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Evaluating Preparedness and Overcoming Challenges in Electricity Trading: An In-Depth Analysis Using the Analytic Hierarchy Process and a Case Study Exploration

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Abstract: The economy of South Asia is experiencing growth, yet it faces constraints due to heavy reliance on fossil fuels and frequent power outages. Access to diverse energy sources, particularly electricity, is crucial for sustaining this growth. One feasible solution involves neighbouring countries engaging in the trade of renewable electrical energy. Hydropower stands as one of the many energy sources available in South Asia. However, sectorial constraints pose significant challenges to energy trade initiatives. This study utilises the Analytic Hierarchy Process (AHP) to evaluate Nepal's readiness and identify obstacles to its cross-border energy trade with India and Bangladesh. A comprehensive analysis of these obstacles is imperative for formulating effective strategies and policies. Additionally, this study offers recommendations for enhancing preparedness and resolving issues related to energy trading, which may apply to similar cross-border situations. This study ranks energy trading obstacles with neighbouring nations using the AHP, offering key insights for stakeholders and policymakers. Using a non-probabilistic purposeful sampling technique, 25 expert respondents from the energy sector and prominent academicians were selected as part of the data collection procedure. At every level of the interview process, their perspectives were invaluable in guaranteeing a thorough and rigorous investigation.

Keywords: Analytic Hierarchy Process (AHP); cross-border energy trade; hydropower; Multi-Criteria Decision Making

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1. Introduction

1.1. General Introduction

Nepal possesses enormous hydropower potential, offering strategic economic opportunities for power trade with neighbouring countries like India and Bangladesh, which have limited energy reserves. Out of 83 GW, 43 GW is technically and commercially feasible for power generation [1]. The Nepal Electricity Authority (NEA), the sole government-owned organisation responsible for generation, transmission, and distribution, predicts that many hydropower projects will be commissioned with a cumulative installed capacity above 6000 MW, while the peak load on the Integrated Nepalese Power System (INPS) is anticipated to reach only 3000 MW. NEA forecasts that Nepal will achieve energy self-reliance after 2025, with a surplus energy capacity exceeding 20 TWh by 2028. Additionally, the Government of Nepal aims to harness 15 GW of electricity from hydropower and other renewables by 2030 [2]. Based on past data on electricity demand and per capita consumption, Nepal is unlikely to consume its entire generation.

Despite having surplus energy to export to neighbouring countries, prevailing barriers may hinder Nepal's dream of bulk power trade. This paper analyses Nepal's present and future energy production scenarios based on secondary data and qualitative techniques to rank these barriers. Additionally, it assesses Nepal's infrastructure policy and organisational setup for cross-border electricity trade readiness in the latter part of the study.

Cross Border Electricity Trade (CBET) has already begun worldwide. The Greater Mekong Sub-region (GMS) Energy Programme, the Central American Electricity Interconnection System (SIEPAC), the South African Power Pool (SAPP), and the Nordic Power Pool (Denmark, Finland, Norway, and Sweden) are international agreements for power pools in advanced stages of development. Several studies have flagged the opportunities and benefits of Nepal's hydropower in the South Asian region, particularly in the Bhutan–Bangladesh–India–Nepal (BBIN) sub-region, highlighting cost savings, enhanced system reliability, and reduced carbon emissions as key drivers of CBET [3]. An uninterrupted and continuous supply of electricity is an essential factor assisting in the socio-economic development of a country [4,5]. Regional trade in electricity can help reduce costs, increase reliability, mitigate power outages, facilitate decarbonisation, and benefit from market integration and extension [6]. Collaboration among South Asian countries can reduce the cost of energy by trading energy within the region and with other countries, meeting the growing energy demand with ample and reliable sources [7,8].

Robust cooperation among member countries enables the South Asia region to benefit from power trade. Cross-border electricity trade can attract foreign investment to ensure the availability of electricity and the cost-effective expansion of renewable electricity [9]. The Indian Energy Exchange (IEX) outlined significant benefits of regional power trade, including enhanced energy access and security, an integrated power market, competitive power prices, transparent and efficient power procurement, and resource optimisation. Haq et al. [10] revealed that barriers to cross-border electricity trade in the South Asian Association for Regional Cooperation (SAARC) region include the lack of price-based energy costs for energy trading, low generation capacity, and underperforming financial institutions. Ogino et al. [11] found that geopolitical and political instability delay hydropower construction, serving as primary barriers to hydropower trading. Dhakal et al. [3] identified significant barriers for Nepal in cross-border electricity trade with India, including the declining cost of renewable energy systems globally, inadequate trans-border transmission line interconnections, and the substantial initial investment required for developing projects. Nag [12] highlights Nepal's transmission capacity as a barrier to electricity trade with India, while Strahorn [13] points to the legacy of decade-long failed hydro-diplomacy as a barrier to electricity trade between Nepal and India. Mcbennet et al. [14] suggest that energy trading benefits could include increasing net energy exports from Nepal to India by up to threefold, lessening hydro curtailment, and drastically reducing the production cost of hydropower in both countries.

1.2. Statement of Problem and Authors' Contributions

Past studies have underscored the potential and benefits of CBET to both Nepal and the global community. These studies have also delineated the CBET opportunities and advantages associated with Nepal's hydropower, particularly within South Asia and the Bangladesh–Bhutan–India–Nepal (BBIN) sub-region, offering insights both qualitatively [15–17] and quantitatively [18,19]. This paper not only identifies the barriers to CBET but also analyses present and future power generation, which is crucial for assessing Nepal's readiness for bulk cross-border electricity trade. By examining Nepal's preparedness for energy commerce with its neighbouring countries, this study addresses a significant gap in the literature.

This research explores several novel questions, including (i) the current and future scenario of power generation in Nepal, (ii) Nepal's readiness for bulk cross-border electricity trade with neighbouring countries, and (iii) the implications of applying the AHP method to assess barriers to cross-border electricity trading.

This research is structured into two main sections: the first part comprises a literature review and expert opinions regarding questionnaire preparation, while the second part details the outcomes of interviews and the analysis of data collected through the questionnaire. Multi-Criteria Decision Making (MCDM) was utilised for a quantitative analysis of barriers, employing the Python library AHPy for the Analytical Hierarchy Process (AHP). Additionally, the survey's reliability was assessed using a statistical approach in Python. Furthermore, the country's readiness for CBET was evaluated qualitatively. The MCDM-AHP methodology was chosen to identify the sectorial barriers that are the most prevalent for CBET in the context of Nepal, as revealed through the literature review.

A notable strength of this paper is its dual focus on identifying barriers to cross-border electricity trade and proposing remedies for those barriers. The findings of this study will hold significant implications for other cross-national situations involving collaboration in energy trading, particularly in terms of prospects and opportunities.

1.3. Review of Electricity Export Potential

With over 6000 rivers, Nepal's electricity generation primarily relies on hydroelectricity. Both government utilities like the Nepal Electricity Authority (NEA) and Independent Power Producers (IPPs) contribute to power generation from their plants. Numerous hydroelectric projects owned by the private sector are at various stages of development, indicating substantial progress in Nepal's electricity generation sector. However, the development of transmission infrastructure poses a significant challenge to the country's power system development, potentially impeding power trade. The absence of adequate transmission lines has prevented many hydropower projects from operating at their full capacities.

Despite its significant hydropower potential, the Nepal Electricity Authority (NEA) continues to rely on energy imports from India to fulfil domestic demands, amounting to 32% of its total electricity import from India in 2021. However, Nepal is anticipated to transition into a net energy exporter by 2025 [2]. Currently, Nepal has commenced exporting a portion of its generated electricity to India during the wet season, albeit insignificantly compared to its imports.

In Nepal's nominal generation market structure, there are multiple sellers but a single buyer, with the Nepal Electricity Authority (NEA) acting as the exclusive purchaser of electricity at the wholesale level [3]. The prevailing power purchase agreements (PPAs) between NEA and Independent Power Producers (IPPs) operate on a take-or-pay basis. This means that the buyer, NEA, is obligated to pay the contract rate of the electricity price regardless of actual consumption or sales. Consequently, if cross-border electricity trade with neighbouring countries does not materialise as anticipated, the NEA may face significant financial losses due to this energy procurement model.

The transition towards a shared electricity market pool has the potential to encompass the sub-regional and, ultimately, the regional level [20]. This concept is seen as a solution to India's escalating energy demand while simultaneously providing an economic boost for Nepal by reducing its trade deficit.

