, commodities encompass dynamic natural resources like solar radiation, wind velocity, and basin flow rates, each characterized by its unique set of hourly time series spanning 8760 time steps. In contrast, natural gas, diesel, heavy oil, biogas, geothermal energy, and electricity are considered as stable, non-fluctuating stock commodities. Additionally, *urbs* incorporates essential conversion processes specific to the Ecuadorian scenario, encompassing hydropower plants, thermal plants, PV systems, wind farms, geothermal plants, biogas facilities, and bagasse plants. Water reservoirs serve as the representation of stored commodities within the model.

In this one-node representation of Ecuador, internal transmission lines are not taken into account. To execute the model effectively, it requires the following inputs: (i) total usable area allocations for each designated site; (ii) comprehensive data on energy resources, including renewable sources like solar, wind, geothermal, biomass, and biogas, as well as non-renewable resources such as heavy oil, diesel, and natural gas. It also considers imported electricity and transaction prices; (iii) technical specifications for each type of power plant, encompassing installed and maximum capacities, operational lifetime, minimum load fractions, maximal power gradients, investment costs, and fixed and variable costs; (iv) electricity demand, represented by a series of time data for each analyzed year; and (v) scenarios, as described in Section 3.3.

The model generates several outputs, including (i) a comprehensive database and plots illustrating the power system's profile with hourly resolution; (ii) the total installed capacity for each year under examination; (iii) an assessment of the system's costs during the analyzed timeframe; and (iv) detailed consumption data for commodities at each time step. The urbs model scheme for the Ecuadorian power system [89] used in this work appears in Figure 3.5.

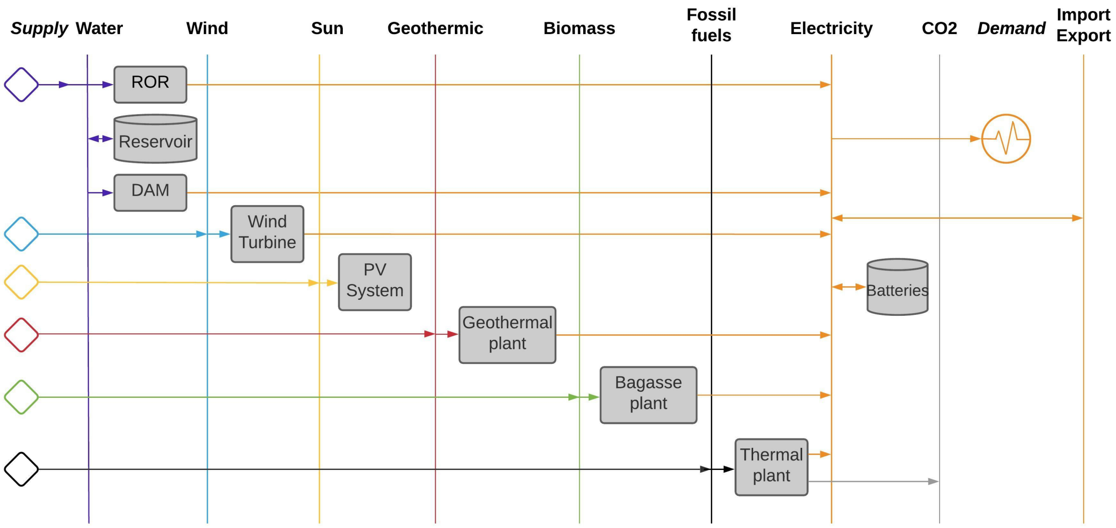


Figure 3.5: Ecuadorian power sector reference system

3.2.2 Supply side modeling

The simulation framework covers a significant temporal span, extending from the year 2019 to 2050, structured as a cascading setup with specific focus years at 2019, 2030, 2040, and 2050. Within this simulation approach, the input data undergoes systematic updates for each of these chosen years, facilitating a comprehensive projection of the Ecuadorian power system's evolution over the entire time frame. This simulation process encompasses various critical aspects of the power system's development, including capacity expansion by technology, the augmentation of transmission capacity, the integration of advanced storage technologies, the overall generation of clean energy, and the assessment of total system costs. These simulations are conducted under the purview of three distinct scenarios, each of which is detailed in Section 3.3 of the analysis.

The modeling process of the Ecuadorian power sector initiates by anchoring to the base year, which is 2019 in this context. This choice serves as a foundational point from which the subsequent years are modeled. In this pivotal year, the actual electricity supply to the Interconnected National System (SNI) is sourced from a diverse array of energy resources. Specifically, 76.3% of the electricity generation is attributed to hydropower, while 21.9% comes from thermal power generation, relying on fuels like diesel, natural gas, and heavy oil. Furthermore, 1.8% of the electricity generation is attributed to renewable resources, encompassing biomass, solar, wind, and biogas. The total installed capacity for electricity generation in 2019 amounts to 8,511.65 megawatts [74], [68] . Notably, the majority of this capacity is comprised of hydropower plants, predominantly located in the Highlands and the Amazon region, where water resources are abundant. In contrast, thermal power plants are primarily situated in the Amazon and Coast regions, reflecting regional variations in energy generation and consumption patterns. This detailed characterization of the 2019 energy landscape serves as the foundational context for subsequent modeling and analysis, providing valuable insights into the power system's historical configuration and performance. For the other modeled years in the three scenarios, the power plant portfolio detailed in the PME, and the theoretical potential for wind and PV [70] is used, and it is shown in Table 3.14.

Resource	**Technology**	**Capacity in 2019 [MW]**	**Capacity for 2024 [MW]**	**Capacity for 2027 [MW]**	**Remaining potential [MW]**
Amazon watershed	DAM > 450 MW	1,075	-	595.6	-
	DAM 50-450 MW	403	-	-	368
	ROR >450 MW	1,987	-	-	7,840
	ROR 50-450 MW	410	-	100	710.7
	ROR 10-50 MW	326.86	30	94.6	1,238.7
	ROR < 10 MW	33.27	22.16	11.2	32.95
	Total Hydro Amazon	4,235.13	52.16	801.4	9,190
Pacific watershed	DAM > 450 MW	-	-	-	460
	DAM 50-450 MW	213	205.4	-	201
	ROR 50-450 MW	338.36	-	-	656.4
	ROR 10-50 MW	234.63	49	80	570
	ROR < 10 MW	57.92	5.95	15	204.7
	Total Hydro Pacific	843.91	260.35	95	2,092.1
Solar	PV-US	25	100	590	22,000
	PV-DG	-	-	-	10,000
	Total Solar	25	100	590	32,000
Wind	Wind parks onshore	16.5	270	130	7,000
Geothermal	Geothermal plants	-	-	-	900
Biomass	Bagasse plants	144.3	30	100	370
Biogas	Municipal solid waste biogas	7.3	1.02	-	n.a
Natural gas	OCGT	19.42	77	-	-
	CCGT	644.18	-	510	-
	Total Natural gas	663.6	77	510	-
Heavy oil	ICE	1,359.91	-	-	-
Diesel	ICE	1,216	-	-	-
All resources	**All technologies**	**8,511.65**	**790.53**	**2,226.4**	**51,552.1**

Table 3.14: Type of technology, installed capacity, and resource potential for the Ecuadorian *urbs* model

In addition to the parameters shown in Table 3.14, the incorporation of economic data is essential for each specified technology. This economic data has been meticulously gathered from [160] and documented in Table 3.15, providing a comprehensive overview of the technoeconomical aspects associated with these technologies.

	2019	2030	2040	2050
Amazon DAM > 450 MW				
Plant life [years]	75	75	75	75
Plant factor	0.6	0.6	0.6	0.6
Investment [USD/MW]	3’360,000	3’360,000	3’360,000	3’360,000
Fixed [USD/MW]	42,000	42,000	42,000	42,000
Variable [USD/MWh]	0.07	0.07	0.07	0.07
Amazon DAM 50-450 MW				
Plant life [years]	75	75	75	75
Plant factor	0.6	0.6	0.6	0.6
Investment [USD/MW]	5’065,000	5’065,000	5’065,000	5’065,000
Fixed [USD/MW]	63,300	63,300	63,300	63,300
Variable [USD/MWh]	0.07	0.07	0.07	0.07
Amazon ROR >450 MW				
Plant life [years]	75	75	75	75
Plant factor	0.7	0.7	0.7	0.7
Investment [USD/MW]	3’465,000	3’465,000	3’465,000	3’465,000
Fixed [USD/MW]	42,000	42,000	42,000	42,000
Variable [USD/MWh]	0.07	0.07	0.07	0.07
Amazon ROR 50-450 MW				
Plant life [years]	75	75	75	75
Plant factor	0.8	0.8	0.8	0.8
Investment [USD/MW]	3’518,000	3’518,000	3’518,000	3’518,000
Fixed [USD/MW]	50,000	50,000	50,000	50,000
Variable [USD/MWh]	0.07	0.07	0.07	0.07
Amazon ROR < 50 MW				
Plant life [years]	75	75	75	75
Plant factor	0.7	0.7	0.7	0.7
Investment [USD/MW]	5’275,000	5’275,000	5’275,000	5’275,000
Fixed [USD/MW]	65,900	65,900	65,900	65,900
Variable [USD/MWh]	0.07	0.07	0.07	0.07
Pacific DAM > 450 MW				
Plant life [years]	75	75	75	75
Plant factor	0.6	0.6	0.6	0.6
Investment [USD/MW]	3’360,000	3’360,000	3’360,000	3’360,000
Fixed [USD/MW]	42,000	42,000	42,000	42,000
Variable [USD/MWh]	0.07	0.07	0.07	0.07
Pacific DAM 50-450 MW				
Plant life [years]	75	75	75	75
Plant factor	0.6	0.6	0.6	0.6
Investment [USD/MW]	3’166,000	3’166,000	3’166,000	3’166,000
Fixed [USD/MW]	63,300	63,300	63,300	63,300

	2019	2030	2040	2050
Variable [USD/MWh]	0.07	0.07	0.07	0.07
Pacific ROR >450 MW				
Plant life [years]	75	75	75	75
Plant factor	0.5	0.5	0.5	0.5
Investment [USD/MW]	2'100,000	2'100,000	2'100,000	2'100,000
Fixed [USD/MW]	42,000	42,000	42,000	42,000
Variable [USD/MWh]	0.07	0.07	0.07	0.07
Pacific ROR 50-450 MW				
Plant life [years]	75	75	75	75
Plant factor	0.5	0.5	0.5	0.5
Investment [USD/MW]	2'513,000	2'513,000	2'513,000	2'513,000
Fixed [USD/MW]	50,000	50,000	50,000	50,000
Variable [USD/MWh]	0.07	0.07	0.07	0.07
Pacific ROR < 50 MW				
Plant life [years]	75	75	75	75
Plant factor	0.7	0.7	0.7	0.7
Investment [USD/MW]	5'275,000	5'275,000	5'275,000	5'275,000
Fixed [USD/MW]	65,900	65,900	65,900	65,900
Variable [USD/MWh]	0.07	0.07	0.07	0.07
PV-US				
Plant life [years]	30	30	30	30
Investment [USD/MW]	1'980,000	1'080,000	1'020,000	960,000
Fixed [USD/MW]	19,800	10,800	10,200	9,600
Variable [USD/MWh]	-	-	-	-
PV-DG				
Plant life [years]	25	25	25	25
Investment [USD/MW]	2'680,000	2'169,000	1'704,000	1'240,000
Fixed [USD/MW]	27,000	21,600	16,900	12,000
Variable [USD/MWh]	-	-	-	-
Wind parks				
Plant life [years]	25	25	25	25
Investment [USD/MW]	2'530,000	1'800,000	1'479,000	1'115,000
Fixed [USD/MW]	37,950	27,000	22,185	17,370
Variable [USD/MWh]	-	-	-	-
Geothermal plants				
Plant life [years]	30	30	30	30
Investment [USD/MW]	5'855,000	4'424,000	4'424,000	4'424,000
Fixed [USD/MW]	117,000	88,000	88,000	88,000
Variable [USD/MWh]	-	-	-	-
Bagasse plants				
Plant life [years]	30	30	30	30
Investment [USD/MW]	1'500,000	1'500,000	1'500,000	1'500,000
Fixed [USD/MW]	96,000	96,000	96,000	96,000

	2019	2030	2040	2050
Variable [USD/MWh]	-	-	-	-
Municipal solid waste biogas				
Plant life [years]	20	20	20	20
Investment [USD/MW]	2'350,000	2'300,000	2'277,000	2'250,000
Fixed [USD/MW]	94,000	92,000	91,000	90,000
Variable [USD/MWh]	-	-	-	-
Natural gas OCGT				
Plant life [years]	25	25	25	25
Investment [USD/MW]	869,000	805,000	778,000	744,000
Fixed [USD/MW]	35,000	20,100	19,400	18,600
Variable [USD/MWh]	1.44	2.16	2.16	2.16
Natural gas CCGT				
Plant life [years]	25	25	25	25
Investment [USD/MW]	1'190,000	983,000	967,000	913,000
Fixed [USD/MW]	23,800	19,660	19,360	18,260
Variable [USD/MWh]	2.16	2.16	2.16	2.16
Heavy oil ICE				
Plant life [years]	20	20	20	20
Investment [USD/MW]	1'070,000	1'070,000	1'070,000	1'070,000
Fixed [USD/MW]	20,000	20,000	20,000	20,000
Variable [USD/MWh]	1.04	1.04	1.04	1.04
Diesel ICE				
Plant life [years]	15	15	15	15
Investment [USD/MW]	1'000,000	1'000,000	1'000,000	1'000,000
Fixed [USD/MW]	20,000	20,000	20,000	20,000
Variable [USD/MWh]	1.04	1.04	1.04	1.04

Table 3.15: Power plants technologies and their parameter's evolution up to 2050

To further enrich the modeling process, Figure 3.6 serves as an illustrative resource, offering a visual depiction of the dynamic nature of natural resources such as solar radiation and wind velocity. These fluctuations are represented as time series availability factors, which play an important role in the model's accuracy. These availability factors have been sourced from Renewables.ninja, an online tool developed by Pfenninger and Staffell [126], [144]. Moreover, it's worth noting that the availability factors for hydropower plants are derived from precise calculations based on the average flow rates observed within the reservoirs of Ecuadorian hydropower installations [27], [89]. This level of granularity and specificity in data sourcing ensures that the *urbs* model is anchored in robust, real-world data, allowing for a thorough and accurate representation of the Ecuadorian power system's dynamics and performance.

3.2.3 Demand side modeling

During the reference year of 2019, the combined electricity consumption across the residential, industrial, commercial and public lighting, and construction sectors amounted to a total of 21.91

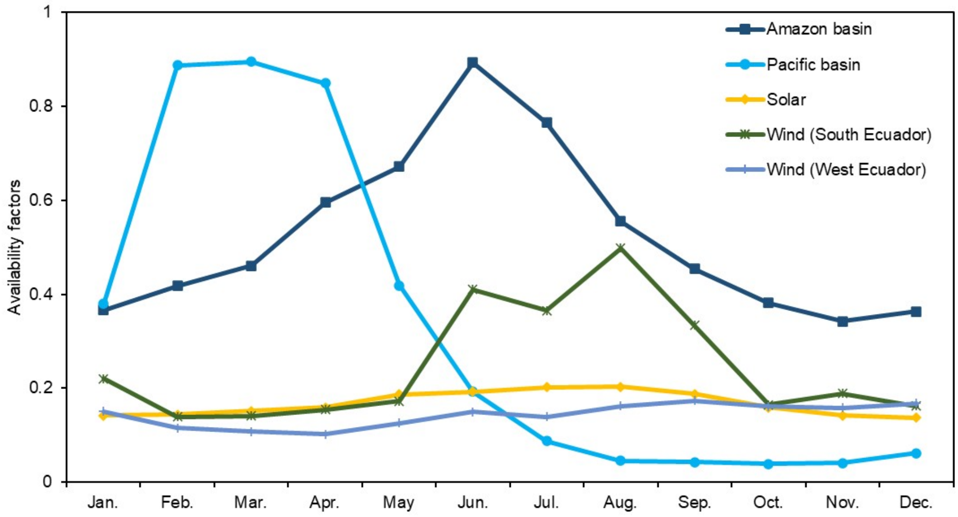


Figure 3.6: Monthly normalized availability factors for hydropower plants in the Amazon and Pacific basins, wind parks in Western and Southern Ecuador, and photovoltaics

TWh [72].

The projection of electricity demand in Ecuador up to the year 2050 relied upon two primary reference documents, namely, the Electrification Master Plan [70] and the Energy Outlook [67]. These documents provided essential insights into the anticipated trajectory of electricity consumption within the nation.

To derive a comprehensive estimate of electricity demand across various sectors, encompassing residential, industrial, commercial and public lighting, and others, a consistent annual growth rate of 4% was employed, while the electrification of the land transport sector is very low. This rate corresponds to the highest growth scenario outlined in the Electrification Master Plan and aligns with alternative 2 of the scenarios presented in the Energy Outlook for Ecuador up to the year 2050.

However, it is imperative to clarify that the calculations pertaining to electricity demand made within this study did not factor in the significant economic and security challenges that Ecuador has encountered during the last years. Consequently, the results presented in this work should be interpreted within the context of energy policies proposed in 2016 and may not fully encapsulate the subsequent developments or constraints that the nation has faced in the intervening years. Table 3.16 displays the projected baseline electricity demand for the primary five consumer sectors. It's worth noting that we have detailed the electricity demand values for the years 2024 and 2027. These specific years are of particular interest because the Electrification Master Plan outlines the commencement of certain electricity generation projects during these times, as described in Table 3.14 of Sub-section 3.2.2. These projects are expected to play a crucial role in shaping the future energy landscape. Additionally, having data for these years allows for meaningful comparisons across different scenarios, providing valuable insights into the effectiveness of the proposed energy policies and generation projects.

Within this study, we have computed two distinct categories of electrical demand, hereafter referred to as "Medium" and "High" demand. The selection of these categories is contingent

Sector	2019	2024	2027	2030	2040	2050
Residential	7.66	8.72	9.81	11.03	16.33	24.17
Industrial	6.48	6.59	7.42	8.34	12.35	18.28
Commercial and Public lighting	5.31	5.95	6.69	7.53	11.14	16.49
Land transport	0	0.07	0.10	0.13	0.21	0.30
Others	2.46	2.92	3.28	3.70	5.47	8.10
Total	**21,91**	**24,25**	**27,30**	**30,73**	**45,50**	**67,34**

Table 3.16: Base electricity demand by consumption sector up to 2050 in [TWh]

upon the incorporation of specific new consumption sectors, beyond the initial five outlined in Table 3.16. In the context of Medium demand, the additional consumption sectors encompass the oil sector and singular loads of the industrial group, thereby yielding a total of seven distinct consumption groups. On the other hand, the High demand category extends the analysis to include a consumption group known as basic industries, resulting in a total of eight consumption groups.

The degree of electrification for each of these consumption groups, tailored to each type of demand, is detailed below, shedding light on the specific energy requirements and electrification status of each sector. This comprehensive breakdown serves as a foundation for understanding the energy landscape and planning strategies tailored to the distinctive needs of each consumption group.

Transport sector

In the realm of the transport sector, the approach taken involves a shift away from individual transport in favor of promoting mass public transportation modes, while still accounting for the persisting trend of private car ownership and usage. In the context of Medium demand, the electricity demand for the transport sector mirrors that of the moderate scenario (referred to as the "Mod scenario") documented in Table 6 in [89].

Specifically, for land passenger transport, the energy consumption is primarily derived from natural gas, amounting to 9.63 petajoules (PJ), closely followed by gasoline with 8.9 PJ, and diesel with 7.84 PJ. These three fuel sources collectively constitute 82.3% of the total energy consumption within the transport sector in the year 2050. Electricity, although a minority contributor, constitutes 17.7% of the total energy mix in this context. Conversely, in the case of land freight transport demand, the role of electricity as an energy source for freight transportation is relatively modest, accounting for 5.9% of the total energy requirements. The bulk of the energy, approximately 94.1%, is furnished by diesel fuel as of the year 2050.

In the context of the High demand category, which aligns with the deep decarbonization scenario (referred to as the “DDP scenario”) discussed in Table 6 in [89], there is a notable shift in the energy landscape, particularly within the transport sector. In this case, natural gas is excluded as a transportation fuel, and instead, electricity takes the forefront. Electricity accounts for 15.31 PJ, constituting a significant 47.8% of the total energy consumption for land passenger transport in the year 2050. This transition underscores the pivotal role of electrification the passenger transport.

Concurrently, gasoline and diesel remain relevant, comprising 27.8% and 24.5% of the total passenger transport sector, respectively, emphasizing their ongoing significance. However, the absence of natural gas in the transport sector represents a marked deviation from the Medium demand category. In the case of land freight transport demand, the energy dynamics remain consistent with the Medium demand category, as it is unchanged.

To summarize, the combined electricity demand specific to the land transport sector is itemized in Table 3.17 below, offering a comprehensive breakdown of energy requirements for planning and assessing future strategies for the sector.

Demand category	**2019**	**2024**	**2027**	**2030**	**2040**	**2050**
Medium	0	0.46	1.10	1.70	3.60	5.85
High	0	0.46	6.10	7.13	7.68	8.54

Table 3.17: Electricity demand for land transport by demand category up to 2050 in [TWh]

Oil sector

The oil industry is of great importance in Ecuador's socioeconomic landscape. It is the cornerstone of the national economy and contributes substantially to government revenues and export earnings. As a primary source of energy, oil plays a key role in meeting national energy needs, fueling electricity generation and transportation. Its export revenues provide Ecuador with essential foreign exchange, helping to maintain the balance of trade and meet international financial obligations. In addition, revenues from the oil sector used to fund social programs that improve education, health and poverty alleviation. However, the industry also poses environmental challenges and exposes the nation to volatile global oil prices, highlighting the need for a delicate balance between economic benefits and environmental and social considerations in Ecuador.

The Ecuadorian oil sector operates as a self-generator, producing its electricity predominantly from fossil fuels. However, there is a clear impetus for change. The aim is to integrate the oil sector into the wider Ecuadorian national transmission system, which primarily relies on cleaner hydropower sources. This transition seeks to mitigate the significant levels of CO_2 emissions associated with self-generation within the oil sector, while recognizing the likelihood that Ecuador will continue to heavily depend on oil for export. Currently, the electricity demand of the oil sector stands at 3.78 TWh. However, for the purpose of our calculated Medium demand, it is estimated that only 46% of this electricity demand will be successfully integrated into the broader Ecuadorian national transmission system by 2050. Conversely, under the High demand category, the entire 3.78 TWh of demand from the oil sector is projected to be seamlessly incorporated into the national interconnected system by 2050.

Table 3.18 provides a detailed breakdown of the electricity demand of the oil sector, encompassing the years from 2019 to 2050. This transition toward cleaner energy sources marks a pivotal step in Ecuador's effort to align its energy infrastructure with environmental sustainability goals, while acknowledging the enduring significance of the oil sector in its economic landscape.

Singular loads of the industrial sector

As outlined in the Electrification Master Plan, the concept of singular loads of the industrial group is integral to the projection of electricity demand. Singular loads pertain to the electricity

Demand category	2019	2024	2027	2030	2040	2050
Medium	0	1.51	1.51	1.55	1.63	1.72
High	0	1.51	1.72	2.24	3.78	3.78

Table 3.18: Electricity demand for the oil sector by demand category up to 2050 in [TWh]

requirements of industries with anticipated growth or expansion. This includes pre-existing industries that were operational in 2018 and new industries slated for establishment in the short and medium term. The latter are expected to be integrated into the distribution systems of distribution companies and CNEL EP, as well as the National Transmission System. These singular loads are primarily affiliated with key sectors like mining, cement, steel, oil, and transportation, all of which play important roles in Ecuador's industrial landscape. The specifics of these singular loads can be found in Table 3.19.

Project	Industry	Status	Current capacity [MW]	Future capacity [MW]
Golden Valley	Mining	in operation	1.10	3
Autoridad Portuaria	Port	in operation	3	5
Unión Cementera Nacional Chimborazo	Cement	in operation	33	39
Novacero	Steel	in operation	34	39
Estación Bombeo 1 y 2 Trasvase Daule Pedro Carbo SENAGUA	Pumping	expected	-	36
Complejo Industrial NOVOPLANT Hyundai-Montecristi	Automotive	expected	-	6
DIACELEC	Steel	expected	-	8
EMPRESA POLAR (Harina Pescado)	Milling	expected	-	5
Adelco del Litoral	Steel	expected	70	90
Puerto de Aguas Profundas (DP World)	Port	expected	-	21
Astillero Posorja	Shipyards	expected	6	18
Río Blanco	Minning	expected	-	9
San Carlos Panatanza	Minning	expected	-	100
Producto Pascuales-Cuenca-Cañar	Pumping	expected	-	2
EDEC Nuevo Parque Industrial	nd.	expected	-	5
Emurplag Nuevo Camal Municipal	nd.	expected	-	1
Loma Larga	Minning	expected	-	13
Yachay	Research	expected	3	14

Project	**Industry**	**Status**	**Current capacity [MW]**	**Future capacity [MW]**
Petroecuador (Papallacta)	Pumping	expected	-	16
Petroecuador (Baeza)	Pumping	expected	-	16
Petroecuador (El Salado)	Pumping	expected	-	11
Fruta del Norte	Minning	expected	-	24
Mirador	Minning	expected	-	110
Sector Camaronero	Shrimp	expected	11	189
Total			**161.1**	**780**

Table 3.19: Singular loads of the industrial sector with their current and future capacity

Notably, the electricity demand projections for these singular loads remain consistent across both the Medium and High demand categories, as detailed in Table 3.20. This uniformity underscores the intrinsic importance of these industrial activities in the nation's energy landscape and their unchanging role in shaping electricity demand projections.

Demand category	**2019**	**2024**	**2027**	**2030**	**2040**	**2050**
Medium/High	0	2.87	3.22	3.47	3.74	3.89

Table 3.20: Electricity demand for singular loads up to 2050 in [TWh]

Basic industries

In the context of Ecuador's shift in the productive matrix, basic industries refer to fundamental sectors that are crucial for economic development and self-sufficiency. These encompass steel, copper, shipyards and petrochemical. These industries play a crucial role in diversifying the economy and reducing reliance on a single sector, such as oil. By strengthening these foundational sectors, Ecuador aims to promote a more balanced and sustainable economic model, enhancing overall economic resilience and stability while fostering growth and diversification. These industries are in the pre-feasibility studies stage and their demand projection is considered just for the high demand category and is shown in Table 3.21.

Demand category	**2019**	**2024**	**2027**	**2030**	**2040**	**2050**
High demand	0	0	7.4	10.95	12.07	13.31

Table 3.21: Electricity demand for basic industries up to 2050 in [TWh]

In summary of Sub-section 3.2.3, a comprehensive demand analysis yielded two distinct demand profiles for various consumption groups. The total outcome of the total electricity demand in Ecuador up to 2050, is shown in Figure 3.7. This total demand is an aggregation of the requirements specified for each distinct consumption sector, thoughtfully detailed from Table 3.16 to Table 3.21. These demand projections extend to the year 2050, representing an input for the modeling of Ecuador's electricity sector. The next section, Section 3.3, will delve into the intricate delineation of three distinct scenarios, each leveraging these demand projections as fundamental drivers. These scenarios will provide an in-depth exploration of possible energy trajectories, guiding strategic decision making and policy formulation for Ecuador's changing electricity landscape.

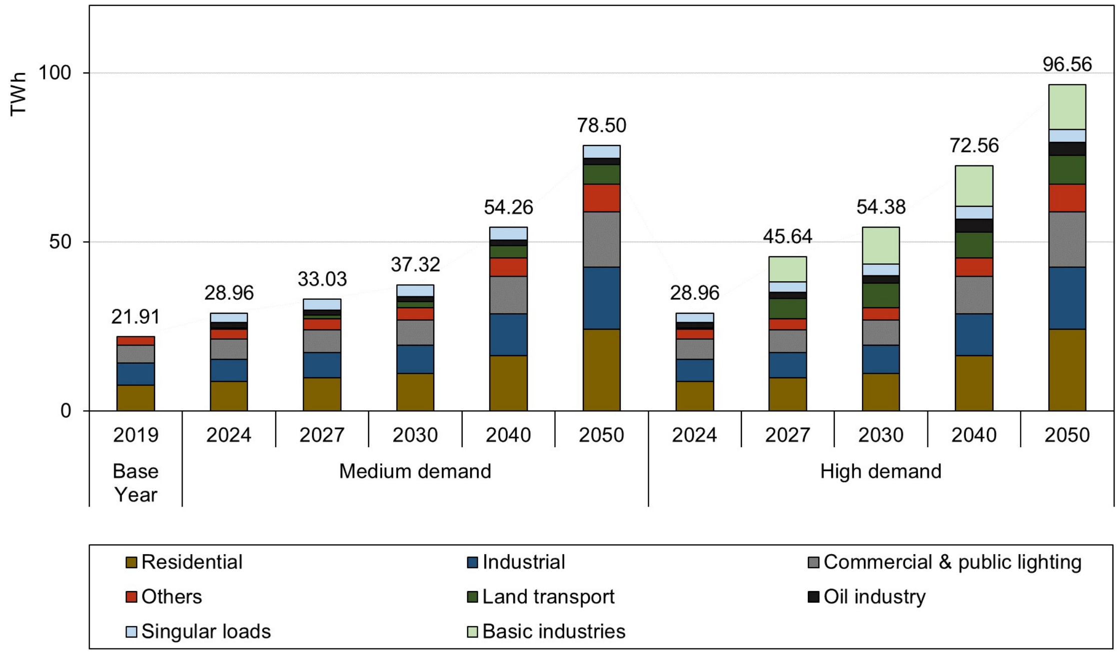


Figure 3.7: Total electricity demand projection up to 2050 in [TWh]

3.2.4 Model validation

In 2019, the total electricity output from the Ecuadorian power system reached 31.95 TWh [74]. The installed capacity for this year, as detailed in Table 3.14, was modeled using *urbs* to simulate the cost-optimal operation of the system. This modeling exercise facilitated an assessment of the electricity generation patterns, determining the quantity of electricity produced by each technology at various time intervals. Within this section, we embark on a comparative analysis, contrasting the results of the electricity generation simulation (Base 2019) with the officially recorded data from ARCONEL, as illustrated in Figure 3.8. This comparative evaluation provides valuable insights into the accuracy and alignment of the modeling with the real-world performance of the Ecuadorian power system.

Within the *urbs* model, the simulated electricity generation stands at 30.99 TWh, providing an accurate representation of the contribution of various technologies, as compared to real-world data provided by the ARCONEL. Notably, both the *urbs* model and the actual data exhibit the prominent role of hydropower in the overall power generation, constituting 76.2% and 76.6% of the mix, respectively.

Thermal technologies, primarily fueled by heavy oil, diesel, and natural gas, collectively account for 21.9% of the power generation according to the ARCONEL and 21.5% in the modelled Base 2019. Renewable resources, including solar, wind, biomass, and biogas, contribute 1.9% in both the *urbs* model and the actual data.

