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Multi-Criteria Analysis of Regional Collaboration for Lithium-Ion Battery and Electric Vehicle Production in Paraguay

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Abstract: Lithium-ion batteries are essential for electric vehicles, requiring critical resources such as lithium and cobalt. Paraguay's integration into the electric vehicle supply chain presents an opportunity to leverage its renewable energy and strategic location. This study evaluates potential partners for Paraguay to establish a lithium-ion battery and electric vehicle assembly plant in the Chaco region. A multi-criteria decision analysis using the Analytic Hierarchy Process and expert opinions assessed Argentina, Brazil, Bolivia, and Chile based on economic, energy, environmental, social, political, and geopolitical factors. The results indicate Chile as the most favorable partner (29.5%), followed by Argentina (25.9%), Bolivia (22.8%), and Brazil (21.6%). Chile's strengths lie in its environmental policies and political stability, while Argentina offers logistical advantages and resource availability. The findings highlight strategic pathways for Paraguay's integration into the electric vehicle supply chain and the importance of targeted collaboration to enhance regional lithium-ion battery production and commercialization.

Keywords: electric vehicle; lithium-ion; electric mobility; regional integration

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1. Introduction

Energy is an essential resource for humans, but major energy sources are predicted to become scarce in the coming years as a result of population growth [1]. Fossil fuels currently supply approximately 84% of global energy consumption, with oil accounting for 33.05% in 2019, natural gas for 24.20%, and coal for 27.30% [2]. This heavy reliance on fossil fuels exerts significant pressure on their availability. Although these resources continue to form naturally, their regeneration occurs at an extremely slow rate compared to the speed at which they are consumed [3].

The rapid urbanization and growth of the fossil fuel-dependent vehicle fleet not only imposes a serious impact on human life and the environment, but also on the environment [2], but also underscores the vulnerability of the global economy to price fluctuations and geopolitical risks associated with potential future energy crises [4]. In response to climate change and the urgent need to reduce greenhouse gas emissions, governments and organizations worldwide are actively seeking sustainable alternative resources across multiple sectors, with transportation being a primary focus due to its significant contribution to global emissions [5,6].

The transportation sector relies on fossil fuels more than any other industry and is therefore a major contributor to CO_2 emissions [1]. Electric vehicles (EVs) are widely regarded as a key solution for reducing greenhouse gas emissions and energy consumption in transportation [7]. Their growing adoption is driven by sustained public policy support worldwide and plays a crucial role in achieving climate change mitigation and transport diversification objectives [8].

In this context, electric mobility has emerged as a promising solution, not only for its potential to reduce environmental impact, but also for its ability to reshape the economic and energy landscape of countries that effectively implement this technology [6,8].

Paraguay is strategically located in the center of South America, placing it in a unique position to capitalize on the transition to electric mobility. The country generates 100% of its electricity from hydroelectric sources, creating a favorable environment for the development of electromobility [6,9]. This comparative advantage in clean energy production can not only meet the growing domestic demand for EVs but also position Paraguay as a key player in the regional electromobility value chain.

Additionally, Paraguay benefits from a privileged geographical location, with connections through the Bioceanic Route and the Paraná–Paraguay Waterway, which facilitate trade and regional logistics. These infrastructures enhance economic integration with neighboring countries such as Brazil, Argentina, Chile, and Bolivia while also offering Paraguay the potential to become a logistics hub for the distribution of EVs and related components in the region [10].

However, despite these advantages, Paraguay faces significant challenges in integrating into the electric mobility value chain. Keys areas requiring attention include the development of the regulatory framework, financing mechanisms, information availability, market supply and demand, as well as incentives and infrastructure. Strengthening these aspects is essential to fostering and enabling environment for the adoption and growth of electric mobility [11]. Additionally, competition with other regional countries seeking to establish themselves in this emerging market adds complexity to Paraguay's national strategy.

This study aims to identify the opportunities for Paraguay to integrate into the electric mobility supply chain in South America, focusing on its energy, geographic, and political advantages. It will analyze potential strategies for developing a local EV industry, emphasizing the importance of regional collaboration and the integration of advanced technologies.

A methodological approach will be employed, combining a review of the existing literature, analysis of secondary data, and validation of the results through a panel of experts to ensure their robustness.

By providing an analytical framework, this research seeks to enhance knowledge on electromobility in Paraguay, offering valuable insights for policy makers, the private sector, and other stakeholders interested in promoting the sustainable and competitive development of electric mobility. Successfully integrating electric mobility into the supply chain could not only diversify the Paraguay's economy but also position the country as a regional leader in the transition to a low-carbon economy.

2. Literature Review

The study builds upon prior research that explores the opportunities for the EV supply chain in South America's Gran Chaco region [12]. The existing literature examines the stages of the EV supply chain, the primary actors involved, and the extent of South American countries' participation in this global industry. However, limited research has focused on strategies to enhance regional integration and value-added production.

2.1. EV Supply Chain Findings

The global EV industry relies on a complex supply chain divided into three key stages: upstream (raw material extraction), midstream (component production and distribution), and downstream (battery and vehicle assembly) [13,14]. Key stakeholders include material and component suppliers, original equipment manufacturers (OEMs), distributors, consumers, recyclers, and energy providers, who are strategically positioned across the supply chain [15]. Notably, the production of battery cells and other critical components is often concentrated in a few regions, with battery assembly typically occurring near final EV assembly to minimize transportation costs [16].

In the upstream stage, companies such as *Sociedad Química y Minera (SQM) de Chile*, Pilbara Minerals, and Allkem dominate lithium and nickel production. The midstream stage is led by Asian manufacturers like Sumitomo, Tianjin B&M Science Technology, and Ningbo Shanshan in the production of cathodes and anodes. Meanwhile, firms such as CATL, LG Energy Solution, and Panasonic lead in battery pack production, while Tesla, VW Group, and BYD are major players in EV manufacturing and sales [14].