After a prolonged wait, Nepal is on the brink of exporting its surplus energy to neighbouring countries, signalling a swift transition from a chronic power deficit country to a power surplus country. This transformation marks a significant paradigm shift in cross-border electricity trade between Nepal and its neighbours. According to the NEA's forecast based on the Required Commercial Operation Date (RCOD) of hydropower plants, Nepal is expected to have an installed capacity of approximately 4000 MW by 2026. However, this figure is not substantial compared to Nepal's hydropower production potential. To address this, the Government of Nepal (GoN) has devised plans to develop hydropower projects with an installed capacity exceeding 10,000 MW, aiming to meet domestic needs and facilitate cross-border trade [21]. Despite limited power infrastructure and a small economy, there is little likelihood of a sharp increase in electricity consumption for all energy generated within Nepal. The NEA has planned the commissioning of hydropower projects by Independent Power Producers at various stages of development up to 2028, as depicted in Figure 1. This illustrates a notable increase in the number of projects set to commence between 2022 and 2027, with the highest installed capacity reaching 1128 MW by 2026. Additionally, the data reveal that by 2027, a total of 219 hydropower projects are expected to be commissioned, boasting a cumulative capacity of around 5300 MW and indicating a considerable surge in hydropower project commissioning in the coming years.

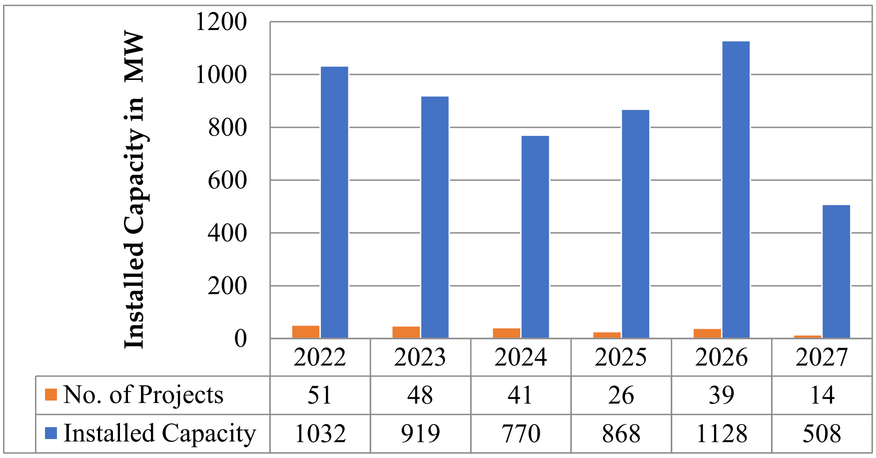

Figure 1. Hydropower projects are expected to be commissioned by 2027, with installed capacity in MW [21]. Reproduced with permission from NEA, Vidyut; published by NEA, 2023.

Hydro Projects of Independent Power Producers (IPPs) in the Pipeline

After decades of opening doors to the private sector, the electricity industry has witnessed substantial contributions from private power project generators in the Integrated Nepalese Power System (INPS). In 2021, the private sector accounted for 36.5% of the total system energy in the INPS [2], reflecting a significant upward trend in contribution. However, the rapid proliferation of Runoff River (ROR) hydropower projects has introduced the risk of a financial burden on the Nepal Electricity Authority (NEA) [3]. These ROR-type hydropower projects have led to a considerable seasonal energy imbalance, presenting a significant challenge for the INPS during both wet and dry seasons.

The visual representation presented in Figure 2 below offers a comprehensive overview of private hydropower projects, categorising them according to their development stages, with a focus on those boasting substantial installed capacity. This visualisation underscores the significant investment made by the private sector in the hydropower sector.

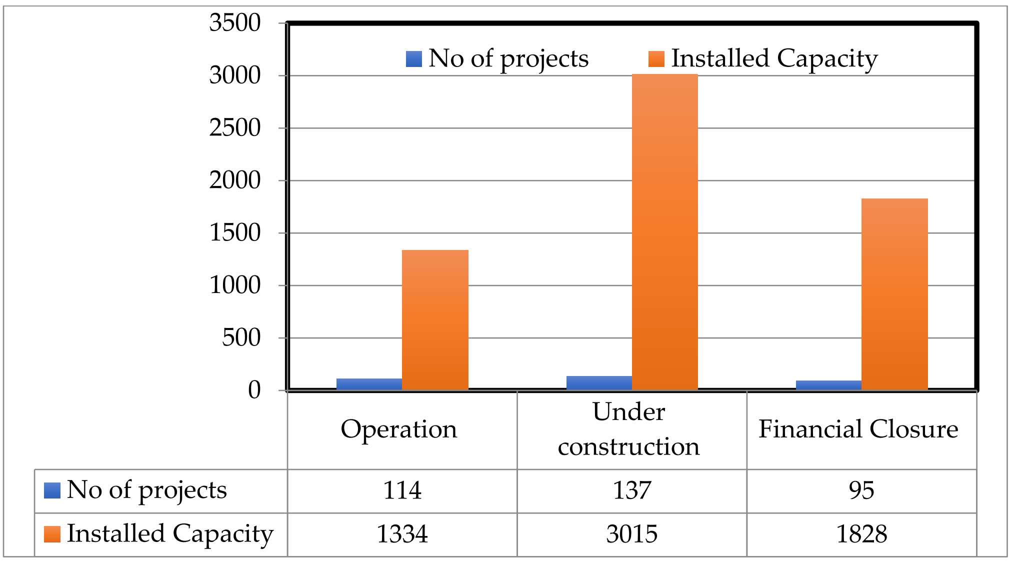

Figure 2. Private sector projects under different stages [21]. Reproduced with permission from NEA, Vidyut; published by NEA, 2023.

While the rise in generation surpasses the growth rate of internal electricity consumption, the average energy consumption growth over the past decade, as indicated in Table 1, appears to be only 8.3%. Figure 3 below illustrates the cumulative capacity of power plants developed by private sector entities awaiting power purchase agreement (PPA) approval from the NEA, measured in megawatts (MW).

Table 1. The growth in domestic energy consumption in the past ten years [2].

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Average
Energy Consumption Growth %	13	12	4	4	5	10	10	9	8	7	**8.3**

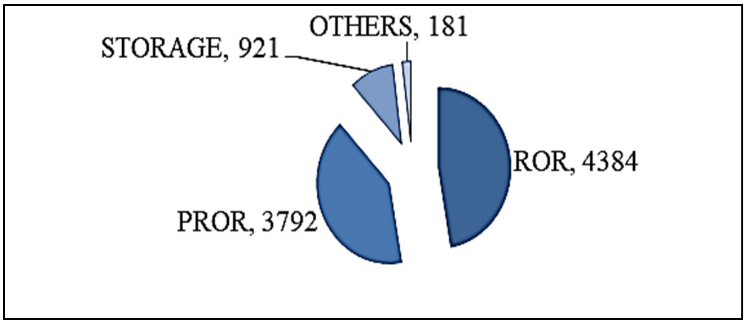

Figure 3. Capacity of private developers awaiting PPA approval from NEA in MW [21]. Reproduced with permission from NEA, Vidyut; published by NEA, 2023.

Figure 4 below provides an overview of the Integrated Nepalese Power System (INPS), including imports, generation capacity, surplus, and peak load over the years. It indicates Nepal's reliance on energy imports from India during the dry season. Additionally, Figure 5 clearly demonstrates the substantial surplus of energy expected in the INPS due to Runoff River (ROR) hydropower projects. A study conducted by the Government of Nepal's Water and Energy Commission Secretariat forecasts an availability of 14.8 TWh by 2025 compared to a peak demand of only 2.95 GW [22]. This surplus presents a significant challenge for the NEA in managing excess energy during the wet season, especially as India has approved the purchase of only 364 MW of surplus power from Nepal via the Indian Energy Exchange (IEX) [23]. Consequently, cross-border electricity trade becomes imperative during this period and will play a crucial role in mitigating substantial financial losses for the NEA [3].

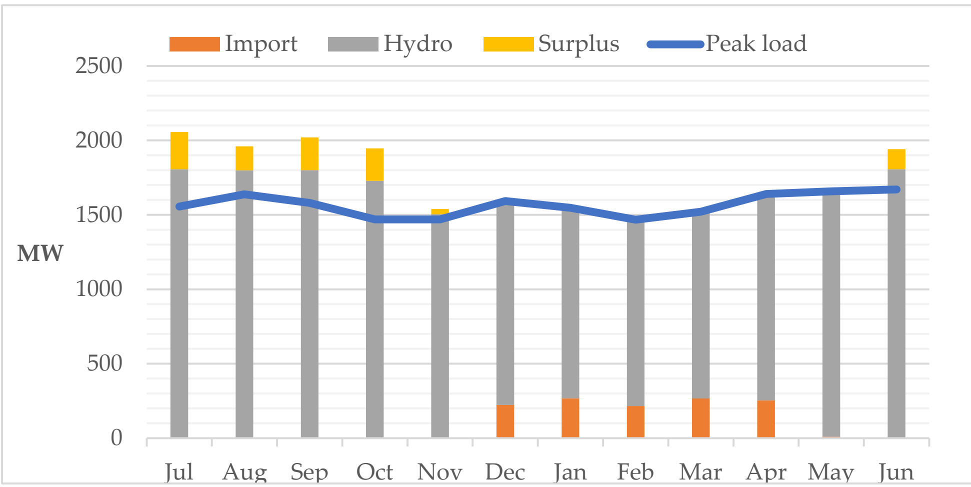

Figure 4. Capacity simulations for power in MW for the 2021/2022 period [21]. Reproduced with permission from NEA, Vidyut; published by NEA, 2023.

