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STRATEGIC GRID DEVELOPMENT IN THE ANDES: INTEGRATING GEOSPATIAL INTELLIGENCE FOR RESILIENT TRANSMISSION NETWORKS

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ABSTRACT

This article investigates the crucial role of geospatial considerations in the strategic planning and expansion of electricity transmission networks within the unique geographical context of the Andean region. It delves into how the rugged mountainous terrain, diverse ecosystems, and susceptibility to natural hazards significantly influence the design, cost, and resilience of transmission infrastructure. The paper reviews advanced Transmission Expansion Planning (TEP) methodologies, including AC models and AI-driven approaches for managing uncertainties, and specifically highlights their adaptation to Andean realities through the integration of topographical, geological, and hydrological data. The results demonstrate that a geospatial-informed approach leads to more robust network designs, enhanced resilience against seismic events and climate change impacts, and optimized cross-border interconnections. While acknowledging challenges such as data availability and modeling complexity, the discussion emphasizes the necessity of multi-criteria decision-making and regional collaboration. Future directions include leveraging advanced AI/ML, refining climate change resilience modeling, and fostering supportive policy frameworks to ensure sustainable and adaptable electrical grids in the Andes.

Keywords: Transmission Expansion Planning, Geospatial Analysis, Andean Electrical Systems, Power Systems, Grid Resilience, Renewable Energy Integration, Cross-Border Interconnections, AC Models, Artificial Intelligence.

INTRODUCTION

The planning of electricity transmission networks is a multifaceted and critical endeavor, essential for ensuring reliable, secure, and economic power supply to consumers. In the context of the evolving global energy landscape, marked by increasing renewable energy integration and distributed generation, Transmission Expansion Planning (TEP) has become more complex and vital than ever [1]. The imperative for modern TEP extends beyond merely meeting future demand; it must also navigate challenges such as grid modernization, the seamless integration of diverse energy sources (both conventional and renewable), and the pressing need for enhanced flexibility and resilience against various disruptions [3]. While foundational TEP methodologies date back to pioneering works like Garver's linear programming approach, which laid the groundwork for network theory applications in power systems [2], contemporary planning demands far more sophisticated models to address the intricate and dynamic nature of modern electrical systems.

The global energy transition, driven by climate change concerns and technological advancements, has fundamentally reshaped the objectives of TEP. The proliferation of intermittent renewable energy sources, such as wind and solar, necessitates a more robust and flexible transmission infrastructure capable of handling variable generation and ensuring grid stability. Simultaneously, the decentralization of power generation, with the rise of distributed energy resources (DERs) and microgrids, adds another layer of complexity, requiring planners to consider both large-scale transmission projects and localized grid enhancements. Furthermore, the increasing frequency and intensity of extreme weather events, coupled with the inherent vulnerabilities of aging infrastructure, underscore the critical importance of designing resilient transmission networks that can withstand and rapidly recover from disruptions.

Andean electrical systems present a unique set of challenges and opportunities for TEP, primarily due to their distinctive geographical characteristics. The region, encompassing countries like Ecuador, Colombia, Peru, and Bolivia, is defined by its rugged mountainous terrain, significant elevation differences, and diverse ecosystems ranging from coastal lowlands to high-altitude Andean peaks and Amazonian rainforests. These varied topographies pose significant obstacles to the development of electricity infrastructure, impacting everything from the feasibility and cost of construction to the operational efficiency and maintenance of transmission lines. For instance, the challenges of building and maintaining infrastructure at elevations exceeding 4000 meters above sea level are substantial, influencing material selection, construction techniques, and overall project economics. The susceptibility of the region to natural hazards, including seismic activity, landslides, and volcanic eruptions, further complicates planning, demanding the integration of resilience measures into network design [15].

Despite these formidable challenges, the Andean region also boasts immense opportunities. Its rich hydropower potential, stemming from abundant water resources and significant elevation drops, represents a cornerstone of its energy supply and a key driver for transmission development [22]. Moreover, the strategic importance of cross-border interconnections within the region cannot be overstated. These interconnections facilitate energy trade, enhance regional energy security, and provide mutual support during periods of high demand or supply disruptions, leveraging the diverse energy resource endowments of neighboring countries [14], [16].