2.2. South America's Role in the EV Supply Chain

South America's primary contribution to the EV supply chain lies in the extraction and production of lithium, with Chile, Argentina, and Bolivia playing a crucial role in supplying this key raw material [16].

- Chile, the world's second-largest lithium producer, has well-established operations through companies like Albemarle and SQM in the Atacama region. As a strategic supplier for battery manufacturing, Chile is investing in higher-value activities such as lithium hydroxide and cathode production through partnerships with companies like SQM and LG Energy Solution. Additionally, the country is exploring battery recycling initiatives to enhance sustainability in the EV industry, positioning itself for deeper integration into the electromobility supply chain [17].
- Argentina hosts more than 38 projects at various stages of development, attracting foreign investments [16]. The country is gradually transitioning to electric mobility through policies like the Mesa de Vehículos y Movilidad Alternativa and the Estrategia Nacional de Movilidad Eléctrica, supported by the UN Environment Programme. Legislative efforts, such as the Régimen de Fomento para el Desarrollo y Utilización de Vehículos Eléctricos, aim to regulate EV production and adoption. Despite limited incentives, EV sales grew by 32.7% in early 2024, with models like the Coradir Tito and Renault Kwid E-Tech gaining traction. Investment is rising, with BYD planning an electric bus factory in Buenos Aires, signaling steady progress towards sustainable mobility [18].
- The Bolivian government is promoting the transition to clean energy through tax incentives established in Supreme Decree 4539, support for distributed energy generation under Supreme Decree 4477, and green financing. Additionally, over 10 charging stations have been installed in key cities, with regulations in place for their operation. Despite its vast lithium reserves, Bolivia needs greater investment and technology transfer to establish itself in the global EV value chain [19].
  However, Bolivia is making strides in electromobility with Quantum Motors, which exports EVs to several countries, and Quantum Batteries, the region's first private lithium battery pack factory. With a 3000 kWh per shift production capacity, it supplies both local and international markets [20].
- Brazil also plays a significant role in the battery supply chain, contributing 2% of global lithium production and substantial shares of graphite (7%) and nickel (3%) [21]. The country leads Latin America in low-emission bus manufacturing, producing hybrid, biofuel, electric, and hydrogen fuel cell buses. Its well-established internal combustion bus supply chain could facilitate a transition to electric bus production. However, the lack of large-scale battery manufacturing makes Brazil reliant on imports and vulner-

able to supply risks. Companies like BYD, Eletra, Marcopolo, and Mercedes-Benz manufacture electric buses domestically, but challenges remain, including competition from Chinese manufacturers and an underdeveloped regulatory framework for low-emission public transport [22].

Studies highlight South America's potential to move into higher-value stages. Chile, with its well-developed lithium industry, could serve as a foundation for expanding into battery cell production [19]. Additionally, regional collaboration is identified as a key strategy. Brazil has advantages in component manufacturing, while proposals suggest Bolivia and Paraguay could jointly produce lithium-ion batteries and EVs, leveraging Bolivia's natural resources and Paraguay's hydroelectric energy surplus [20].

Such initiatives could drive sustainable and innovative advancements, strengthening the region's role in the global EV industry. However, advancing downstream requires strategic policies and investments to develop industrial capabilities, where the production scale is crucial for competitiveness. These countries must focus on understanding the critical determinants guiding multinational automotive companies' expansion—whether they seek resources, markets, efficiency, or strategic assets [21].

Current analyses on EV manufacturing in South America often focus on domestic production, reflecting a nationalistic approach to vehicle and electric bus manufacturing. A clear example is Brazil, which, given its advanced industrial capabilities, has prioritized the local production of electric buses rather than regional integration. While this inward-looking strategy may be logical for countries with a high level of industrial complexity, such as Brazil, it is less viable for nations like Bolivia and Paraguay, which have more limited manufacturing capacities. In this context, productive integration and regional cooperation are not only relevant but essential for developing a competitive EV industry that leverages the unique strengths of each country.

Despite previous advancements, there is still a critical gap in collaborative models that could enable South America to transition from a raw material supplier to a key player in the battery and EV industry.

This study proposes a regional approach to developing an integrated supply chain, identifying the best partnerships to establish a battery and EV assembly hub in Paraguay and strengthen South America's role in the global EV industry.

2.3. Identified Criteria

Ref. [12] identified several strategic criteria relevant to assessing regional opportunities for industrial participation:

- Geopolitical: Proximity to mining operations, availability of mineral resources for batteries, accessibility to transportation networks, and governance structures.
- Economic and financial: Cost factors such as labor wages, corporate tax rates, equipment and maintenance expenses, skilled labor availability, materials, construction, and electricity costs.
- Political: Political stability index, measured by a country's political protests and violence.
- Energy and environmental: Carbon footprint of energy production, availability of resources associated with energy production, damage to human health, and impact on biological ecosystems.
- Demographic: Population growth, fertility rates, and youth demographics.
- Knowledge and innovation: Volume of scientific publications, citation impact, graduates in the areas of science, engineering, production and construction, and human capital index.

Evaluating environmental, social, political, economic, energy, and geopolitical factors is essential to identifying the right conditions for collaboration in EV and battery manufacturing, ensuring a competitive position in the global value chain.

3. Materials and Methods

This study employs a mixed-method approach, integrating both qualitative and quantitative data to comprehensively address the research problem. By combining numerical analysis with expert insights, this methodology provides a holistic perspective, enabling a structured and thorough evaluation of potential collaboration opportunities for establishing a battery and EV assembly plant in Paraguay.

Moreover, the study follows both a descriptive and an exploratory approach. On one hand, it seeks to define the properties, characteristics, and profiles of different countries based on specific criteria.

On the other hand, its exploratory nature stems from the limited research on this topic in Paraguay, as demonstrated by a review of the existing literature. By investigating this emerging issue, the study lays a conceptual foundation that can support future, more in-depth research.