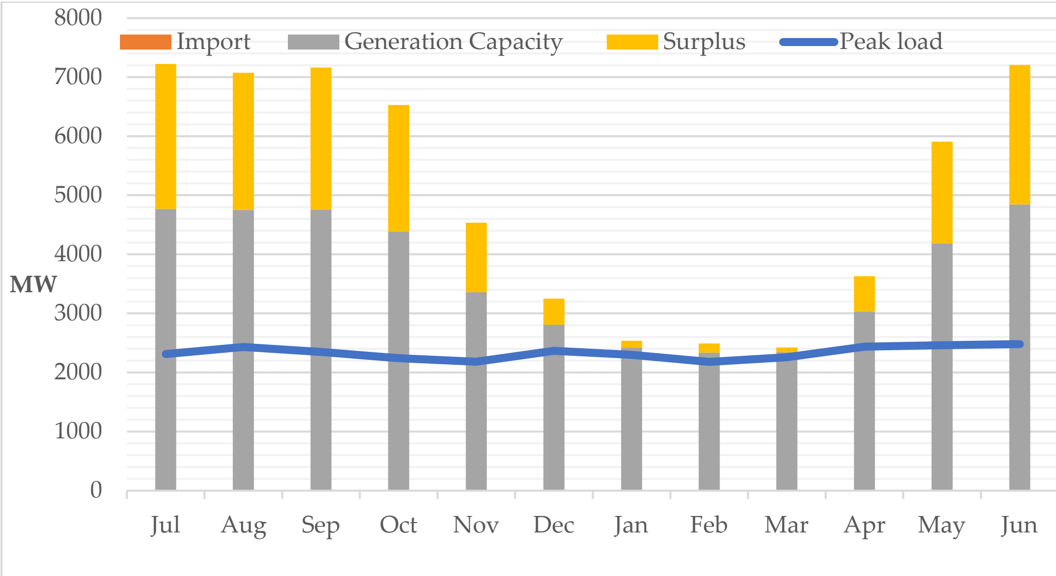

Figure 5. Capacity simulation of power in MW for the 2025/2026 period [21]. Reproduced with permission from NEA, *Vidyut*; published by NEA, 2023.

1.4. Review of Electricity Demand in Neighbouring Countries

1.4.1. India

Electricity production from fossil fuels accounts for over thirty percent of global greenhouse gas emissions [24]. Nepal shares borders with two countries that are heavily reliant on fossil fuels for electricity generation, namely India and Bangladesh. As the world's largest coal consumer, India imports costly coal for power generation, boasting the fifth largest electricity generating capacity and accounting for around 3.4% of global energy consumption [25]. Coal dominates India's energy mix, comprising 44% of its energy sources in 2020, followed by petroleum products at 24%. Fossil fuels, including coal, oil, and solid biomass, satisfy over 80% of India's energy needs, leaving more than 660 million people without access to clean fuel technologies. India stands as the largest emitter of carbon dioxide, with the power sector being a major contributor to carbon emissions [26]. Recently, India announced its commitment during the 26th session of the Conference of the Parties to (i) develop 500 GW of non-fossil energy capacity by 2030, (ii) source 50% of its energy demand from renewable sources, and (iii) achieve net zero emissions by 2070 [27].

Nepal's hydropower potential presents an opportunity to replace India's coal generation. Additionally, hydropower offers greater flexibility and grid stability compared to wind and solar power. As a result, India's cross-border energy trade guidelines have introduced the Hydropower Purchase Obligation (HPO) requirement for imported power [23]. This recent development provides Nepal with an opportunity to export its electricity to India. According to Wijayatunga et al. [28], the significant hydropower resources in Nepal coupled with high demand growth, a coal-dominated power system in India, and coal shortages serve as key drivers for electricity trade between Nepal and India.

1.4.2. Bangladesh

Facing numerous challenges in its power sector, Bangladesh initiated the import of electricity from India in 2013 to alleviate domestic energy shortages. Like India, fossil fuels account for over ninety percent of Bangladesh's total installed capacity for electricity generation. Moreover, Bangladesh grapples with operating at a reduced capacity due to natural gas shortages. Consequently, imported electricity serves as a viable alternative to in-house generation. Hydroelectricity imported from abroad has the potential to reduce reliance on expensive, pollution-intensive fuels, lower greenhouse gas emissions, minimise investments in energy infrastructure expansion, and alleviate the government's subsidy burden on environmentally harmful fuels. In light of these benefits, Bangladesh has signed a Memorandum of Understanding (MoU) for power trade with Nepal, expressing interest in investing in large hydropower projects in Nepal to facilitate energy imports [29]. This presents another opportunity for Nepal to export clean energy to Bangladesh.

1.5. Existing and Planned Transmission Line Infrastructure for CBET with India

Power transactions between Nepal and India commenced in the mid-1960s. This power trade not only fosters cooperation, but also facilitates cross-border power exchange and trading through enhanced transmission interconnection and grid connectivity. Tables 2 and 3 provide an overview of the current status of cross-border transmission interconnection between Nepal and India. According to Table 2, the cross-border transmission interconnection has a whirling power capacity of 1035 MW.

Table 2. Existing cross-border links and quantum of power with Nepal and India [23]. Reproduced with permission from NEA, Nepal Electricity Authority a Year in Review Fiscal Year 2022/2023; published by NEA, 2023.

Interconnection Points	Voltage Level (kV)	Conductor Type	Nominal Aluminium Cross Section Area (Sq.mm)	Import/Export Capacity (MW)
Dhalkebar (Nepal)–Muzzafarpur (India)	400	MOOSE	500	600
Kusaha (Nepal)–Katiya (India)	132	BEAR	250	205
Parwanipur (Nepal)–Rauxal (India)	132	BEAR	250	90
Gandak (Nepal)–Ram Nagar (India)	132	BEAR	250	65
MahendraNagar (Nepal)–Tanakpur (India)	132	BEAR	250	75
Total				1035

Table 3. Planned India–Nepal 400 kV cross-border interconnection [23].

Interconnection	Expected Date of Commissioning
Sitamarhi–Dhalkebar 400 kV D/c (Quad) line	April 2023
Gorakhpur–New Butwal 400 kV D/c (Quad) line	2025–2026
Purnea (New)–Inaruwa 400 kV D/c (Quad) line	2026–2027
Bareilly–Lumki (Dododhara) 400 kV D/c (Quad) line	2027–2028

Figure 6 below illustrates the power development map of Nepal, highlighting existing major hydropower plants along with existing transmission lines, as well as those under construction and planned. Meanwhile, Figure 7 provides a representation of Nepal's integrated power system, depicting cross-border transmission links and additional information regarding the type and length of conductors used across the country.