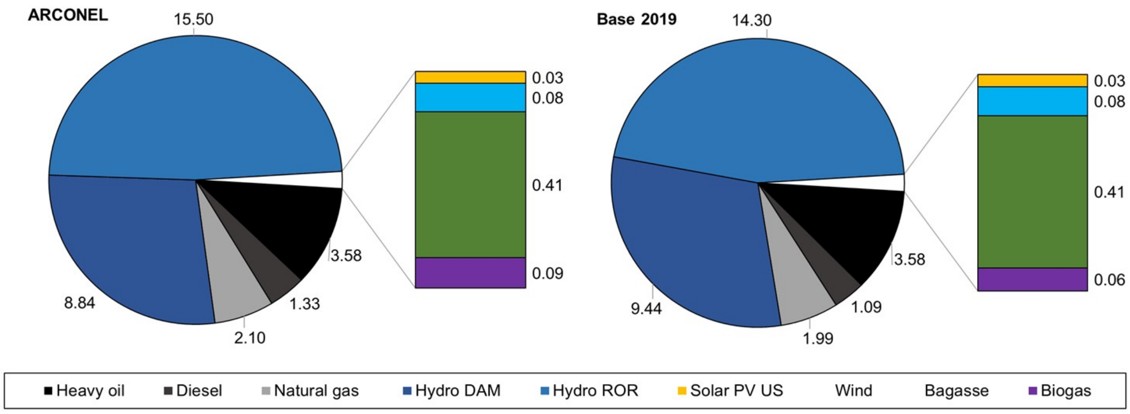


Figure 3.8: Annual electricity generation in [TWh] according to the ARCONEL statistics of 2019 and the *urbs* model Base 2019

When comparing the *urbs* model to the official data, a relative error of 3.04% is observed for the total power generation, with specific errors of 2.5% for hydropower, 4.9% for thermal technologies, and 3.2% for other renewable sources. It's noteworthy that the largest error occurs within the thermal power plants, particularly in the calculation involving diesel. This discrepancy may be attributed to factors like technology efficiency or fluctuations in commodity prices, which are areas warranting further investigation. This comparative analysis sheds light on the strengths and areas of improvement within the *urbs* model's representation of Ecuador's power generation.

3.3 Scenarios creation for the Ecuadorian power system model until 2050

These study's scenarios draw their foundations from the National Energy Forecast [67], which presents a comprehensive evaluation of Ecuador's energy trajectory until 2050, aligning with the policies articulated in the Ecuadorian Master Electricity Plan [70], the National Energy Agenda [77], and the National Plan of Energy Efficiency (PLANEE) [69].

The National Energy Agenda's central thrust is to harness the country's substantial hydropower potential, with the objective of making it the predominant electricity source, contributing at least 70% of the total power generation by 2040. This ambitious goal is underpinned by the PME, which has set out a phased plan. By 2024, this plan envisions the integration of 312.51 MW from hydropower, alongside 401.02 MW from other renewable sources, complemented by 77 MW of natural gas power plants. Furthermore, by 2027, the PME outlines an expansion strategy, foreseeing the incorporation of 896.4 MW from hydropower, coupled with 510 MW of photovoltaic capacity, 230 MW from wind and biomass projects, and an additional 510 MW from combined cycle power plants. Detailed information regarding these endeavors is outlined in Table 3.14 within Sub-section 3.2.2

Simultaneously, the PLANEE introduces a suite of measures intended to enhance energy consumption efficiency, thereby bridging the gap between energy supply and demand. These measures are instrumental in bolstering energy conservation efforts and can be further explored in [69]. This integrated approach to energy policy and planning underscores Ecuador's commitment to ensuring sustainable, efficient, and diversified energy sources while concurrently promoting prudent energy consumption practices.

Policies scenario

In this scenario, the driving force is the Medium demand previously calculated in Subsection 3.2.3, an instrumental foundation rooted in the comprehensive demand analysis discussed earlier. This demand projection serves as the keystone, enveloping all the essential determinants employed to gauge electricity requirements across various consumption sectors. On the supply side, the model operates under the guiding principle of cost-efficiency, striving to optimize energy generation while adhering to the most economical solutions.

The supply-side dynamics, underpinning the Policies Scenario, incorporate constraints and directives set forth in the Ecuadorian Master Electricity Plan, building upon its foundational base scenario. However, this scenario adds a new dimension by including the latest updates to the PME. The aim is to align the energy landscape with evolving policies and strategic directions, translating these imperatives into a cohesive model that encompasses electricity generation, distribution, and consumption.

MCA scenario

Similar to the Policies Scenario, this iteration harnesses the Medium demand projection as its cornerstone. However, it introduces a compelling twist by taking into account the results of a Multi-Criteria Analysis applied to the renewable energy portfolio. This represents a fundamental departure from the former scenario, as not all the projects detailed in the PME and its subsequent updates may be deemed viable post-MCA analysis.

The MCA Scenario is characterized by a nuanced approach, where feasibility is determined through a rigorous evaluation process. This analytical lens ensures that only the most promising and sustainable projects within the renewable portfolio are chosen for implementation. It reflects a critical strategic shift, introducing a layer of selectivity and sustainability that is integral to Ecuador's energy transition.

High demand with CO_2 restrictions scenario

In stark contrast to preceding scenarios, the High Demand with CO_2 restrictions scenario adopts a more ambitious stance, building upon the High Demand category outlined in Subsection 3.2.3. This classification denotes a notable surge in electricity demand, surpassing previous benchmarks. The primary objective of this scenario is to showcase the viability of meeting this heightened electricity demand while addressing energy governance and democracy concerns, and aligning with international climate change agreements.

Operationalizing this concept involves aiming for carbon neutrality in the electricity sector by 2040. Achieving this goal hinges on the comprehensive integration of knowledge and experience from diverse stakeholders in the decision-making process. This collaborative methodology, informed by the outcomes of the Multi-Criteria Analysis conducted in the early stages of this study, underscores the potential of collective expertise in shaping a sustainable energy landscape. In summary, by pursuing carbon neutrality while navigating the intricacies of escalating electricity demand, this scenario exemplifies a forward-looking model illustrating how well-informed, inclusive, and pioneering strategies can steer Ecuador's energy future.

3.4 Chapter Summary

In this chapter, we delved into the comprehensive methodology employed in this research. The first section provided an in-depth account of the six-step process of Multi-Criteria Analysis tailored to the unique context of Ecuador. Firstly, the chapter outlined the primary objectives of our analysis, which were to identify strategies and approaches for mitigating conflicts arising from power plant projects. These objectives guided the subsequent steps in our research. Next, we defined the diverse array of stakeholders involved in this intricate process, representing the public sector, civil society, the private sector, and academia. Understanding these stakeholders was essential for assessing the multifaceted dynamics surrounding electricity generation projects. Furthermore, we elucidated the nine criteria, categorized into three major clusters: social, environmental, and technical. These criteria encompassed aspects such as project perception, job creation, displacement of people, deforestation, proximity to natural reserves, threat to fauna and wildlife, project size, accessibility, and distance to transmission lines. This delineation was vital to comprehending the factors guiding project evaluation. The fourth step involved the application of the analytic hierarchy process (AHP), wherein we conducted interviews with 40 stakeholders to discern their preferences regarding the nine chosen criteria. These insights played an important role in the subsequent project evaluations. In the fifth step, we selected and profiled 101 electricity generation projects within Ecuador's portfolio of future initiatives. These projects were analyzed based on the established criteria, ultimately allowing us to rank them from best to worst using the PROMETHEE method.

The second section of this chapter shifted focus to the structural elements of the model developed for the Ecuadorian electricity sector. We discussed the essential inputs required for this model, including two types of electricity demand and the potential for electricity generation, which incorporated the outcomes of the Multi-Criteria Analysis. Furthermore, we presented our model's validation for the year 2019, corroborating it with real-life data published by the Agency for Regulation and Control of Electricity (ARCONEL). Finally, the chapter concluded by elucidating the three scenarios created to model the Ecuadorian electricity system up to the year 2050. These scenarios encompassed the Policies scenario, aligned with the Electricity Master Plan, the MCA scenario, integrating the results of our Multi-Criteria Analysis and stakeholder preferences, and the High Demand with CO_2 restrictions scenario, which represented an ambitious approach by accommodating higher electricity demand, stringent emissions restrictions, aiming for carbon neutrality in the electricity generation sector by 2040, and the inclusion of the MCA results.

Chapter 4

Results

This chapter is dedicated to unveiling the culmination of the extensive work conducted, bringing to the forefront an exploration of the results and findings. The results are thoughtfully segmented into two distinct sections, each offering insights into Ecuador's evolving energy landscape. The initial Section 4.1 shows the outcomes of steps 4 and 6 within the Multi-Criteria Analysis . Step 4, dubbed Weight Allocation, delves into the process of weight assignment, a task undertaken collaboratively by four distinct groups of stakeholders, each deeply vested in shaping the energy landscape. These assigned weights resonate with the nine carefully selected criteria, a veritable roadmap for comprehensive analysis. Following this, in Step 6, Alternatives Ranking takes center stage, spotlighting the selection of power generation projects that have met the stringent requirements set by the stakeholders. These projects, having successfully navigated the rigorous MCA evaluation, represent invaluable inputs that will be channeled into the overarching optimization model. Section 4.2 serves as a panoramic overview of the Ecuadorian energy future, casting light on the installed capacities, electricity generation, and the comprehensive economic tapestry of the electricity system. This outlook extends across the temporal horizon, embracing the years 2024, 2027, 2030, 2040, and 2050. These temporal waypoints offer a canvas upon which the three scenarios — Policies, MCA, and High demand with CO_2 restrictions — paint distinct trajectories. These scenarios shed light the strategic dimensions of the country's energy trajectory, scrutinizing the interplay of policies, stakeholder collaboration, and sustainability imperatives on the evolving energy landscape. In essence, this chapter is an exploration of possibilities and pathways, an embodiment of the multifaceted strategies that define Ecuador's energy transformation.

4.1 The MCA results

In this section, we dive deep into the Weight Allocation in Sub-section 4.1.1, and Alternatives Ranking results in Sub-section 4.1.2, breaking them down to understand how the insights and perspectives of various stakeholders, coupled with the practicality of the projects, come together to shape Ecuador's energy journey. It's a story of collective wisdom, careful decision-making, and the path we're charting for the nation's energy landscape.

4.1.1 Weight Allocation results

In Chapter 3, Sub-section 3.1.4 delves into the Weight Allocation by stakeholders representing diverse sectors, including academia, the public sector, civil society, and private sector, to the nine chosen criteria introduced in Sub-section 3.1.3. These interviews provided valuable insights that are graphically presented in plots for each respective stakeholder category. This section outlines the collaborative process through which the weighting was accomplished, highlighting the contributions of various stakeholder groups to the ensuing multi-criteria analysis.

For the actors in the Academy

Within the Multi-Criteria Analysis process, the engagement of the Ecuadorian academic community stands as a robust representation of how diverse stakeholders can reach a substantial consensus. Leveraging the Analytical Hierarchy Process, this group demonstrated a collective understanding that extends beyond just the final numerical values. Their high 71.8% consensus signifies a shared sense of urgency regarding the electricity generation project criteria, with each criterion carrying a unique weight in their collective judgment. In the case of interviews with academic stakeholders in Ecuador, a revealing visual representation emerged to depict their criteria preferences when considering the development of electricity generation projects, showcased in Figure 4.1.

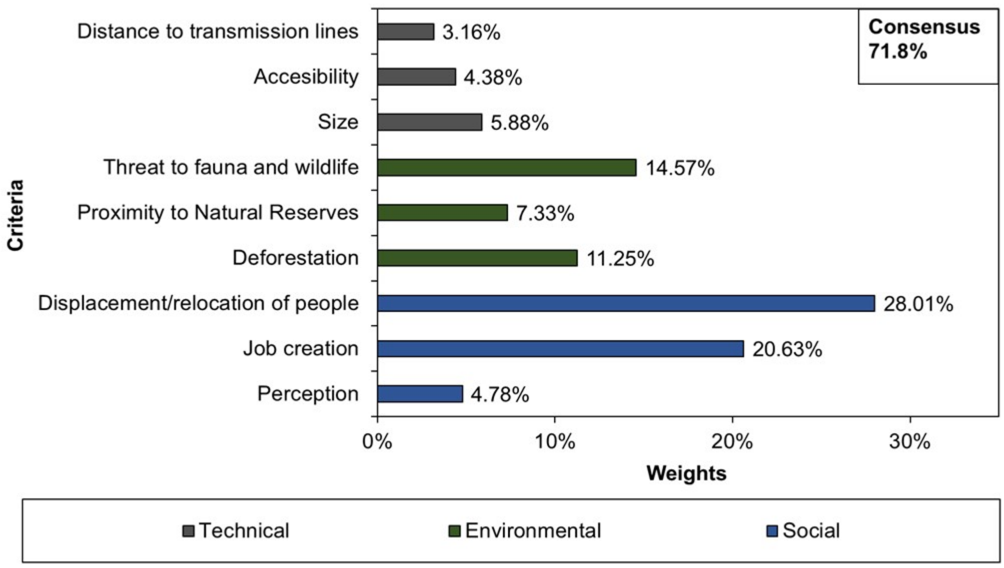


Figure 4.1: Criteria weights in [%] as perceived by representatives in Ecuador's Academic spheres

The prominence of the displacement of people as the leading criterion, with a weight of 28.01%, underscores the acute sensitivity to social impacts. The academic sector recognizes that energy projects have the potential to disrupt communities and is intent on minimizing such disruptions. Simultaneously, the strong emphasis on job creation at 20.63% reveals a commitment to sustainable development. Academic stakeholders understand the significance of energy projects in job generation and their lasting socio-economic contributions.

Furthermore, their acknowledgment of the threat to fauna and wildlife at 14.57% highlights their ecological consciousness. The academic community is not just focused on human concerns but extends their care to the broader ecosystem. Their recognition of the deforestation criterion (11.25%) reinforces their commitment to sustainable practices and biodiversity conservation. The academic community places a reasonable emphasis on proximity to nature reserves at 7.33%, showcasing their concern for conserving crucial ecological areas, although it's not their top priority. The criterion of project size at 5.88% suggests they don't overly fret about a project's scale and its potential impact. With a low weight of 4.78%, perception appears on their radar, acknowledging its role but not deeming it highly significant. Their balanced approach is evident in the similar weights for accessibility and distance to transmission lines at 4.38% and 3.16%, respectively. This reflects a clear focus on social and environmental considerations, with less emphasis on technical aspects within the academic sector's evaluation framework.

For the actors in the Energy public sector

The 10 participants in the interviews demonstrated a noteworthy level of consensus, with an overall agreement rate of 65.6%. This signifies that, as a group, these stakeholders have effectively harmonized their viewpoints and priorities concerning the critical criteria that bear significance in the context of energy project decision-making. These criteria encompass various dimensions, spanning environmental, social, and technical considerations, all of which pertain to the landscape of electricity generation projects within Ecuador. Although some degree of diversity might still exist among their individual stances and preferences, the 65.6% consensus figure underscores the group's ability to identify common ground and unite around a shared comprehension of the important factors that necessitate assessment prior to the implementation of such projects. This consensus level provides a foundation for the formulation of well-informed decisions and policies that duly encapsulate the collective perspective held by these stakeholders.

In the context of interviews with actors in the public energy sector in Ecuador, where these stakeholders had the task of selecting the most pertinent criteria for considering the establishment of electricity generation projects, a compelling graphic representation of their preferences emerged as shown in Figure 4.2.

The nine criteria under consideration were thoughtfully grouped into three distinct clusters: environmental, social, and technical. Within the social cluster, the data revealed that for this group of stakeholders, the top priority criterion was the displacement of people, holding a substantial weight of 27.48%. Following closely was the criterion related to the threat to wildlife, accounting for 17.13%. In third place stood deforestation, representing the potential environmental impact of the projects, with a weight of 13.20%. This was followed by the criterion of job creation, assessed by evaluating the employment opportunities generated during the construction and operation phases of an electric generation plant, which carried a weight of 10.27%. Further down the line, the project size criterion, pertaining to the physical magnitude of the project, was assigned a weight of 8.76%. Proximity to nature reserves was also a significant factor, with a weight of 6.93%. This criterion gauged the potential proximity of electricity generation projects to the boundaries of national parks, and biosphere reserves. In the realm of technical considerations, accessibility to the project site, measuring the ease of access from

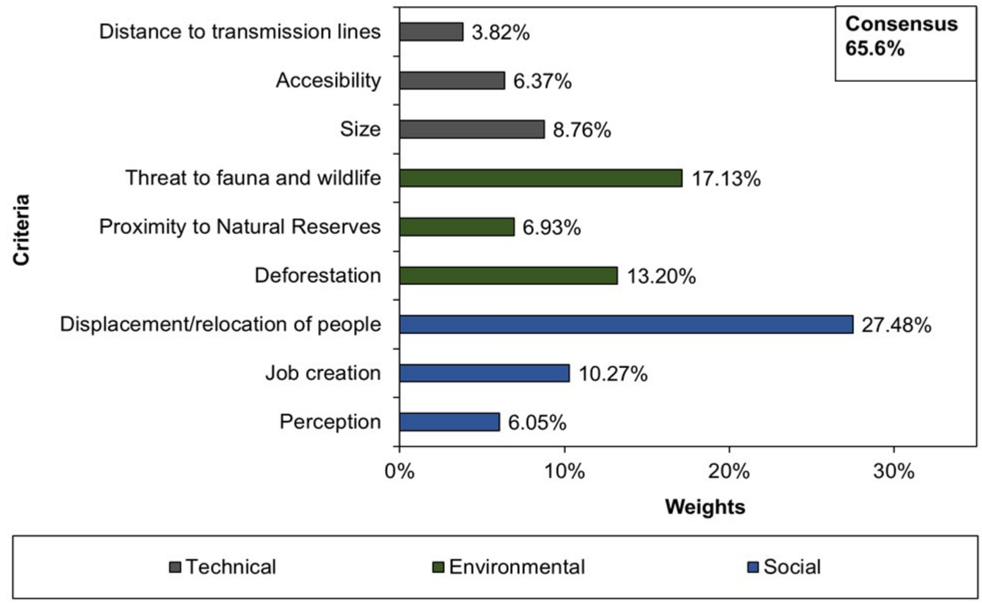


Figure 4.2: Criteria weights in [%] as perceived by representatives in Ecuador's public Energy sector

existing roads, claimed a notable share with 6.37%. Evaluating how a project impacts the senses for the population that live in the surroundings, the project perception criterion, held a weight of 6.05%, signifying the importance of public perception in their decision-making process. Lastly, the distance to transmission lines criterion, denoting the proximity to power transmission and distribution lines, was accorded a weight of 3.82% by this group of stakeholders.

For the civil society actors

The civil society group's substantial consensus of 74.9% derived from their interviews reveals a collective alignment of perspectives that strongly emphasize environmental and social aspects when evaluating electricity generation projects. Their clear preferences are evident in the weightings assigned to the various criteria, providing valuable insights into their priorities and guiding principles that can be observed in Figure 4.3.

At the forefront of their considerations, the civil society group gives top priority to the threat to fauna and wildlife criterion, assigning it the highest weight of 29.07%. This indicates their strong commitment to protecting biodiversity and wildlife habitats from potential harm caused by energy projects. The second most important criterion for them is deforestation with a weight of 25.50%, showing their dedication to conserving Ecuador's diverse ecosystems by minimizing forest loss. Proximity to natural reserves is ranked third, with an 11.06% weight. This reflects their concern for preserving these vital ecological areas and the recognition of their importance in maintaining untouched natural environments. These preferences reveal their commitment to environmental sustainability and the preservation of Ecuador's natural heritage. The consideration given to the displacement of people criterion (10.99%) demonstrates the civil society group's commitment to social justice and the welfare of local communities. This suggests a strong focus on minimizing any negative social impacts that might result from energy projects,

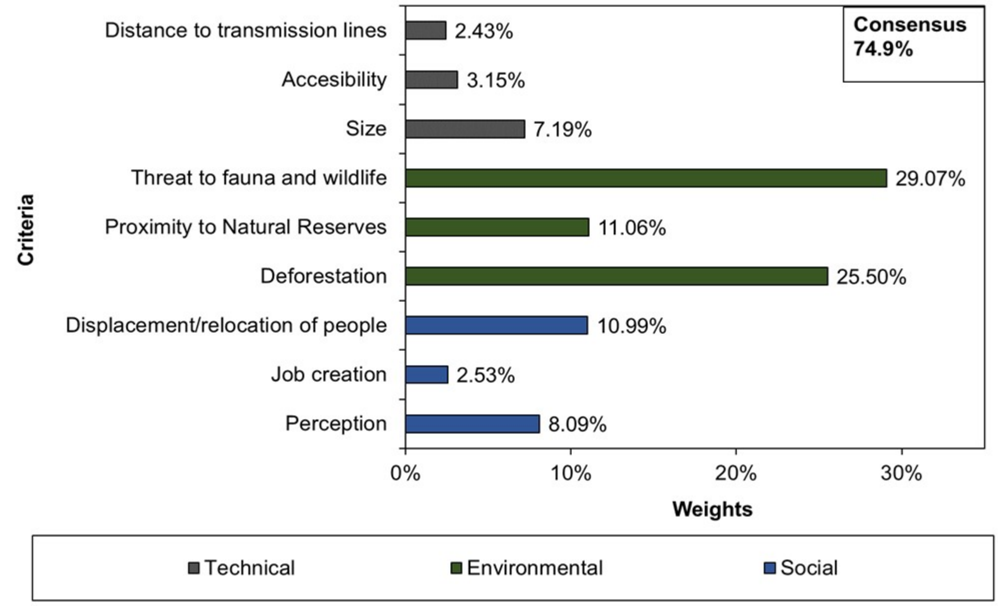


Figure 4.3: Criteria weights in [%] as perceived by representatives of the Civil society

such as the forced relocation of people. Furthermore, the perception criterion, valued at 8.09%, sheds light on the group's recognition of the importance of public opinion and community involvement in the success of energy projects. However, these two social criteria relatively lower ranking was unexpected and led to some contemplation during the result analysis. The rationale for this outcome, in the view of this researcher, could be attributed to the substantial cultural diversity prevalent in Ecuador. Many of the interviewees hold profound beliefs that regard animals, the earth, plants, and water as sacred entities, elevating them above humanity and emphasizing the need for their protection. These respondents exhibit a deep respect for Mother Earth, or as is called in quechua language "Pacha Mama", the Andean worldview that venerates nature as a living, spiritual being, perhaps contributing to the unique prioritization of criteria within this group. The weight assigned to the project size criterion (7.19%) underlines its recognition of the possible environmental and social implications associated with larger-scale projects. This hints at their consideration of the trade-offs between power generation capacity and the impacts such projects can bring. The other technical criteria such accessibility and distance to the transmission lines scored for 3.15% and 2.43% respectively. Finally, the social criteria, such as job creation (2.53%), are lower, indicating that the civil society group prioritizes environmental factors over social and technical considerations in its decision-making process. The civil society group's significant prioritization of environmental criteria in the context of electricity generation projects can be attributed to their strong environmental awareness, deeply ingrained cultural values that emphasize the sacredness of nature, and concerns about the potential ecological impacts of such projects, particularly in Ecuador's diverse and ecologically sensitive regions. Ecuador's status as a global biodiversity hotspot further underscores their commitment to preserving its rich natural heritage. Their relatively lower emphasis on the "perception" criterion suggests a belief in the importance of direct community involvement and individual values over public perception alone. This emphasis on environmental and cultural preservation underscores their dedication to upholding the ecological and cultural integrity of their nation.

For the actors in the Energy private sector

The private sector stakeholders in Ecuador's electricity generation projects exhibit a distinct pattern of priorities compared to other sectors, characterized by a somewhat lower consensus of 50.3%. Their weighted preferences shed light on their practical, often economics-driven perspective that can be shown in Figure 4.4.

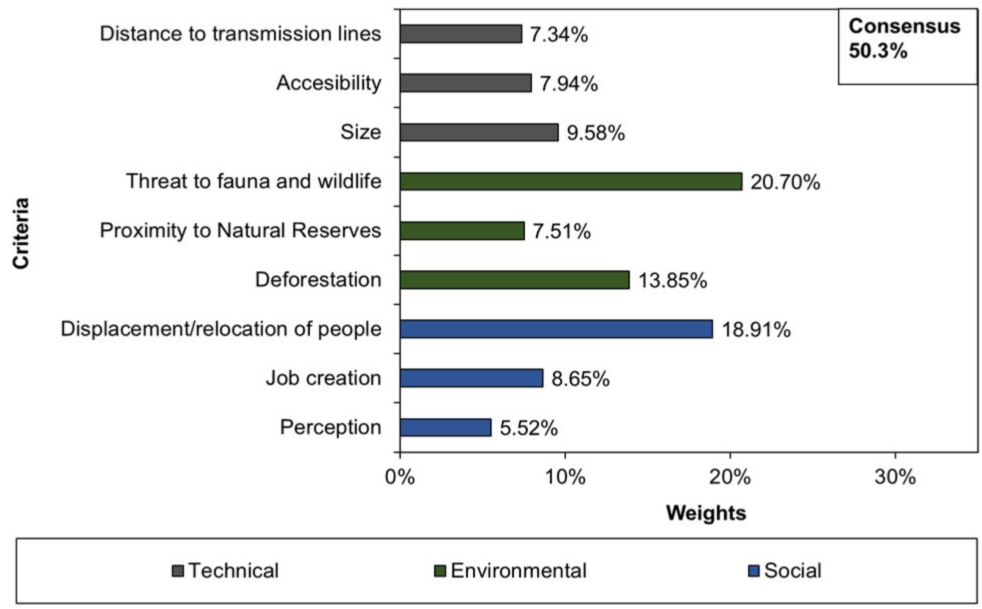


Figure 4.4: Criteria weights in [%] as perceived by representatives of the Private sector

At the forefront of their considerations lies threat to fauna and wildlife with a substantial weighting of 20.70%. This prioritization underscores a keen awareness of the potential ecological and regulatory challenges linked to impacts on biodiversity. It highlights their understanding of the rigorous environmental standards and regulations that, if not met, can pose significant roadblocks to project development. Additionally, displacement of people ranks second, with a weight of 18.91%. This choice is intriguing, as it reflects their recognition that any perceived threats to local communities can lead to opposition and potentially disruptive protests during the project's construction phase. This emphasis on social criteria, mainly driven by the potential for social backlash, illustrates their pragmatic approach, grounded in real-world experiences where public opposition has caused significant project delays and financial losses. The third most critical criterion for this group is deforestation, weighted at 13.85%. This emphasis indicates their concern for the environmental consequences of forest removal and habitat disruption. It's a logical concern, as Ecuador's lush forests are ecologically significant and must be preserved to maintain the region's biodiversity. Size of the project follows, at 9.58%, implying that they appreciate the scale-related impacts that large projects can have, both in terms of environmental and social effects. Interestingly, job creation receives a noteworthy weighting of 8.65%. This signals their recognition of the potential economic benefits and job opportunities that energy projects can bring to the region. This pragmatic consideration is in line with the private sector's primary focus on economic growth and development. The technical criteria, accessibility (7.94%) and distance to the grid (7.34%), are mid-rankings, indicating that the private sector recognizes the technical challenges and infrastructure requirements of power projects but doesn't place them at the forefront. The proximity to natural reserves criterion is weighted at 7.51%, reflecting their awareness of the significance of these ecological areas but not prioritizing them as much as other factors. The perception criterion is weighted at 5.52%, which is somewhat surprising given their acknowledgement that public perception and community buy-in are essential in the context of opposition and project success. This lower ranking may be attributed to the complexity of quantifying perception or perhaps reflects the belief that, in practice, tangible, real-world impacts hold more sway over public opinion and project success. In summary, the private sector's priorities reflect a practical, experience-driven approach, placing considerable importance on addressing issues related to social backlash, ecological preservation, and economic development. They recognize that community perceptions and environmental regulations can significantly impact project outcomes, resulting in their somewhat divergent criteria weighting compared to other sectors. This nuanced perspective underscores the intricate interplay of social, environmental, and economic factors in shaping the private sector's stance on electricity generation projects in Ecuador.

All four groups

The AHP methodology has offered profound insights into the contrasting priorities of various actor groups in Ecuador concerning the nine criteria influencing electricity generation projects. Notably, both the public sector and the academy exhibit a significant focus on minimizing the displacement of people, emphasizing their shared commitment to safeguarding community well-being and reducing social disruption. However, the academy distinguishes itself by additionally valuing job creation, reflecting a perspective more attuned to economic development. Concurrently, the civil society sector champions wildlife preservation and ecological sustainability, highlighting their profound environmental concerns. Conversely, the private sector demonstrates a heightened focus on potential conflicts arising from threats to fauna and wildlife, underlining their recognition of the necessity for social acceptance to avoid operational disruptions.

This comparative analysis underscores the nuanced balancing act required when formulating energy policies or projects to align with the multifaceted needs and values of these distinct actor groups. As depicted in Figure 4.5, the collective consensus among the four actors stands at 55.1%, highlighting the challenge of reconciling these diverse preferences.

These results form the basis for the subsequent ranking phase in the Multi-Criteria Analysis. The most important criterion to consider is the threat to fauna and wildlife, commanding 21.04% of the total weight, closely trailed by the displacement of people at 20.38%. In third place is deforestation, carrying a significant 16.01% weight. Strikingly, the three foremost criteria, each accounting for over 10% of the total weight, fall under the environmental and social clusters, emphasizing their paramount importance. Conversely, the criteria scoring the lowest weights encompass distance to transmission lines at 4.18% and accessibility to the project construction

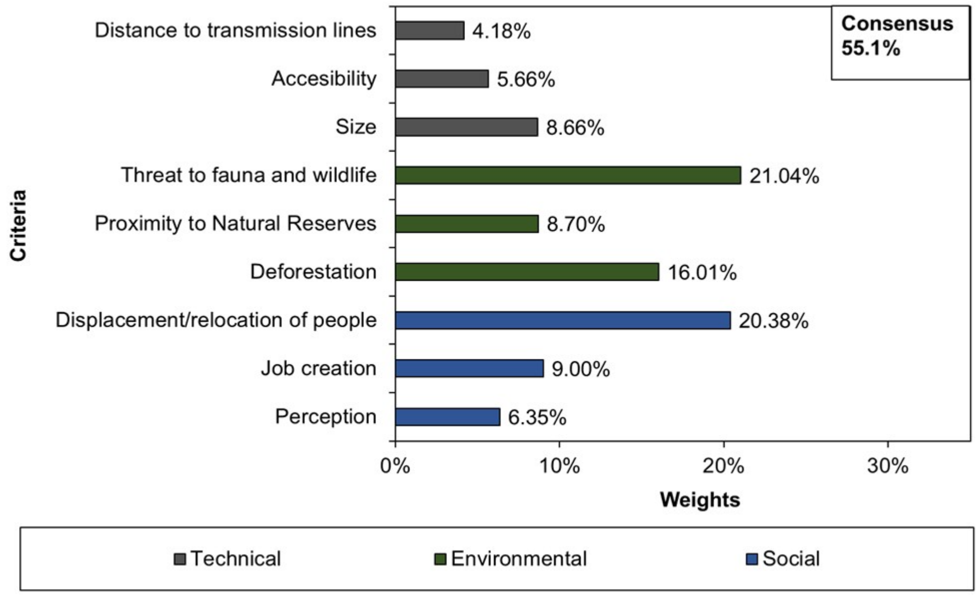


Figure 4.5: Criteria weights in [%] as perceived by representatives of all 4 sectors

at 5.66%. The size project criterion registers a weight of 8.66%, while proximity to natural reserves and job creation hold comparable weights of 8.70% and 9%, respectively. Remarkably, these criteria represent the technical, environmental, and social clusters, further emphasizing the need for a holistic approach in decision-making that respects these diverse dimensions.