This article explores the critical role of geospatial considerations in developing robust, economically viable, and environmentally sustainable transmission network expansion strategies tailored for Andean electrical grids. It aims to highlight how the systematic integration of detailed geographical data into advanced TEP models can lead to more resilient, cost-effective, and environmentally conscious infrastructure development. The focus will be on addressing the specific needs and constraints of countries such as Ecuador [4], [18], [21], Colombia [14], Peru [35], and Bolivia [32], which serve as representative examples of the complex interplay between geography and grid development in the region. By examining both conventional and non-conventional expansion strategies, this study seeks to provide a comprehensive framework for navigating the unique challenges of TEP in the Andean context.

METHODS

Transmission Expansion Planning (TEP) methodologies have undergone a significant evolution, moving from simplified representations to highly complex and detailed models capable of capturing the intricate dynamics of modern power systems. This section delves into the foundational and advanced TEP methodologies, the crucial aspect of uncertainty and flexibility in planning, and the specific adaptations required for geospatial integration within the unique Andean context.

TEP Methodologies and Advanced Modeling

The core objective of TEP is to determine the optimal timing, location, and type of new transmission lines and associated equipment to meet future electricity demand reliably and economically. Historically, TEP problems were often formulated as mixed-integer linear programming (MILP) models. These models typically aimed to minimize the sum of investment and operational costs while adhering to a set of operational and physical constraints, often simplified using Direct Current (DC) load flow approximations [13]. The classical model proposed by L. Garver in 1970, based on network theory and DC load flow, was pioneering in this regard, providing an initial framework for solving TEP problems [2].

However, the inherent limitations of DC models, which neglect reactive power flows, voltage magnitudes, and system losses, became increasingly apparent with the growing complexity of power systems. The shift towards Alternating Current (AC) models has been crucial for accurately representing the operational reality of power systems, including precise power flow calculations, voltage profiles, and the critical need for reactive power compensation [5], [6]. AC-based TEP formulations, while offering greater accuracy, introduce non-linearities, transforming the problem into a mixed-integer non-linear programming (MINLP) challenge, which is significantly more complex to solve and often difficult to guarantee a global optimum [1].

To overcome these computational challenges, various advanced optimization techniques have been employed:

- Heuristic and Metaheuristic Algorithms: These algorithms are designed to find good, though not necessarily optimal, solutions to complex problems within a reasonable computational time. Examples include constructive heuristic algorithms that solve non-linear programming problems during their solution steps [5]. Particle Swarm Optimization (PSO) has also been utilized, particularly in load-shedding formulations that incorporate shunt compensation to solve TEP problems through local optimization [6].
- Non-linear Mathematical Programming: Techniques like non-linear mathematical programming combined with differential evolution-based metaheuristics have been used to achieve optimal transmission configurations, considering multi-voltage approaches and reactive power compensation simultaneously [7], [8].
- Unified AC TEP Formulations: Recent advancements have led to unified AC TEP formulations that provide a more holistic and technically sound expansion plan. These formulations incorporate a wider range of modern technologies, including Voltage Source Converter-based Multi-Terminal DC (VSC-MTDC) systems, which offer enhanced control over power flow and can connect different AC grids asynchronously. Flexible AC Transmission Systems (FACTS) devices, such as Static Var Compensators (SVCs) and Thyristor Controlled Series Capacitors (TCSCs), are also integrated to manage reactive power, improve voltage stability, and enhance power transfer capabilities. Comprehensive reactive power compensation strategies are crucial for maintaining voltage profiles and reducing losses across the network

[7].

● Multi-stage and Multi-voltage Approaches: To manage the long-term evolution of the grid and address different voltage levels (e.g., 230 kV, 500 kV) simultaneously, multi-stage and multi-voltage approaches are now considered in TEP. These allow for phased investments and coordinated development across different parts of the grid, ensuring a cohesive and efficient expansion over time [8].