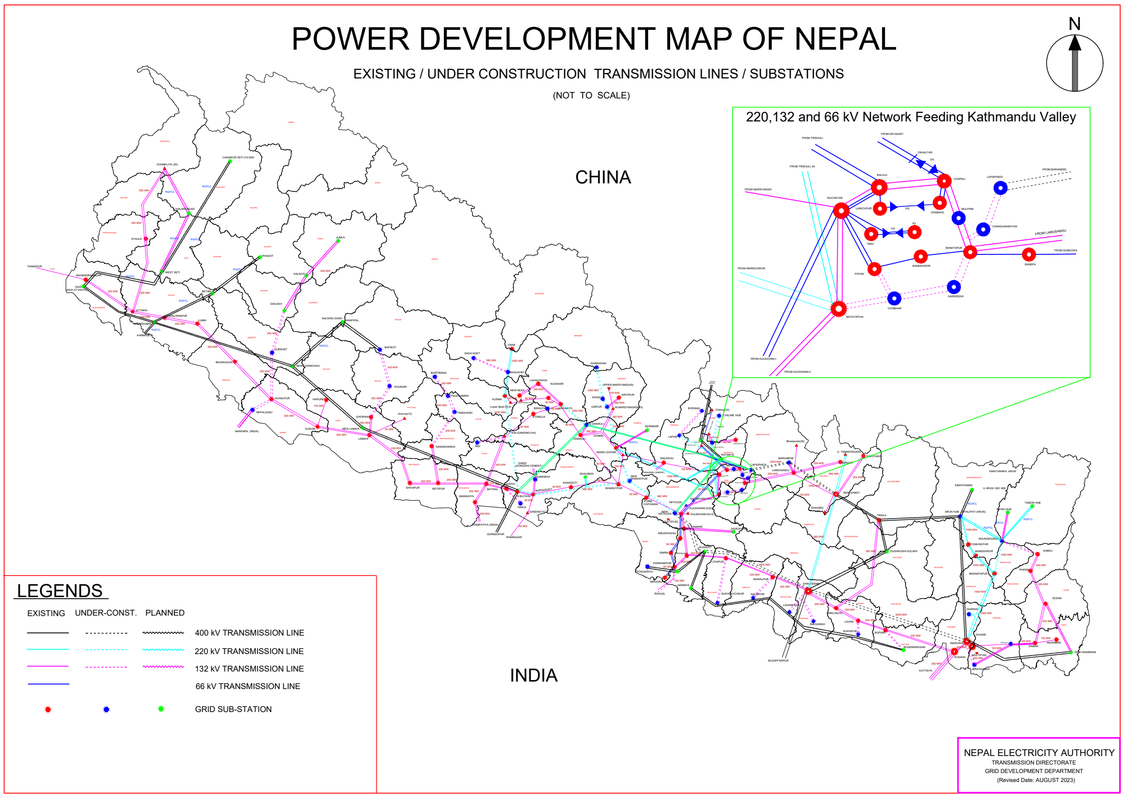

Figure 6. Power development map of Nepal [23]. Reproduced with permission from NEA, Nepal Electricity Authority a Year in Review Fiscal Year 2022/2023; published by NEA, 2023.

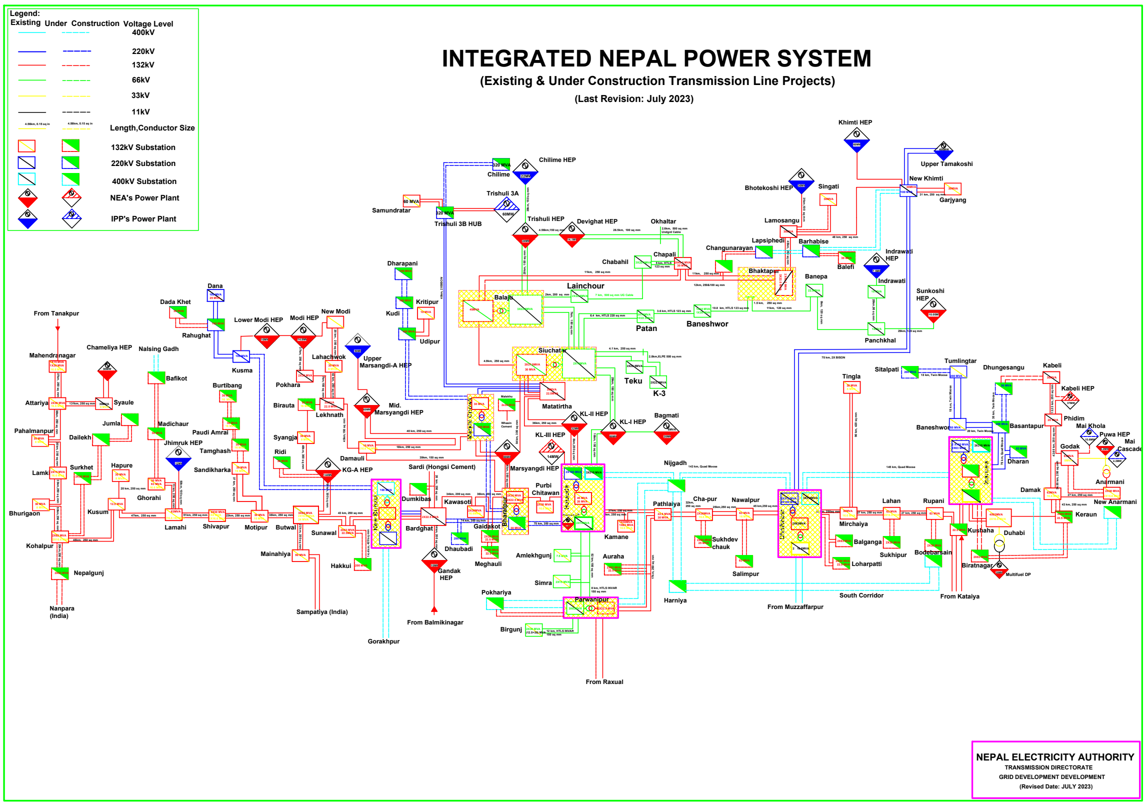

Figure 7. Integrated Nepal power system [23]. Reproduced with permission from NEA, Nepal Electricity Authority a Year in Review Fiscal Year 2022/2023; published by NEA, 2023.

1.6. Review of Preparedness of Nepal for Cross-Border Electricity Trade

The objective of preparedness assessments is to enable policymakers and regulators to swiftly evaluate the effectiveness of the current policy and regulatory framework, including how well they facilitate cross-border electricity trade (CBET). Vaidya et al. [17] identified six critical factors that are crucial for the successful operation of CBET, drawing from global experiences in regional power pools. These factors include provisions for CBET, third-party transmission access, domestic power sector reforms, power trading protocols, regional institutions with supranational authority, and cross-border interconnections. Similarly, the Institute for Sustainable Energy Research (ISER) conducted a readiness analysis on Indonesia's energy transition across the political and regulatory, investment and finance, techno-economic, and social sectors [30]. Additionally, the National Renewable Energy Laboratory assesses 21 criteria covering system characteristics, policies, and regulations to evaluate the readiness of utility-scale renewable energy systems [31]. While these factors may not be universally applicable due to differing local, social, and political contexts, they offer valuable insights for assessing readiness for CBET [17]. The International Energy Agency (IEA) has also established minimum standards for multilateral power trade within the Association of Southeast Asian Nations (ASEAN), as outlined in Figure 8.

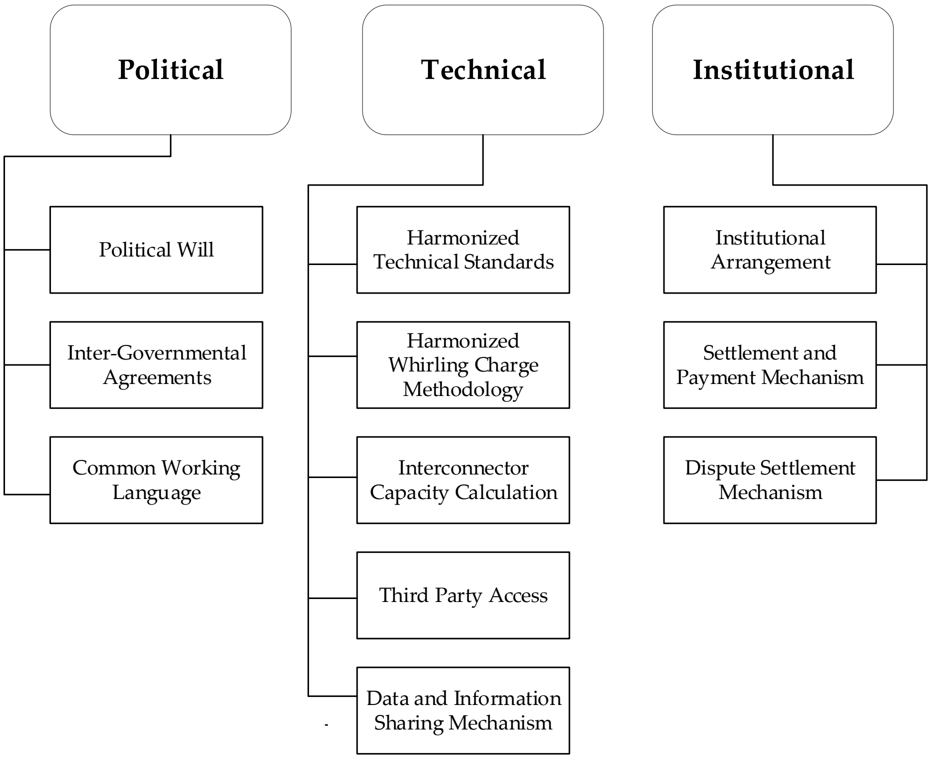

Figure 8. Minimum standards to establish multilateral power trade [32].

2. Methodology

The data collection process commenced with the identification of respondents and was conducted in two stages, as shown in Figure 9. Initially, in-depth interviews were conducted with the respondents to identify the prevailing barriers to Nepal's hydropower market beyond its borders. Subsequently, a survey questionnaire was developed based on the insights gathered from both the expert interviews and a comprehensive literature review. The questionnaire design ensured that expert opinions aligned closely with the findings from the literature review.