Furthermore, the research design is non-experimental, as it does not involve the deliberate manipulation of independent variables to observe their effects on dependent variables. In addition, it employs a cross-sectional approach, ensuring data comparability by collecting information at a single point in time across all alternatives.

The methodological framework (Figure 1) consists of three clearly defined stages: (i) a systematic literature review, (ii) structuring and application of the AHP model, including expert interviews, and (iii) sensitivity analysis and interpretation of results.

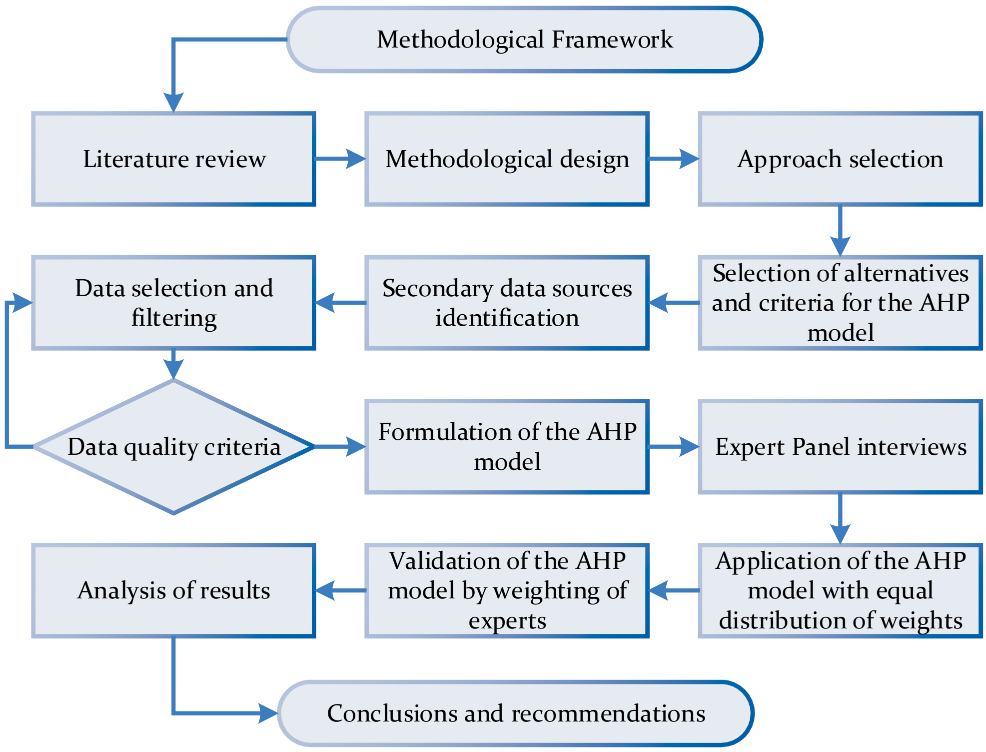

Figure 1. Methodological framework.

3.1. First Stage: Literature Review

To formulate the methodological design, a literature review was conducted, focusing on contributions from the South American region to the EV supply chain. The review aimed to identify existing research gaps and establish the foundation for selecting the criteria and alternatives evaluated in the AHP model. The need to explore this topic in Paraguay was reinforced by the lack of prior studies on the country's integration into the EV industry.

3.2. Second Stage: Structuring for the AHP Application and Interviews with a Panel of Experts

The study applies the Analytical Hierarchy Process (AHP), a widely recognized multi-criteria decision-making method that allows the structuring of complex problems into a hierarchy of attributes for systematic comparison [23].

The AHP model was structured based on a literature review and official sources (Figure 2).

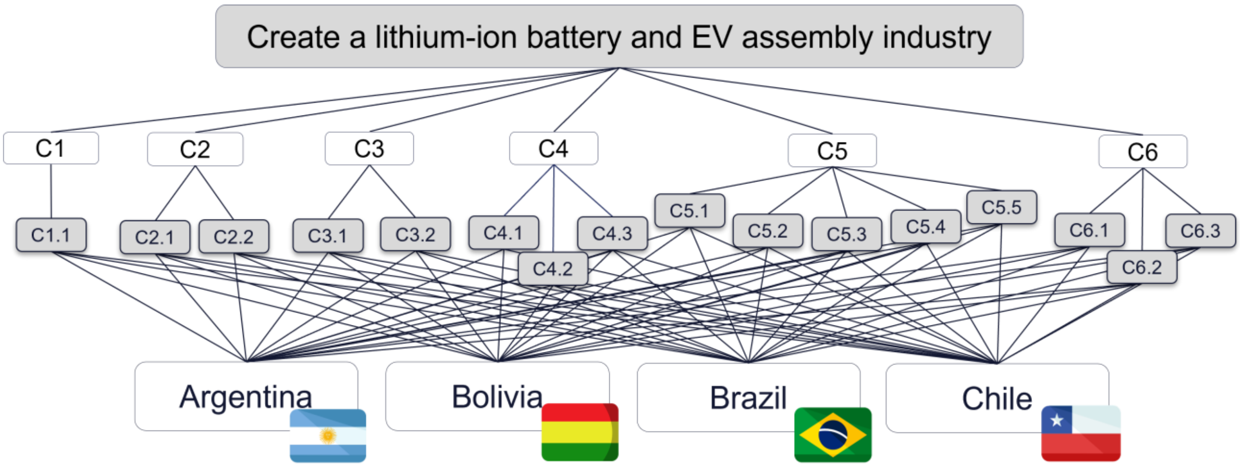

Figure 2. Hierarchical structure of the AHP model.

Table 1 shows that a total of six criteria and 16 sub-criteria were selected to evaluate four alternatives that meet the objective of "Create a lithium-ion battery and EV assembly industry", through the importation of lithium-ion cells from one of the countries considered as alternatives, to the location of the plant in Paraguay.

Table 1. Selection of sub-criteria for use in the AHP model.