The observed consensus among the interviewed actors fell somewhat short of the anticipated levels. To bolster consensus-building efforts among these stakeholders, several critical strategies can be employed. Enhancing stakeholder engagement through open dialogue and active participation can foster a better understanding of diverse perspectives. Transparency and information sharing, including comprehensive environmental and social impact assessments, are vital to ensure stakeholders are well-informed. The implementation of a structured decision-making framework, involving a clear delineation of roles and responsibilities, can facilitate consensus-building. Expert facilitators can guide discussions and facilitate compromise, while iterative feedback loops allow for ongoing refinements in decision-making processes. Additionally, establishing a conflict resolution mechanism ensures that disputes are addressed promptly and fairly. Inclusivity and representation of all stakeholder groups are crucial to ensure that a broad spectrum of views is considered. Providing training and capacity-building for stakeholders can empower them to make informed contributions. Adopting a long-term perspective that considers the lasting effects of energy projects, coupled with public awareness campaigns, can help align stakeholder interests with the broader goals of environmental sustainability and social well-being. In this multifaceted landscape, comprehensive, well-informed decision-making becomes imperative to navigate the intricacies and complexities effectively.

This exercise provides a profound insight into the intricate relationship that exists between energy projects and Ecuador's remarkable biodiversity. The nation's ecological diversity, spanning its National Parks, Biosphere Reserves, and crucial wildlife habitats, demands meticulous consideration within the context of project assessments. While stakeholder consensus exhibits variations, these findings emphasize the paramount importance of fostering an integrated approach to energy project evaluations. Such an approach must delicately balance the imperatives of biodiversity preservation, the safeguarding of local communities, and the promotion of sustainable economic development. Ecuador's natural heritage makes this comprehensive scrutiny essential, ensuring that its ever-evolving energy landscape remains in harmony with its steadfast commitment to environmental stewardship and the well-being of its society.

4.1.2 Alternatives Ranking results

In this section, we'll reveal the outcomes of the final step in the Multi-Criteria Analysis: ranking the available power generation projects based on stakeholder preferences. For context, we examined a diverse portfolio of 101 projects with a total installed capacity of 12,532.45 MW, as detailed in Chapter 3, Table 3.4. Of these projects, 54.5% successfully met the MCA criteria, resulting in the approval of 55 power generation projects represented by the ones with the positive net outranking flow Phi in Table 4.1. Keep in mind that the net preference flow, denoted as Phi, serves as a comprehensive measure that balances both positive Phi (+) and negative Phi (-) preference flows related to a specific action. By aggregating the action's strengths and weaknesses into a single score, it provides a holistic evaluation. Phi can assume positive or negative values, with a greater positive indicating a more favorable evaluation of the action's overall impact and desirability.

Position	Name	Type	Capacity [MW]	Phi	Phi (+)	Phi (-)
1	Alausí	Hydro	7.50	0.2968	0.3790	0.0821
2	El Laurel	Hydro	2.37	0.2932	0.3768	0.0836
3	PV-residential	Solar	0.003	0.2892	0.3793	0.0900
4	Chimbo-Guaranda	Hydro	3.80	0.2847	0.3700	0.0853
5	Rayo	Hydro	7.50	0.2568	0.3659	0.1091
6	Echeandía bajo 2	Hydro	8.40	0.2559	0.3533	0.0974
7	Chanchán	Hydro	7.30	0.2486	0.3500	0.1014
8	Chinambi	Hydro	5.00	0.2453	0.3497	0.1044
9	La Concepción	Hydro	3.17	0.2452	0.3558	0.1106
10	Lachas	Hydro	6.00	0.2430	0.3450	0.1020
11	Mandur	Hydro	7.80	0.2397	0.3549	0.1152
12	Tululbi	Hydro	1.60	0.2392	0.3417	0.1025
13	Huarhuallá	Hydro	4.60	0.2389	0.3679	0.1290
14	Monte Nuevo	Hydro	1.70	0.2332	0.3526	0.1193
15	San Pedro II	Hydro	9.50	0.2285	0.3596	0.1310
16	M.J. Calle	Hydro	1.44	0.2281	0.3498	0.1217
17	Campo Bello	Hydro	1.70	0.2094	0.3328	0.1235
18	Ganancay	Hydro	2.29	0.2058	0.3344	0.1287
19	Río Luis 2	Hydro	1.13	0.2002	0.3282	0.1280
20	Vacas Galindo 1	Hydro	1.20	0.1994	0.3321	0.1327
21	Uchucay	Hydro	8.40	0.1986	0.3385	0.1399

Position	Name	Type	Capacity [MW]	Phi	Phi (+)	Phi (-)
22	Balsapamba	Hydro	8.10	0.1976	0.3382	0.1405
23	Cebadas	Hydro	6.95	0.1952	0.3395	0.1443
24	Ambato	Hydro	4.00	0.1936	0.3392	0.1456
25	Salunguire	Hydro	1.70	0.1911	0.3351	0.1440
26	Sucua	Hydro	31.6	0.1762	0.3256	0.1494
27	Milpe	Hydro	43.7	0.1723	0.3194	0.1471
28	Intag 2	Hydro	1.70	0.1695	0.3243	0.1548
29	Guayabal	Hydro	39.80	0.1621	0.3173	0.1552
30	Palmar	Hydro	7.80	0.1594	0.3272	0.1678
31	Mariano Acosta	Hydro	1.68	0.1468	0.3180	0.1712
32	Calderón II	Hydro	38.70	0.1367	0.3202	0.1834
33	Puniyacu	Hydro	35.60	0.1308	0.2972	0.1664
34	Villonaco II	Wind	46.00	0.1057	0.2774	0.1717
35	Villonaco III	Wind	54.00	0.1044	0.2762	0.1717
36	Santiago G8	Hydro	3,600	0.0996	0.2799	0.1804
37	Paquishapa	Hydro	26.00	0.0842	0.2865	0.2023
38	El Aromo	Solar	200.00	0.0830	0.2987	0.2156
39	Chilma	Hydro	23.70	0.0817	0.2872	0.2055
40	Minas de Huascachaca	Wind	50.00	0.0728	0.2552	0.1824
41	Victoria 2	Hydro	25.00	0.0688	0.2604	0.1915
42	Mira 2	Hydro	47.80	0.0660	0.2601	0.1941
43	Gualleturo	Hydro	27.70	0.0623	0.2526	0.1903
44	Pamplona	Hydro	40.50	0.0577	0.2756	0.2179
45	Cuyes	Hydro	51.30	0.0509	0.2562	0.2053
46	Río Zamora	Hydro	2,320	0.0423	0.2731	0.2308
47	Blanco 2	Hydro	8.00	0.0393	0.3143	0.2750
48	Guapulo	Hydro	3.20	0.0392	0.3270	0.2878
49	Casacay	Hydro	6.10	0.0353	0.3230	0.2877
50	Lelia	Hydro	62.30	0.0313	0.2693	0.2380
51	La Barquilla	Hydro	40.10	0.0312	0.2359	0.2048
52	Chachimbiro	Geothermal	178.00	0.0292	0.2417	0.2125
53	Chingual	Hydro	25.60	0.0215	0.2307	0.2092
54	Tandapi	Hydro	8.90	0.0196	0.3080	0.2884
55	Mira	Hydro	41.00	0.0045	0.2444	0.2400
56	Chuquiraguas	Hydro	2.35	-0.0132	0.2924	0.3056
57	Numbala	Hydro	39.20	-0.0312	0.2248	0.2560
58	Los Bancos	Hydro	92.20	-0.0417	0.2008	0.2425
59	Vacas Galindo 2	Hydro	42.00	-0.0433	0.2155	0.2588
60	Verdeyacu Chico	Hydro	1,172	-0.0547	0.2122	0.2669
61	Chalupas	Geothermal	283.00	-0.0568	0.2111	0.2679

Position	Name	Type	Capacity [MW]	Phi	Phi (+)	Phi (-)
62	Catachi	Hydro	748.00	-0.0587	0.2121	0.2709
63	Cedroyacu	Hydro	270.00	-0.0626	0.2102	0.2728
64	Pilatón-Santa Ana	Hydro	58.50	-0.0704	0.2070	0.2781
65	Tufiño-Chiles Cerro Negro	Geothermal	330.00	-0.0745	0.2003	0.2748
66	Cinto	Hydro	45.80	-0.0768	0.1891	0.2660
67	Lucarquí	Hydro	8.80	-0.0862	0.1804	0.2667
68	Quijos 1	Hydro	24.20	-0.1013	0.2250	0.3263
69	Las Cidras	Hydro	77.30	-0.1150	0.1800	0.2951
70	El Retorno	Hydro	261.00	-0.1168	0.2222	0.3390
71	San Francisco II	Hydro	9.40	-0.1244	0.1587	0.2831
72	Chacana Cachiyacu	Geothermal	83.00	-0.1317	0.1618	0.2935
73	Jamanco	Geothermal	26.00	-0.1339	0.1611	0.2949
74	Rircay	Hydro	3.10	-0.1373	0.1467	0.2840
75	Collay	Hydro	5.80	-0.1464	0.1694	0.3158
76	El Burro	Hydro	10.20	-0.1496	0.1694	0.3190
77	Solanda	Hydro	3.00	-0.1498	0.1642	0.3140
78	El Cañaro	Hydro	5.60	-0.1524	0.1645	0.3169
79	Langoa	Hydro	26.00	-0.1536	0.1603	0.3139
80	Negro (2)	Hydro	36.00	-0.1627	0.1610	0.3236
81	Calderón	Hydro	147.00	-0.1689	0.1400	0.3089
82	San Pedro	Hydro	83.40	-0.1818	0.1316	0.3134
83	Bravo Grande	Hydro	10.00	-0.1841	0.1505	0.3346
84	Cosanga	Hydro	27.00	-0.1883	0.1452	0.3335
85	Pucayacu	Hydro	4.80	-0.2010	0.1410	0.3420
86	Las Juntas	Hydro	27.70	-0.2126	0.1835	0.3962
87	Chirapi	Hydro	160.00	-0.2165	0.1339	0.3504
88	Bellavista	Hydro	11.60	-0.2519	0.1578	0.4096
89	Tulipe	Hydro	7.80	-0.2630	0.1470	0.4101
90	Yacuchaqui	Hydro	32.20	-0.2692	0.1436	0.4128
91	Isimanchi	Hydro	51.10	-0.2867	0.1464	0.4331
92	Alambi	Hydro	9.50	-0.2916	0.1505	0.4421
93	Chillayacu	Hydro	3.92	-0.2950	0.1248	0.4198
94	Vivar	Hydro	5.90	-0.3010	0.1238	0.4248
95	Cubí	Hydro	53.00	-0.3010	0.1041	0.4051
96	Mirador 1	Hydro	1.15	-0.3115	0.1163	0.4278
97	Tomebamba 1	Hydro	6.00	-0.3481	0.1133	0.4614
98	Tortugo	Hydro	201.00	-0.3590	0.1603	0.5193
99	Abitagua	Hydro	198.00	-0.3939	0.1442	0.5381
100	Ligua-Muyo	Hydro	170.00	-0.3988	0.1392	0.5380

Position	Name	Type	Capacity [MW]	Phi	Phi (+)	Phi (-)
101	Chespi Real	Hydro	460.00	-0.4732	0.1162	0.5894

Table 4.1: MCA results for the evaluated alternatives

Notably, 49 of these approved projects are in the hydropower category, contributing a significant 6,670.93 MW, which represents 53.2% of all evaluated projects. Likewise, all analyzed solar PV projects, totaling 200.003 MW, passed the MCA, as did all the assessed wind projects with a combined capacity of 150 MW. Among the geothermal projects, one out of the five, with an installed capacity of 178 MW, met the MCA criteria. At the end, a total capacity of 7,198.93 MW surpassed the Multi-Criteria Analysis, and 5,333.52 MW did not fulfill the preferences of the interviewed actors. For a comprehensive overview of the results, please refer to Table 4.2 for insights into the ranking and classification of these energy projects.

	Total		Passed MCA		Failed MCA	
Type	Number	Capacity [MW]	Number	Capacity [MW]	Number	Capacity [MW]
Hydro	91	11,282.5	49	6,670.93	42	4,611.52
Solar PV	2	200.003	2	200.03	0	0
Wind	3	150	3	150	0	0
Geothermal	5	900	1	178	4	722
Total	101	12,532	55	7,198.93	46	5,333.52

Table 4.2: Summary of the analysis of alternatives ranking

Hydropower plants constitute a significant portion of the analyzed projects, with a total of 91, each assessed based on several parameters. To classify these plants, we considered two primary basins in Ecuador: the Amazon and the Pacific. Furthermore, we categorized them as run-of-river or with reservoirs and grouped them by size into four categories: greater than 450 MW, 50 to 450 MW, 10 to 50 MW, and less than 10 MW. A detailed breakdown of power plant types and sizes, along with MCA outcomes, is presented in Table 4.3.

In the Amazon basin, we scrutinized 25 power plants with a collective capacity of 9,190 MW. Following the MCA, ten power plants passed the evaluation, accounting for a cumulative capacity of 6,109.15 MW. Notably, none of these were hydropower plants with reservoirs; all were run-of-river projects. Among these, four fell within the 10-50 MW size range, collectively amounting to 122.3 MW, while three had a size smaller than 10 MW each, with a total capacity of 15.55 MW. Two hydropower plants with sizes exceeding 450 MW, totaling 5,920 MW, and one with a capacity between 50 to 450 MW and a total of 51.3 MW also met the MCA criteria. For the Pacific basin, we assessed 66 power plants, of which 40 were smaller than 10 MW each. Following the MCA, 39 power plants, with a combined capacity of 561.78 MW, aligned with the stakeholders' preferences and successfully met the MCA criteria. Among these, 28 were smaller than 10 MW each, amassing a total capacity of 134.98 MW, while ten had a size between 10 to 50 MW, with a combined capacity of 364.5 MW. There was only one plant in the 50 to 450 MW size category, with a capacity of 62.3 MW. Notably, all these plants in the Pacific basin that passed the MCA were run-of-river, and none featured reservoirs.

Type	**Number**	**Capacity [MW]**	**Passed MCA**	**Capacity [MW]**	**Failed MCA**	**Capacity [MW]**
Amazon DAM >450 MW	0	0	0	0	0	0
Amazon DAM 50-450 MW	2	368	0	0	2	368
Amazon ROR >450 MW	4	7,840	2	5,920	2	1,920
Amazon ROR 50-450 MW	5	710.7	1	51.3	4	659.4
Amazon ROR 10-50 MW	8	238.70	4	122.3	4	116.4
Amazon ROR <10 MW	6	32.95	3	15.55	3	17.4
Total Amazon	**25**	**9,190.12**	**10**	**6,109.15**	**15**	**3,081.2**
Pacific DAM >450 MW	1	460	0	0	1	460
Pacific DAM 50-450 MW	1	201	0	0	1	201
Pacific ROR >450 MW	0	0	0	0	0	0
Pacific ROR 50-450 MW	7	656.40	1	62.3	6	594.1
Pacific ROR 10-50 MW	17	570	10	364.5	7	205.5
Pacific ROR <10 MW	40	204.7	28	134.98	12	69.72
Total Pacific	**66**	**2,092.1**	**39**	**561.78**	**27**	**1,530.32**
Total Hydro	**91**	**11,282.22**	**49**	**6,670.93**	**42**	**4,611.52**

Table 4.3: Summary of the hydropower plants after the MCA

The better performance of run-of-river power plants in Ecuador's basins during the MCA can be explained by their smaller environmental footprint compared to reservoir-based hydropower projects. Reservoirs created by larger hydropower plants often lead to habitat loss, disrupt natural flow patterns, and harm wildlife. Run-of-river plants, on the other hand, avoid these large reservoirs, causing fewer environmental disturbances. This perception of lower environmental impact, particularly in areas like deforestation and habitat preservation, aligns with the preferences of the actors in the MCA, contributing to the higher success rate of run-of-river plants. It's important to note, however, that not all run-of-river hydropower plants successfully passed the MCA. Additionally, the size and location of power plants play a significant role in these results, challenging the assumption that smaller projects necessarily have fewer impacts, as the following paragraphs will illustrate.

To gain a visual understanding of the results presented in Table 4.1, Table 4.2, and Table 4.3 we will conduct a graphical comparison of select plants shown in Figure 4.6. Due to spatial limitations and to maintain a manageable thesis length, we've chosen a representative subset of comparisons. We will center our analysis on the profiles of six specific alternatives. These encompass four hydropower plants, two of which have a capacity less than 10 MW (Alausí, and Mirador 1), and two that exceed 1000 MW (Santiago G8, and Verdeyacu Chico). Our selection of these projects is strategically founded on the substantial role of hydropower within Ecuador's energy landscape, aiming to scrutinize the influence of size on sustainability, addressing the hypothesis that smaller plants may offer advantages over larger ones. Additionally, we've included one wind (Villonaco III), and one geothermal (Jamanco) project for assessment, each with different net preference flows Phi. This method permits us to present insightful comparisons derived from the results. Appendix B provides a comprehensive overview of the result profiles derived from the evaluation of 101 alternatives through the multi-criteria analysis.

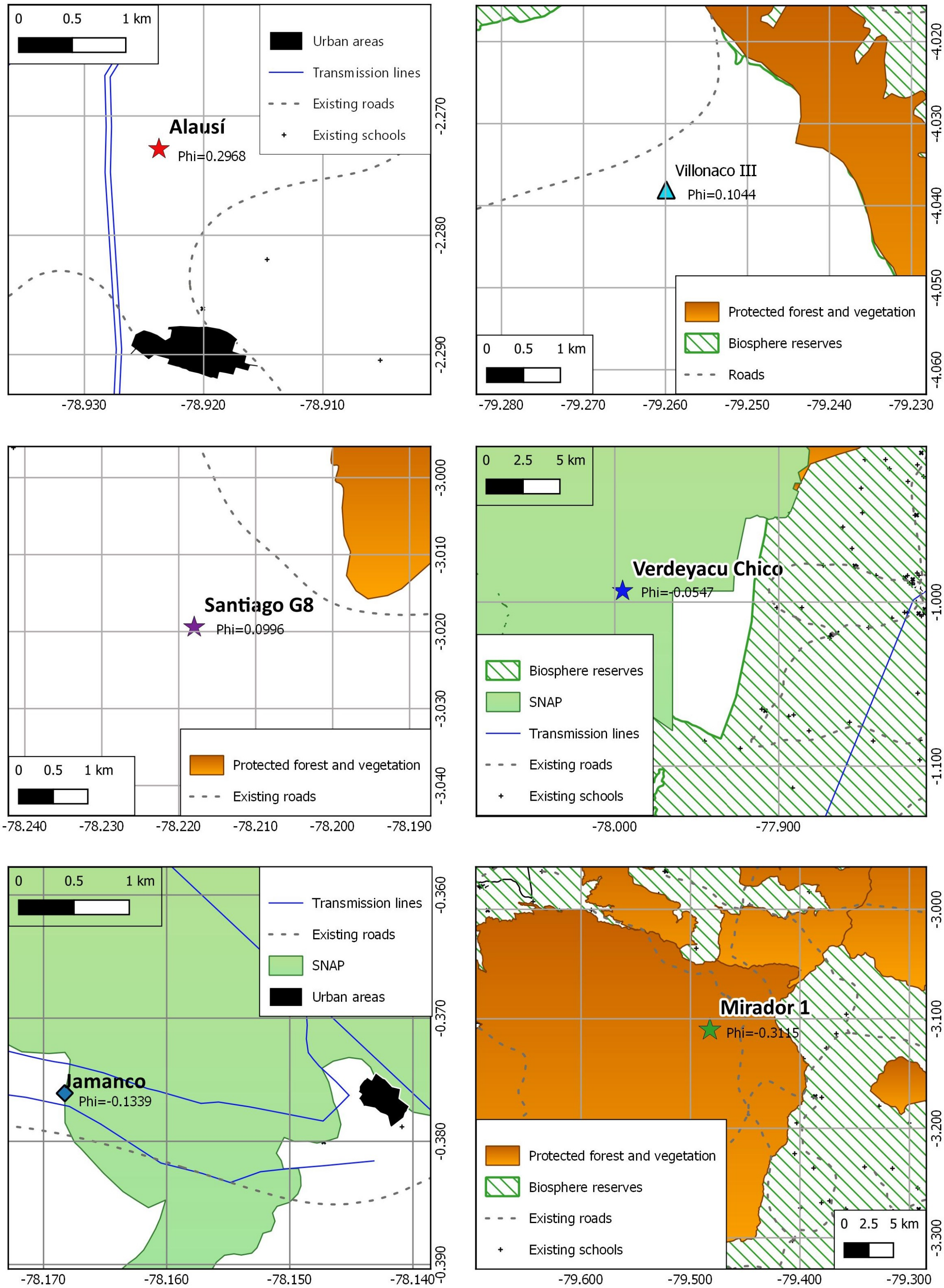


Figure 4.6: Chosen projects for MCA analysis and their approximately location on the mainland Ecuador map

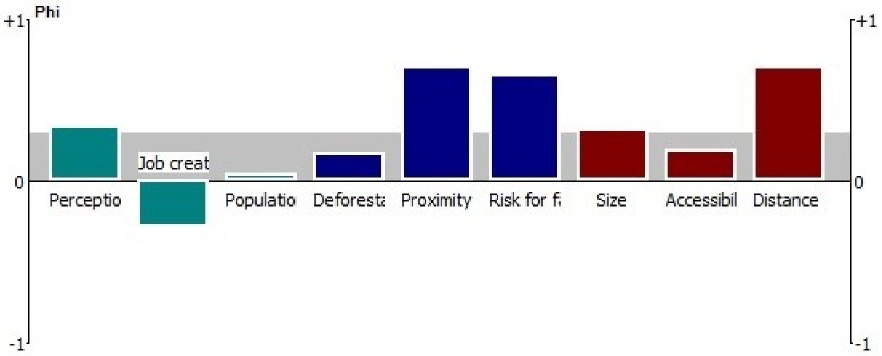


Figure 4.7: Alternative profile after the MCA for Alausí hydropower plant - Visual PROMETHEE outcome

Alausí hydropower

The Alausí run-of-river hydroelectric power plant, boasting a capacity of 7.50 MW, secured the top position in the multi-criteria analysis, achieving a net preference flow (Phi) of 0.2968. Its success stems from earning a positive evaluation in eight of the nine analyzed criteria, aligning with the preferences of the interviewed actors, as displayed in Figure 4.7. The only criterion with a negative evaluation was job creation, primarily due to its smaller capacity (less than 10 MW), which translates to fewer employment opportunities compared to larger projects exceeding 1000 MW. As demonstrated in Figure 4.6, this project's location does not encroach upon any national system of protected areas of Ecuador (SNAP), biosphere reserves, or protected forests within the country. Consequently, it poses no environmental threats within protected areas. Furthermore, thanks to its manageable size, lack of a reservoir, and a location at a safe distance from the nearest urban area (1.5 km), it presents a low risk of displacing the local population, as indicated in Table 3.8. In addition, the hydropower plant is located close to existing roads and the national transmission grid, less than 1 km and less than 500 m respectively, making it ideal for construction in technical terms (see Table 3.12 and Table 3.13).

Villonaco III wind park

The Villonaco III wind farm, boasting a capacity of 54 MW, obtained a net preference flow (Phi) of 0.1044 through the multi-criteria analysis. It's essential to highlight that its Phi value is lower than that of the Alausí project, primarily because three criteria didn't align with the interviewees' preferences, see Figure 4.8.These criteria included job creation, proximity to natural reserves, and size. The lower Phi value associated with job creation results from this being a criterion to maximize, and since Villonaco III's size isn't among the largest, it acquires a negative reference flow. In terms of its proximity to natural reserves, Villonaco III's location is slightly more than 2.5 km from the boundaries of the protected forest "Cuenca del Río Malacatos en Loja" and the biosphere reserve "Podocarpus el Cóndor." This places it at a relatively high risk concerning these protected areas, in line with the criteria expressed in Table 3.10. Despite this, the wind farm doesn't pose a significant threat to the local fauna, as indicated in Table 3.11. Additionally, its size is perceived as a negative factor since it exceeds the median size of all projects, which stands at 24.2 MW. In terms of perception and the displacement of people, Villonaco III doesn't represent a considerable risk due to its location more than 5 km away from the nearest urban areas. Finally, concerning accessibility and proximity to transmission lines, Villonaco III is positioned less than 1 km from the nearest road and 6 km from the national transmission system. This signifies that the project's construction would be highly accessible and moderately distant from transmission lines, as outlined in Table 3.12 and Table 3.13, respectively.

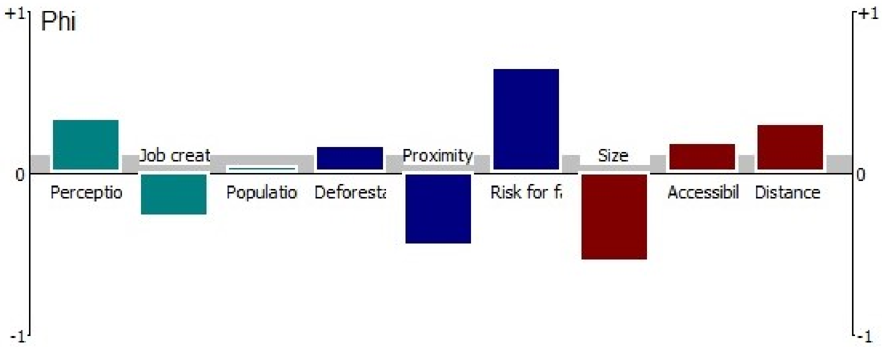


Figure 4.8: Alternative profile after the MCA for Villonaco III wind park - Visual PROMETHEE outcome

Santiago G8 hydropower plant

Santiago G8 hydroelectric project, boasting a substantial capacity of 3,600 MW, achieved a favorable net preference flow (Phi) of 0.0996. Its large size significantly influenced the job creation criterion, which garnered the highest positive preference flow (Phi+), shown in Figure 4.9. Santiago G8 was expected to generate numerous jobs, exceeding the employment prospects of all the other projects analyzed. However, size, while advantageous for job creation, became a disadvantage within this multi-criteria analysis. This analysis sought to minimize project sizes, resulting in a considerable negative preference flow (Phi-). In evaluating the project against other social criteria, Santiago G8 excelled in terms of perception due to its location more than 24 km away from the nearest town. As a reservoir-less project, it posed a low risk of displacing local communities. Considering environmental criteria, Santiago G8 is situated 2 km from the protected forest "Cordillera Kutuku and Shaimi," signifying a low risk of deforestation, as indicated in Table 3.9. While it posed no threat to nearby nature reserves and biosphere reserves, its extensive size and location in the Ecuadorian Amazon resulted in a moderate risk concerning wildlife, see in Table 3.11. Addressing technical criteria, Santiago G8's proximity to existing roads, located 2 km away, facilitated easy construction access. Nevertheless, its distance of more than 30 km from the nearest transmission line would necessitate the construction of new transmission lines, increasing the overall project costs. Santiago G8, despite its considerable size of 3,600 MW, effectively fits the collective preferences of all stakeholders interviewed. This is because, according to the consensus among the four stakeholder groups, shown in Figure 4.5, Santiago G8 does not pose a major threat and risk for the highest weighted criteria, which are threat to wildlife (21.04%), displacement of people (20.38%), and deforestation (16.01%).

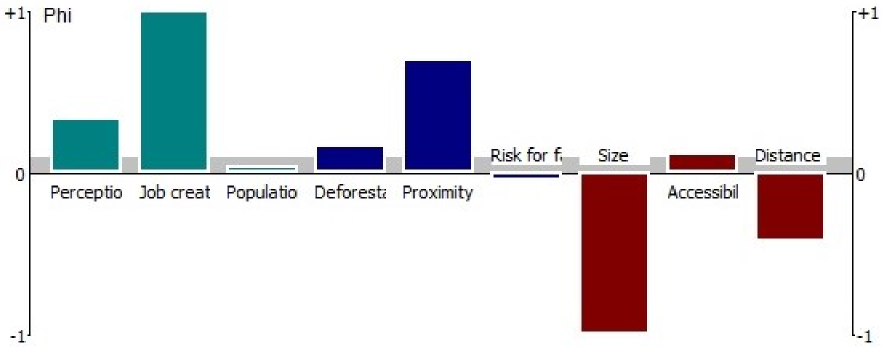


Figure 4.9: Alternative profile after the MCA for Santiago G8 hydropower plant - Visual PROMETHEE outcome

Verdeyacu Chico hydropower plant

Verdeyacu Chico hydroelectric plant, with a capacity of 1,172 MW, recorded a net preference flow (Phi) value of -0.0547, indicating that it did not successfully pass the multi-criteria analysis. This outcome arises from the fact that, out of the nine analyzed criteria, five of them yielded values of negative preference flow (Phi-), as demonstrated in Figure 4.10. Much like Santiago G8, Verdeyacu Chico excelled in terms of job creation but suffered due to its considerable size when attempting to minimize this criterion. Considering social criteria, Verdeyacu Chico boasted a positive perception, largely attributed to its remote location from urban areas, presenting a low risk concerning population displacement also due to the absence of a reservoir. On the environmental front, Verdeyacu Chico is situated at a considerable distance from any protected forest. However, it falls within the boundaries of the "Colonso Chalupas" biological reserve and is located less than 10 km from the "Sumaco" biosphere reserve (see Figure 4.6), rendering it a high-risk factor regarding proximity to natural reserves, particularly for the threat to animals and wildlife. In terms of technical criteria, Verdeyacu Chico did not offer any distinct advantages due to its location more than 7.5 km from the nearest road and over 10 km from the closest transmission lines, resulting in economic risks during construction.