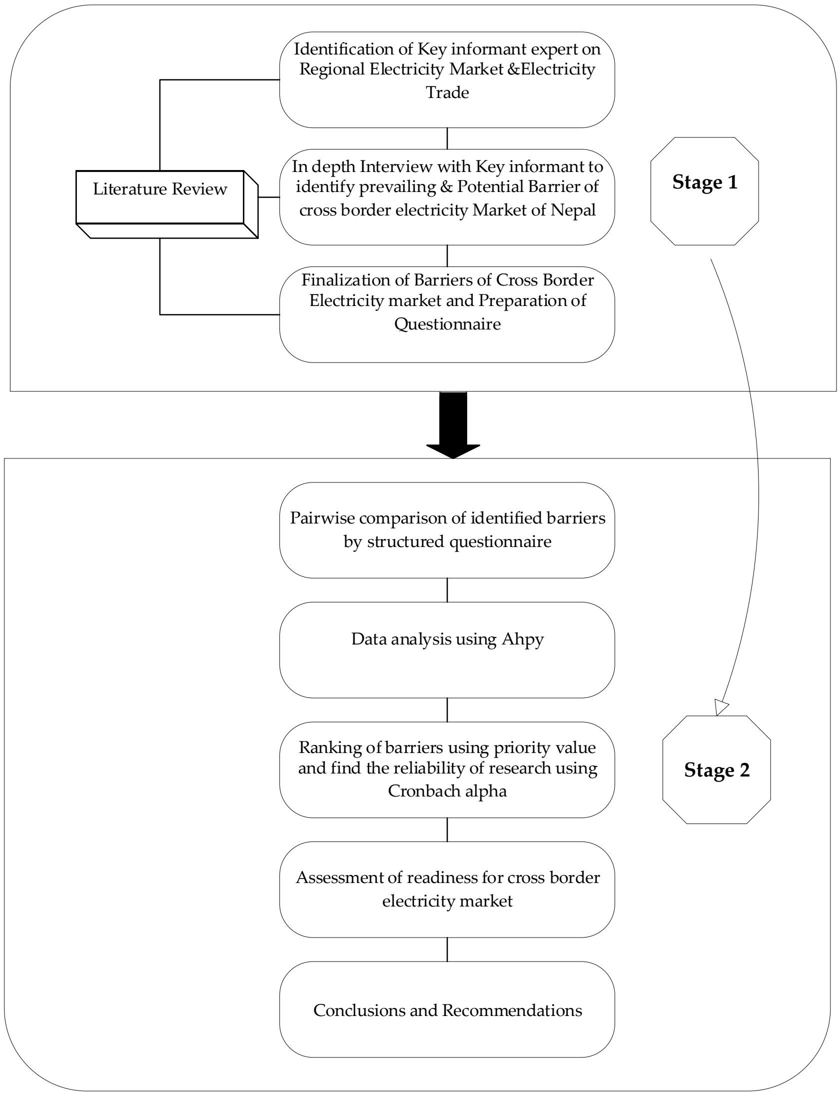

Figure 9. Details about the methodology and workflow of the research.

In the second stage, respondents were tasked with performing pairwise comparisons of sub-criteria related to policy, technical, financial, social, and geopolitical barriers. The objective of these comparisons was to assess the relative importance or priority of each sub-criterion within its respective barrier category. By systematically comparing the sub-criteria, we aimed to elucidate which factors within each barrier category exerted the most significant influence on cross-border electricity trading. Additionally, pairwise comparisons were also conducted to evaluate the barriers themselves, providing insights into their relative severity and impact. Further details regarding the data collection process are available in Supplementary Materials: Annex A. To analyse the data collected from the survey conducted in the second stage, the Python code and the AHPy library were used, facilitating the systematic processing and interpretation of the pairwise comparison results.

The second phase of the study employed the Analytic Hierarchy Process (AHP) to systematically rank the barriers hindering energy trading with neighbouring countries. AHP is a decision-making method that structures complex problems hierarchically, facilitating the comparison of multiple criteria and alternatives [33–35]. In this study, the AHP is utilised as a part of the second stage to assess the relative importance of various barriers to energy trading. The process involves organising the identified barriers into a hierarchical structure, with overarching criteria such as technical, policy, financial, social, and geopolitical barriers. Under each criterion, specific sub-criteria are delineated, representing the dimensions or aspects of the overarching barrier category. Expert respondents then conduct pairwise comparisons of these sub-criteria to derive priority weights, indicating the relative significance of each factor in influencing energy trading dynamics. These priority weights are aggregated to generate a consolidated ranking of barriers, which is instrumental in identifying key areas for intervention and strategic planning in the energy sector.

Table 4 presents the identified barriers and their categorisations according to the hierarchical structure used in the AHP analysis. Each barrier category, along with its corresponding sub-criteria, is listed to provide a comprehensive overview of the factors considered in the ranking process. The table serves as a reference point for subsequent discussions and analyses in the Results Section, where the impact of each barrier category on energy trading outcomes is examined in detail. Detailed information about the barriers and their categorisation can be found in Table 4, ensuring clarity and transparency in the presentation of results.

The reliability of the AHP method depends on the careful selection of respondents for the research. In our study, experts were chosen through a non-probabilistic purposive sampling approach, ensuring a sample of individuals possessing specialised knowledge in the selected domain [36]. These experts were drawn from diverse backgrounds, including government sectors, private sector entities, academia, and donor organisations, to capture a wide range of perspectives. The 25 experts interviewed were specifically chosen for their expertise in the Nepalese power system and their decision-making roles within their respective organisations. Out of the 25 participants, only 20 participants responded with a consistency ratio of less than ten percent, which means that out of the 25 participants, only 20 provided responses that demonstrated a high level of consistency in their pairwise comparisons. The consistency ratio (C.R.) is a measure used in the AHP to assess the reliability of the pairwise comparisons made by respondents. A consistency ratio of less than ten percent indicates that the responses were largely consistent with the principles of the AHP methodology. As a result, five responses were excluded from the analysis due to their inconsistency, ensuring the robustness of our findings.

Following the compilation of responses, we proceeded to analyse the data using the Python programming language and the AHPy library. Specifically, we utilised the Python code to calculate the local weights, global weights, and consistency ratio (C.R.) of the criteria. The local weights represent the relative importance of sub-criteria within each criterion, while the global weights indicate the overall importance of criteria in relation to the research objective. The Python code utilized for generating the research output is available in Supplementary Materials: Annex B.

Additionally, we computed Cronbach's alpha (α) using Python to assess the internal consistency of the research survey, ensuring the reliability of our findings. Cronbach's alpha (α) is a statistical measure used to evaluate the reliability and consistency of a set of survey questions or items. It measures the extent to which all items in a survey instrument measure the same underlying construct or concept [37]. A high Cronbach's alpha value (typically above 0.7) indicates strong internal consistency among the survey items, suggesting that they are measuring the intended construct reliably [38]. By calculating Cronbach's alpha for our research survey, we ensured that the responses obtained from the expert participants were internally consistent, further validating the reliability of our findings. The Python code employed for calculating Cronbach's Alpha is provided in Supplementary Materials: Annex C.

In the final stages of the second phase, we synthesised the results obtained from the AHP analysis to draw conclusions about the prioritisation of barriers hindering energy trading with neighbouring countries. By aggregating the local and global weights of the criteria and sub-criteria, we identified the most significant barriers and their respective contributions to the overall challenge of energy trading. These conclusions were then integrated with insights from previous stages of the research, including the literature review and data collection, to provide a comprehensive understanding of the factors influencing energy trading dynamics in Nepal.

A structured three-tier model is adopted to apply the Analytical Hierarchy Process (AHP) to assess the ranking of barriers in cross-border electricity in Nepal, as presented in Figure 10. At the top of the hierarchy lies the goal, defined as “Ranking Barriers of Cross-Border Electricity Trading in Nepal”. This overarching objective guides the entire decision-making process. As we move to the second tier, we delineate the main criteria that are critical for achieving our goal. These criteria include technical barriers, policy barriers, financial barriers, and sociopolitical and geopolitical barriers, each representing key dimensions influencing cross-border electricity trading. By means of pairwise comparisons between these criteria, we ascertain their global factors, clarifying their respective significance in the overall assessment. At the third tier, we examine each criterion in further detail and find sub-criteria unique to the corresponding domains. Pairwise comparisons among these sub-criteria yield local factors, offering granular insights into the nuances of each criterion’s contribution to the overarching goal.