Criteria	Sub-Criteria	Indicator	Desirable Direction
Economy	Transportation cost	Cost related to fuel consumption (USD) per kilometer traveled	↓
Energy	Final electricity consumption	Kilowatt hours per capita (kWh/inhab.)	↑
	Access to electricity	Proportion of the population with access to electricity (%)	↑
Environment	Low-emission energy mix	Proportion of renewable energy sources (%)	↑
	Manufacturing sector emissions	Kilograms of CO_2 per constant USD	↓
Social	Unemployment rate	Percentage of population not employed (%)	↓
	Human capital index (HCI)	Score on a percentage scale (%)	↑
	Level of compliance with labor rights	Score on a numerical scale (units)	↑
Political	Ease of doing business	Score on a numerical scale (units)	↑
	Political stability	Score of a standard normal distribution	↑
	Government effectiveness	Score on a numerical scale (units)	↑
	Regulatory quality	Score on a numerical scale (units)	↑
	Corruption control	Score on a numerical scale (units)	↑
Geopolitical	Policy Perception Index	Score on a numerical scale (units)	↑
	Mineral Potential Index	Score on a numerical scale (units)	↑
	Lithium resources	Estimated lithium in kt (thousand tons)	↑

Note: the "desirable direction" column indicates whether the indicator value, such as annual tons of CO_2, should increase (↑) or decrease (↓) to approach the most preferable option.

The evaluation focused on four collaboration alternatives for lithium-ion cell imports: Argentina, Bolivia, Brazil, and Chile.

Secondary data for the sub-criteria were sourced from international repositories (Table 2). To ensure consistency and minimize potential biases from temporal discrepancies, the selection process prioritized data from the most recent year in which comparable information was available for all countries.

Table 2. International database used for the analysis.

Dimension	Database
Economic	Google Maps (2024).
Energy and Environment	Ministry of Energy and Mining of the Argentine Republic (2020); Ministry of Hydrocarbons and Energy of the Plurinational State of Bolivia (2020); Ministry of Mines and Energy of the Federative Republic of Brazil (2020); Ministry of Energy of the Republic of Chile (2020); United Nations (UN) (2021).
Social	UN (2021 and 2022), World Economic Forum (2017).
Political	World Bank Group (2022).
Geopolitical	Survey Of Mining Companies 2020, Geological Survey (2024).

Note: These databases were used to obtain criteria data used for analysis in the model.

Expert Panel

Element preference is determined based on informed judgments about the relative importance of each element compared to others. These judgments are based on experience, available data, in-depth knowledge of the problem, and the intuition of experts in the field.

To validate the model and assign weights to the AHP criteria, semi-structured interviews were conducted with an expert panel. This panel comprised professionals specializing in technical-, economic-, social-, environmental-, and energy-related domains, ensuring a multidisciplinary perspective in the decision-making process. Experts were selected based on their experience in industrial and energy sector decision-making and their contributions to regional projects.

Subsequently, nine semi-structured interviews were conducted with a panel of experts to provide collective and consensual judgments on the research, contributing to the validation of the proposed analytical model. This panel comprised professionals specializing in technical, economic, social, environmental, and energy domains (Table 3).

Table 3. Participation of organizations in the semi-structured interviews.

Affiliation	Description	Areas of Expertise
Vice Ministry of Mines and Energy	Responsible for establishing and guiding policies on the use and management of mineral and energy resources. It conducts technical, economic, financial, and legal studies to promote the industrial utilization of the country's available resources.	Technical Energy Economic Political
Parque Tencológico Itaipu Paraguay (PTI)	An initiative of *ITAIPU Binacional* aimed at promoting human development through science, technology, and innovation.	Technical Energy
Administración Nacional de Electricidad (ANDE)	State-owned company responsible for generating, transmitting, distributing, and commercializing electric power in the Republic of Paraguay.	Technical Energy
Comisión Nacional de la Competencia (CONACOM)	Safeguards and promotes free market competition to foster economic development for the benefit of society.	Economic
Youth Advisory Group, United Nations (UN)	Provides the Secretary-General with practical, outcome-oriented advice, diverse youth perspectives, and concrete recommendations, with a strong emphasis on accelerating the implementation of the climate action agenda.	Environmental Social

Table 3. *Cont.*

Affiliation	Description	Areas of Expertise
Yacimientos de Litio Bolivianos (YLB)	Drives the industrialization of evaporite resources from Bolivia's salt flats and lagoons.	Technical
ATOME Paraguay	Leading developer of international green fertilizer projects.	Energy Economic
Private company for renewable energies	Focused on providing energy solutions through the application of renewable energy technologies, contributing to energy efficiency and sustainability in all processes.	Economic Energy

The interviews followed a multi-dimensional psychological scaling approach based on pairwise comparisons, enabling a structured assessment of subjective judgments. This process facilitated the assignment of relative importance to the AHP criteria and sub-criteria.

Following the formulation and structuring of the AHP model, its application was implemented.

3.3. Third Stage: Application of the AHP Model

To assign values, a simplified version of the AHP pairwise comparison table, ranging from 1 to 6, was used (Table 4). In this method, each criterion is compared against another, and if both are considered equally important, a value of 1 is assigned. However, if one criterion is significantly more important than the other, a value of 6 is assigned.

Table 4. The simplified AHP comparison scale.

Verbal Scale	Equally Preferable	Moderately Preferable	Between Moderately and Strongly Preferable	Strongly Preferable	Very Strongly Preferable	Extremely Preferable
Numerical Scale	1	2	3	4	5	6

The AHP model was initially applied under the assumption of equal importance among all criteria (Table 5). This equal weighting was also applied to the sub-criteria.

Table 5. Comparisons between criteria using the simplified AHP comparison scale, equal weighting.