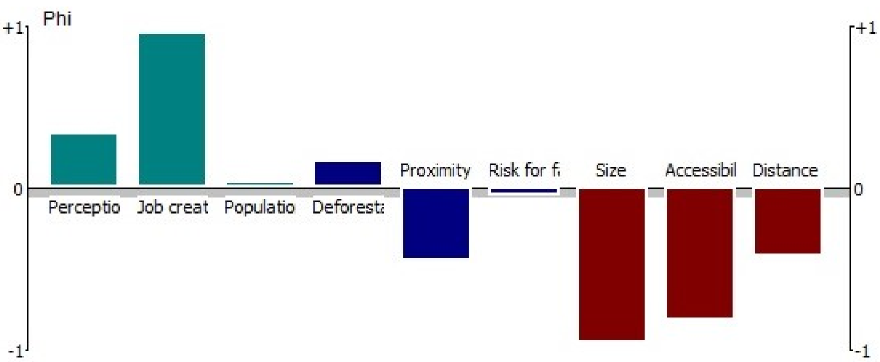


Figure 4.10: Alternative profile after the MCA for Verdeyacu Chico hydropower plant - Visual PROMETHEE outcome

Analyzing the case of Verdeyacu Chico, a 1,200 MW project smaller in size than Santiago

G8's 3,600 MW, it's essential to consider why the larger capacity project passed the MCA while the smaller one did not. Here, the key factor appears to be the location of the two projects and their potential impact on local wildlife. Santiago G8 is situated away from any national park or biosphere reserve, while Verdeyacu Chico is within Colonso Chalupas biological reserve. According to Ecuador's Ministry of the Environment, this park is known for its diverse species, including pumas, ferrets, foxes, deer, tapirs, and various bird species like condors, hawks, and owls, among others. For the stakeholders interviewed, the threat posed by a power generation project to local fauna and flora takes precedence over the size of the project, and it is this factor that places Verdeyacu Chico at significant risk.

Jamanco geothermal plant

Jamanco geothermal project, boasting a capacity of 26 MW, yielded a net preference flow (Phi) of -0.1339 after undergoing the multi-criteria analysis as is shown in Figure 4.11. When considering social criteria, Jamanco garnered a positive perception due to its location over 2 km away from the nearest town. As we had earlier emphasized in Table 3.6, this project is not expected to disturb the senses of the surrounding communities. However, owing to its relatively modest size, Jamanco faced a negative preference flow (Phi-) for job creation. Smaller projects, like Jamanco, would naturally create fewer job opportunities compared to larger projects such as Santiago and Verdeyacu Chico. However, somewhat surprisingly, the size criterion showed a slightly negative value of the preference flow (Phi-), which is justified since Jamanco, with 26 MW, is above the average size of all projects, which is 24.2 MW. Concerning the final social criterion, displacement of people, Jamanco presented a low-risk scenario due to its favorable location. Regarding environmental criteria, Jamanco posed a threat due to its placement within the "Cayambe Coca" national park which has implications for the local fauna. Although it wasn't regarded as a deforestation risk since it isn't in proximity to any protected forests, it's essential to note that, since Jamanco is within the Cayambe Coca national park, there could be potential risks to the flora in the park. In technical criteria, Jamanco displayed a favorable evaluation. It's located less than 1 km from existing roads and transmission lines, indicating it would be a feasible choice in terms of construction. However, its position within Cayambe Coca national park presents high risks to the local fauna and flora in the park.

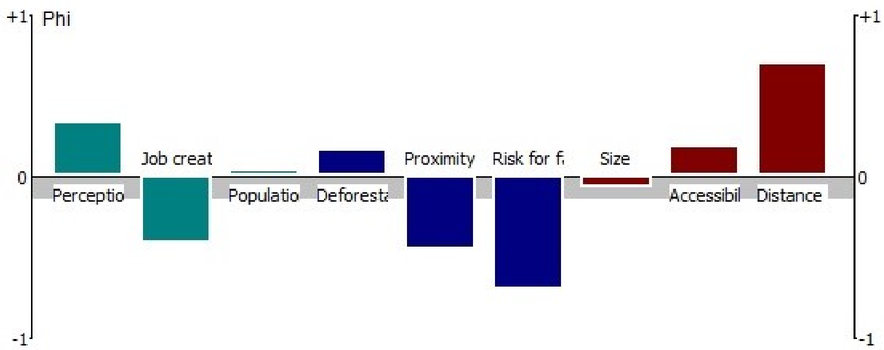


Figure 4.11: Alternative profile after the MCA for Jamanco geothermal plant - Visual PROMETHEE outcome

Mirador 1 hydropower plant

The last project chosen for analysis is the Mirador 1 hydroelectric power plant, with a capacity of 1.15 MW, ranked 96th out of 101 projects analyzed with a net preference flow Phi of -0.3115. This negative result for a project of such a size is due to the fact that 5 of the 9 criteria analyzed are negative, see Figure 4.12. Its small size allows it to be rated positively in terms of size, but at the same time, it is rated negatively in terms of job creation. Regarding the perception and displacement of people, Mirador 1 is positively evaluated because its location is totally distant from urban areas and because of its small size and lack of a reservoir, it represents a low risk for the displacement of people. Mirador 1 represents a high risk for environmental criteria, as it is located in the protected forest "Uzhcurrumi" and at the same time in the biosphere reserve "Macizo del Cajas" (see Figura 4.6), which makes it particularly dangerous for the fauna and flora of these protected areas. In terms of accessibility, the project is located approximately 3 km from existing roads, but more than 10 km from existing transmission lines in the area.

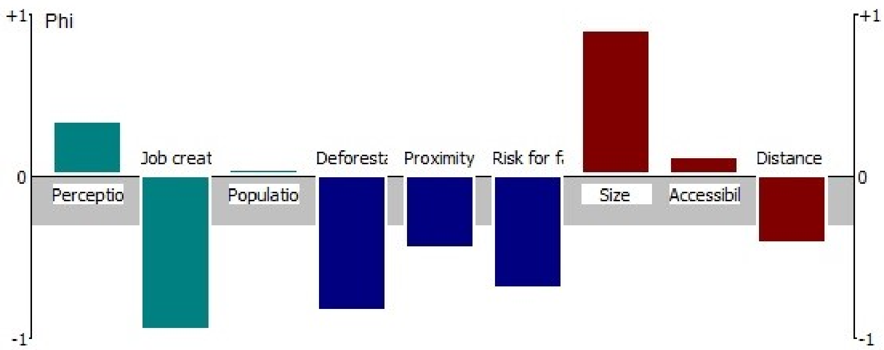


Figure 4.12: Alternative profile after the MCA for Mirador 1 hydropower plant - Visual PROMETHEE outcome

In the end, this small size project did not meet the requirements of our stakeholders interviewed. Despite its small size, the project is not feasible to build due to its location. Finally, comparing large projects such as Santiago G8 (3,600 MW) and Verdeyacu Chico (1,200 MW) with small projects such as Alausí (7.50 MW) and Mirador 1 (1.15 MW), their degree of acceptance does not depend on their size but on their location and implications in terms of social and environmental aspects. In our analysis, the four stakeholder groups have agreed that the protection of fauna is the most important thing to consider before building a power generation project; therefore, projects located in areas whose ecosystems are delicate in terms of fauna will not meet the expectations of the stakeholders and therefore will not be approved.

The outcomes of the multi-criteria analysis reveal the substantial influence of stakeholder perspectives on the future of Ecuador's power generation projects. The distinctive attributes of each project, whether related to its size, geographical placement, or environmental footprint, dynamically intersect with the preferences and priorities of various stakeholders, shaping a complex landscape that profoundly guides the trajectories of these projects. Consider Jamanco, in spite of being a geothermal project, its location within a national park raises critical questions. On the other hand, hydropower Alausi's modest 7.50 MW capacity and its strategically favorable environmental and technical aspects advocate for more sustainable projects, reflecting the potential of well-located smaller-scale initiatives. In contrast, Villonaco III, a 54 MW wind farm, faces a few reservations in the MCA analysis due to its proximity to protected forests and biosphere reserves, despite its renewable energy attributes, however, in general, the project is viable. Similarly, hydropower plant Verdeyacu Chico grapples with obstacles owing to its presence in ecologically sensitive areas. Mirador 1, another hydropower plant, with its unassuming 1.15 MW capacity, encounters restrictions because of its location within a protected forest and biosphere reserve, emphasizing the intricate path policymakers, project developers, and stakeholders must tread when balancing energy demands with environmental preservation in a biodiverse nation like Ecuador. This underscores the need for a delicate equilibrium in decision-making, aligning construction feasibility with ecological sustainability.

Thus, multi-criteria analysis results effective in energy planning because of its ability to consider various factors and actors simultaneously. As we have seen, it facilitates the evaluation and comparison of various energy options based on multiple criteria such as technical feasibility, environmental impact and social acceptability. With these results the MCA allows decision makers to make informed decisions by quantifying and prioritizing these criteria.

4.2 The optimization model results

After selecting projects that met the multi-criteria analysis and determining their total installed capacity based on the type of energy resource, we used the *urbs* model to simulate the Ecuadorian power system. We considered different scenarios including Policies, MCA, and high demand with CO_2 restrictions as outlined in Section 3.3. Here are the results, including installed capacity, energy production, and system costs until 2050 for all three scenarios.

4.2.1 Policies scenario results

In the Policies scenario, the primary objective is to evaluate the proposed expansion of Ecuador's electricity generation system as outlined in the PME. This expansion serves as a reference point for comparing results in other scenarios. The analysis reveals a significant increase in the country's total installed capacity, surging from 8,511.9 MW in 2019 to 17,820.2 MW by 2050. This expansion results in a 51 TWh increase in electricity generation by 2050, compared to 2019 levels, see Figure 4.13.

The expansion of other renewable energy projects is noteworthy. In 2019, Ecuador's installed capacity in solar, wind, biogas and biomass projects was just 193.1 MW. However, by 2050, Ecuador is projected to have an installed capacity of just over 4 GW in renewable energy projects, excluding hydroelectricity. Solar and wind energy emerge as the fastest growing segments. It is worth noting the absence of distributed solar energy expansion in this scenario, mainly due to its high installation cost, which makes it uncompetitive compared to the low electricity costs prevailing in the country. In addition, the lack of policies to encourage this type of installation in Ecuadorian households makes its adoption even more difficult.

Hydroelectricity remains a consistent and dominant component of Ecuador's electricity generation throughout the analysis. In each year, it maintains the highest share of generation. The percentages are as follows: 77% in 2024, 72% in 2027, 80% in 2030, 84% in 2040, and 72% in 2050. In contrast, other renewable energy sources like solar, wind, geothermal, and biomass maintain a share of total electricity generation of less than 10% in each year until 2040. However, by 2050, this percentage increases to 17%. Ecuador's electricity generation continues to maintain a presence of fossil fuel-based sources in all years analyzed. However, the percentage of electricity generated from fossil fuels decreases from 22% in 2019 to 12% in 2050. Consequently, in this Policies scenario, emissions from Ecuador's electricity system decrease by 48% in 2050 compared to 2019 due to reduced reliance on fossil fuel-based electricity generation. Despite the expansion and transformation of its electricity generation, Ecuador continues to rely on electricity imports from Colombia and Peru, though in small quantities. Approximately 4 GW of electricity imports are still necessary in 2050.

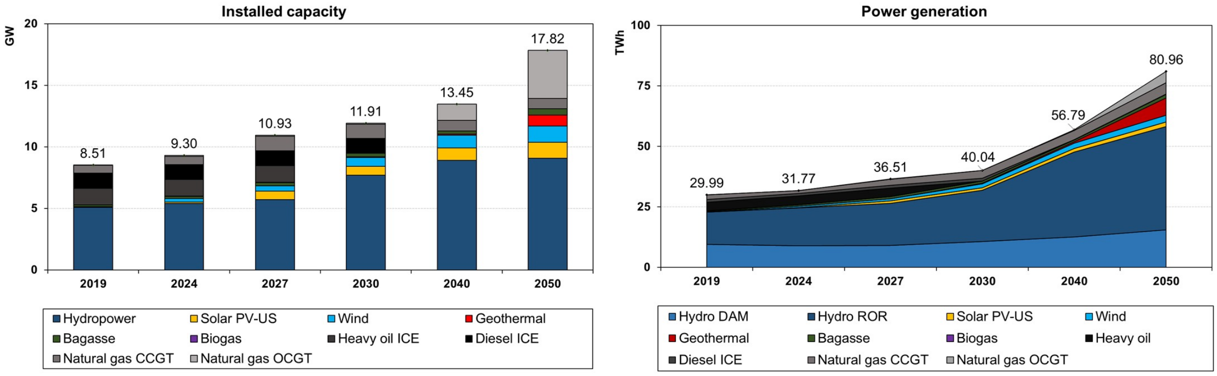


Figure 4.13: Evolution of installed capacity and power generation up 2050 in the Policies scenario

Figure 4.14 and Figure 4.15 show the expansion of the installed capacity and power generation in the two basins. In the Amazon basin, a significant expansion in the installed capacity of hydroelectric plants becomes apparent, starting around 2030. This expansion is primarily due to the Santiago project, a run-of-the-river hydroelectric plant, with a 1,200 MW capacity in its first stage in 2030 and an additional 1,200 MW in its second stage in 2040, there is no prevision for the third stage of Santiago until 2050. Consequently, electricity generation in this basin increases from 22.93 TWh in 2027 to 28.35 TWh in 2030 and 43.39 TWh in 2040. In contrast, the Pacific basin experiences a progressive increase in installed capacity, rising from 843.9 MW in 2019 to 1,437.8 MW in 2050. The ratio between installed capacity in the Amazon basin and the Pacific basin is approximately 5 to 1. It's essential to note that despite these developments, total complementarity between hydroelectric power plants in the two hydrographic basins of Ecuador is unattainable. Their flow curves shown in Figure 3.6 exhibit partial complementarity from January to March, and low water levels coincide from October to December. This underscores the need for diversification and the exploration of new sources of generation using other renewable energies to address the hydroelectric imbalance in Ecuador.

In conclusion, the Policies scenario sheds light on the development plans for electricity generation projects in Ecuador, as outlined in the PME. These plans reveal a significant dependence on hydroelectricity within the country's electricity sector. This strong dependence raises concerns about future supply vulnerability, especially during periods of low water availability due to seasonal processes, as well as rainfall projections from available climate models [91]. Consequently, it underscores the pressing need for rapid and substantial deployment of solar, wind and geothermal energy sources. These alternative energy solutions are considered

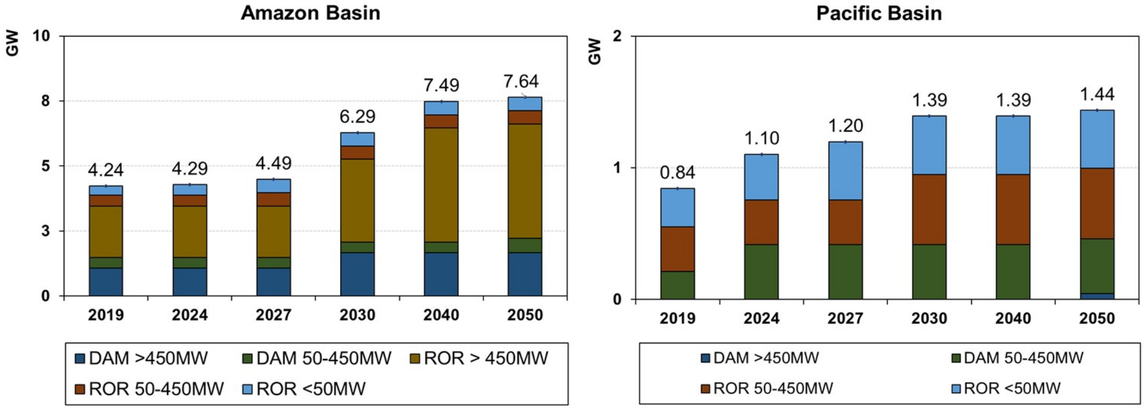


Figure 4.14: Evolution of hydro installed capacity in the Amazon and Pacific Basins in Policies scenario

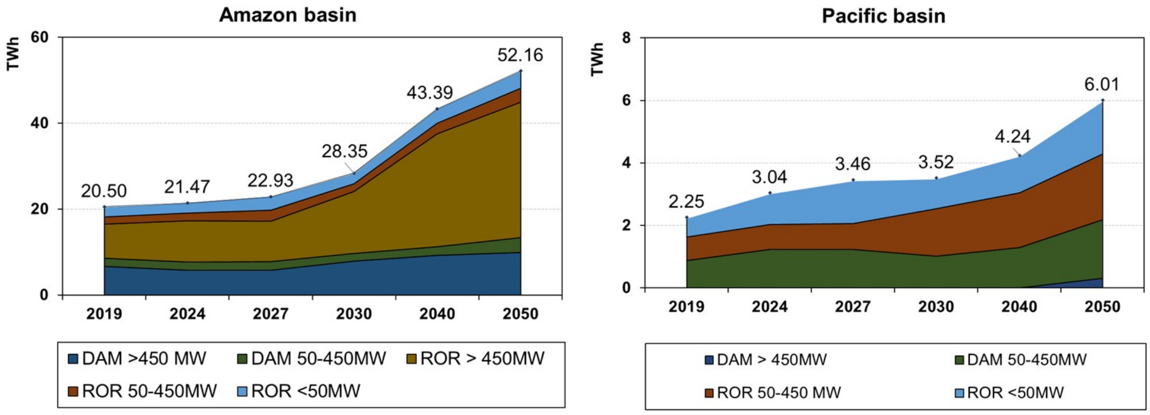


Figure 4.15: Evolution of hydro power generation in the Amazon and Pacific Basins in Policies scenario

essential and must be accelerated to ensure the nation's energy resilience.
At the time of writing (November 2023), Ecuador is facing power outages attributed to the dry season, a well-known climatic phenomenon in the country. However, the root cause of these outages lies in the lack of comprehensive planning of the electricity sector and the inefficiency of the current government authorities. The projects planned for 2023, detailed in the PME, which included a 500 MW NCRE (Non-Conventional Renewable Energy) block, composed of the El Aromo solar photovoltaic project (200 MW), Villonaco II and III wind projects (100 MW) and others, together with a 400 MW Combined Cycle I project have not been built to date. As a result, Ecuador, a country that was once an exporter of electricity, is now forced to interrupt the supply of electricity to its citizens. This abrupt interruption will surely have serious economic repercussions for Ecuador and underscores the urgent need for timely planning of the country's energy sector in light of updated circumstances.

4.2.2 MCA scenario results

What sets this scenario apart is the integration of results stemming from the Multi-Criteria Analysis. Notably, 46 projects originally slated for development within the PME were excluded from this scenario due to their failure to align with the stringent social, environmental, and technical criteria established by the involved stakeholders. It's important to note that this scenario exclusively incorporates the 55 projects with a positive net preference flow Phi, which are comprehensively outlined in Table 4.1, Table 4.2, and Table 4.3. Furthermore, this scenario maintains an identical projected demand to that of the Policies scenario, enabling a direct comparison between these two scenarios to be undertaken. Figure 4.16 illustrates the installed capacity evolution up to 2050 in the MCA scenario. Notably, the hydroelectric capacity in 2050 reaches 7,730.4 MW, which is 1,347.2 MW less than what is observed in the Policies scenario for the same year. A detailed examination, as presented in Figure 4.17, reveals that the installed capacity in the Amazon basin amounts to 6.82 GW by 2050, reflecting a reduction of 815.6 MW compared to the Policies scenario. This discrepancy arises primarily because the MCA scenario excludes the expansion of hydroelectric projects with reservoirs of any size and features a lower expansion of run-of-the-river hydroelectric plants in contrast to the Policies scenario. Similarly, in the Pacific basin, the installed capacity until 2050 stands at 0.91 GW, which is 531.6 MW less than the Policies scenario. In this basin, hydroelectric projects with reservoirs are not planned for development.

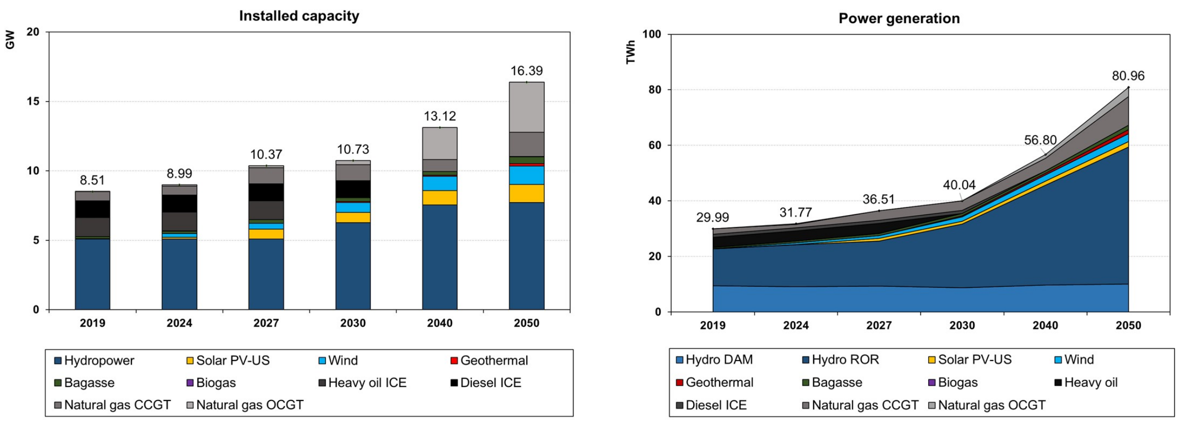


Figure 4.16: Evolution of installed capacity and power generation up 2050 in the MCA scenario

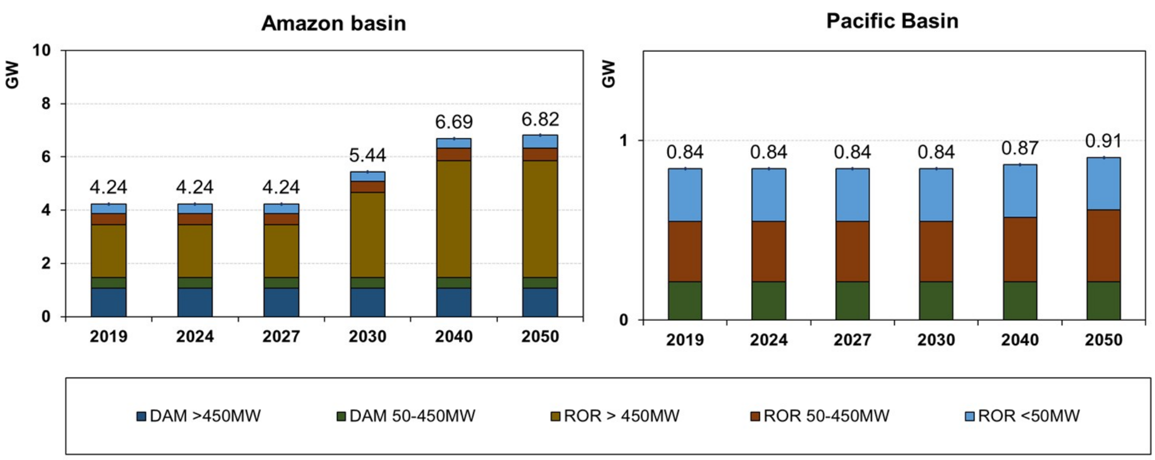


Figure 4.17: Evolution of hydro installed capacity in the Amazon and Pacific Basins in MCA scenario

Furthermore, while the Policies scenario foresees 900 MW of geothermal project installations, the MCA scenario only achieves 178 MW. This variance in installed capacity from renewable energy between the MCA and Policies scenarios is compensated by the inclusion of Natural Gas Combined Cycle Gas Turbine projects, which increase from 817.5 MW in the Policies scenario to 1,753.4 MW in the MCA scenario, as detailed in Table 4.4.

Technology	Base	Policies scenario			MCA scenario		
	2019	2027	2040	2050	2027	2040	2050
DAM >450 MW	1,075	1,075	1670.6	1,670.6	1,075	1,075	1,075
DAM 50-450 MW	403	403	403	554.2	403	403	403
ROR >450 MW	1,987	1,987	4,387	4,387	1,987	4,387	4,387
ROR 50-450 MW	410	510	510	510	410	461.3	461.3
ROR <50 MW	360	518	518	518	360	360	497.9
Total Amazon	**4,235**	**4,493**	**7,488.6**	**7,639.8**	**4,235**	**6,686.3**	**6,824.2**
DAM >450 MW	0	0	0	44.6	0	0	0
DAM 50-450 MW	213	418.4	418.4	418.4	213	213	213
ROR 50-450 MW	338.4	338.4	532.4	532.4	338.4	360.5	400.7
ROR <50 MW	292.6	442.5	442.5	442.5	292.6	292.6	292.6
Total Pacific	**843.9**	**1,199.3**	**1,393.3**	**1,437.8**	**843.9**	**866**	**906.2**
Total Hydro	**5,078.9**	**5,692.2**	**8,881.8**	**9,077.6**	**5,078.9**	**7,552.3**	**7,730.4**
Solar PV-US	25	715	1,015	1,290	715	1,015	1,290
Wind	16.5	416.5	1,036.5	1,320	416.5	1,036.5	1,320
Geothermal	0	0	75	900	0	75	178
Bagasse	144.3	274.3	274.3	500	274.3	274.3	500
Biogas	7.3	8.3	7.3	8.3	8.3	8.3	8.3
Total ERNC	**193.1**	**1,414.1**	**2,408.1**	**4,018.3**	**1,414.4**	**2,409.1**	**3,296.3**
Diesel ICE	1,216.4	1,216.4	0	0	1,216.4	0	0
NG OCGT	19.4	96.4	1,310.9	3,906.7	142.7	2,311.3	3,609.7
NG CCGT	644.2	1,154.2	851.6	817.5	1,154.2	851.6	1,753.4
Heavy oil ICE	1,359.9	1,359.9	0	0	1,359.9	0	0
Total non-renewables	**3,239.9**	**3,826.9**	**2,162.5**	**4,724.3**	**3,873.2**	**3,162.9**	**5,363.1**
Total all resources	**8,511.9**	**10,933.2**	**13,452.4**	**17,820.2**	**10,366.2**	**13,124.3**	**16,389.3**

Table 4.4: Installed capacity comparisson in [MW] between Policies and MCA scenario

It's worth noting that, across all the years analyzed, the MCA scenario consistently exhibits lower installed capacity for hydro power plants while higher installed capacity for technology base on non-renewable resources when compared to the Policies scenario. This disparity highlights the discernible impact of the multi-criteria analysis on the expansion of electricity generation in Ecuador through the year 2050. The pertinent question at hand pertains to Ecuador's ability to meet its electricity demand in the years under consideration, given the non-construction of several generation projects as originally outlined in the PME and advocated by the public energy sector authorities. A comparative examination between Figure 3.7, which represents electricity demand, and Figure 4.16, reflecting electricity generation, demonstrates the feasibility of fulfilling this demand through socially, environmentally, and technically viable electricity generation methods. The predominant source of this electricity generation stems from hydroelectric power plants, constituting more than 70% of the total electricity generated across all the analyzed years. Within this percentage, the Amazon basin hosts the majority of hydroelectric plants, as delineated in Figure 4.18. Notably, run-of-the-river hydroelectric plants assume a more significant share in this scenario than in the Policies scenario, a consequence of the absence of reservoir-based hydroelectric plant expansion in the MCA scenario. This scenario underscores a heightened reliance on the availability of water resources; any reduction in water flow to the hydroelectric plants could potentially impact the electricity supply.

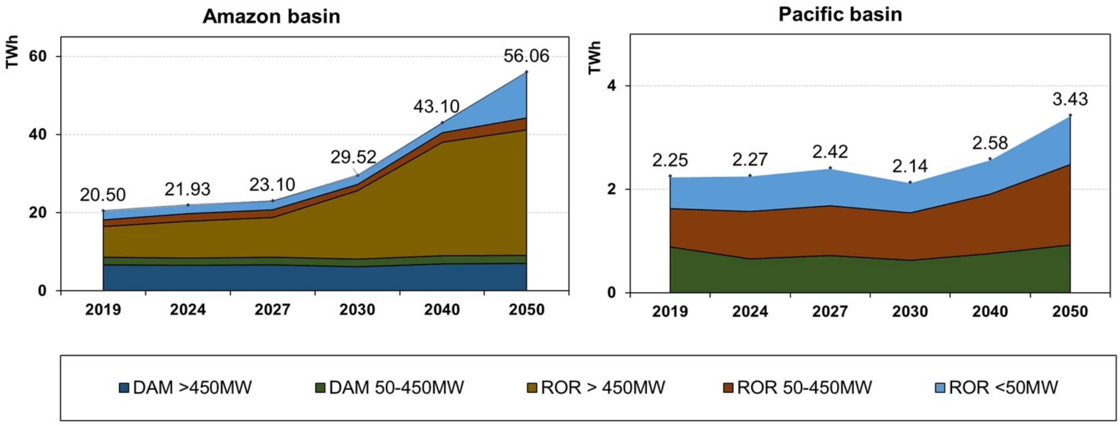


Figure 4.18: Evolution of hydro power generation in the Amazon and Pacific Basins in MCA scenario

In the context of solar and wind energy, the MCA scenario exhibits similar generation patterns when compared to the Policies scenario. Nevertheless, geothermal energy generation experiences a notable decline in the MCA scenario. This reduction, amounting to 5.63 TWh, stems from the constraint on construction of geothermal projects compared to the Policy scenario. To compensate for this energy deficit, open cycle and combined cycle natural gas plants, as discussed earlier, come into play. By 2050, these gas-based power generation facilities contribute 13.66 TWh of electricity, marking an increase of 4.3 TWh in comparison to the Policies scenario for the same year. It is of paramount significance to underscore that comprehensive planning that aligns with the requisites and demands of diverse stakeholders, encompassing the academic, private, civil, and public sectors, is entirely feasible. The essential requirement is a willingness to attentively consider and respect the diverse forms of knowledge. This entails a political commitment to embracing novel planning approaches, recognizing that insights into the Ecuadorian electricity sector and its repercussions are not the exclusive domain of technical experts but also pertain to those directly and indirectly affected by the decisions made. The potential exists to establish an electricity sector that minimizes risks to Ecuador's delicate ecosystem and its people, provided we remain receptive to innovative methodologies and adept at fostering open dialogue. In the context of CO_2 emissions arising from electricity generation in Ecuador within the MCA scenario, a reduction of 29% relative to the 2019 baseline is observed. However, it's worth noting that this reduction is less substantial compared to the Policies scenario, which achieved a 48% decrease. The primary factor contributing to this disparity is the continued utilization of fossil fuels in the MCA scenario.

While the MCA scenario indeed offers a comprehensive perspective on energy planning, it introduces an emissions challenge. Consequently, the High demand with CO_2 restrictions scenario has been introduced to address this issue, and the subsequent findings are presented below.

4.2.3 High demand with CO_2 restrictions scenario results

This scenario aims to attain carbon neutrality within the Ecuadorian electricity generation system by the year 2040. It does so while adhering to the principles of the multi-criteria analysis and accommodating a greater electricity demand compared to the levels proposed in the two preceding scenarios.