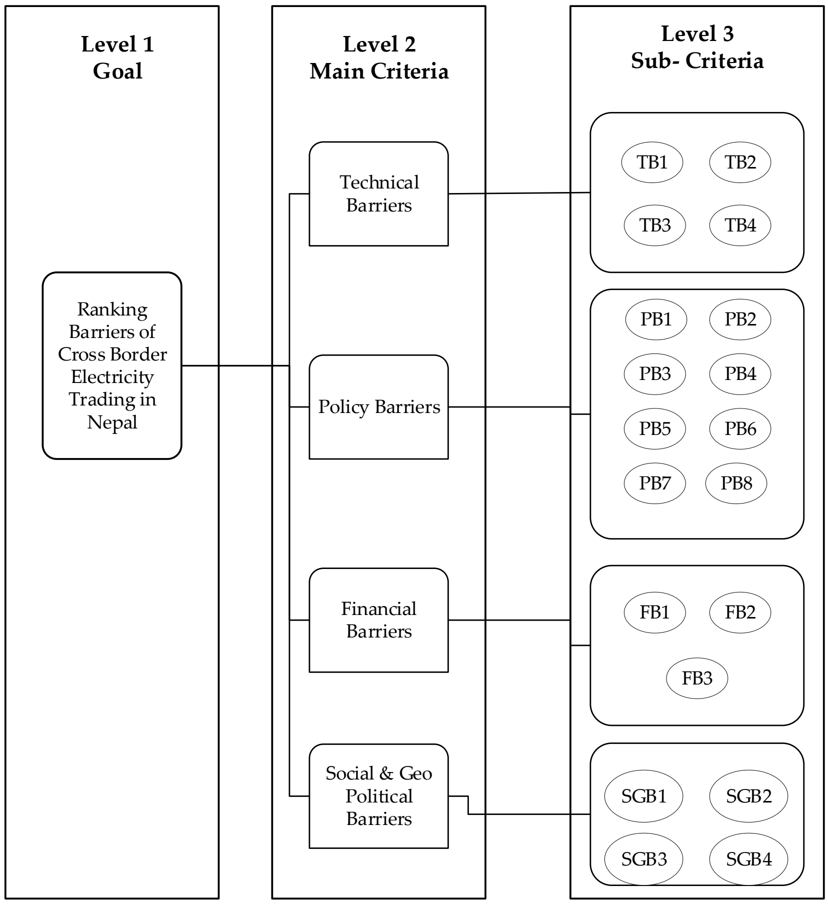

Figure 10. Three-tier model of hierarchical structure of AHP analysis.

Table 5 illustrates the comparison scale utilised within the Analytic Hierarchy Process (AHP) model, delineating the relative importance of the criteria and sub-criteria to the overarching objective. The scale assigns numerical values from 1 to 9, with corresponding explanations elucidating the significance of each rating. A rating of 1 suggests that two sub-criteria are perceived as equally vital to the objective, while higher ratings indicate increasing disparities in importance. For instance, a rating of 3 implies a slight edge of importance for one sub-criterion over another, while a rating of 9 asserts an absolute superiority of one criterion over another. Intermediate values (2, 4, 6, and 8) serve to capture nuanced differentials in importance. Additionally, the concept of reciprocal value acknowledges instances where the importance of one criterion is deemed more significant than another, further enhancing the precision of the comparative assessment within the AHP framework. Table 6 provides a brief overview of the respondents.

Table 4. Identified barriers to cross-border electricity trade in Nepal.

Category	ID	Barrier Description
Policy Barriers (PBs)	PB1	No provision for cross-border electricity transmission in Electricity Act 1992 [17]
	PB2	Lack of private sector involvement in CBET [9,39]
	PB3	Lack of open and non-discriminatory transmission grid access for CBET [17]
	PB4	Absence of regional mechanisms (market modality) for cross-border electricity trade [9]
	PB5	Ambiguous policies related to CBET issued by India to control trading in the region and threat of similar policies in future [15]
	PB6	Absence of regional mechanisms market modality for cross-border electricity trade [17]
	PB7	No separate supranational institution/entity responsible for CBET in South Asia [17]
	PB8	Lack of regulatory harmonisation [9]
Technical Barriers (TBs)	TB1	Lack of sufficient number of cross-border interconnections [15]
	TB2	Rising domestic generation (including solar power) in India [15]
	TB3	Lack of generation capacity for fulfilling domestic demand in dry season [40]
	TB4	Lack of grid code synchronisation between Nepal and its neighbouring countries [39]
Financial Barriers (FBs)	FB1	Relatively higher cost of hydroelectric energy [15]
	FB2	Need for huge investment in construction of cross-border interconnections [15]
	FB3	Cost of renewable energy (especially solar power) in India [15]
Sociopolitical and Geopolitical Barriers	SGB1	Internal pressure of prioritising domestic consumption over exports [40]
	SGB2	Lack of continuity in political support for energy project development and weak political capacity to facilitate regional electricity cooperation [15]
	SGB3	National energy security concerns and trust deficit issues among neighbouring countries [39,40]
	SGB4	Lack of transmission line facilities via India's grid to export power from Nepal to Bangladesh [15]

Table 5. Comparison scale under AHP model [40].

Importance	Explanation
1	Two sub-criteria seem equally important to the objective
3	The importance of sub-criteria i is slightly more than that of j to the objective
5	The importance of criteria i is strongly higher than that of j to the objective
7	The importance of criteria i is much stronger than that of j to the objective
9	The importance of criteria i is absolutely higher than that of j to the objective
2, 4, 6, 8	Used to represent intermediate values
Reciprocal value	The importance of criteria j is more important than i to the objective

Table 6. Key informant interviews and survey/scoring.

Experts	Title	Affiliations
E1	Senior Energy Specialist	Donor
E2	Commissioner	Nepal Electricity Regulatory Commission
E3	Engineer	Hydropower Company
E4	Director	Nepal Electricity Authority
E5	Assistant Professor	IOE, TU
E6	Manager	Nepal Electricity Authority (NEA)
E7	Deputy Manager	Power Trade Department, NEA
E8	Deputy Manager	System Planning Department, NEA
E9	Chief Executive Officer	Hydropower Company
E10	Member	Independent Power Producers of Nepal (IPPANs)
E11	Member	System Planning Department, NEA [1]
E12	Executive Member	Independent Power Producers of Nepal (IPPANs)
E13	Joint Secretary	Ministry of Energy, Water Resources, and Irrigation, GoN [2]
E14	Superintendent Engineer	Water and Energy Commission Secretariat, GoN
E15	Senior Divisional Engineer	Department of Electricity Development, GoN
E16	Project Officer	Donor
E17	Assistant Manager	Power Trade Department, NEA
E18	Associate Professor	IOE, TU [3]
E19	Associate Professor	Kathmandu University
E20	Executive Member	Independent Power Producers of Nepal (IPPANs)

[1] NEA: Nepal Electricity Authority, [2] GoN: Government of Nepal, [3] IOE: Institute of Engineering, TU: Tribhuvan University.

3. Results

In the initial phase, our focus was on identifying key informant experts who are well versed in the regional electricity market and electricity trade dynamics. Following this, we engaged in detailed interviews with these experts to uncover both existing and potential barriers that impede cross-border electricity trading in Nepal. Through a meticulous analysis and rigorous discussions, we refined our understanding of these barriers and compiled them into a comprehensive list. This foundational phase set the stage for our subsequent analysis in Stage 2, offering valuable insights into the intricate challenges and dynamics of cross-border electricity trading in Nepal.

In Stage 2, we rigorously analysed the identified barriers hindering cross-border electricity trading in Nepal. Through pairwise comparisons facilitated by a structured questionnaire, we assessed the relative significance of each barrier. By utilising the AHPy library for the data analysis, we calculated priority values for the barriers, enabling us to rank them based on their impact on cross-border electricity trading dynamics. Furthermore, the computation of Cronbach's alpha ensured the reliability of our research findings.

In the subsequent sections, detailed outcomes of our analysis are presented, including the rankings of barriers and readiness assessments. Tables 7–11 provide a comprehensive illustration of the comparison matrices for sub-criteria under their respective main criteria. Specifically, Table 7 showcases the pairwise comparison matrix using elements within the technical barriers criteria, while Table 8 depicts the same for policy barriers, and so forth for Tables 9–11. Each cell in the matrix represents the relative importance or preference between two sub-criteria, with values derived from the expert respondents' assessments. These comparison matrices are pivotal in evaluating the relative importance of each sub-criterion within its respective barrier category. For example, the comparison matrix in Table 7 enables us to assess the relative significance of technical barriers such as TB1, TB2, TB3, and TB4 in influencing cross-border electricity trading dynamics. It is essential to note that the average method was consistently applied in all comparisons shown in Tables 7–11, ensuring the accuracy and reliability of our analysis.

Table 7. Pairwise comparison matrix using elements within technical barriers criteria.

Technical Barriers	TB1	TB2	TB3	TB4
TB1	1	8	1	1
TB2	1/8	1	1/5	1/6
TB3	1	5	1	2
TB4	1	6	1/2	1

Table 8. Pairwise comparison matrix using elements within policy barriers.

Policy Barriers	PB1	PB2	PB3	PB4	PB5	PB6	PB7	PB8
PB1	1	1/7	1/7	1/6	1/6	1/8	1	1
PB2	7	1	1	1	1/5	1/6	1/2	1/4
PB3	7	1	1	2	2	1/5	1	1/3
PB4	6	1	1/2	1	1	1/5	1	6
PB5	8	5	1/2	1	1	1/5	1	2
PB6	6	6	5	5	5	1	8	8
PB7	1	2	3	1	1		1	3
PB8	8	4	3	1/6	1/6	1	5	1

Table 9. Pairwise comparison matrix using elements within financial barriers.