Criteria	Economy	Energy	Environment	Social	Political	Geopolitical
Economy	1	1	1	1	1	1
Energy	1	1	1	1	1	1
Environment	1	1	1	1	1	1
Social	1	1	1	1	1	1
Political	1	1	1	1	1	1
Geopolitical	1	1	1	1	1	1

Subsequently, the expert panel's comparisons evaluations were incorporated to adjust the weightings, where they rated the importance of each criterion according to the pairwise comparison (Table 6). In this analysis, while the criteria were assigned different weights, the sub-criteria remained equally weighted.

Table 6. Comparisons between criteria using the simplified comparison scale, expert panel weighting.

Criteria	Economy	Energy	Environment	Social	Political	Geopolitical
Economy	1	3	5	6	2	3
Energy	1/3	1	3	4	1/4	1
Environment	1/5	1/3	1	2	1/3	1/3
Social	1/6	1/4	1/2	1	1/4	1/3
Political	1/2	4	3	4	1	2
Geopolitical	1/3	1	3	3	1/2	1

Table 7 shows the weights that represent the extent to which the criteria will impact the analysis of each scenario.

Table 7. Final criteria weights for each scenario.

Criteria	Equal Weights	Expert Panel Weights
Economy	16.7%	36.4%
Energy	16.7%	13.6%
Environment	16.7%	6.6%
Social	16.7%	4.6%
Political	16.7%	25.0%
Geopolitical	16.7%	13.8%

A sensitivity analysis was performed to assess the robustness of the results by examining variations in outcomes based on different weight assignments. This analysis ensures the model's reliability across different scenarios and enhances the validity of the conclusions. Finally, the findings were analyzed to formulate strategic recommendations for Paraguay's role in the EV industry, emphasizing the most viable collaboration model for establishing a battery and EV assembly hub.

4. Results

4.1. Participation Opportunities

Paraguay has great potential to promote and take advantage of electric mobility due to its favorable conditions. Thanks to its abundant production of renewable energy, through the hydroelectric power plants of *ACARAY*, *ITAIPU*, and *YACYRETA*, the country is positioned as the largest per capita producer of clean energy in the world [24].

Despite Paraguay's potential to be a key player in the EV supply chain, support remains limited, with efforts relying mainly on the Paraguay 2030 Development Plan (2014), the Electric Mobility Master Plan (2023), and policies like Law No. 6925/2022 on electric transport incentives (2022).

The Paraguay 2030 Development Plan identifies that Paraguay's sustainable development will depend on taking advantage of its renewable energy as an engine to boost the economy, promoting industrialization and transforming the energy consumption matrix in the transportation sector towards the use of clean and renewable energy. Similarly, studies such as [24] suggest that allocating Paraguay's hydroelectric surpluses to the development of industrial clusters is an effective strategy.

With the implementation of the Electric Mobility Master Plan for Urban Public Transport and Logistics in Paraguay (PMME), the country could position itself as a leader in electric mobility in Latin America, by achieving a significant transformation of its public transport fleet, cabs, and delivery vehicles towards electric options [25].

To support these goals, Paraguay has established a policy of tax incentives and trade agreements to promote the production and assembly of vehicles, such as Law No. 6925/2022, "On incentives and promotion of electric transport in Paraguay", which seeks to promote electric transport in Paraguay, establishing a regulatory framework that regulates and encourages its adoption through tax incentives, tax exemptions, and public policies for the production and assembly of vehicles and auto parts, with the aim of promoting zero-emission transport throughout the country.

However, successful implementation of the initiatives also depends on adequate transportation infrastructures, which plays a crucial role in industrial location, as highlighted by previous studies [25].

Paraguay's location in this regard is strategic due to logistical corridors such as the Bioceanic Route that connects the Atlantic with the Pacific through Brazil, Paraguay, Argentina, and Chile, promoting regional trade. This corridor facilitates Paraguay's integration into international supply chains by improving access to Eastern (Asia) and Western (Europe) markets [26]. Paraguay, by improving its infrastructure and connecting to this route, can benefit from the flow of products through its territory, increasing exports and imports and, therefore, regional economic activity.

At the same time, the Paraná–Paraguay Waterway is another key infrastructure that allows the commercialization of Paraguayan products. From north to south, the Paraná–Paraguay Waterway extends from Puerto Cáceres in the state of Mato Grosso, Brazil, to the port of Nueva Palmira in the department of Colonia. There it meets the Uruguay River and together they flow into the Atlantic, through the Rio de la Plata Bay. This river course, 3442 km long, connects Bolivia, Brazil, Paraguay, Argentina, and Uruguay, linking more than 20 cities. The waterway offers significant advantages over land and air transport, such as lower investment and maintenance costs, greater energy efficiency, and a higher carrying capacity [27].

Thanks to these advantages, the waterway has become the main corridor for Paraguay's exports and imports. In addition, more than 90% of the cargo that circulates in the region under the Paraguayan flag transits through this waterway, with annual traffic exceeding 30 million tons. Paraguay has the third largest river fleet in the world, operated by some 46 international and national companies, contributing 2.3% of GDP in services and generating more than 5000 direct jobs [27]. This waterway is crucial for transporting goods, reducing logistics costs and improving the competitiveness of Paraguayan exports.

The combination of the waterway and the Bioceanic Route amplifies Paraguay's capacity to integrate into regional and global value chains, facilitating the efficient transport of products such as raw materials and agricultural products. In this way, Paraguay's centrality in South America marks its strategic regional importance and favors the generation of stable and ever-present links in the most diverse bilateral spheres.

Paraguay thus has strategic resources at its disposal: hydroelectricity and a privileged location.

4.2. Results of the Multi-Criteria Analysis (AHP) Considering Equal Weighting

Since the study started from the premise that all criteria are equally important, i.e., all criteria have the same weight in relation to the objective (Table 5), the prioritization of the alternatives resulted in the following Table (Table 8):

Table 8. Preference of different alternatives considering equal weights.