Figure 4.19 displays the evolution of installed capacity, encompassing the utilization of fossil fuels like natural gas, diesel, and fuel oil up to the year 2030. From 2040 onward, Ecuador exclusively relies on power generation plants fueled by renewable sources, including water, solar energy, wind, geothermal energy, bagasse, and solid waste. The installed capacity of power plants relying on fossil fuels commences at 3.2 GW in 2019, steadily increasing to 3.3 GW in 2024 and reaching 4.6 GW in 2027. However, from 2030, there is a decline in their participation, with a capacity of 4.2 GW. Ultimately, these fossil-based plants are phased out entirely starting from 2040. This cessation of fossil-based plants necessitates the extensive deployment of renewable energy projects. The capacity surges from 2.7 GW in 2030 to 18 GW in 2040 and further to 25 GW in 2050. This substantial expansion of renewable energy projects is compelled by the imperative to meet the steadily growing electricity demand while concurrently mitigating CO_2 emissions in electricity generation. Furthermore, this surge in renewable energy is accompanied by the implementation of storage systems, notably batteries, which attain a significant installed capacity of 5 GW by 2050. On the other hand, the challenges associated with the adoption of photovoltaic systems on residential rooftops in Ecuador primarily stem from several key factors. Firstly, the high initial costs involved in installing these systems present a considerable barrier. Secondly, the relatively low cost of traditional electricity bills in Ecuador reduces the immediate financial incentive for homeowners to invest in solar energy. Additionally, the absence of substantial incentives or supportive policies from the national government further compounds the difficulties associated with widespread photovoltaic system integration. As a result, the widespread adoption of this technology in the Ecuadorian context faces significant impediments. To increase the economic attractiveness of PV systems to homeowners, a number of policies and incentives can be employed. These include financial incentives such as grants and subsidies, tax credits, and net metering, which allows homeowners to sell excess electricity. Feed-in tariffs with premium rates for solar electricity fed back into the grid can make PV systems more economically viable for homeowners by ensuring a consistent income stream. Low-interest loans, rebates, and educational campaigns can further encourage PV adoption. Streamlined building permits, community solar programs and green building standards help make PV installation easier and more affordable. By implementing these measures, governments can encourage homeowners to invest in solar energy, consistent with both their environmental goals and economic interests.

Similarly, Figure 4.19 presents the progression of electricity generation within Ecuador. In 2019, hydropower constituted the predominant source, contributing 75.9% to the country's

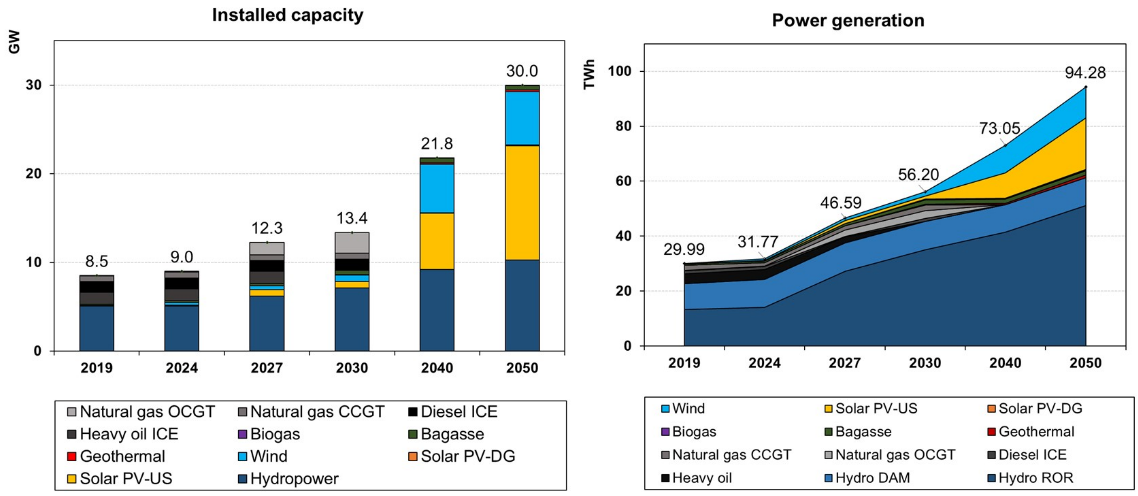


Figure 4.19: Evolution of installed capacity and power generation up 2050 in the High demand with CO_2 restrictions scenario

electricity production, while fossil fuels represented 22.2% of the total generation, and other renewables accounted for 1.9%. As we move to the year 2027, hydropower's prominence remains evident, generating 80.6% of the nation's electricity, while fossil fuels diminish to 13.2%, and other renewables expand to 6.1%. By 2040, electricity generation from fossil fuels becomes negligible, rendering the Ecuadorian electricity generation predominantly reliant on renewables. Specifically, the matrix consists of 70.5% hydropower and 29.5% other renewables, encompassing solar, wind, geothermal, biogas, and bagasse. As the analysis extends to 2050, the Ecuadorian electricity matrix comprises 65.1% hydropower, 20.2% solar, 11.8% wind, 1% geothermal, 1.6% bagasse, and 0.3% biogas. Figure 4.20 graphically illustrates the evolution of the Ecuadorian electricity matrix spanning the years from 2019 to 2050.

As observed in this scenario, hydropower remains the dominant force in the nation's electricity generation. The clear prevalence of hydropower unfolds consistently over the years, with installed capacity in the Amazon basin reaching 8.87 GW by 2050 and 1.41 GW in the Pacific basin for the same year, as illustrated in Figure 4.21.

Of particular interest is the substantial contribution of run-of-the-river hydroelectric plants smaller than 50 MW to electricity generation within the country. In the Amazon basin, these installations generate 15 TWh, constituting 27.6% of the total hydroelectric generation, and 3 TWh, representing 64% of the total hydroelectric generation in the Pacific basin for the final year of the analysis, as depicted in Figure 4.22. This scenario manifests a transformation in the nature of hydropower generation in Ecuador in comparison to 2019 when larger hydropower plants, with capacities exceeding 100 MW, held greater prominence, and hydropower below 50 MW contributed to only about 11% of the total generation in the Amazon basin and 28% in the Pacific basin. By the conclusion of the analysis period, the share of run-of-river hydroelectric plants under 50 MW in the total hydropower generation has doubled compared to 2019. This transformation marks a substantial paradigm shift within the Ecuadorian electricity sector. It is characterized by a significant increase in the contribution of smaller hydroelectric plants to the nation's electricity generation. One of the noteworthy advantages of this shift is the potential to minimize the impact on both human populations and ecosystems, provided that these smaller

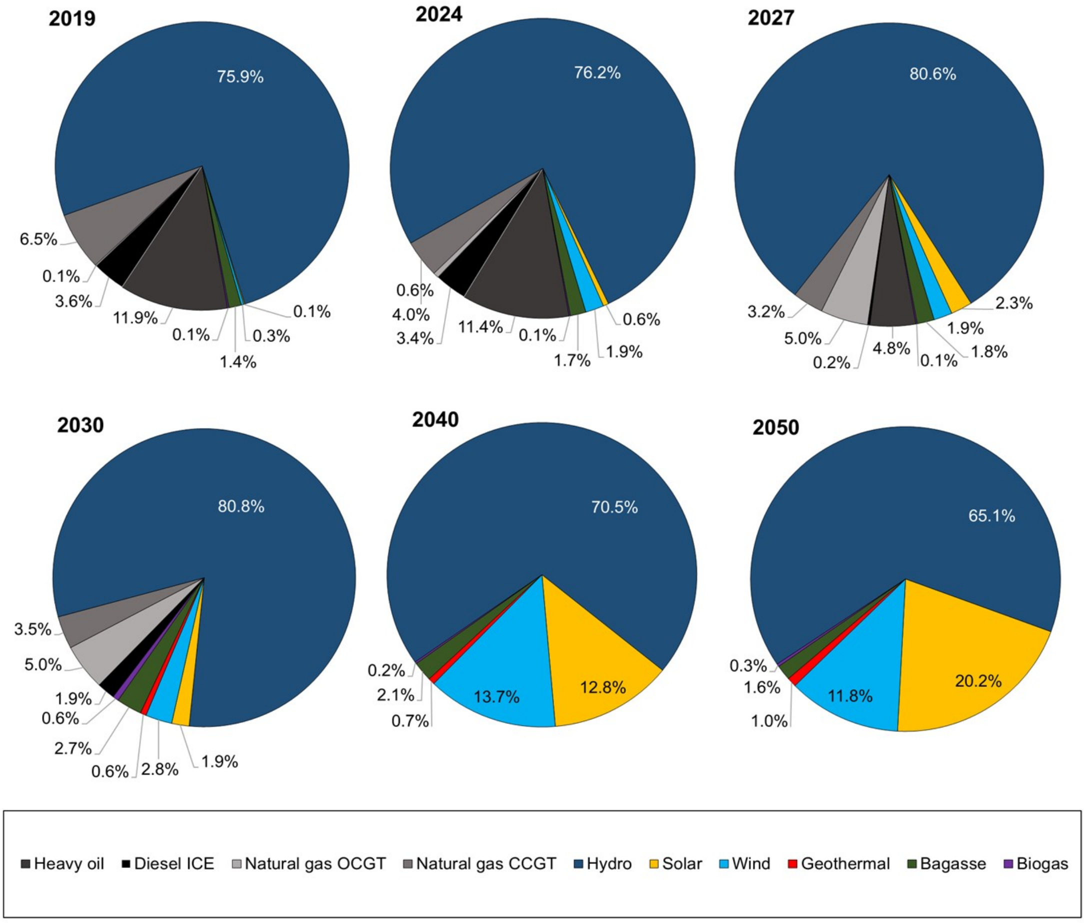


Figure 4.20: Evolution of Ecuadorian electricity mix in the High demand with CO_2 restrictions scenario

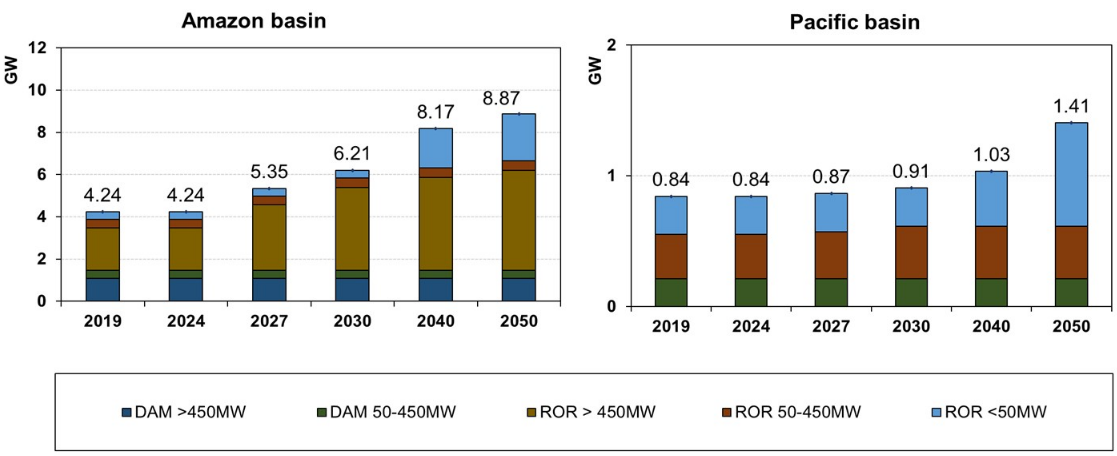


Figure 4.21: Evolution of hydro installed capacity in the Amazon and Pacific Basins in High demand with CO_2 restrictions scenario

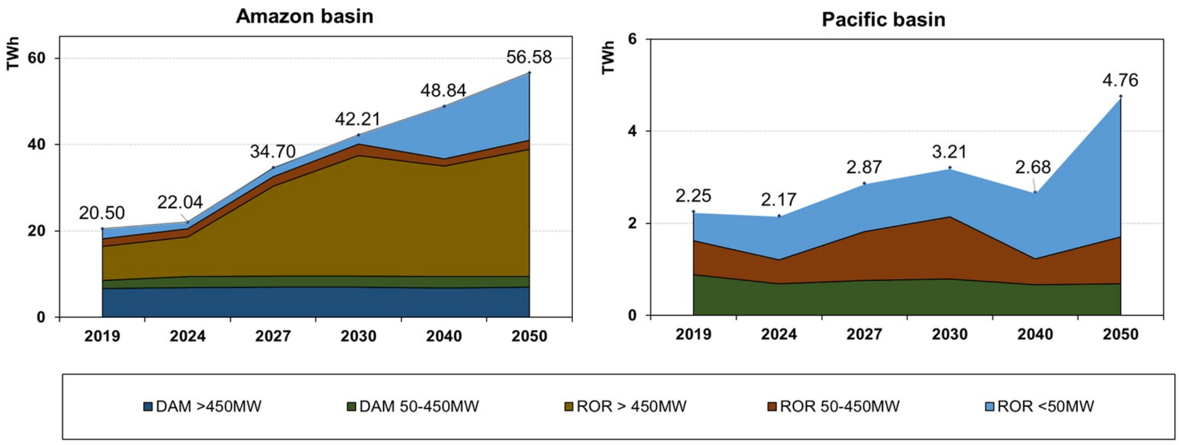


Figure 4.22: Evolution of hydro power generation in the Amazon and Pacific Basins in High demand with CO_2 restrictions scenario

hydroelectric plants are sited outside ecologically protected regions.

To facilitate comprehension, Figure 4.23 exclusively illustrates the load curves corresponding to the High demand with CO_2 restrictions scenario. These load curves effectively demonstrate the impact of diversifying natural resources for electricity generation, allowing for the utilization of each resource in accordance with its hourly availability. Over the course of the day (from 06:00 to 18:00), electricity production from various sources, including hydropower plants, solar PV panels, wind parks, geothermal facilities, and biomass-based plants (bagasse and biogas), collectively contributes to the energy mix. Any surplus generated during this period is efficiently stored for utilization during peak hours, spanning from 19:00 to 22:00. Remarkably, when combined, these renewable technologies exhibit the capacity to fulfill the entire electricity demand without relying on fossil fuels. However, it is important to note that potential surges in energy demand, particularly during the dry season (from October to March), may necessitate electricity imports from neighboring countries, Colombia and Peru, as depicted in the figure. While an electrical interconnection network exists with neighboring countries, such imports may lead to a geographical displacement of greenhouse gas (GHG) emissions. Moreover, given that these countries share the same time zone and experience similar peak demand periods, it is plausible that the purchased electricity originates from non-renewable sources. That import dependency could be mitigated by augmenting the storage system's capacity within this scenario. Additionally, a substantial proliferation of residential solar PV systems accompanied by battery storage could reduce reliance on the grid during evening hours. Notably, there exists a demand valley in the electricity consumption curve from 1:00 to 8:00, a low consumption timeframe that could be leveraged to recharge electric vehicle batteries, particularly through the implementation of favorable electricity tariffs. Such incentives hold the potential to enhance the attractiveness of electric vehicles and ensure that an expanding electric vehicle fleet does not impose additional stress during peak demand periods. Presently, in Ecuador, electricity subsidies are determined based on overall consumption levels. Transitioning to time-based electricity pricing may effectively curtail peak-time consumption, addressing a major concern from the generation side. Thus, the insights provided by these load curves shed light on the efficacy of resource diversification in meeting electricity demand and the potential benefits of time-based pricing models. These considerations hold significance not only for the High demand with CO_2 restrictions scenario but also as topics worthy of exploration in future research.

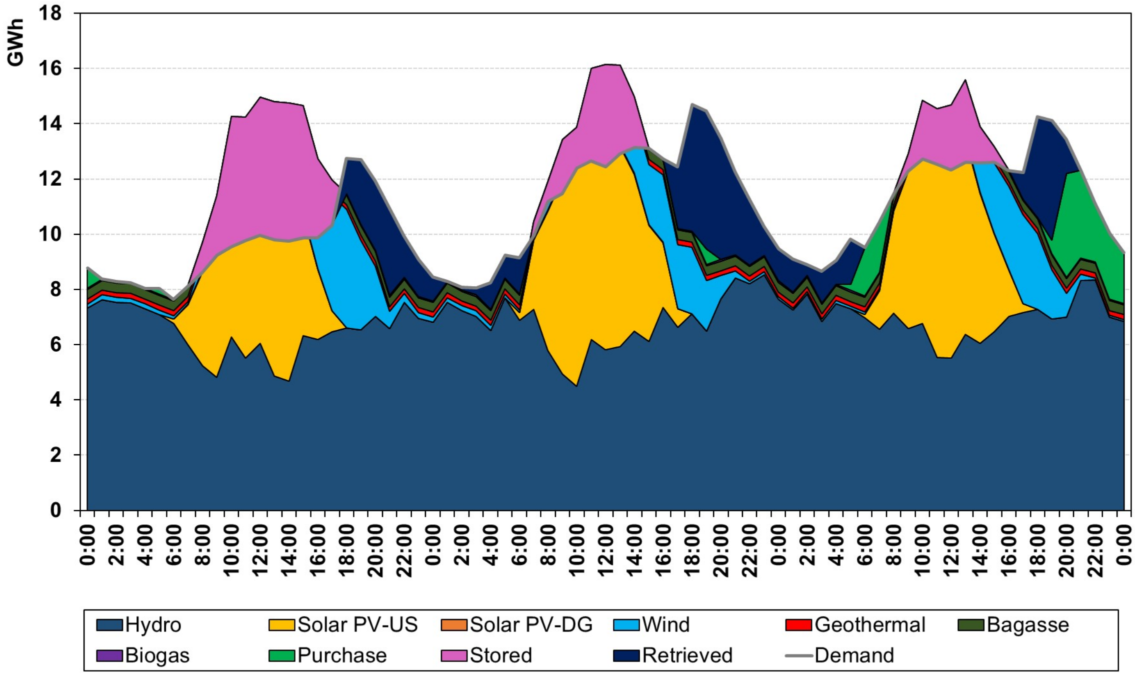


Figure 4.23: Electricity dispatch per hour in GWh during three days in October 2050 for the High demand with CO_2 restrictions scenario

In summary, the High demand with CO_2 restrictions scenario, despite its ambitious nature, is a viable and achievable course of action. Its realization necessitates a fundamental shift in the mindset of the authorities overseeing the Ecuadorian electricity sector, evolving from traditional practices that have persisted for decades. One key facet of this evolution is the active engagement of diferent stakeholders right from the inception of sector planning. Rather than being passive participants, stakeholders should play an integral role in shaping the sector's future. Their input and expertise are invaluable in devising effective strategies, considering diverse perspectives, and fostering collaboration. Additionally, it entails expanding the sector's focus beyond hydropower to harness the considerable potential of solar and wind resources within the country. This diversified approach enhances the sector's resilience, particularly in the face of climatic uncertainties. Substantial adjustments in policies and incentives supporting distributed energy projects are also essential. These initiatives should align with the country's broader energy goals and encourage the adoption of renewable technologies, such as solar panels and wind turbines, at residential and small-scale levels. Lastly, recognizing the current sector's dependence renders it vulnerable to potential climatic variations, underlining the need for enhanced resilience and adaptability. In essence, the High demand with CO_2 restrictions scenario represents not just an evolution in the electricity sector but a transformation in mindset and approach, one that aligns with the broader goals of sustainability, resilience, and environmental responsibility. By embracing these changes, Ecuador can navigate the path towards a more sustainable and secure energy future.

In terms of economic considerations, it is evident that the High demand with CO_2 restrictions scenario is the most financially demanding among the three scenarios under examination. This heightened cost is primarily attributed to the elevated electricity demand associated with this scenario, necessitating a larger installed capacity for electricity generation. In comparison to the MCA scenario, the High demand with CO_2 restrictions scenario exhibits a nearly 60% increase in total investment costs over the entire analysis period, and it surpasses the Policies scenario by nearly 50%. Notably, the elevated investment costs for electricity generation in this scenario are partially offset by reduced expenditures on fuel procurement, amounting to a 45% decrease compared to the MCA scenario and a 26% reduction compared to the Policies scenario. However, it's essential to acknowledge that a direct comparison between the High demand with CO_2 restrictions scenario and the other two scenarios is not entirely equitable due to the contrasting electricity demands. Remember that the High demand with CO_2 restrictions scenario proposes a very ambitious scenario in terms of industrial development for Ecuador which is reflected in the increasing of electricity consumption. Therefore, a more meaningful comparison arises when evaluating the Policies and MCA scenarios. It is important to recall that the MCA scenario was developed through a multi-criteria analysis focusing on social, technical, and environmental considerations, and it consequently excluded the construction of certain power plants that failed to meet the criteria in these three dimensions. Notably, economic factors were not a primary consideration within its assessment. Consequently, our optimization model introduces an economic dimension to the analysis. Regarding investment costs, the MCA scenario emerges as approximately 28% more cost-effective compared to the Policies scenario. However, when considering fuel costs, it's essential to bear in mind that the MCA scenario entailed the deployment of combined cycle plants using natural gas, resulting in a 13% increase relative to the Policies scenario. When incorporating a comprehensive perspective that encompasses investment costs, fixed and variable expenditures, as well as fuel costs, the MCA scenario remains marginally more economical than the Policies scenario, exhibiting cost savings of approximately 7%. Importantly, it is crucial to acknowledge the latent economic benefits associated with efficient energy planning, where multi-criteria analyses are employed to ensure alignment with the social, technical, and environmental requisites. Specifically, these analyses help mitigate challenges arising from opposition by communities and entire villages when proposed projects fail to meet their criteria. The economic advantages of the MCA scenario may indeed surpass the 7% figure presented here when considering the potential hidden costs associated with inefficient energy planning practices. In summary, the integration of economic criteria underscores the economic viability of the MCA scenario and highlights the broader benefits of multi-dimensional analyses in energy planning.

Chapter 5

Discussion and Conclussions

The current manner of energy planning solely based on techno-economic optimization exhibits various shortcomings. Firstly, it often fails to adequately consider environmental and social impacts associated with energy decisions. Externalities, such as pollution and public health effects, are either underestimated or disregarded. This lack of comprehensive consideration undermines the sustainability of chosen energy pathways. Moreover, the inherent inflexibility of techno-economic optimization models presents a significant drawback. These models struggle to adapt to changes in market conditions or shifting societal preferences. This inflexibility can result in suboptimal decisions over the long term. Additionally, a deficiency in citizen participation characterizes this approach, as it predominantly focuses on technical and economic aspects, neglecting the active involvement of communities. The absence of citizen engagement can lead to resistance against energy projects and undermine their societal acceptance. The focus on short-term profitability can further lead to a bias against long-term beneficial investments from social and environmental perspectives. Furthermore, there is a risk of favoring established conventional technologies over more innovative and sustainable options, limiting the diversification of the energy mix. The lack of consideration for the resilience of the energy system to unexpected events or natural disasters poses a potential threat to the security and continuity of the energy supply. Lastly, the inability to adapt to changes in societal and cultural preferences is a notable limitation. Evolution in societal demands is not always adequately reflected in optimization models, potentially leading to decisions misaligned with the shifting expectations of society.

Despite the existence of Environmental Impact Assessments (EIAs) in energy projects, issues and abuses against nature and local communities have arisen for various reasons. Inadequate impact assessment, often due to insufficient data or inappropriate methodologies, can lead to the omission of significant environmental and social impacts. Lack of transparency and effective public participation also contributes, as non-transparent processes may result in overlooking potential issues and triggering conflicts. Economic and political pressures, favoring short-term profitability over long-term sustainability, can influence decision-making and diminish the effectiveness of impact assessments. Additionally, changes in project conditions over time, non-compliance with proposed measures, and the inherent complexity of certain ecosystems all contribute to unforeseen issues.

The identified shortcomings in the existing approach to planning national energy systems have culminated in the rejection of proposed electricity generation projects. While some of these projects may hold potential benefits for the transition towards renewable energies, their implementation has been marred by negative social and environmental impacts, triggering socio-environmental conflicts. Simultaneously, these issues have given rise to delays or stoppages in the construction of such energy projects. In essence, the current planning model exhibits significant flaws that hinder progress towards a more just and equitable energy transition. Overcoming these deficiencies is imperative to pave the way for a transition that not only embraces renewable energies but also prioritizes social and environmental considerations, fostering a sustainable and harmonious integration of new energy initiatives.

The multi-criteria analysis stands as a framework for effectively implementing the theory of energy governance and energy democracy. By addressing the inherent complexity in energy decisions, this approach allows for the integration of a diverse range of criteria beyond technical and economic aspects, encompassing environmental, and social considerations. Active participation from various actors, including local communities and interest groups, is facilitated through this analysis, fostering an inclusive and participatory decision-making process. In addition to incorporating diverse perspectives, multi-criteria analysis provides the ability to assess trade-offs among different objectives, such as economic efficiency, social equity, and environmental sustainability. This systematic process not only helps identify solutions that balance these sometimes conflicting objectives but also contributes to more informed and transparent decision-making. The capability to adapt and learn continuously means that criteria can be revisited and adjusted in response to feedback from involved actors and changes in social, technological, or environmental conditions.

5.1 The strengths of MCA as a tool for energy planning

In this section, we will delve into the strengths of multi-criteria analysis and its contribution to energy planning. MCA attributes, including comprehensive assessment, incorporation of stakeholder preferences, environmental emphasis, and transparency, will be explored in the context of Ecuador's unique challenges and opportunities.

5.1.1 A holistic evaluation and integration of stakeholder preferences

Multi-criteria analysis offers advantages that play an important role in national energy planning. First, MCA enables the comprehensive evaluation of energy projects and options by considering a diverse range of criteria, including environmental, social, economic and technical aspects. This approach aligns with the complexities observed in Ecuador, where energy initiatives frequently give rise to socio-environmental conflicts. The MCA is a tool capable of reconciling disparate criteria, facilitating consensus, and thereby improving the overall success and resilience of power generation projects in the country. On the other hand, the value of the MCA is achieved through its ability to include the preferences of different stakeholder groups. In our case study, Ecuador, stakeholders involve a broad spectrum of actors, ranging from academia and government agencies to industry players and civil society representatives. By recognizing the preferences of these groups, the MCA provides solutions that are not only technically sound, but also socially acceptable and politically viable.

Our work proposed the inclusion of social, environmental, technical, and economic criteria in the planning of the Ecuadorian power sector. The MCA incorporated the first three criteria while the economic criterion is incorporated in the optimization model of the Ecuadorian electricity sector covered in Section 5.2. In the multi-criteria analysis, a certain contradiction was observed among our specific criteria. However, through stakeholder consensus, priority was ultimately given to one criterion over another. This contrast was evident in the case of the job creation criterion and project size. One of our objectives was to maximize employment opportunities that an electricity generation project could generate while favoring smaller projects. This specification arose from interviews and literature reviews, revealing that large-scale projects have the potential to create a significant number of job opportunities, considered a positive aspect. However, these same projects were negatively assessed due to concerns about their big size, seen as potential risks to the population, flora, and fauna.

It is noteworthy that project evaluations based on these criteria could be harmonized by assigning different degrees of importance to each criterion. Academics and the public sector, for instance, placed a clear emphasis on job creation over project size. Conversely, stakeholders from civil society and the private sector considered the quantity of jobs generated less important than the project's size. Ultimately, with a consensus of over 50%, all four actor groups concluded that job creation is more important than project size.

This emphasizes the contribution MCA in the planning of an energy system, highlighting its ability to go beyond depending on a single criterion or seeking input from a singular group of experts to establish the relative importance of one criterion over another. In contrast to traditional decision-making approaches, we proposes to involve and consider the perspectives of diverse stakeholder groups. By doing so, it enables a more comprehensive and inclusive evaluation of different criteria, ensuring that the planning process reflects a broader range of considerations.

The participation of diverse stakeholders with different points of view is a key aspect to consider in the energy planning process. This inclusive approach facilitates a thorough consideration of the trade-offs and priorities that different groups may have. The ultimate goal is to achieve a consensus that aligns with the preferences of the majority, recognizing that their decisions affect a broad spectrum of interests and concerns within society. In addition, the consensus-building process fostered by the MCA contributes to the overall robustness of optimization models. The collective input from diverse stakeholders helps refine and validate the criteria used in the analysis, making the resulting models more resilient and more reflective of the complex realities of energy planning. This collaborative approach increases the legitimacy and acceptance of the chosen strategies.

5.1.2 Environmental emphasis and transparency

The implementation of MCA in the context of the Ecuadorian electricity sector has brought about a transformation in the consideration of environmental criteria. Historically, these criteria were either entirely omitted or accorded insufficient importance in the planning phase of the sector. They were typically only addressed during the environmental impact assessment, conducted prior to project construction. However, with the introduction of MCA, the Ecuadorian electricity sector now incorporates environmental criteria as integral elements in the planning process, aligning their significance with the unanimous consensus among all four stakeholder groups. The utilization of MCA, particularly with an environmental emphasis, stands as a mechanism in the evaluation of hydroelectric projects, as exemplified by the Ecuadorian case.

It serves as a pivotal means of addressing environmental concerns and promoting sustainable project development.

The environmental emphasis underscores a growing global concern for sustainability and the environment in project evaluation. It acknowledges the need to protect ecosystems, wildlife, and the delicate balance of nature while pursuing energy generation initiatives. For this thesis, the environmental criteria encompass aspects like the threat to fauna and wildlife, deforestation, and proximity to natural reserves. These criteria have proven to be of utmost importance for all stakeholder groups, particularly those representing civil society, which includes individuals residing in or near hydroelectric generation projects. It is remarkable that these actors rank social criteria, which directly affect them, as second in importance relative to environmental criteria. The emphasis on environmental criteria found in Ecuador is rooted in a long history of environmental concerns arising from similar projects not just in the country, but also in South America. For instance, the Belo Monte Dam in Brazil has been associated with deforestation, habitat destruction, and adverse impacts on fish species, such as the Amazonian manatee and giant otter, due to altered river flow. In Chile, the proposed HidroAysén project raised concerns about the potential impact on pristine rivers, forests, and aquatic ecosystems, with a particular focus on the endangered Southern Huemul deer. The Tucuruí Dam in Brazil led to alterations in river flow, water quality issues, and adverse effects on local fish populations and surrounding deforestation. The Yacyretá Dam in Argentina and Paraguay disrupted river ecosystems and resulted in the loss of wetlands, adversely affecting bird species and aquatic life, just to name a few.

Interestingly, for the actors in public institutions for the power sector, environmental criteria are ranked second in importance, just after the displacement of people. This ranking signifies the acknowledgment of the environmental dimension, even though it may not take precedence in project planning considerations. This disparity between the significance attributed to environmental criteria in discourse and their tangible influence in project planning raises important questions regarding the alignment of policy intent with practical implementation. The chasm between the acknowledged importance of environmental criteria and their limited integration into project planning is starkly illuminated by the fact that 46 projects, of the 101 analysed ones, failed to pass the MCA, primarily due to negative ratings for environmental criteria. Notably, 12 of the failed projects exhibited unfavorable ratings across all three environmental criteria, while 33 received negative ratings for their proximity to nature reserves and biosphere reserves, and one for deforestation (please refer to Appendix B). This stark reality underscores the need for a more effective translation of policy considerations into concrete actions during the project planning phase, especially concerning environmental aspects. Enhancing this translation from policy discourse to project planning requires a comprehensive reassessment of the methodologies, ensuring that environmental criteria receive the weight and attention they deserve in the practical implementation of power projects.