Financial Barriers	FB1	FB2	FB3
FB1	1	2	1
FB2	1	1	1/5
FB3	1	5	1

Table 10. Pairwise comparison matrix using elements within social and geopolitical barriers.

Social and Geopolitical Barriers	SGB1	SGB2	SGB3	SGB4
SGB1	1	1	3	1/7
SGB2	1	1	1	1/7
SGB3	1/3	1	1	5
SGB4	7	7	1/5	1

In continuation with the methodology outlined earlier, the results of ranking all barriers, including technical, policy, financial, and social and geopolitical barriers, are presented in Tables 12–16. These tables showcase the prioritisation of sub-criteria within each barrier category.

Table 11. Pairwise comparison matrix using all four barriers.

Barriers	Technical	Policy	Financial	Social and Geopolitical
Technical	1	1	1/6	1
Policy	1	1	5	6
Financial	6	1/5	1	3
Social and Geopolitical	1	1/6	1/3	1

Table 12. Priority vector and rank of sub-criteria of technical barriers.

Criteria/Sub-Criteria		Priority Vector	Rank
Technical Barriers	TB1	0.330	2
	TB2	0.050	4
	TB3	0.357	1
	TB4	0.262	3

Table 12 presents the ranking under the technical barrier criteria, revealing that the most prevalent barrier is the lack of generation capacity in Nepal to fulfil domestic demand during the dry season. The consistency ratio (CR) of the technical barriers sub-criteria is calculated to be 0.037, which is less than the threshold value of 0.1, indicating satisfactory consistency.

Table 13 illustrates the ranking of policy barriers, with ambiguous policies related to cross-border electricity trading issued by India being identified as the most significant barrier. The consistency ratio (CR) of the policy barriers sub-criteria is 0.087, also meeting the acceptable threshold of 0.1.

Table 13. Priority vector and rank of sub-criteria of policy barriers.

Criteria/Sub Criteria		Priority Vector	Rank
Policy Barriers	PB1	0.023	8
	PB2	0.057	7
	PB3	0.084	5
	PB4	0.136	2
	PB5	0.091	4
	PB6	0.341	1
	PB7	0.082	6
	PB8	0.135	3

Table 14 depicts the ranking among financial barriers, highlighting the relatively higher cost of hydro energy as the top-ranked barrier. The consistency ratio (CR) of the financial barriers sub-criteria is calculated to be 0.09, indicating satisfactory consistency.

Table 14. Priority vector and rank of sub-criteria of financial barriers.

Criteria/Sub-Criteria		Priority Vector	Rank
Financial Barriers	FB1	0.498	1
	FB2	0.135	3
	FB3	0.367	2

Table 15 presents the ranking of social and geopolitical barriers, with the lack of electricity transit facilities via India's grid to export power from Nepal to Bangladesh being identified as the most prevalent barrier. The consistency ratio (CR) of the social and geopolitical barriers sub-criteria is 0.082, indicating acceptable consistency.

Table 15. Priority vector and rank of sub-criteria of social and geopolitical barriers.

Criteria/Sub-Criteria		Priority Vector	Rank
Social and Geopolitical Barriers	SGB1	0.143	2
	SGB2	0.080	3
	SGB3	0.073	4
	SGB4	0.668	1

Table 16 describe the weightage of the research's main criteria, with policy and financial barriers being identified as the most prevailing among others in the same group. The consistency ratio (CR) of the barriers criteria is calculated to be 0.05, meeting the acceptable threshold.

Table 16. The global factor of the barriers criteria.

Criteria		Priority Vector	Rank
Barriers	Technical	0.113	3
	Policy	0.639	1
	Financial	0.160	2
	Social and Geopolitical	0.087	4

The ranking of the groups, namely barriers, was determined based on the weightage of global factors, as outlined in the Methodology Section. The overall ranking and group-wise ranking are presented in Table 17, which provides a comprehensive overview of the prioritisation of sub-criteria within each barrier category.

As seen in Table 17, the analysis indicates that policy barriers, particularly ambiguous Indian policies related to cross-border electricity trading, are the most significant obstacles, with PB6 receiving the highest overall priority value of 20.7% among the 19 barrier factors examined. Following closely are PB4, PB8, and FB1, with overall priority values of 8.8%, 8.5%, and 8.0%, respectively. This underscores the prominence of policy-related challenges in impeding cross-border electricity trade between Nepal and India.

Furthermore, this study finds that policy barriers prevail more prominently than other sectoral barriers, such as technical, financial, and social and geopolitical barriers. This conclusion is corroborated by the overall rankings, where policy barriers consistently occupy the top positions. Specifically, PB6, relating to ambiguous Indian policies, emerges as the most critical barrier, followed by PB4 and PB8, highlighting the importance of regulatory harmonisation and regional mechanisms in facilitating cross-border electricity trading.

The guidelines of the cross-border electricity trade (CBET) 2018 [41] issued by the Government of India considered electricity trade an issue of strategic, national, and economic importance. One of the conditions outlined in the CBET guidelines is that only power projects having 51% ownership or financing by Indian entrepreneurs will be eligible for exporting power to India. This precondition not only restricts Nepal's free access to the Indian market but also discourages foreign direct investment (FDI) in the Nepalese power sector. This is the major policy barrier for Nepal to export hydropower to India. So, the provision listed in the CBET guidelines is against the vision of the Power Trade Agreement 2014 held between Nepal and India.

Moreover, the Government of Nepal has nominated the Nepal Electricity Authority as the nodal agency for electricity trade with India. But due to the vertically integrated nature of NEA, it will be difficult to regulate policies in India's big, mature, deregulated electricity market. Finally, the cost of solar panels and solar power has drastically decreased due to innovations in solar energy. In comparison with solar energy, hydro energy is expensive. So, the higher costs of hydro energy affect the Nepalese government's bargaining power in the sale of hydroelectricity to India.

Table 17. The overall ranking of the sub-criteria based on the priority vector (PV).

Criteria (1)	Sub-Criteria (2)	Global Factor (3)	Local Factor (4)	Overall PV (5) = (3) × (4)	Rank (6)
Technical Barriers	Lack of sufficient number of cross-border interconnections (TB1)	0.113	0.330	0.037	12
	Rising domestic generation (including solar power) in India (TB2)	0.113	0.050	0.005	19
	Lack of generation capacity for fulfilling domestic demand in dry season (TB3)	0.113	0.357	0.040	11
	Lack of grid code synchronisation between Nepal and its neighbouring countries (TB4)	0.113	0.262	0.029	13
Policy Barriers	No provision of cross-border ET in Electricity Act 1992 (PB1)	0.639	0.020	0.013	15
	Lack of private sector involvement in CBET (PB2)	0.639	0.103	0.066	5
	Lack of open and non-discriminatory transmission grid access for CBET (PB3)	0.639	0.073	0.047	10
	Absence of regional mechanisms (market modality) for cross-border electricity trade (PB4)	0.639	0.137	0.088	2
	Lack of domestic power sector reforms (PB5)	0.639	0.075	0.048	9
	Ambiguous policies related to CBET issued by India to control trading in region and threat of similar policies in future (PB6)	0.639	0.324	0.207	1
	No separate supranational institution/entity responsible for CBET (PB7)	0.639	0.081	0.052	8
	Lack of regulatory harmonisation (PB8)	0.639	0.133	0.085	3
Financial Barriers	Relatively higher cost of hydro energy (FB1)	0.087	0.143	0.080	4
	Need for huge investment for construction of cross-border interconnection (FB2)	0.087	0.080	0.022	14
	Declining cost of renewable energy (especially solar power) in India (FB3)	0.087	0.073	0.059	6
Social and Geopolitical Barriers	Internal pressure of prioritisation of domestic consumptions over export (SGB1)	0.087	0.143	0.012	16
	Lack of continuity in political support for hydro project development and weak political capacity to facilitate regional electricity cooperation (SGB2)	0.087	0.080	0.007	17
	Energy security concerns and trust deficit issues (SGB3)	0.087	0.073	0.006	18
	Electricity transit facilities via India's grid to export power from Nepal to Bangladesh (SGB4)	0.087	0.668	0.058	7

Further, while evaluating the sub-criteria by considering both local and global factors, there seems to be differences in the ranking of barriers. However, we should emphasise ranking local sub-criteria during policy formulation.

3.1. Reliability of Survey

Cronbach's alpha verifies the internal consistency of the research surveys or questionnaires [38]. The reliability of the research was calculated, and the results are shown in Table 18.

Table 18. Calculation of Cronbach's alpha (α).