Alternatives	Preference (%)
Argentina	25.96%
Bolivia	22.84%
Brazil	21.62%
Chile	29.56%

The result showed that Chile is the country with the highest preference over the others, which implies its leadership in several criteria such as environmental and political, and a strong performance in the energy criterion. Close behind Chile is Argentina, which stands out for its economic performance, benefiting from its proximity to the *Chaco Para-guayo*, which facilitates logistics and economic cooperation, as well as its remarkable performance in social and geopolitical criteria; in third place is Bolivia, which, although it showed a favorable performance in social criteria due to its low unemployment rate and good human capital index, its performance in other criteria such as political and energy was less competitive.

Lastly, Brazil, despite having a good mix of low-emission energies, presented a lower performance in criteria such as social and geopolitical, affecting its overall preference in the analysis.

4.3. Results of the Expert Panel

This section presents the results of the expert panel interviews, where the initial assessment determined the percentage importance of each criterion for the analysis.

Figure 3 presents the results of the expert panel interviews, where participants were asked to rank six criteria based on their perceived importance to the study. Instead of assigning specific weights, experts indicated which criteria they would prioritize in a higher position, reflecting their relevance in the analysis. Figure 3 illustrates the percentage distribution of responses, highlighting which criteria were considered the most relevant by the interviewees.

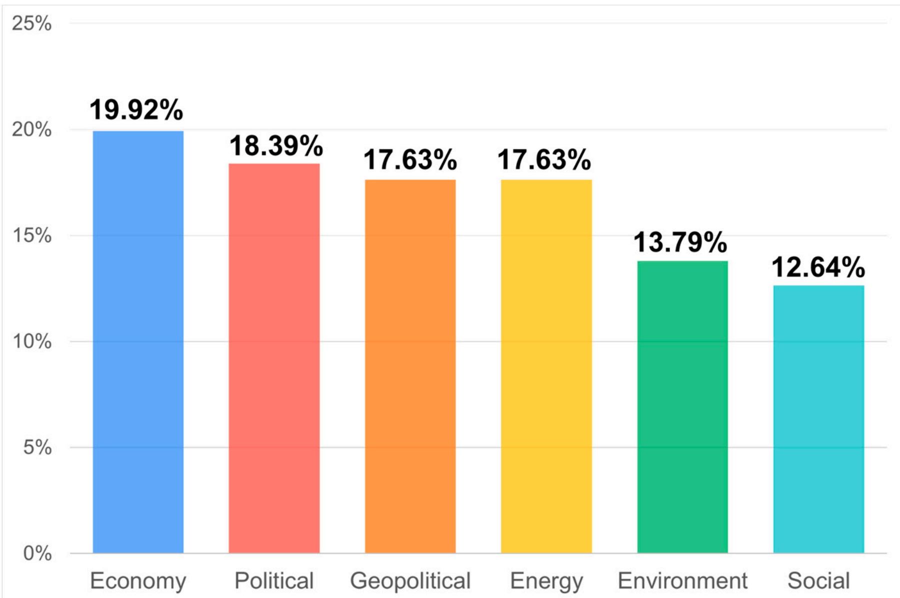

Figure 3. Importance of each criterion according to expert panel.

Additionally, the interviews provided insights into each criterion, reflecting the experts' perspectives and considerations.

4.3.1. Expert Panel Key Findings

According to the panel of experts, in a highly competitive market, economic criteria are fundamental for decision-makers, as they play a crucial role in cost reduction and project viability. Reducing the cost of transporting lithium-ion cells from a country of origin to the lithium-ion battery assembly plant in the Paraguayan Chaco represents a significant reduction in raw material supply costs. However, when considering cell imports, it is suggested to take into account other economic criteria that influence the implementation of these projects.

The assessment of a country's political situation is a determining factor for decision-makers when analyzing international business. A stable political and geopolitical environment is essential for the integration of electric mobility markets. As for the environmental aspect, decision-makers agree that, although it is a key criterion for energy transition projects, the environmental impacts of the energy sources used in Latin America are not yet comparable to those of regions such as Europe, Asia, or the United States and are not considered a priority. On the social side, although the need for a commitment to workers is recognized, decision-makers point out that battery production is an industry that relies heavily on specialized machinery. Since much of the production process is automated, the role of labor is less central compared to other industries. For this reason, the social aspect, although important, tends to be relegated in strategic decisions.

4.3.2. Expert Panel AHP Analysis

In the context of the AHP, when considering the hierarchization of the expert panel's criteria, Table 9 shows that, although the percentages associated with the alternatives vary compared to the initial analysis, the order of priority among the alternatives remains constant. This type of analysis is valuable because it demonstrates the stability of the decision and provides confidence in the results obtained by AHP, even in the face of variations in the experts' opinions on the relative importance of the different criteria.

Table 9. Preference of different alternatives from the expert panel analysis.

Alternatives	Preference (%)
Argentina	28.35%
Bolivia	22.50%
Brazil	19.98%
Chile	29.18%

Chile holds the highest preference (29.18%), emerging as the most favorable option according to the AHP model. Argentina follows closely with 28.35%, showing a value very similar to Chile's. Bolivia and Brazil rank next, with 22.50% and 19.98%, respectively. These results align closely with the previous analysis, as Chile and Argentina consistently score higher in the criteria that experts prioritized. This reinforces their position as the most suitable alternatives for lithium cell imports, regardless of variations in the perception of criteria weights.

4.4. Sensitivity Analysis Varying One Criterion at a Time

When performing the calculations for the criteria preference ratings, the robustness of the result obtained was confirmed, since the change in preferences had a minimal effect on the results. Figure 4 shows the results obtained, where each shaded area represents an alternative and the points of the generated polygon represent the final preferences.