5.1.3 The MCA in the Ecuadorian energy planning

In countries like Ecuador, the history of electric development has been characterized by a significant reliance on hydroelectric technology. Over time, this orientation has stirred discontent among residents in regions hosting hydroelectric projects, escalating social tensions. Furthermore, there has been a notable impact on environmentally sensitive areas of the country. The Ecuadorian experience underscores the pressing need for a profound shift in electrical system planning. This call for transformation is not solely rooted in the pursuit of technological alternatives beyond the conventional; it also advocates for a paradigmatic change in decision-making. The voice of civil society is deemed equally pertinent to that of technical experts in the electric sector. Public dissatisfaction and conflicts associated with hydroelectric project implementation underscore the necessity of incorporating broader perspectives into the planning process.

In response to this challenge, the multi-criteria analysis emerges as an effective tool. By considering the perspectives of four key stakeholder groups (academia, private sector, public sector, and civil society), an objective classification of 101 electricity generation projects (12,532 MW) was achieved. The results revealed that 55 projects, with a total capacity of 7,198.93 MW, meet the requirements and expectations of the involved stakeholders. In contrast, 46 projects, representing just over 5,000 MW, do not satisfy the established criteria, foreseeing potential conflicts if implemented.

This initial step in applying the multi-criteria analysis provides valuable insights. It underscores the disparity between technical proposals and the preferences of diverse stakeholders. Consequently, there is a proposal to systematically incorporate this methodology into future energy planning, expanding the scope beyond conventional technologies. The study also sheds light on the feasibility of solar photovoltaic projects. A pilot project of this nature garnered the third-highest score, albeit facing the challenge of affordability for the majority of Ecuadorians. Nevertheless, it emphasizes the need not to perceive this limitation as an insurmountable barrier but rather as an opportunity to explore incentives that can make solar photovoltaic energy both economically viable and socially accepted. The strength of the methodology lies in its ability to evolve and adapt to changing environmental circumstances. This flexible approach serves as a response to the complexity of environmental, social, and technical factors influencing energy planning. In the current study, nine criteria were analyzed, and future analyses should consider new criteria, such as water availability, as an essential factor, given Ecuador's high vulnerability to potential variations in precipitation. The acknowledgment of this vulnerability is grounded in the study titled "Proyecciones climáticas de precipitación y temperatura para Ecuador, bajo distintos escenarios de cambio climático" [91]. These projections outline a diverse precipitation outlook for different regions of the country between 2071 and 2100. The eastern Amazon would experience reductions in the range of 2-10%, while increases of 5-10% are projected to the south. Significant increases of 10-20% are anticipated in the central, northern, and western continental regions of Ecuador, with even higher percentages exceeding 15% projected for Galápagos. Consequently, the need to consider these climatic values and projections is amplified when proposing the construction of new hydroelectric plants with a vision extending to the year 2100. The variability in precipitation, as indicated by the cited study, could have significant implications for water availability in electricity generation. The Amazon region, crucial for Ecuador's current hydroelectric matrix, might experience reductions that would impact the capacity of these installations.

Long-term planning, extending until the end of the century, demands a perspective beyond current conditions and considers diverse climate scenarios. The possibility of reductions in precipitation in the Amazon, coupled with increases in other regions, raises critical questions about the sustainability and viability of relying exclusively on hydroenergy. It is essential, therefore, that decisions regarding new hydroelectric plants are based on a comprehensive analysis that incorporates not only current conditions but also anticipated climate trends. The inclusion of climate variability in the planning methodology, as proposed by the multi-criteria analysis, provides a valuable tool for evaluating the suitability of long-term investments in energy infrastructure. This approach would not only mitigate the risk of excessive dependence on a single source of electricity generation but also enable a smoother transition to more sustainable and climate-resilient technologies.

Ultimately, crucial questions are raised regarding the diversification of the electrical matrix and the selection of technologies that are not only technically efficient but also socially and environmentally acceptable. The study's results not only provide a clear overview of which projects meet these criteria but also establish a robust starting point for the future proposition of electricity generation projects that respect the priorities of the involved stakeholders. Currently, the country possesses studies on the potential of electricity generation from solar, wind, and bioenergy sources. Through this investigation, we have identified critical aspects to consider, namely threats to fauna, community displacement, and deforestation of protected wooded areas. Conversely, the distance to transmission lines and accessibility to project construction zones emerge as criteria of lesser relevance. These findings form a solid foundation for formulating proposals for electricity generation projects. By acknowledging that preserving fauna, protecting local communities, and conserving forests are fundamental priorities, there is an opportunity to design projects that, despite being distant from transmission infrastructure and roads, do not compromise the integrity of fauna or pose a threat to protected forests and local communities. In essence, this detailed knowledge clearly guides us on what actions to take and avoid when proposing new electricity generation projects.

5.2 Scenarios discussion and political implications

Having addressed the advantages of multi-criteria analysis in the planning of the Ecuadorian electric sector and specified projects that meet the social, environmental, and technical requirements of our stakeholders, it is time to incorporate the economic criterion into our analysis. This criterion is introduced through the cost optimization of Ecuador's electric system up to 2050 under three scenarios. We will examine the role played by hydroenergy, as well as other renewable and non-renewable energy sources. Additionally, we will assess the cost associated with achieving carbon neutrality in Ecuador while meeting the growing demand for electricity in the country.

5.2.1 The role of hidroenergy in the Ecuadorian electricity matrix

The discussion in this section does not intend to diminish the importance of hydropower. Instead, it seeks to underscore its fundamental role in contributing to Ecuador's cleanest electricity generation. However, it is crucial to address substantial challenges during the construction phase of hydropower plants. A comprehensive analysis provides opportunities to alleviate these adverse impacts. This effort seeks to contribute valuable insights, encouraging a proactive approach to prevent the repetition of past mistakes that have precipitated socio-environmental conflicts.

In all three scrutinized scenarios, hydroelectricity maintains its position as the predominant energy source in Ecuador, and this dominance is rooted in several key factors. Firstly, the country has a well-established and mature hydroelectric technology, dating back to 1979. This historical legacy signifies a robust foundation and accumulated expertise in harnessing hydropower. Secondly, Ecuador boasts enormous water potential, providing abundant resources for hydroelectric generation. The availability of ample water sources enhances the feasibility and efficiency of hydroelectric projects. Lastly, the elevated investment costs associated with other renewable technologies contribute to the sustained prominence of hydroelectricity in the country's energy landscape.

Figure 5.1, within the MCA and High demand with CO_2 restrictions scenarios, elucidates an envisioned expansion of hydropower plants. This expansion not only serves the purpose of contributing to the country's electricity supply but also takes into account the preferences of diverse stakeholder groups. This inclusive approach considers their perspectives and requirements to ensure that hydropower development aligns with Ecuador's sustainable goals, avoiding the generation of additional negative impacts. Of particular significance, specially for the authorities in Ecuador's public energy sector, is the observation that the MCA scenario does not exhibit a substantial variance in terms of hydropower development compared to the Policies scenario. In both the Amazon and Pacific basins, the total installed capacity within the MCA scenario is, at most, 1 GW less than that in the Policies scenario for each analyzed year. This nuanced distinction suggests that the national government's hydropower plans are not inherently flawed; rather, they may benefit from refinement. The key takeaway is that diverse stakeholder groups are not advocating against the construction of hydroelectric plants in the country. Instead, their emphasis is on strategic limitations, driven by concerns related to the potential risks these projects pose to local fauna, flora, and residents. The actors express reservations about the potential hazards associated with the overexploitation of water resources and the exclusive focus on hydroelectric plant construction, advocating for a more balanced and cautious approach to ensure environmental and societal well-being.

Our multi-criteria analysis addressed these concerns when assessing the plans for future hydroelectric projects. Consequently, the deployment of new hydroelectric reservoir projects was not included in either the MCA or the high demand with CO_2 restrictions scenarios.

In the ambit of the most ambitious scenario, the High demand with CO_2 restrictions, which stands as the pinnacle among the three analyzed, there emerges a noteworthy endorsement for run-of-river hydropower plants smaller than 50 MW. This signifies a highly viable option for electricity generation, aligning seamlessly with the preferences expressed by stakeholders during interviews. The specific emphasis on smaller-scale run-of-river hydropower plants delineates a clear path for necessary adjustments in the selection of hydroelectric projects from the existing portfolio in the country. It underscores that, with judicious considerations, it is feasible to meet the escalating demand for electricity in Ecuador while accounting for a spectrum of factors beyond purely technical and economic dimensions. Furthermore, it is imperative to acknowledge that the costs associated with small hydroelectric plants tend to be higher than those of larger counterparts. However, this apparent economic disparity can be offset by the widespread public acceptance of smaller projects. Such acceptance contributes to a reduction in opposition to project construction—a factor that has historically resulted in delays, interruptions, and, in some instances, irreparable harm to delicate ecosystems and the

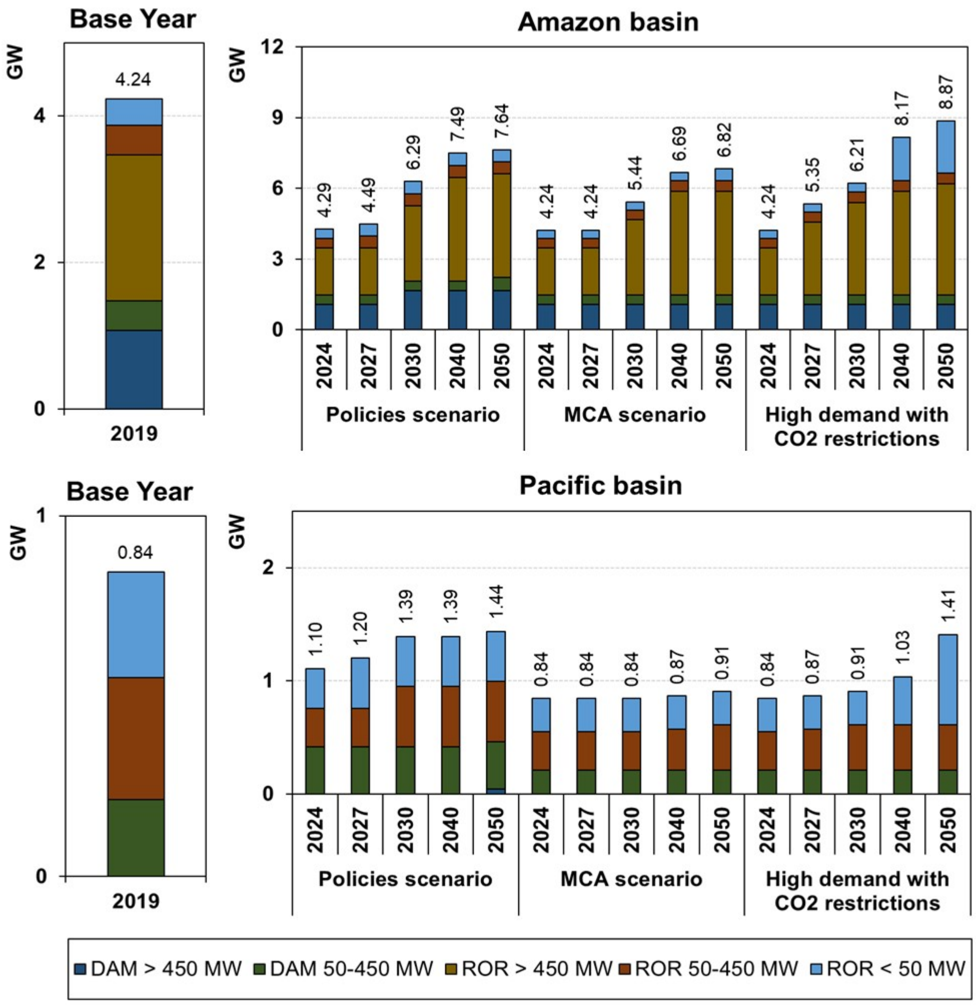


Figure 5.1: Assessment of hydroenergy integration across three analyzed scenarios

local populace residing in the proximity of these ventures.

All three scenarios involve considering different potential futures for hydropower in Ecuador. This includes assessing the feasibility of smaller run-of-river hydropower plants, adjusting plans to address environmental and social concerns, and seeking a balance between meeting electricity demand and minimizing negative impacts.

5.2.2 The role of non-renewable energies in the Ecuadorian electricity matrix

In the year 2019, thermal generation plants fueled by diesel, heavy oil, and natural gas accounted for 38% of Ecuador's installed capacity for electricity generation. Among these, thermal plants relying on heavy oil and diesel emerged as the most prominent, boasting capacities of 1,359.9 MW and 1,216.4 MW, respectively. In terms of energy output, these thermal power facilities contributed significantly, generating 6.6 TWh, constituting 22.2% of Ecuador's total electricity production in 2019.

The operational magnitude of these thermal power plants is underscored by the consumption of 1,734,276.11 ktOE to achieve this generation, translating to 5,027 kt CO_2eq. Remarkably, this accounted for 12.9% of the total CO_2 emissions in Ecuador during the specified year. While electricity production is not the primary contributor to pollution in the nation, the imperative to curtail emissions from the electricity generation system is unmistakable. The task of CO_2 emission reduction in this sector is particularly challenging in a country where the foundation of the national economy rests on the production and export of oil, an intricate reality that necessitates a strategic and gradual approach.

In both the Policy and MCA scenarios, there were no imposed restrictions on CO_2 emissions or limitations on the expansion of thermal power plants throughout the analyzed period. Despite this absence of constraints, the results indicate that by 2030, heavy oil-dependent thermal power plants will cease operation, resulting in a 61% reduction in CO_2 emissions compared to 2027. Similarly, by 2040, diesel-based thermal power plants will be phased out, leading to a 26% decrease in CO_2 emissions compared to 2030. This projection is based on a convergence of factors, including the end of the operational life of these thermal plants and economic considerations.

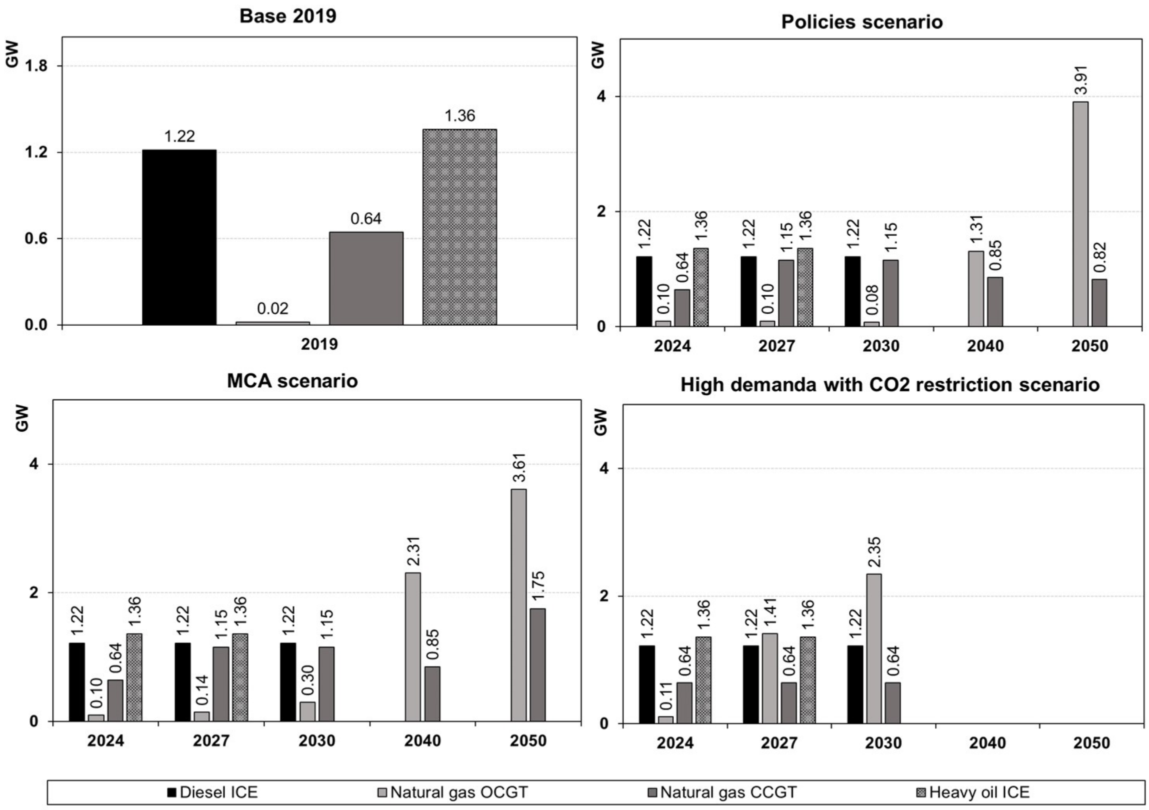


Figure 5.2: Assessment of non renewable energy integration across three analyzed scenarios

On the other hand, it is anticipated that natural gas will play a central role in meeting the electricity demand in both open-cycle and combined-cycle thermal power plants, as depicted in Figure 5.2. In the MCA scenario, the expansion of natural gas is primarily attributed to the decrease in installed hydroelectric capacity resulting from the previous outcomes of our multi-criteria analysis. Natural gas assumes a predominant role, particularly for its capability to fuel flexible open-cycle gas turbines and combined-cycle gas turbines. Specifically, technologies such as OCGT and CCGT exhibit relatively lower investment costs compared to other renewable alternatives like wind, solar, geothermal, and biomass. Natural gas becomes an economically viable alternative to other renewable energies, although it is undoubtedly more polluting.

In 2050, CO_2 emissions in both the Policies and MCA scenarios have decreased compared to 2019, which is attributed to the use of natural gas instead of heavy oil or diesel. However, emissions are still not negligible. In the MCA scenario, CO_2 emissions are higher than in the Policies scenario by 2050, indicating that a scenario that considers socially acceptable and less impactful projects with flora and fauna does not necessarily include a decrease in CO_2 emissions. To demonstrate that it is possible to be socially, environmentally and emission friendly, the high demand with CO_2 restrictions scenario emerges as a solution. In this scenario, a transformational change is foreseen by 2040, which will make electricity production using any form of fossil fuel, including natural gas, unviable. This translates into the elimination of CO_2 emissions from the electricity sector, effectively achieving carbon neutrality by that year. The elimination of fossil fuel-based thermal power plants presents Ecuador with a strategic window to promote and invest in the development of renewable energy facilities.

5.2.3 Contributions of other renewables to the Ecuadorian electricity matrix

Let us recall that in 2019, the Ecuadorian electricity matrix revealed a relatively modest contribution of 2.27% from renewable energy, excluding hydropower, with an installed capacity of 193.1 MW. Noteworthy transformations emerge in the three analyzed scenarios, projecting a substantial increase in the share of renewable energies, excluding hydropower, up to the year 2050—an escalation clearly depicted in Figure 5.3.

The increase in proportions of solar, wind, biomass, and biogas energy remains the same in both the Policies and MCA scenarios throughout the analysis period, reaching a total installed capacity of 3,118.3 MW by 2050. However, for geothermal energy, the multi-criteria analysis has constrained its expansion to 178 MW in the MCA scenario, as opposed to the 900 MW projected in the Policies scenario. This limitation in the growth potential of renewable energies is attributed to the rising share of natural gas, which has increased at the expense of hydroenergy in both scenarios. It is clear that the deployment of renewable energies, such as solar and wind, is subject to specific conditions, including a drastic reduction in emissions, as proposed in the scenario of high demand with CO_2 restrictions. This scenario places solar energy as the second most important source of electricity in Ecuador, closely followed by wind energy in third place. This ambitious deployment of renewable energy is also achieved through a substantial increase in energy storage systems that will reach 5 GW by 2050.

The presence of hydropower in the Ecuadorian electricity mix is and will remain significant, and the multi-criteria analysis showed that it is possible to utilize hydropower without generating negative impacts on residents, flora, and fauna. However, given the high dependence of the Ecuadorian electrical system on this resource and its vulnerability to the potential effects of climate change on water availability in Ecuador, it is imperative to diversify the electrical matrix. This entails a more prominent participation of solar, wind, biomass, and geothermal projects, all of which must receive approval from academia, the private sector, the public sector, and civil society. This diversification is achieved in the high demand with CO_2 restrictions scenarios starting from 2040, as it proposes a diversified and decarbonized electricity generation matrix.

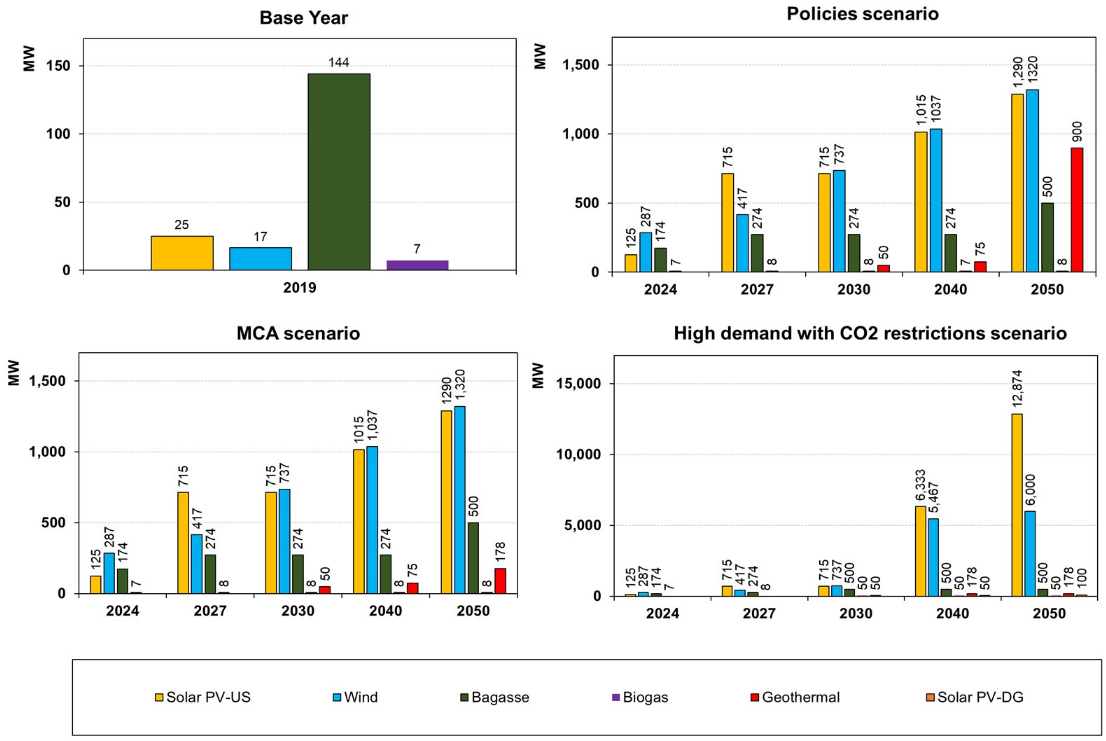


Figure 5.3: Assessment of renewable energy integration (excluding hydropower) across three analyzed scenarios

In this scenario, by 2050, the installed capacity of other renewable sources reaches 71.4%, in comparison to the 28.6% from hydropower, with a complete absence of energy derived from fossil fuels.

Achieving that 71.4%, equivalent to just over 25 GW of installed capacity in other renewable energies, will pose a significant challenge. Nevertheless, government institutions play a crucial role in this effort to overcome the economic barriers faced by renewable energies. The primary obstacle to installing other sources of renewable energy in Ecuador is the subsidy provided by the national government for electricity. In this specific case, redirecting this subsidy towards tax credits to reduce the initial installation costs of renewable energy systems is essential, making them more accessible and financially appealing. Financial institutions could play an important role by providing funding with favorable conditions, such as low-interest rates or extended terms, for renewable energy projects, thereby facilitating capital acquisition. This should be coupled with establishing guaranteed and preferential rates for electricity generated from renewable sources, incentivizing the construction of such facilities. Additionally, it is crucial to promote research and development in renewable technologies through financial incentives and government support. Simultaneously, conducting educational campaigns to raise public awareness about the benefits of renewable energies is of paramount importance, fostering sustainable demand and community support. The combination of these measures should maximize their effectiveness in driving the transition towards more sustainable energy sources.

To conclude this section of the discussion, the results of our work highlight multi-criteria analysis as a tool aimed at benefiting society, the environment, and the economy in sustainable energy development. This approach incorporates diverse dimensions and considerations, promoting citizen participation and transparency in decision-making by involving various stakeholders. Additionally, it conducts a comprehensive assessment of the social impacts of projects. From an environmental standpoint, it facilitates the identification of renewable energy sources that do not compromise biodiversity preservation. In techno-economic terms, the second part of our work, focusing on the model of the Ecuadorian power system, optimizes the expansion of power generation facilities by evaluating financial performance over time, considering both initial and operational costs. This methodology not only seeks financial efficiency but also stimulates innovation by promoting the research and adoption of innovative technologies, contributing to improved efficiency and long-term cost reduction.

Overall, this work offers a balanced and holistic approach that harmonizes social, environmental, technical, and economic interests. This paves the way towards sustainable energy development that benefits society as a whole and preserves our environment.

5.3 Conclussions

The conclusions drawn from this research will center on the three research questions introduced in Chapter 1. Let us proceed to examine each of these inquiries:

1. How to reduce socio-environmental conflicts surrounding power generation projects?

This study addresses the issue of socio-environmental conflicts associated with energy generation projects by proposing a comprehensive and participatory approach to the selection of electrical projects. The methodology employed is the multi-criteria analysis, enabling a systematic evaluation of key aspects such as environmental impact, social implications, and technical considerations for a set of 101 proposed power generation plants intended for future construction.

While the MCA significantly contributes to promoting sustainability in energy development and minimizing socio-environmental conflicts, it is imperative to recognize that it does not guarantee the complete elimination of such conflicts. The diversity of perspectives and interests among stakeholders can complicate the achievement of full consensus. In this context, the study highlights that a consensus of 55.1% was reached among academia, civil society, the private sector, and the public sector in determining the most relevant criteria in the selection of power generation projects. This achievement underscores the importance of considering and respecting various forms of knowledge in the decision-making process. To reach this consensus, there is an emphasis on the need for political commitment supporting the adoption of innovative planning approaches. It is acknowledged that perceptions of the Ecuadorian electricity sector and its implications are not exclusive to technical experts but also belong to those directly and indirectly affected by the decisions made.

The study emphasizes the possibility of establishing an electricity sector that minimizes risks to Ecuador's delicate ecosystem and its population, contingent upon maintaining openness to innovative methodologies and fostering open dialogue. This approach not only involves considering the opinions of experts but also actively including all stakeholders in the decision-making process.

2. What is the influence of integrating environmental and social factors, alongside technical and economical aspects in the modeling of national energy systems?

The integration of socio-environmental criteria, alongside tecno-economic considerations, into the modeling of the Ecuadorian electrical system signifies a substantial shift in the country's energy sector planning. This approach moves from a purely tecno-economic perspective to a more holistic and inclusive methodology. The inclusion of diverse factors in the modeling process facilitates a more robust understanding of the interdependencies among economic growth, environmental preservation, technological advancements, and the well-being of Ecuadorian society. This shift opens the door to the exploration of new technologies (such as solar, wind, biomass, and geothermal) beyond traditional hydroelectric power, capable of collaboratively meeting the continuously growing electrical demand. This process not only benefits the transition to a more advanced energy system but also contributes to economic growth and the development of specialized skills in the energy sector. The implementation of new technologies generates employment opportunities in areas such as engineering, research and development, manufacturing, installation, and maintenance of modern energy infrastructures.

This research underscores that a holistic modeling approach, integrating economic, environmental, technical, and social dimensions, is not just a theoretical necessity but a practical imperative for sustainable and adaptable energy planning at the national level in Ecuador. At a time when the country is grappling with challenges to meet electrical demand, exacerbated by the lack of sector planning over the past six years and a scarcity of rainfall, the integration of diverse factors in energy planning becomes a strategic imperative. This integration is essential to enhance resilience and sustainability in the Ecuadorian energy system.

3. Can a national energy model be developed that effectively integrates economic optimization, social and environmental criteria and stakeholder needs to achieve a sustainable energy system that ensures electricity demand coverage?

The answer to this research question is affirmative. It is feasible to develop a national-level energy model that integrates socio-environmental and techno-economic criteria, meeting the requirements of academia, civil society, the private sector, and the public sector while satisfying Ecuador's electricity demand. The results of the MCA and high demand with CO_2 restrictions scenarios support this assertion. Without CO_2 emissions restrictions, natural gas would be used to compensate for hydroenergy limitations in the MCA scenario. In the second scenario, a completely renewable and emissions-free electricity matrix is projected to be achieved by 2040, socially accepted and posing no risk to Ecuador's protected flora and fauna.

To achieve this 100% renewable matrix, the preceding paragraphs emphasized the need for a paradigm shift in electrical sector planning, realized through the synergy between multi-criteria analysis and the optimization model of the Ecuadorian electrical system that links social justice and economic equity to the transition to renewable energy. Overcoming the challenge of abandoning dependence on hydroenergy, which has been in use in Ecuador for over 40 years, is crucial for governmental authorities to prevent vulnerabilities to potential future climate changes. Exploring alternative sources such as solar and wind, with substantial potential in the country, would genuinely diversify the electricity matrix without compromising the security of the electrical supply in the future.

5.4 Challenges faced

In the Ecuadorian context, conducting the multicriteria analysis posed a significant challenge due to the substantial demand for information and the complexities associated with its collection and quality. This is especially true for energy generation projects, where detailed information is crucial for accurately evaluating each criterion. The geographical characteristics of each project in the Master Electrification Plan's portfolio, coupled with geospatial data on factors like road networks, transmission lines, national parks, and protected forests, are essential for the effective assessment and ranking of these projects. Acquiring this data can be a formidable task, particularly for projects in the feasibility study phase, whose exact location is often uncertain. The viability of a project is intimately linked to its location and potential impact on protected areas. Therefore, ensuring accurate location information becomes a fundamental step for the successful application of MCA in this region.

Another significant challenge is the subjectivity of responses. Although MCA provides a structured and systematic approach to evaluating energy generation projects, it heavily relies on human judgment, introducing a level of subjectivity that can influence the final results. Subjectivity becomes evident in the assignment of weights to criteria. Stakeholders, playing a central role in the MCA process, often come from diverse backgrounds and may have different interests and perspectives. While this diversity is enriching because it ensures a wide range of viewpoints are considered, it is susceptible to groups with particular agendas influencing criterion assessments to benefit their interests, potentially distorting the objectivity of the analysis. To address this challenge, the inclusion of clear weighting methods, diversification of participants, and the minimization of personal biases is crucial.

Despite encountering these challenges in the present study, and acknowledging that results may vary with improved data accuracy or different actor groups, this work proposed an economically viable energy model for Ecuador that contributes to reducing conflicts in the country without jeopardizing its energy dependence. These challenges should be viewed as opportunities to enhance and refine this technique while planning the country's power sector.