Uncertainty and Flexibility in Planning

The future of power systems is inherently uncertain, driven by factors such as fluctuating load growth, the intermittency of renewable energy generation (e.g., wind and solar power), evolving energy policies, and market dynamics. These uncertainties pose significant challenges to traditional deterministic TEP, which assumes fixed future conditions. To address this, flexible transmission network planning has emerged as a critical area, leveraging advanced computational intelligence techniques.

● Artificial Intelligence and Machine Learning (AI/ML): Recent works have increasingly resorted to AI/ML algorithms to develop more adaptive and robust TEP strategies.

○ Deep Q-Networks (DQN) and Double Deep Q-Networks (DDQN): These reinforcement learning algorithms have been explored for dynamic planning, allowing the system to "learn" the most cost-effective and resilient expansion strategies through iterative interactions with the environment. They can adapt to changing conditions and uncertainties by optimizing sequential decision-making processes [9], [10].

○ Multi-Agent DDQN: This advanced approach considers multiple interacting agents within the power system, allowing for the modeling of complex interactions and decentralized decision-making. It is particularly useful for scenarios involving wind power and load uncertainties, leading to more robust and adaptive expansion plans that can handle a wide range of future scenarios [11].

○ Deep ResNet Integration: The integration of Deep Residual Networks (ResNet) with DDQN further enhances the learning capabilities, allowing the models to process complex input data and identify intricate patterns in network behavior, leading to improved decision-making for transmission expansion [10].

● Non-Conventional Expansion Strategies: Beyond constructing new transmission lines, other strategies, referred to as non-conventional solutions, contribute significantly to system flexibility and resource optimization.

○ Reconfiguration: This involves altering the topology of the existing network by utilizing existing transmission lines for building new extensions or creating new connections. For instance, an existing line might be divided into two new segments, with one segment being redirected to connect to a new busbar. This strategy is particularly effective in densely populated or environmentally sensitive areas where the construction of entirely new lines may be limited or prohibitively expensive. It allows the network to adapt to evolving demand patterns without requiring extensive new land acquisition or significant environmental impact [12].

○ Repowering: This involves upgrading the conductor type of existing transmission lines to one with higher capacity, effectively increasing the energy-carrying capability of the existing infrastructure. By replacing the original conductor with a more advanced one (e.g., ACSS conductors which have higher ampacity and can operate at higher temperatures than ACSR conductors), the line's impedance changes, and its capacity is enhanced. This approach leverages existing towers and rights-of-way, significantly reducing investment costs and environmental impact compared to building new lines [12]. The integration of these non-conventional solutions into TEP models, often formulated as mixed-integer linear programming problems, allows for the exploration of a larger search space and can yield superior solutions compared to considering only new line construction [12].

Geospatial Integration and Andean Context Adaptation

The unique and challenging geographical characteristics of the Andean region necessitate a strong emphasis on geospatial integration within TEP. This involves incorporating detailed spatial data into the planning process to account for terrain, environmental sensitivities, natural hazards, and socio-economic factors.

1. Detailed Geospatial Data Acquisition:

○ Topographical Data: High-resolution Digital Elevation Models (DEMs) are crucial for understanding the terrain's slope, elevation differences, and potential routing challenges. This data directly impacts the length of lines, the type of towers required, and the complexity of construction.

○ Geological Information: Detailed geological surveys and seismic hazard maps are essential for identifying areas prone to earthquakes, landslides, and other geological instabilities. This information is critical for designing resilient infrastructure and avoiding high-risk zones.

○ Hydrological Data: Given the significant reliance on hydropower in many Andean countries, comprehensive hydrological data, including river networks, water flow rates, and potential dam sites, are crucial for assessing generation potential and its impact on transmission needs. Hydrological derivative models provide a global, high-resolution database for such analysis [22].

○ Environmental and Land Use Data: Maps of protected areas (national parks, biodiversity hotspots), indigenous territories, agricultural lands, and urban centers are vital for identifying environmental and social constraints. This data helps in minimizing ecological disruption and avoiding land use conflicts.

○ Climatic Data: Information on temperature fluctuations, heavy rainfall patterns, wind speeds, and air pollution levels is necessary to assess their impact on conductor efficiency, durability, and maintenance requirements.