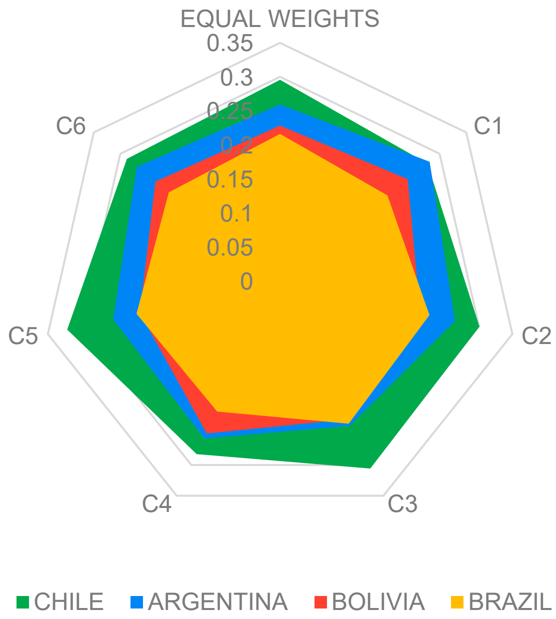

Figure 4. Sensitivity analysis varying one criterion at a time.

The sensitivity analysis shows that Chile is the leader in several key criteria, standing out as the strongest potential partner for Paraguay in the EV supply chain. This leadership is reflected in the economic (C1), energy (C2), environmental (C3), social (C4), political (C5), and geopolitical (C6) criteria, where Chile maintains a prominent position. The figure illustrates how the preferences of each criterion affect each country, showing a stability in the relative positions despite changes in the criteria weights.

Argentina also presents itself as a competitive candidate due to its economic (C1) and geopolitical (C6) strengths, suggesting that its proximity and natural resources are determining factors in its high performance.

Bolivia and Brazil show lower robustness in several criteria compared to Chile and Argentina. Brazil, in particular, has a remarkable performance in the environmental criterion (C3) due to its sustainability policies, but its low preference in the economic and geopolitical criteria reduces its overall competitiveness. Bolivia, on the other hand, although it has strengths in certain criteria, its overall performance is less competitive due to its lower scores on key criteria such as economic and political.

Thus, the sensitivity analysis confirms that the results obtained are consistent and robust, identifying Chile and Argentina as the strongest partners for Paraguay in the creation of an EV industry, with Chile leading in most of the criteria evaluated. Figure 4 clearly illustrates these relationships, showing how each country is positioned in relation to the different criteria evaluated.

4.5. Sensitivity Analysis Varying Two Criteria at a Time

In the second sensitivity analysis, two criteria were varied at the same time, keeping the others fixed. The calculations showed the robustness of the result obtained, since the change in preferences had a minimal effect on the results.

Figure 5 shows that Chile is the leader in several key criteria, once again standing out as the strongest potential partner for Paraguay in the EV supply chain.

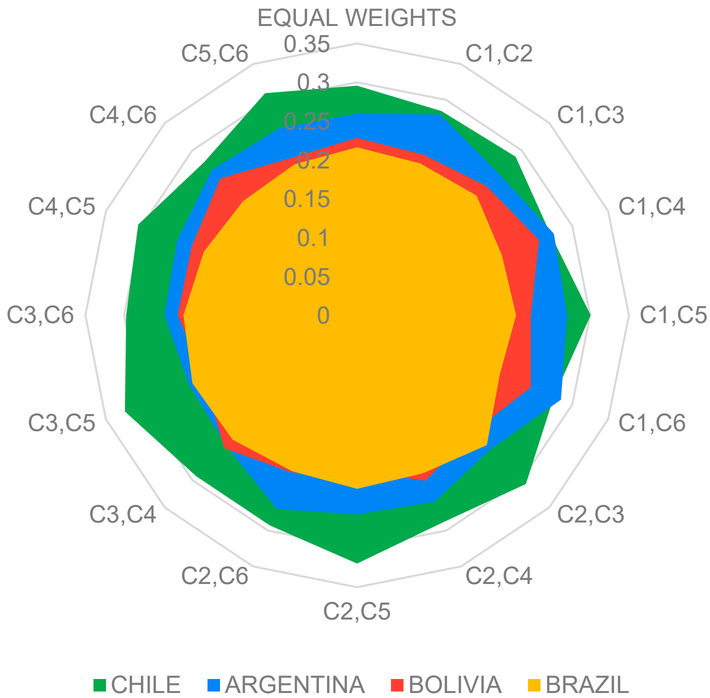

Figure 5. Sensitivity analysis varying two criteria at a time.

Argentina maintains its position in most scenarios, again showing strengths in several combinations due to its economic (C1) and geopolitical (C6) strengths, surpassing Chile as the strongest partner.

Bolivia and Brazil again show lower robustness in several criteria in comparison with Chile and Argentina.

In summary, the sensitivity analysis confirms that the results obtained are consistent and robust, identifying Chile and Argentina as the strongest partners for Paraguay in the creation of an EV industry, with Chile leading in most of the criteria evaluated.

This means that the choice of alternative is fairly stable, but under certain specific conditions reflected in the unlikely minority scenarios, the priorities are reversed.

In the scenario where social and environmental criteria are prioritized, Bolivia surpasses Argentina for the first time, ranking second after Chile. This outcome is noteworthy but represents an unlikely decision-making scenario, as experts indicate that these criteria are typically deprioritized in favor of economic, political, and geopolitical considerations. Bolivia performs well in key social sub-criteria such as unemployment rate, labor rights compliance, and the human capital index, positioning it as the most favorable country in social terms. While it does not lead in environmental aspects, it still ranks ahead of Argentina in this scenario. However, for Bolivia to become a truly viable option, it would need to improve in areas that decision-makers prioritize, such as economic and political stability, as these factors tend to have greater weight in real-world strategic decisions.

The findings of the sensitivity analysis are important because it proves that in most scenarios the decision based on the initial weights is reliable and we can also determine critical scenarios or aspects of the problem where a variation could lead to a different decision.

5. Conclusions

The transition to electric mobility represents a strategic and unprecedented opportunity for Paraguay, a country with a vast production of renewable energy and a geographical location that positions it favorably in the South American context.