Appendix A

PROMETHEE matrix

Name	Type	Project perception	Job creation Jobs/MW	Displ. of people	Deforestation	Proximity to natural reserves	Threat to fauna and wildlife	Size MW	Accessibility	Distance to transmission lines
Isimanchi	Hydro	Bad	66.43	Low	High	High	Medium	51	very good	very bad
Numbala	Hydro	Good	290.08	Low	Low	High	Medium	39.2	very bad	very bad
Langoa	Hydro	Good	192.4	Low	Low	High	High	26	average	very bad
Verdeyacu Chico	Hydro	Good	1,523.6	Low	Low	High	Medium	1,172	bad	very bad
Catachi	Hydro	Good	972.4	Low	Low	High	Medium	748	very bad	very bad
Cedroyacu	Hydro	Good	351	Low	Low	High	Medium	270	very bad	very bad
El Retorno	Hydro	Good	339.3	Low	High	High	Medium	261	very good	very good
Las Cidras	Hydro	Bad	100.49	Low	Low	High	Medium	77.3	very good	very bad
Cuyes	Hydro	Good	66.69	Low	Low	Low	Medium	51.3	very good	very bad
Chingual	Hydro	Good	189.44	Low	Low	High	Medium	25.6	very good	very bad
La Barquilla	Hydro	Good	296.74	Low	Low	High	Medium	40.1	very good	very bad
Quijos 1	Hydro	Good	179.08	Low	High	High	Medium	24.2	good	good
Cosanga	Hydro	Bad	199.8	Low	Low	High	High	27	very good	very bad

Name	Type	Project perception	Job creation Jobs/MW	Displ. of people	Deforestation	Proximity to natural reserves	Threat to fauna and wildlife	Size MW	Accessibility	Distance to transmission lines
Sucua	Hydro	Good	233.84	Low	Low	Low	Medium	31.6	very good	very good
Tomebamba	Hydro	Average	44.4	Low	High	High	High	6	very good	bad
Collay	Hydro	Average	42.92	Low	Low	High	High	5.8	very good	very good
El Cañaro	Hydro	Average	41.44	Low	Low	High	High	5.6	very good	good
Abitagua	Hydro	Bad	214.89	High	Low	High	High	165.3	very good	very good
Cebadas	Hydro	Average	51.43	Low	Low	Low	Low	6.9	very good	very bad
Huarhuallá	Hydro	Average	34.04	Low	Low	Low	Low	4.6	very good	very good
Ambato	Hydro	Average	29.6	Low	Low	Low	Low	4.0	very good	very bad
Chirapi	Hydro	Good	208	Low	Low	High	High	160	very bad	bad
Calderón	Hydro	Good	191.1	Low	Low	High	High	147	very good	very bad
San Pedro	Hydro	Good	108.42	Low	Low	High	High	83.4	good	very bad
Cubí	Hydro	Bad	68.9	Low	Low	High	High	53	average	very bad
Lelia	Hydro	Bad	80.99	Low	Low	Low	Medium	62.3	very good	very good
Yacuchaqui	Hydro	Good	238.28	Low	High	High	High	32.2	very good	very bad
Las Juntas	Hydro	Bad	204.98	Low	High	High	Medium	27.7	very good	very bad
Pilatón Santa Ana	Hydro	Bad	76.05	Low	Low	High	Medium	58.5	very good	very good
Cinto	Hydro	Good	338.92	Low	Low	High	High	45.8	good	average
Los Bancos	Hydro	Good	119.86	Low	Low	High	Medium	92.2	very good	very bad
Milpe	Hydro	Good	323.38	Low	Low	Low	Medium	43.7	good	good
Vacas Galindo 1	Hydro	Good	8.88	Low	Low	Medium	Low	1.2	very good	very bad
Vacas Galindo 2	Hydro	Bad	310.8	Low	Low	High	Medium	42	very good	very bad
Pamplona	Hydro	Bad	299.7	Low	Low	Low	Medium	40.5	very good	very bad
Intag 2	Hydro	Bad	12.58	Low	Low	Low	Low	1.7	very good	very bad
Calderón II	Hydro	Good	286.38	Low	Low	Low	Medium	38.7	average	very good

Name	Type	Project perception	Job creation Jobs/MW	Displ. of people	Deforestation	Proximity to natural reserves	Threat to fauna and wildlife	Size MW	Accessibility	Distance to transmission lines
San Pedro II	Hydro	Bad	70.3	Low	Low	Low	Low	9.5	very good	good
Tulipe	Hydro	Good	57.72	Low	High	High	High	7.8	very good	average
Bellavista	Hydro	Good	85.84	Low	High	High	High	11.6	very good	average
Alambi	Hydro	Average	70.3	Low	High	High	High	9.5	very good	very good
Guapulo	Hydro	Average	23.68	Low	High	Medium	Low	3.2	very good	very good
Tandapi	Hydro	Good	65.86	Low	High	Medium	Low	8.9	average	bad
Paquishapa	Hydro	Good	192.4	Low	Low	Low	Medium	26	average	very bad
Uchucay	Hydro	Average	62.16	Low	Low	Low	Low	8.4	good	very bad
Ganancay	Hydro	Good	16.95	Low	Low	Medium	Low	2.29	very good	very bad
San Francisco II	Hydro	Good	69.56	Low	Low	High	High	9.4	very good	very bad
Rircay	Hydro	Good	22.94	Low	Low	High	High	3.1	good	bad
Mandur	Hydro	Good	57.72	Low	Low	Medium	Low	7.8	good	average
Casacay	Hydro	Average	45.14	Low	High	Medium	Low	6.1	very good	good
Chillayacu	Hydro	Good	29.01	Low	High	High	High	3.9	very good	bad
Vivar	Hydro	Good	43.66	Low	High	High	High	5.9	very good	very bad
El Burro	Hydro	Bad	75.48	Low	Low	High	High	10.2	very good	very good
Mira 2	Hydro	Good	353.72	Low	Low	High	Medium	47.8	very good	average
Mira	Hydro	Bad	303.4	Low	Low	High	Medium	41	very good	very good
Guayabal	Hydro	Good	294.52	Low	Low	Low	Medium	39.8	very good	average
El Laurel	Hydro	Good	17.54	Low	Low	Low	Low	2.37	very good	very good
La Concepción	Hydro	Good	23.46	Low	Low	Medium	Low	3.17	good	good
Chinambi	Hydro	Good	37	Low	Low	Low	Low	5	very good	very bad
Palmar	Hydro	Average	57.72	Low	Low	Medium	Low	7.8	very good	very bad
Chilma	Hydro	Good	175.38	Low	Low	Low	Medium	23.7	average	very bad
Mariano Acosta	Hydro	Average	12.43	Low	Low	Medium	Low	1.68	good	very bad
Negro (2)	Hydro	Good	266.4	Low	Low	High	High	36	bad	very bad

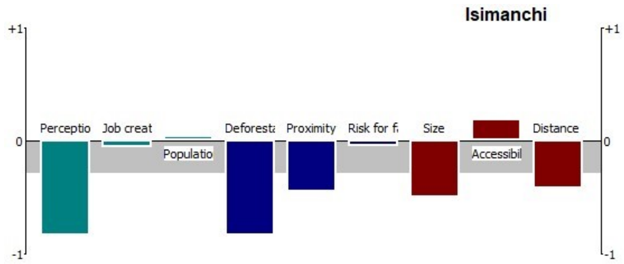
Name	Type	Project perception	Job creation Jobs/MW	Displ. of people	Deforestation	Proximity to natural reserves	Threat to fauna and wildlife	Size MW	Accessibility	Distance to transmission lines
Tululbi	Hydro	Good	11.84	Low	Low	Low	Low	1.6	good	very bad
Puniyacu	Hydro	Good	263.44	Low	Low	Low	Medium	35.6	very good	very bad
Bravo Grande	Hydro	Good	74	Low	Low	High	High	10	very bad	very bad
Lachas	Hydro	Good	44.4	Low	Low	Low	Low	6	good	very bad
Gualleturo	Hydro	Good	204.98	Low	Low	High	Medium	27.7	good	good
M.J. Calle	Hydro	Good	10.66	Low	Low	Medium	Low	1.44	good	average
Lucarquí	Hydro	Good	65.12	Low	Low	High	High	8.8	very good	good
Solanda	Hydro	Average	22.2	Low	Low	High	High	3	very good	good
Mirador 1	Hydro	Good	8.51	Low	High	High	High	1.15	good	very bad
Río Luis 2	Hydro	Good	8.36	Low	Low	Medium	Low	1.13	good	bad
Chuquiraguas	Hydro	Average	17.39	Low	High	Medium	Low	2.35	good	very bad
Echeandía bajo 2	Hydro	Good	62.16	Low	Low	Low	Low	8.4	very good	very bad
Balsapamba	Hydro	Average	59.94	Low	Low	Low	Low	8.1	good	very bad
Blanco 2	Hydro	Average	59.2	Low	High	Low	Low	8	very good	very bad
Alausí	Hydro	Good	55.5	Low	Low	Low	Low	7.5	very good	very good
Rayo	Hydro	Good	55.5	Low	Low	Medium	Low	7.5	very good	very good
Chanchán	Hydro	Good	54.02	Low	Low	Low	Low	7.3	very good	very bad
Pucayacu	Hydro	Good	35.52	Low	Low	High	High	4.8	very bad	very bad
Chimbo Guaranda	Hydro	Good	28.12	Low	Low	Low	Low	3.8	good	good
Campo Bello	Hydro	Good	12.58	Low	Low	Medium	Low	1.7	very good	bad
Monte Nuevo	Hydro	Good	19.98	Low	Low	Medium	Low	2.7	good	average
Salunguire	Hydro	Average	12.58	Low	Low	Low	Low	1.7	very good	very bad
Río Zamora	Hydro	Good	3,016	Low	Low	Low	Medium	2,320	very bad	very bad
Santiago G8	Hydro	Good	4,680	Low	Low	Low	Medium	3,600	good	very bad
Ligua-Muyo	Hydro	Bad	221	High	Low	High	High	170	very good	good

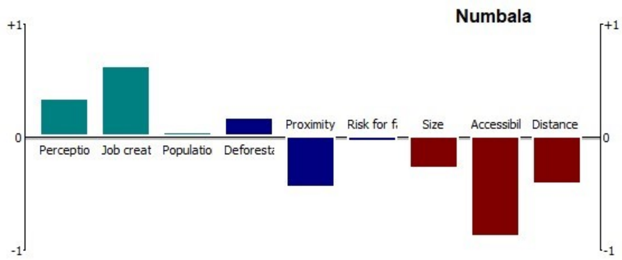
Name	Type	Project perception	Job creation Jobs/MW	Displ. of people	Deforestation	Proximity to natural reserves	Threat to fauna and wildlife	Size MW	Accessibility	Distance to transmission lines
Victoria 2	Hydro	Good	185	Low	Low	High	Medium	25	very good	very good
Chespi Real	Hydro	Bad	598	High	Low	High	High	460	very bad	bad
Tortugo	Hydro	Good	261.3	High	Low	High	High	201	average	very good
Tufiño-Chiles Cerro Negro	Geothermal	Bad	580.8	Low	Low	High	Medium	330	very good	very bad
Chachimbiro	Geothermal	Good	313.28	Low	Low	High	Medium	178	very good	average
Chalupas	Geothermal	Good	498.08	Low	Low	High	Medium	283	bad	very bad
Jamanco	Geothermal	Good	45.76	Low	Low	High	High	26	very good	very good
Chacana Cachiyacu	Geothermal	Good	146.08	Low	Low	High	High	83	very good	good
El Aromo	Solar	Good	793.33	Low	Low	Low	Medium	200	very bad	average
PV-Residential	Solar	Good	0.13	Low	Low	Low	Low	0.003	very good	very good
Villonaco II	Wind	Good	47.53	Low	Low	High	Low	46	very good	average
Villonaco III	Wind	Good	55.8	Low	Low	High	Low	54	very good	average
Minas de Huascachaca	Wind	Good	51.67	Low	Low	High	Low	50	very good	very bad

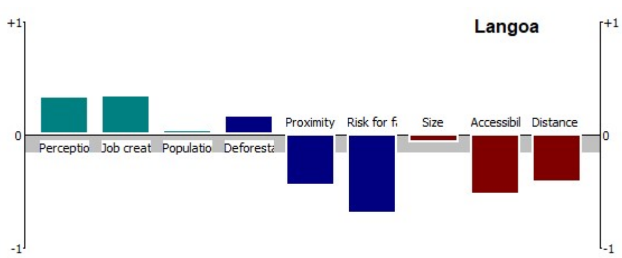
Appendix B

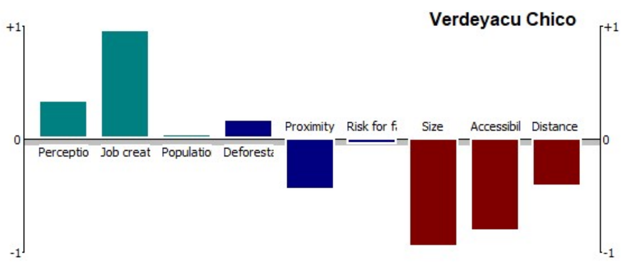
Alernatives profiles after the MCA

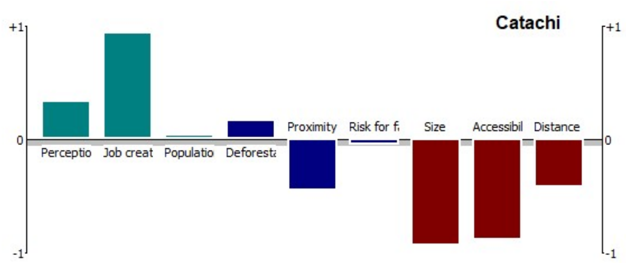
The following figures display the outcomes for each of the 101 analyzed power plants subsequent to the Multi-Criteria Analysis. The Y-axis represents the net preference flow (Phi), ranging from +1 to -1. A positive Phi indicates successful passage of the MCA, whereas a negative Phi signifies the project's failure to meet the MCA criteria.

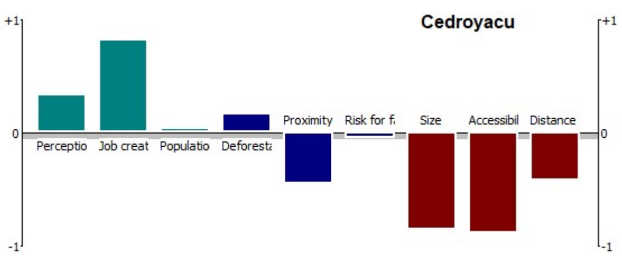


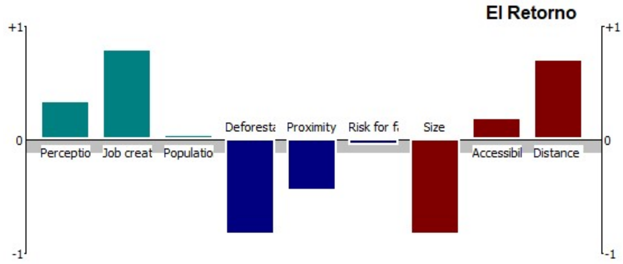


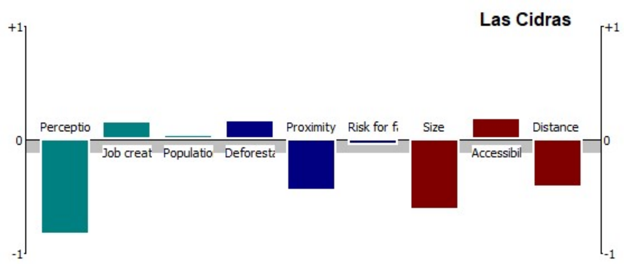









El Retorno
+1
0
-1
Perceptio
Job creat
Populatio
Deforesta
Proximity
Risk for f
Size
Accessibil
Distance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Size
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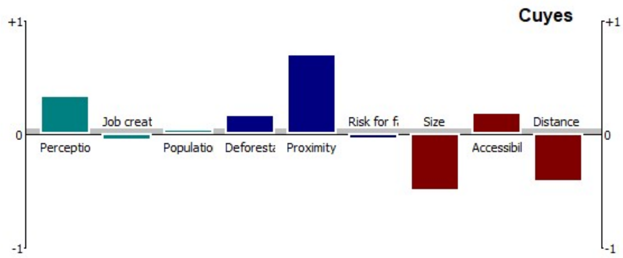
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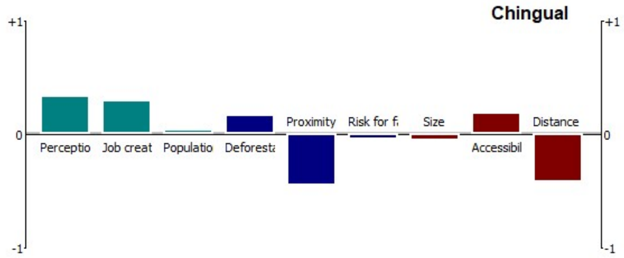
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Size
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Distance


La Barquilla
+1
0
-1
Perceptio
Job creat
Populatio
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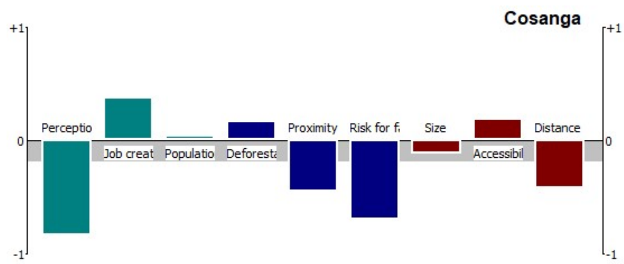
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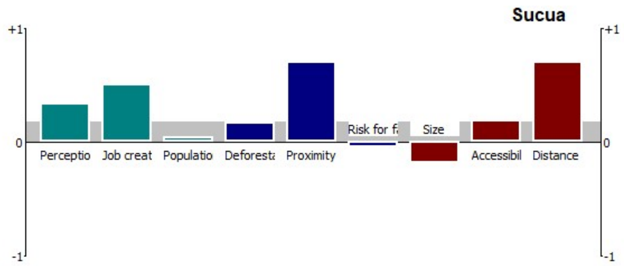
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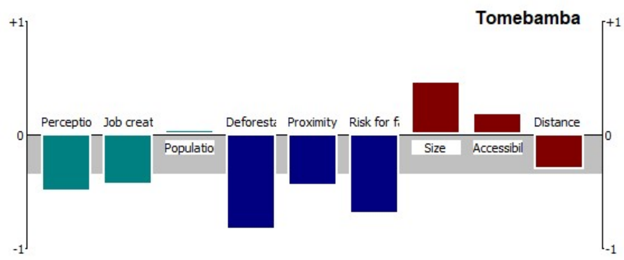
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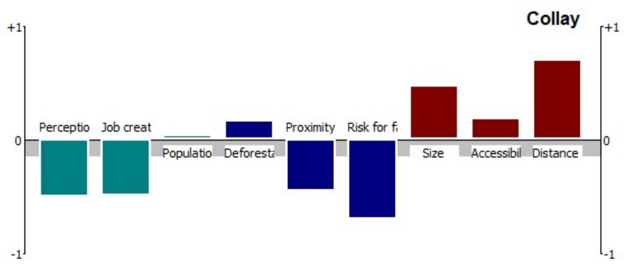
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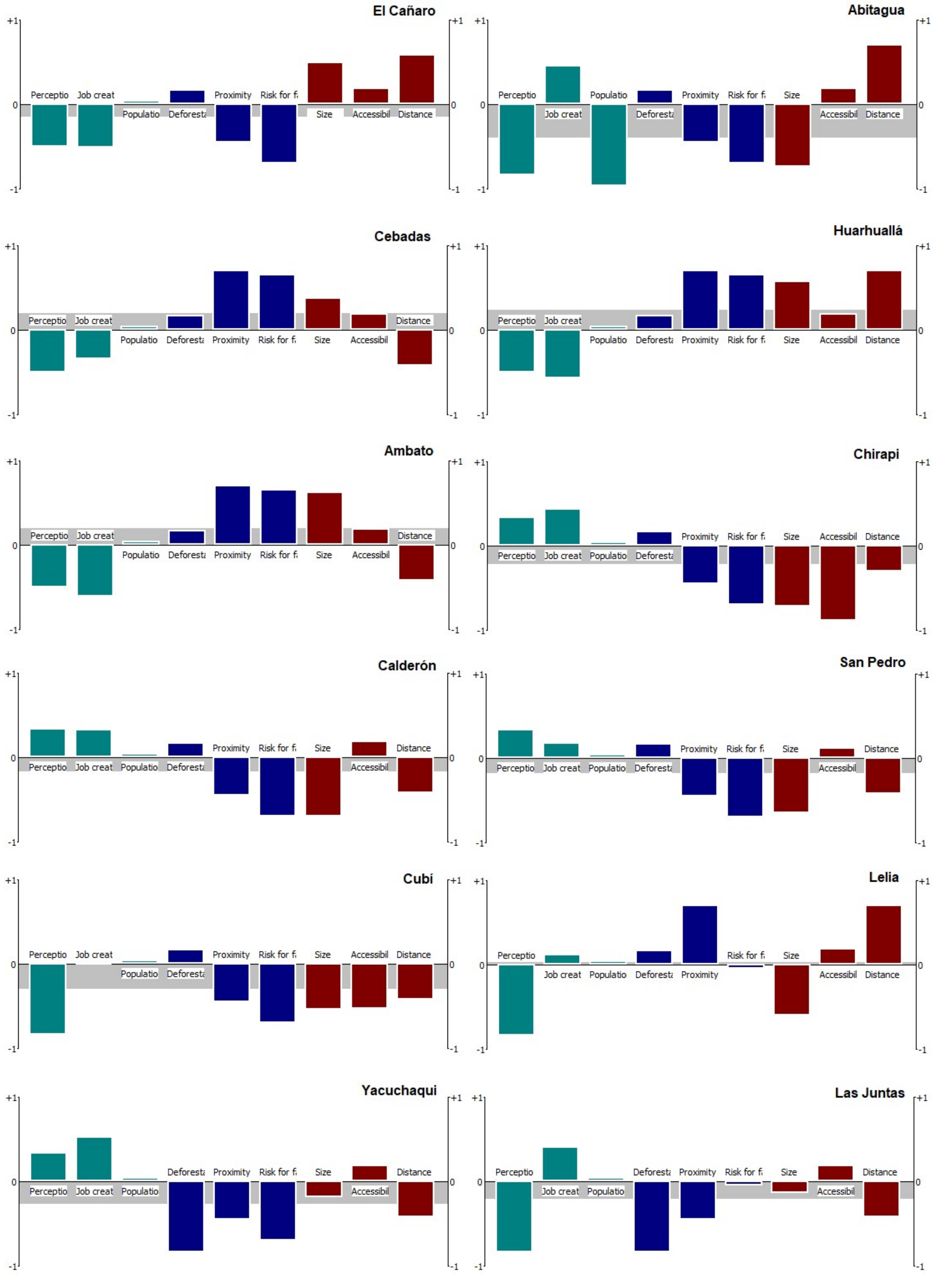
El Cañaro
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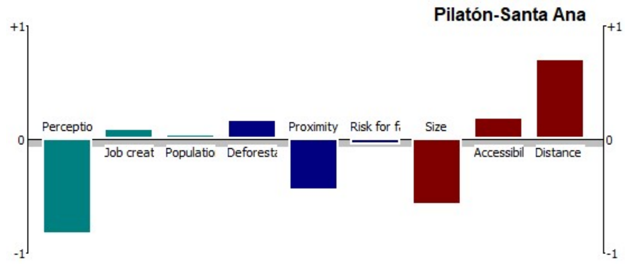
Cebadas
Huarhuallá
Ambato
Chirapi
Calderón
San Pedro
Cubí
Lelia
Yacuchaqui
Las Juntas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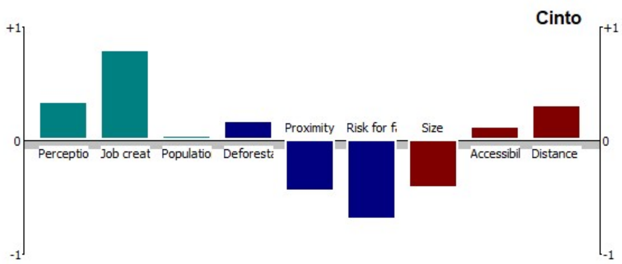
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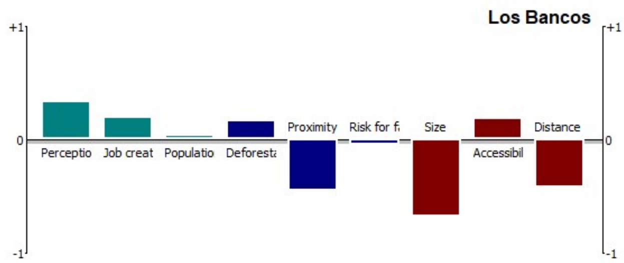
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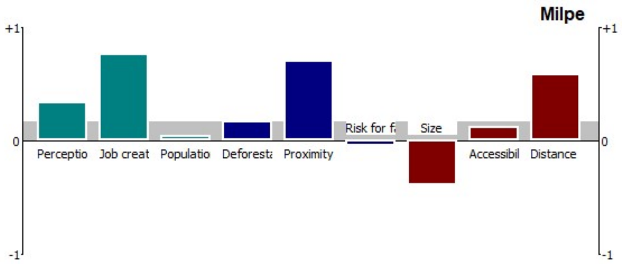
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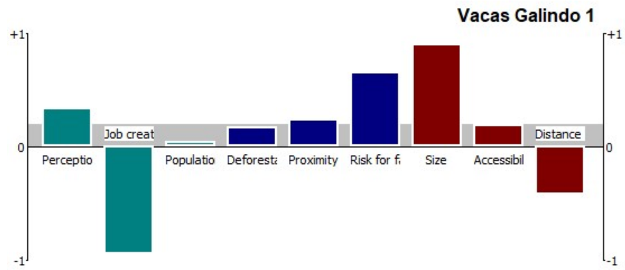
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Size
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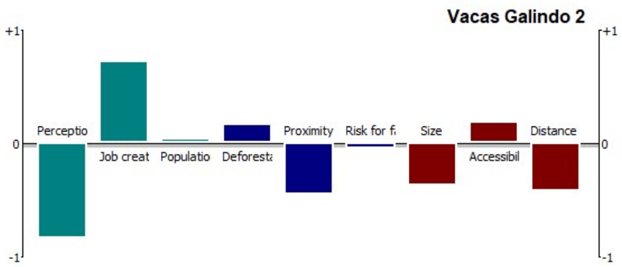
Vacas Galindo 2
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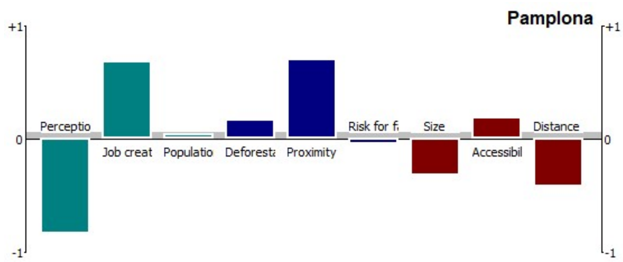
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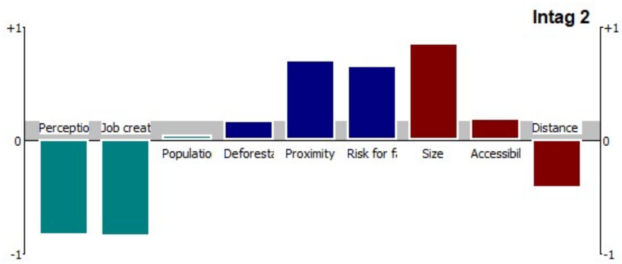
Intag 2
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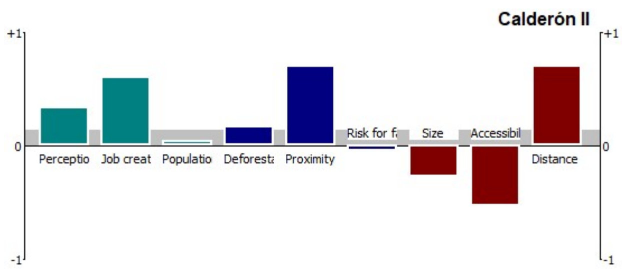
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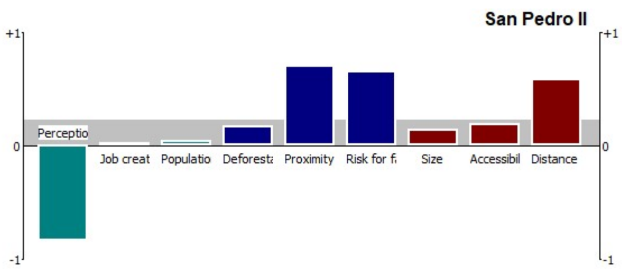
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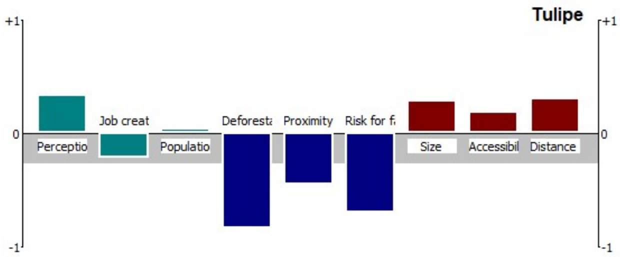
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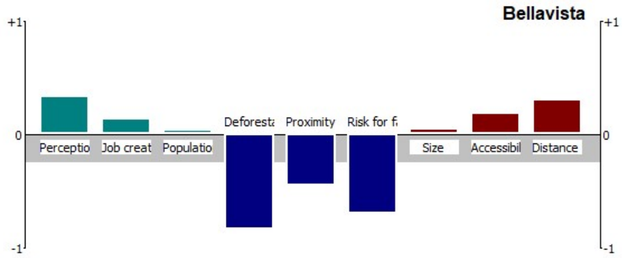
Bellavista
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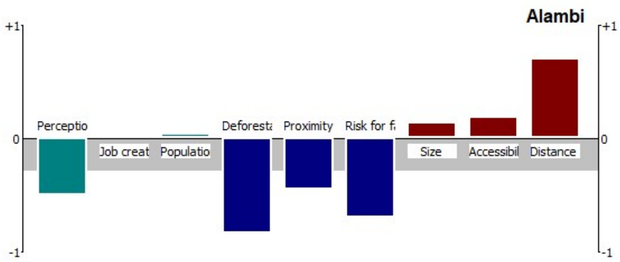
Alambi
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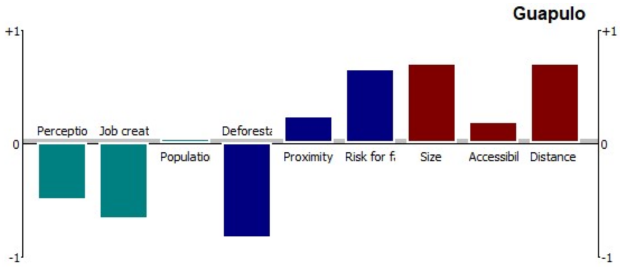
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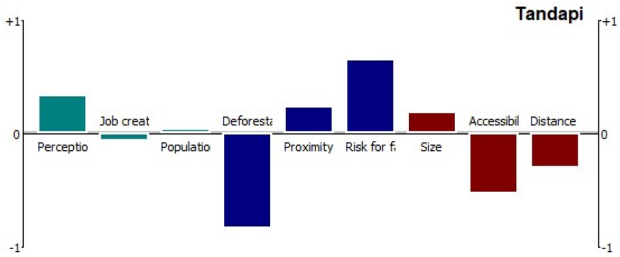
Tandapi
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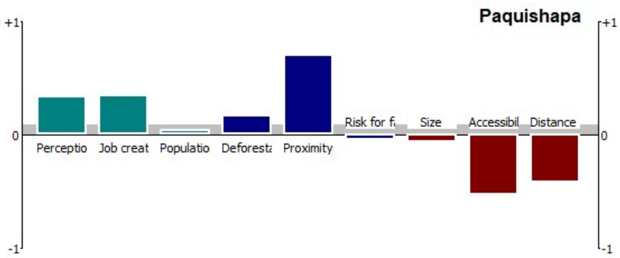
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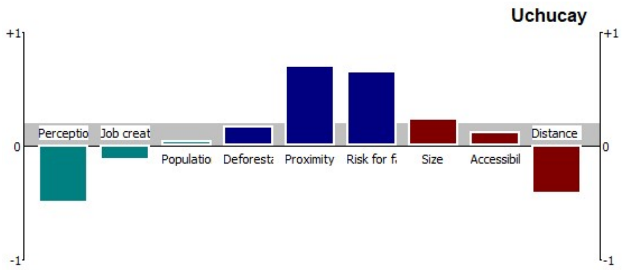
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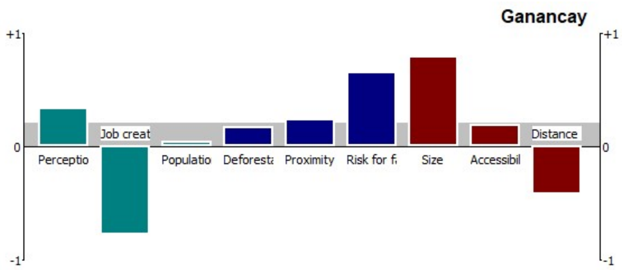
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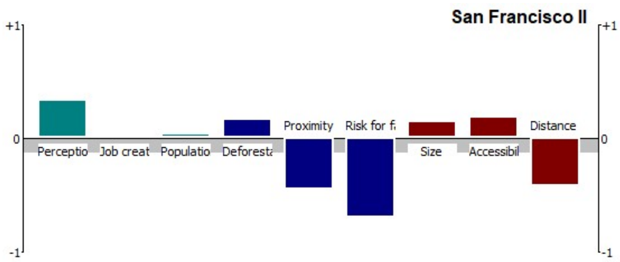
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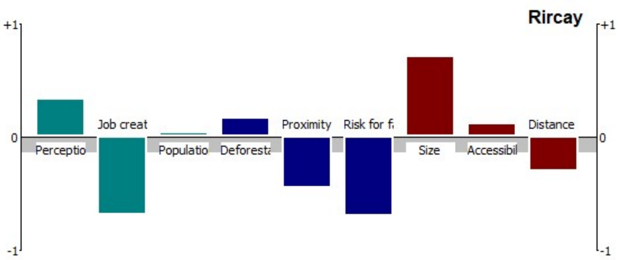
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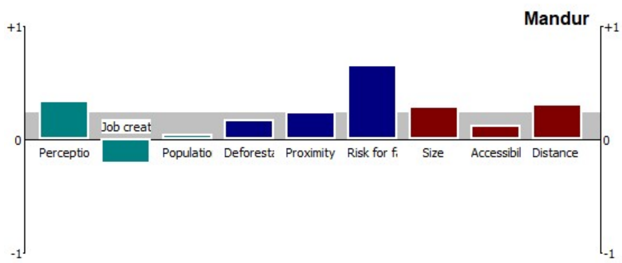
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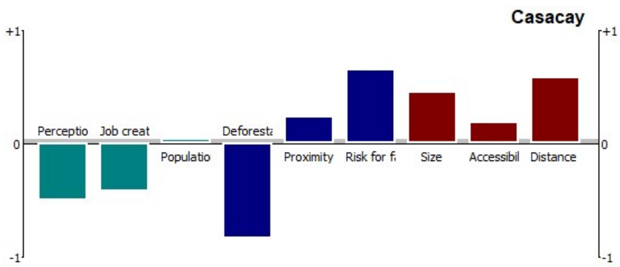
Casacay
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-1
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Proximity
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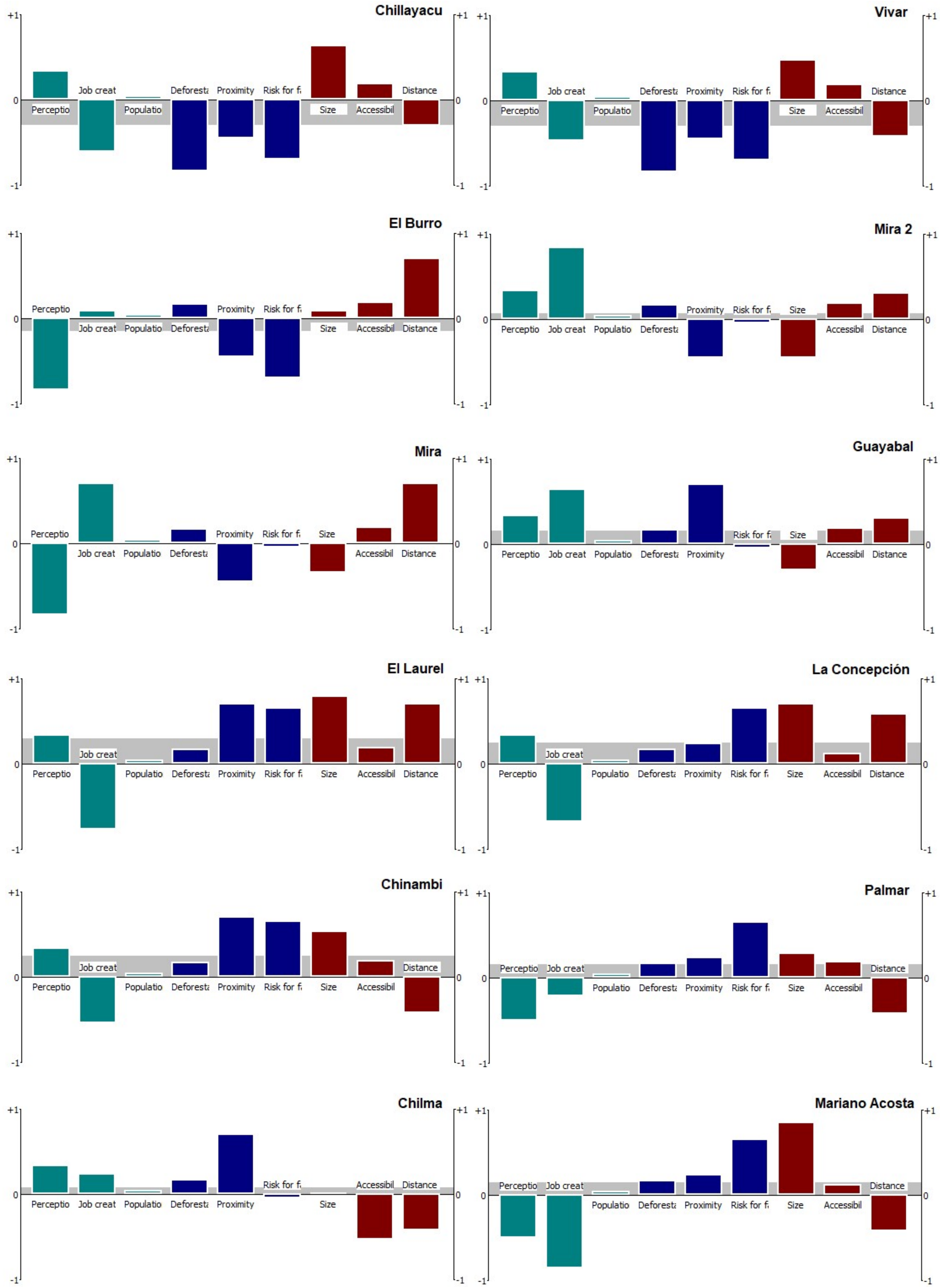
Size
Accessibil
Distance