2. Methodologies for Geospatial Integration:

○ GIS-Based Corridor Identification: Geographic Information Systems (GIS) are extensively used to analyze multiple spatial layers to identify optimal transmission corridors. This involves overlaying terrain data, environmental constraints, population density, and existing infrastructure to determine feasible and cost-effective routes.

○ Cost Surface Modeling: Geospatial analysis enables the creation of "cost surfaces," where each cell in a grid is assigned a cost value based on various geographical factors (e.g., steepness of terrain, proximity to sensitive areas). The optimal path for a transmission line can then be determined by finding the route with the lowest cumulative cost across this surface.

○ Elevation-Dependent Cost Factors: The elevation at which transmission infrastructure is installed significantly impacts construction costs. For instance, higher elevations can lead to lower temperatures and greater dielectric strength of the air, which affects the design and insulation requirements of lines and substations [23]. Conversely, extreme cold or remote access at high altitudes can increase logistical costs. This study introduces a "zone factor" (zfij) to account for the effect of elevation on construction costs, classifying areas into zones based on meters above sea level (m.a.s.l.) [28].

3. Andean Context Adaptation - Specific Challenges and Data Sources:

○ Route Selection and Cost Estimation: The rugged mountainous terrain directly impacts the routing of new transmission lines, often requiring longer routes, specialized construction techniques (e.g., helicopter-assisted construction, extensive civil works), and higher costs compared to flat terrains [26], [31]. Geospatial analysis is indispensable for identifying feasible corridors, avoiding protected areas, and estimating construction costs more accurately. For instance, the cost of high-voltage transmission projects in Ecuador has been a significant consideration, influencing planning decisions [33].

○ Resilience to Natural Hazards: The Andean region is prone to seismic events, landslides, and other natural disasters. Integrating seismic hazard maps and geological stability data into TEP models allows for the design of more resilient networks, identifying vulnerable areas and proposing mitigation measures such as reinforced tower foundations or alternative routing. Studies on the resilience of the Ecuadorian electrical system to seismic events highlight this critical need [15].

○ Cross-Border Interconnections: Geospatial analysis is vital for planning cross-border interconnections, such as the Ecuador-Peru interconnection [16] or projects in Colombia [14], considering the physical constraints, political boundaries, and the need for coordinated development across national grids. These interconnections are essential for regional energy security and market integration [20].

○ Remote Area Electrification and Hybrid Systems: In remote and isolated Andean communities, traditional grid extension may be economically unfeasible or environmentally disruptive. Geospatial analysis helps identify such areas, guiding the optimal sizing and scheduling of hybrid energy systems (e.g., solar-diesel combinations) and localized microgrids, which can reduce the need for extensive grid expansion into challenging terrains [17].

○ National Energy Plans and Data: TEP in Andean countries relies heavily on national energy balances, master plans, and specific case studies. For example, Ecuador's National Energy Balance [18] and Electricity Master Plans [21], [25] provide crucial baseline data, strategic directions, and projections for demand growth and generation capacity. Studies on the Ecuadorian interconnected system [4] and the technical feasibility of technologies like underground HVDC lines [24] further inform the planning process. Regional reports, such as Panama's expansion plan [30], Bolivia's transmission system reports [32], and specific project contracts in Peru [35] and Colombia [34], offer valuable insights into regional planning practices and cost considerations. Information from international bodies like the Agency for the Cooperation of Energy Regulators [29] also provides broader context on electricity infrastructure.

By integrating these diverse data sources and advanced modeling techniques, TEP in the Andean region can move beyond purely economic optimization to encompass geographical realities, environmental impacts, and system resilience, leading to more sustainable and adaptable power infrastructure.

Case Study: Characterization of the Ecuadorian Electrical System

The Ecuadorian electrical system serves as an ideal case study for exploring geography-based transmission network expansion strategies due to its remarkable geographical diversity. The country is broadly divided into three distinct regions: the Coastal Lowlands, the Andean Highlands (Sierra), and the Amazon Rainforest (Oriente). Each region presents unique environmental conditions, population distributions, and energy resource endowments, which profoundly influence the design, planning, and construction of electrical infrastructure, particularly transmission lines. This section provides a detailed characterization of the Ecuadorian electrical system, focusing on its current state, future demand projections, and the critical aspect of investment costs in relation to geographical elevation.