Throughout this research, the opportunities for Paraguay to integrate into the electric mobility value chain in the region have been identified and analyzed, emphasizing its intrinsic strengths to capitalize on these advantages.

First, the evaluation of Paraguay's participation in the regional electric mobility value chain has shown that the Bioceanic Route and the Paraná–Paraguay Waterway are highly relevant logistical assets. These corridors not only improve connectivity and facilitate trade with neighboring countries, but also enhance Paraguay's capacity to become a regional distribution hub for EVs and related components.

Paraguay's strategic location, coupled with its abundant renewable energy potential and the presence of lithium in the region, positions it as a key player for EV production. The combination of a privileged geographical position and a clean energy matrix creates an ecosystem conducive to a sustainable and competitive electric mobility industry.

In order to take advantage of these favorable resources for Paraguay's insertion in the EV supply chain, criteria were identified to evaluate alternatives for the creation of an EV industry in Paraguay. A multi-criteria decision analysis was then carried out using the AHP tool, allowing a systematic evaluation of six fundamental criteria: economic, energy, environmental, social, political, and geopolitical, in order to prioritize the alternatives and determine the best strategic allies to achieve this objective. This type of analysis can also be applied to other countries, serving as a reference for similar evaluations. Additionally, it is a highly flexible methodology that allows the incorporation of other criteria and indicators, making it adaptable to different contexts and research needs.

The AHP results revealed that Chile is the most favorable partner for Paraguay, leading in most of the criteria evaluated. The strong preference for Chile is due to its environmental commitment, reflected in its high percentage of renewable energy and low CO_2 emissions, as well as its political stability and key role in the region's energy development. In energy and environmental terms, Chile is the most suitable partner to boost Paraguay's integration into the EV value chain, providing a solid foundation for the sustainable development of this industry.

On the other hand, Argentina also presents itself as a strategic partner for Paraguay, although with different characteristics than Chile. Argentina stands out not only for its geographic proximity, which facilitates logistics and trade, but also for its potential in the supply of key natural resources, such as lithium, an essential mineral in the production of batteries for EVs.

Although its environmental profile is not as strong as Chile's, Argentina also offers important advantages in infrastructure and connectivity, especially in the transportation of products to regional and international markets. These factors make Argentina an important ally for strengthening the EV supply chain in Paraguay, particularly in terms of access to resources and optimization of trade routes.

Bolivia and Brazil did not achieve the same level of preference as Chile and Argentina in this evaluation phase. Bolivia presented challenges in some energy and political aspects, while Brazil stood out for its strengths in environmental aspects. However, its performance on social and political criteria was not as strong as in the other countries evaluated. These results highlight the need to continue developing these aspects to improve their competitiveness in future regional integration opportunities.

On the other hand, Paraguay, with its total electricity production from hydroelectric sources, is in an enviable position to develop a sustainable EV industry. However, to realize this opportunity and advance the industrialization of the country, it is necessary to develop local capacities for the production of batteries and other critical components.

Finally, by validating the results of regional integration for the creation of a lithium-ion battery and EV industry in Paraguay under conditions of uncertainty, the sensitivity analysis carried out has confirmed the robustness of the conclusions obtained. Through the expert panel and the sensitivity analysis, it was found that changes in the preferences of the criteria did not significantly alter the order of the alternatives, suggesting that the results are consistent and valid even under uncertainty scenarios. The preference for Chile and Argentina as key partners for Paraguay in the EV supply chain remained strong, underscoring the need to establish strategic alliances with these countries to ensure the successful development of the industry in Paraguay.

To establish a joint supply chain with Chile and Argentina, Paraguay should focus on the following:

- Bilateral and Multilateral Agreements: Strengthening diplomatic and economic ties with Chile and Argentina through trade agreements, investment treaties, and cooperation programs focused on technology transfer and infrastructure development.
- Joint Industrial Clusters: Promoting the creation of regional industrial clusters dedicated to battery assembly and EV component manufacturing, leveraging Paraguay's renewable energy and Chile/Argentina lithium production.
- Infrastructure Development: Investing in logistics infrastructure, including port facilities, highways, and intermodal transport hubs, to facilitate the efficient movement of raw materials and finished products across the region.
- Research and Development Collaboration: Establishing joint R&D initiatives between universities, research centers, and private industries to develop advanced battery technologies and improve manufacturing processes.
- Investment Incentives: Implementing policies that attract foreign and domestic investors to develop EV-related industries, including tax incentives and financing mechanisms for green technology companies.
- Workforce Training Programs: Developing educational and vocational training programs in collaboration with Chilean and Argentine institutions to build a skilled labor force specialized in EV technology and battery production.
- Regulatory Harmonization: Aligning regulatory frameworks among the three countries to facilitate cross-border trade, standardize environmental and safety regulations, and ensure compatibility in the EV supply chain.

Future studies could analyze these strategies in greater detail, evaluating their feasibility, potential impact, and implementation challenges to enhance regional collaboration and strengthen South America's role in the EV supply chain.

Paraguay has an opportunity to integrate into the electric mobility value chain, taking advantage of its renewable energy production, strategic location, and available logistics infrastructure. However, to realize these opportunities, it is essential that the country advances in its industrialization process, fosters technological innovation, and develops a regulatory framework that promotes electromobility. Only through a comprehensive and collaborative approach, including active cooperation with Chile and Argentina, will Paraguay be able to position itself as a leader in the transition to sustainable electric mobility in South America.

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Abbreviations

The following abbreviations are used in this manuscript:

EV	Electric vehicle
EVs	Electric vehicles
LIB	Lithium-ion battery
LIBs	Lithium-ion batteries
AHP	Analytic Hierarchy Process
C1	Economic
C2	Energy
C3	Environmental
C4	Social
C5	Political
C6	Geopolitical
SQM	*Sociedad Química Minera de Chile*

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