S. N	Criteria	No of Items	Cronbach's Alpha (α)
1	Technical Barriers	6	0.897
2	Financial Barriers	3	0.856
3	Policy Barriers	21	0.856
4	Social and Geopolitical Barriers	6	0.881

The overall reliability of the survey (α) is 0.867 > 0.7, which is good (0.9 > α > 0.8). The acceptable lower limit value for the reliability of the survey using Cronbach's coefficient alpha (α) is 0.7, and 0.6 can be accepted for exploratory research [42].

3.2. The Status of Preparedness for Cross-Border Electricity Trade

The assessment of Nepal's readiness for cross-border electricity trade (CBET) based on key factors identified by Vaidya et al. [17] is presented in Table 19. This assessment, falling under Step 4 of Stage 2, evaluates Nepal's preparedness for CBET through various criteria, including policy, institutional, and infrastructure aspects. Notably, the status of Nepal's readiness is gauged based on interviews conducted with relevant stakeholders, which are distinct from the AHP analysis conducted earlier.

Table 19. The status of Nepal's preparedness for cross-border electricity trade.

Key Factors	Status	Remark
1. Policy - Provision of cross-border electricity trade - Third-party transmission line access	 ☒ x	 Partially fulfilled Not fulfilled
2. Institutional - National power sector reforms - Power trading protocols	 ☒ ✓	 Partially fulfilled Fulfilled
3. Infrastructure - Construction of cross-border transmission interconnection	 ☒	 Partially fulfilled

Table 20 further elaborates on the key focus areas identified by USAID to enhance Nepal's readiness for CBET [43,44]. These focus areas encompass institutional, regulatory, and strategic/business frameworks that are crucial for facilitating cross-border electricity trading. The status of each focus area is detailed, providing insights into ongoing initiatives and areas requiring further attention.

As seen in the combined insights of Tables 19 and 20, it is evident that Nepal's preparedness for CBET is still evolving, with several critical factors yet to be fully addressed. Despite progress in certain areas, such as the establishment of institutional frameworks and strategic coordination efforts, challenges persist, particularly in regulatory aspects and strategic partnerships with neighbouring countries.

It is important to note that the assessment presented in Table 19 is based on interviews with stakeholders and does not directly relate to the AHP analysis conducted in earlier stages. However, these findings complement the broader analysis of barriers and readiness factors, providing a comprehensive understanding of Nepal's current status in the context of cross-border electricity trading.

Table 20. Key focus areas identified by USAID for the readiness of cross-border electricity trade [43].

Key Factors	Status	Remark
1. Institutional Framework		
- Provision of "competent authority" and delegation of power for CBET	✓	NEA is appointed
- Establishment of Electricity Regulatory Commission	✓	Established in 2019
- Declaration of "Transmission Planning Agency of Nepal"	☒	Task force formed
- Strengthening of system operator	☒	Ongoing
2. Regulatory Framework		
- Open access for CBET lines	☒	Proposed in Electricity Act 2019
- Electricity Regulatory Commission to issue directives on scheduling and deviation settlement	x	Not fulfilled
3. Strategic and Business Framework Status		
- GoN [1] to coordinate with GoI [2] to ensure India's Designated Authority	✓	Received approval
- Agreements with power trading licensees in India	x	Not fulfilled
- GoN to continue exploring opportunities for trade in Bangladesh	☒	MOU signed in 2018

[1] GoN: Government of Nepal; [2] GoI: Government of India

4. Discussion

Learning from successful practices of regional electricity trade worldwide, Nepal should accelerate the construction of significant cross-border interconnections with neighbouring countries.

In line with this strategy, Nepal should promptly commence the construction of the New Butwal–Gorakhpur 400 kV transmission line. This line, slated to be the second 400 kV cross-border connection between Nepal and India, is crucial as numerous hydropower projects are set to be developed in Nepal's Gandaki Basin. The installed capacity far exceeds the region's self-consumption, making this transmission line a vital conduit for supplying electricity from Nepal to the energy-demanding Uttar Pradesh region of India. Likewise, prioritising the development of other high-capacity transmission lines such as Dodohara–Bareilly 400 kV, Inaruwa–Purnia 400 kV, and Dhalkebar–Sitarmani 400 kV is essential.

This study highlights that the provisions outlined in India's CBET guidelines pose hurdles for cross-border electricity trade. Nepal should persist in lobbying through its diplomatic channels with India to enhance cross-border interconnections, promote market-based trading by establishing regional international regulatory bodies, ensure free access to the grid, and establish common protocols for electricity trading. These efforts are essential to maximise the benefits of CBET in the long term.

Nepal's government should strongly advocate for India to facilitate power transmission to Bangladesh through the Indian grid. While prioritising domestic consumption remains paramount, rapidly increasing electricity consumption poses significant challenges. Nonetheless, achieving basic benchmarks such as reliable grid electricity in major cities and incentivising e-mobility, electric trains, and metro-rail in urban areas can contribute to a substantial increase in domestic energy consumption.

The Nepal Electricity Authority (NEA) functions as the sole purchaser of electricity generated by the private sector. NEA has implemented a take-or-pay power purchase agreement (PPA) model with a fixed posted energy rate, allocated on a first-come, first-serve basis. However, with the declining costs of solar and other renewable energy sources, NEA should transition towards competition-based PPAs with private developers, enabling participation in the competitive regional market. This shift would facilitate competitive energy rates in the regional market. Since the introduction of liberalisation policies, the private sector has emerged as a significant stakeholder in Nepal's power sector. Therefore, Nepal should enact policies that allow the private sector to engage in the cross-border power trading business.

Moreover, the construction of high-voltage cross-border transmission links, the development of a robust regulatory framework, the enhancement and harmonisation of institutional capacity, the promotion of regional cooperation for the establishment of a supranational authority for regional power trade, and investment in skill development are all critical steps for Nepal to enhance its readiness for cross-border electricity trade. The NEA should promptly strategize the development of new transmission lines and substations by identifying regions with potential electricity demand and accelerating the construction of ongoing transmission and substation projects.

Furthermore, BBIN member countries should leverage their abundant water resources by prioritising the development of environmentally friendly and financially feasible hydropower projects, emphasising regional integration and cooperation within the South Asian region. Future studies could delve into the economic and environmental benefits of cross-border electricity trade (CBET) for Nepal, India, and Bangladesh. However, it is important to note that this research only ranks barriers to energy trade based on a literature review and respondents' perceptions.

5. Conclusions, Recommendations, Policy Insights, and Future Works

This study employs energy modelling to provide insights into both present and future power generation possibilities. Additionally, the Analytic Hierarchy Process (AHP) is utilised to identify and prioritise obstacles to cross-border electricity trading. Furthermore, a qualitative analysis, incorporating up-to-date literature reviews and expert comments, evaluates Nepal's preparedness for electricity trade across legislative, institutional, regulatory, strategic, and business frameworks.

The increasing concerns regarding Nepal's energy surplus, stemming from uneven hydropower generation, underscore the need to address obstacles to cross-border energy commerce. Significant changes to institutional, regulatory, policy, and strategic frameworks are required. The qualitative survey highlights ongoing issues, such as inadequate cross-border transmission lines and challenges with transmission policies and access.

The New Electricity Act 2023 that was recently submitted to the parliament holds promise for Nepal's electricity industry. Provisions within this legislation, such as the unbundling of vertically integrated utilities and the facilitation of private sector involvement in power trade, are expected to address existing problems and promote cross-border energy trade.

The recommendations in this study emphasise the urgency of Nepal establishing crucial cross-border connections with its neighbours. To utilise Nepal's surplus electricity for regional needs, high-capacity transmission facilities like the New Butwal–Gorakhpur 400 KV transmission line are essential.

This study underscores the significance of India's CBET rules in hindering international energy trade. Diplomatic efforts should focus on promoting market-oriented trading, establishing local regulatory organisations, ensuring grid connectivity, and harmonising energy trading procedures to optimise CBET benefits.

Moreover, Nepal should prioritise domestic power usage while exploring ways to enhance consumption, such as promoting e-cooking and e-mobility. Implementing competitive bidding mechanisms in power purchase agreements with the private sector can foster a more dynamic and cost-effective regional energy market.

Coordinated efforts are necessary to develop high-voltage transmission linkages, enhance regulatory frameworks, bolster institutional capacity, encourage regional collaboration, and invest in skill development programs to enhance Nepal's readiness for cross-border energy trading.

Future research should investigate the economic and environmental impacts of CBET on India, Bangladesh, and Nepal. Additionally, exploring innovative approaches to circumvent identified obstacles is warranted.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/electricity5020014/s1. The accompanying files include Annex A: Questionnaire, providing detailed information on the survey conducted. Additionally, Annex B contains the Python code utilized to generate the research output, facilitating transparency and reproducibility of the computational analysis. Furthermore, Annex C contains the Python code employed for calculating Cronbach's Alpha, a measure of internal consistency reliability.

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