Chillayacu
Vivar
El Burro
Mira 2
Mira
Guayabal
El Laurel
La Concepción
Chinambi
Palmar
Chilma
Mariano Acosta
Perceptio
Job creat
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Proximity
Risk for fa
Size
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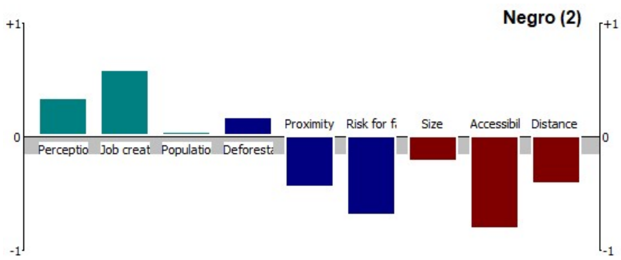
Distance
+1
0
-1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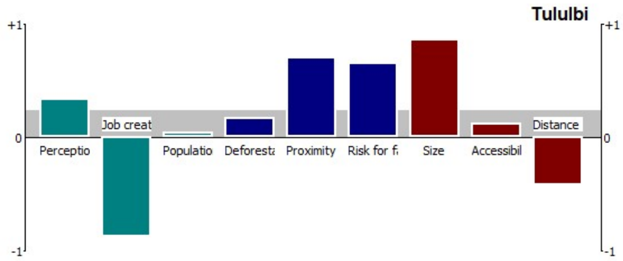
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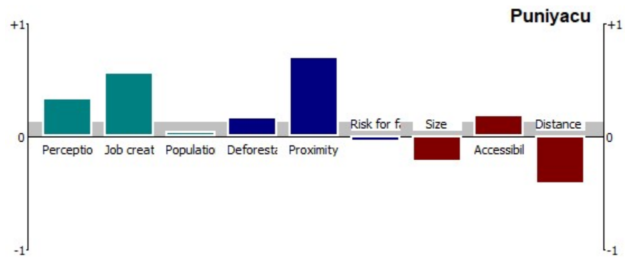
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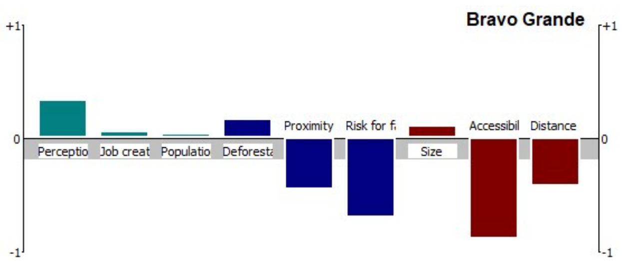
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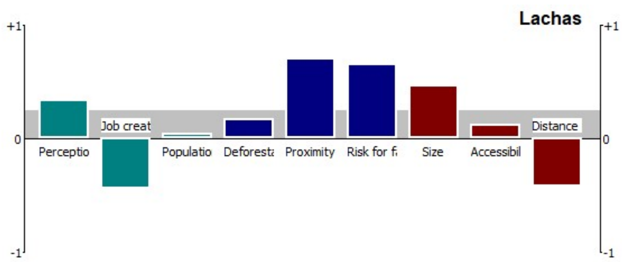
Lachas
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Gualleturo
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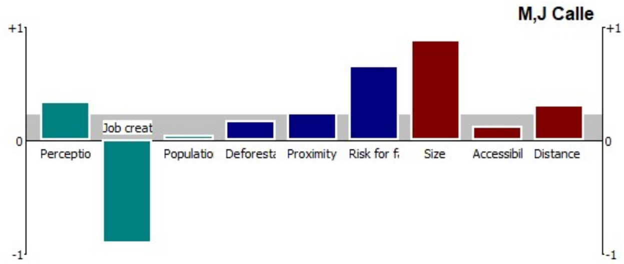
M,J Calle
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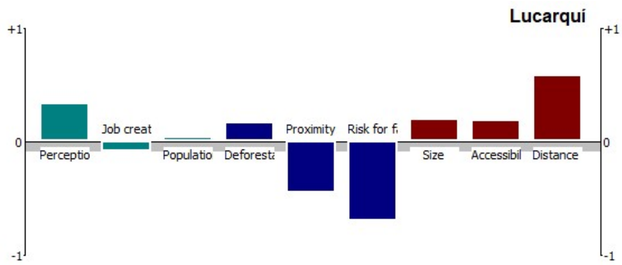
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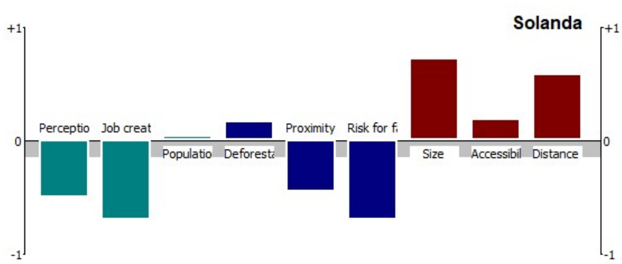
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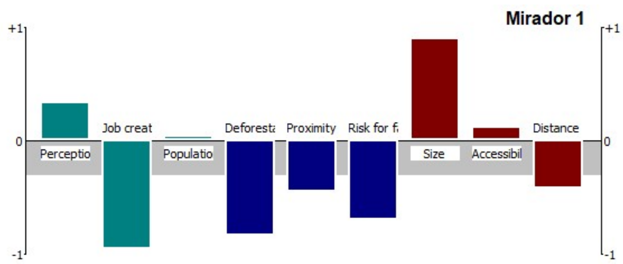
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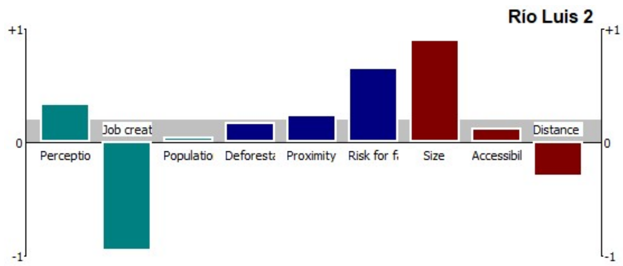
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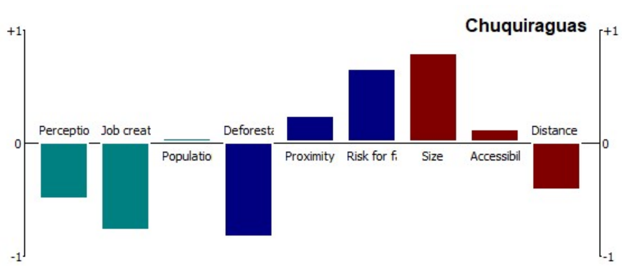
Chuquiraguas
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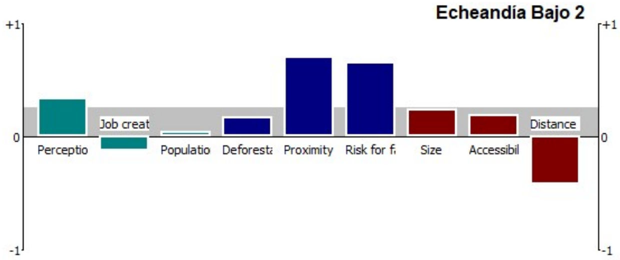
Echeandía Bajo 2
+1
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-1
Perceptio
Job creat
Populatio
Deforest
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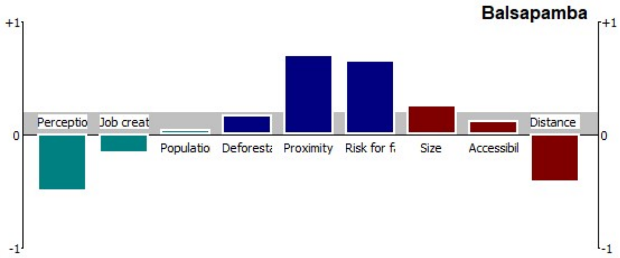
Balsapamba
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-1
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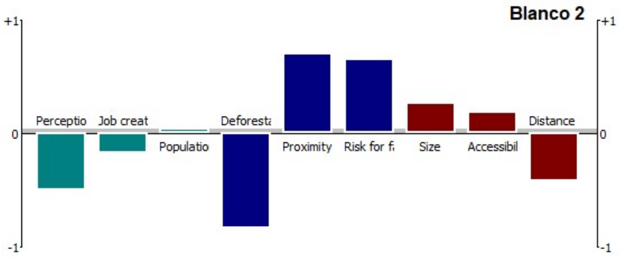
Blanco 2
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Populatio
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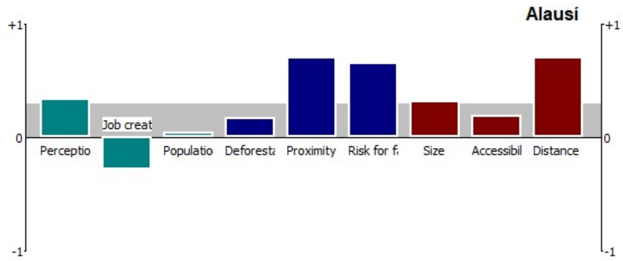
Alausí
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-1
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Job creat
Populatio
Deforest
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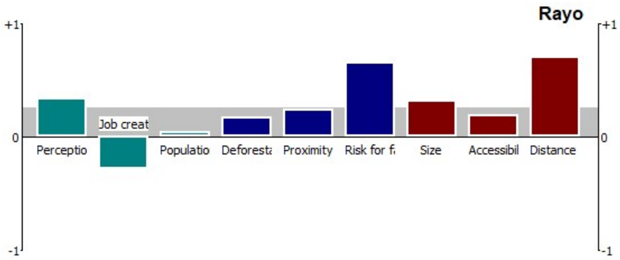
Rayo
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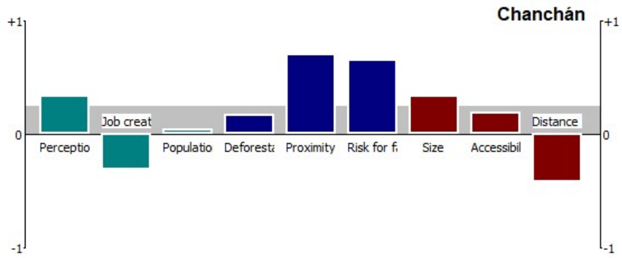
Chanchán
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-1
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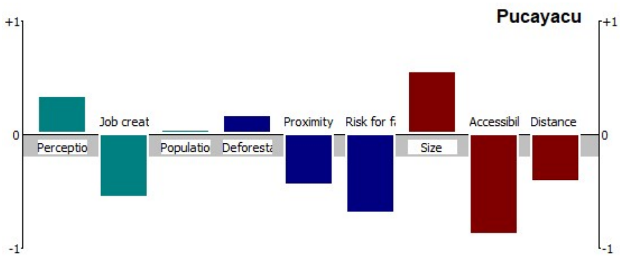
Pucayacu
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-1
Perceptio
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Deforest
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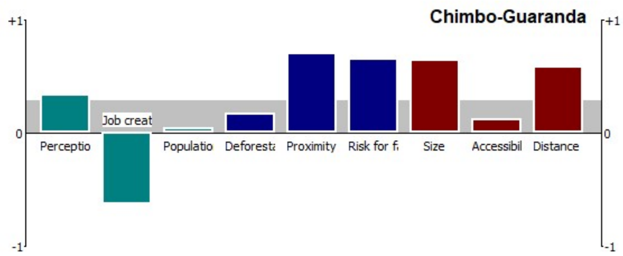
Chimbo-Guaranda
+1
0
-1
Perceptio
Job creat
Populatio
Deforest
Proximity
Risk for f
Size
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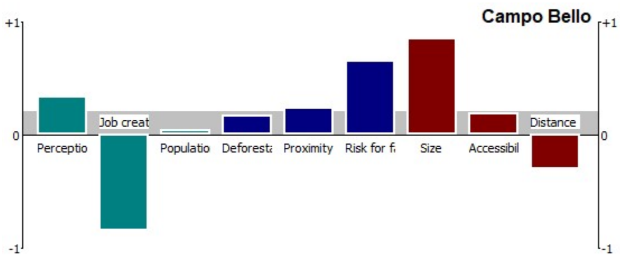
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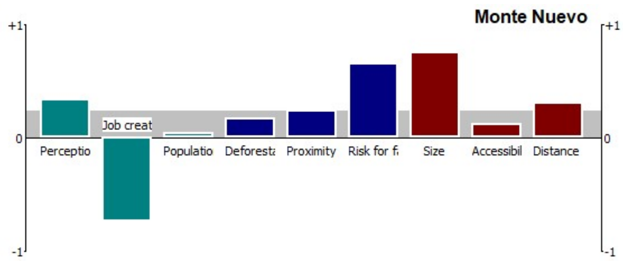
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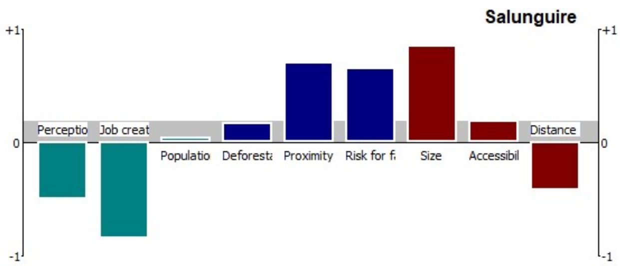
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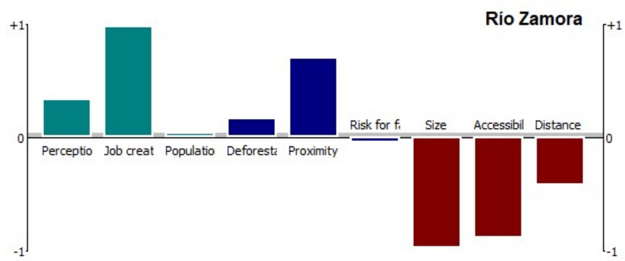
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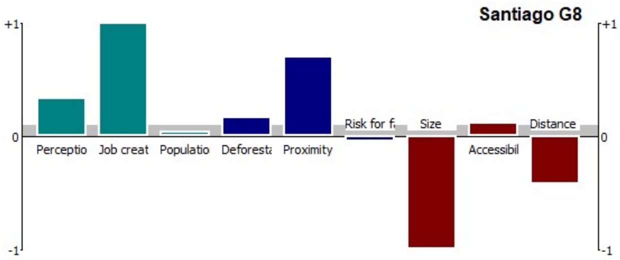
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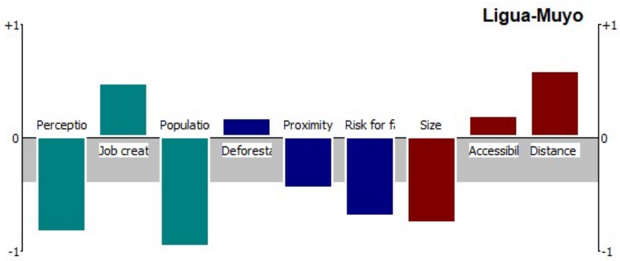
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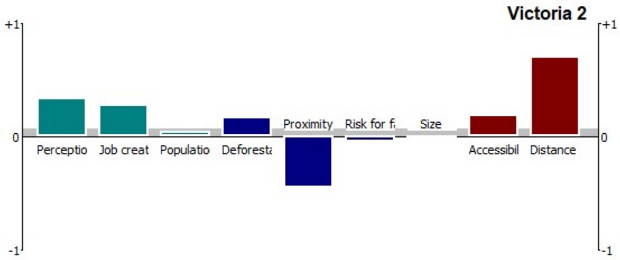
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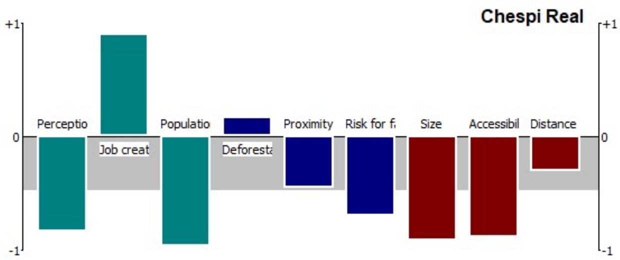
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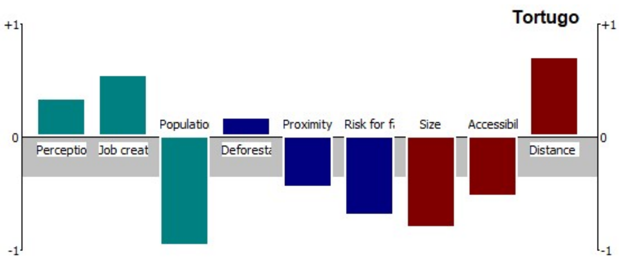
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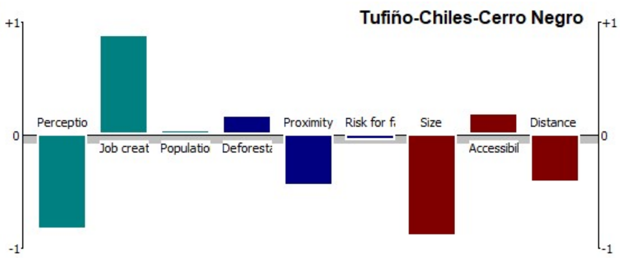
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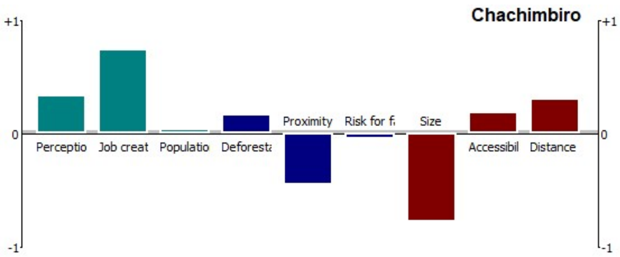
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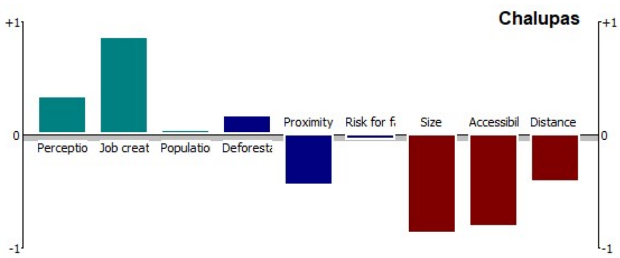
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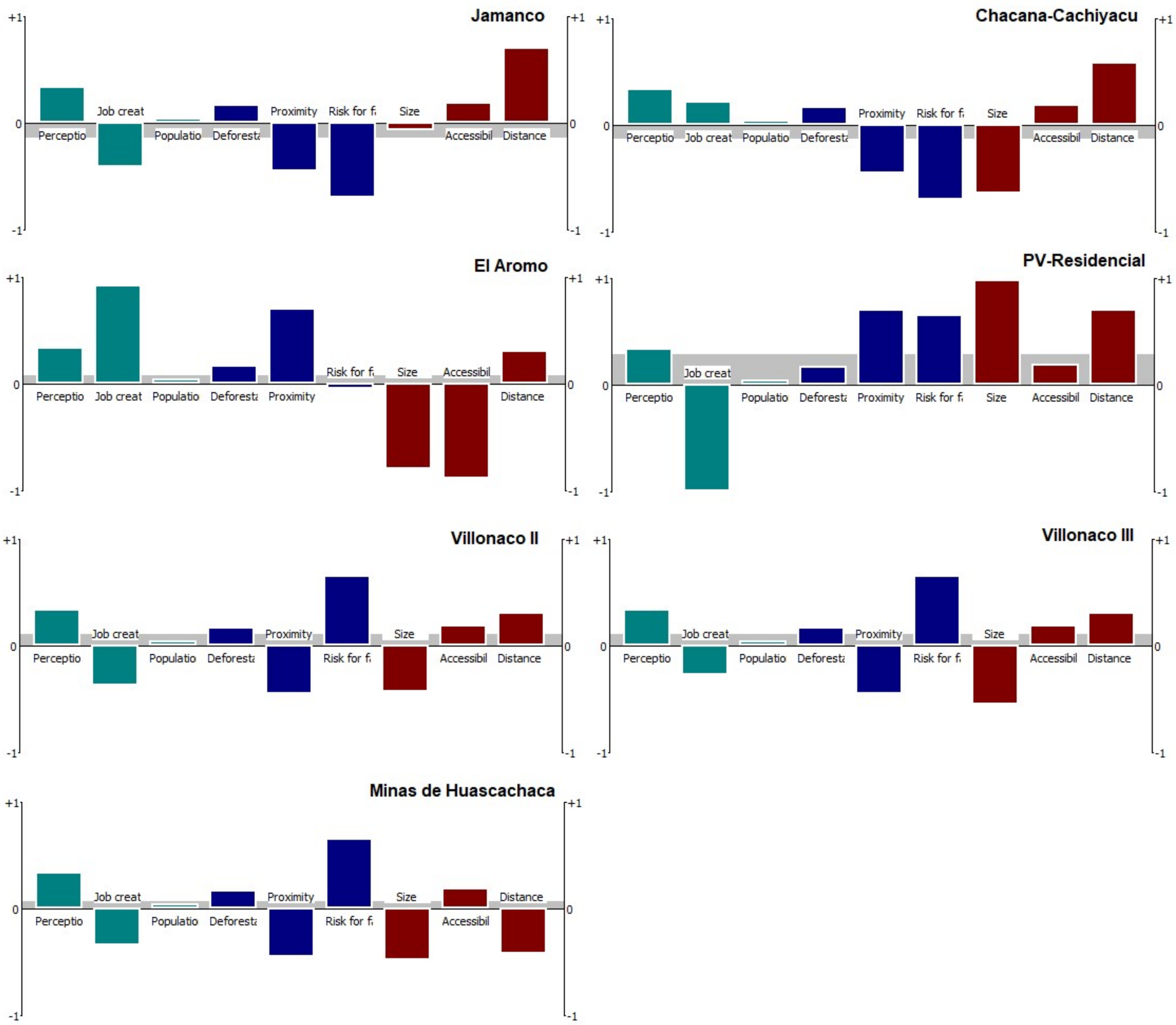
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Appendix C

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