3.1 Characterization of the Ecuadorian Electrical System

Ecuador's energy matrix is predominantly reliant on oil for primary energy production. In 2021, oil accounted for a significant 85.8% of the total primary energy production, followed by natural gas at 4.4%. Other sources, including hydropower, firewood, bagasse, wind energy, photovoltaic, and biogas, collectively contributed 9.8% [18]. In terms of electricity generation, the country heavily leverages its abundant hydrological resources, with hydroelectric sources accounting for 78.5% of electricity generation in 2021. Thermal sources contributed 18.8%, while other renewable sources, such as wind, solar, and biomass, made up 1.5%. The effective installed capacity for electricity generation in 2021 reached 8734.41 MW [18].

Despite its substantial hydroelectric production, Ecuador faces the imperative of preparing its energy sector for a significant reduction in oil production in the coming decades due to the expected depletion of resources. The estimated Reserves-Production ratio for oil in Ecuador is approximately 25 years, while for natural gas, it is estimated to be around 30 years [19], [20]. This looming energy transition necessitates robust long-term power system planning models that are tailored to the nation's unique energy landscape and its diverse geography.

Ecuador has an Electricity Master Plan (EMP) in place, which outlines the strategic direction for the period 2018-2027 [21], [25]. However, these plans may prove inadequate in the event of extreme events affecting electricity production or the integrity of transmission and generation assets. The Andean region, in particular, is known for its high concentration of active volcanoes and seismic activity, which pose a significant threat to the integrity and operation of power generation and transmission systems. Therefore, planning must incorporate resilience against such natural hazards.

To analyze the transmission grid expansion in Ecuador, three distinct geographical zones have been defined, each with unique characteristics and challenges impacting construction and maintenance costs:

- Zone 1 (Coastal Lowlands and Amazon Region): This zone includes transmission assets located at elevations below 1000 meters above sea level (m.a.s.l.). These areas are characterized by a hot and humid climate, which presents specific challenges related to corrosion, vegetation management, and the maintenance of transmission lines.
- Zone 2 (Andean Highlands): This zone comprises assets located at 1000 m.a.s.l. or higher, primarily in the Andes region. Conditions at high elevations, such as lower temperatures, reduced atmospheric pressure, and greater dielectric strength of the air, have a significant impact on the design, construction, and maintenance costs of transmission lines [23]. Construction logistics in rugged mountainous terrain are also more complex and expensive.
- Zone 3 (Combined Zones): This represents a special case where transmission lines cross both Zone 1 and Zone 2, meaning part of the line is in a low-elevation area and part in a high-elevation area. This scenario combines the challenges of both zones, requiring an adaptable approach to design and construction that accounts for varying environmental and logistical conditions along a single corridor.

Figure 4 (from the original PDF, not reproduced here, but conceptually understood as a map of Ecuador with elevation zones and transmission lines) visually illustrates Ecuador's geographic diversity and how transmission lines are distributed across these different elevations. The data for these transmission lines is sourced from OpenStreet Maps, an open-source platform providing georeferenced information on electric power transmission systems, complemented by data from Ecuador's Electricity Master Plan 2018-2027.

To facilitate the analysis of non-conventional strategies for optimal transmission network expansion, a reduced model of the Ecuadorian transmission system, known as the EC-45 bus system, has been developed. This system extends previous work by Reinoso and Guamán [4] and serves as a representative model for the Andean region's geographical diversity. The EC-45 bus system consists of:

- 45 Busbars: These represent the nodes in the electrical network where generation, load, or transmission lines connect.
- 25 Loads: These represent the electricity demand points across the system.
- 20 Generators: These represent the power generation sources, including hydroelectric, thermal, and other renewable facilities.

The distribution and nomenclature of these components are detailed in Figure 5 (from the original PDF, conceptually a single-line diagram of the EC-45 bus system) and Table 1 (from the original PDF, a list of busbar names).

Table 2 (from the original PDF, a list of candidate transmission lines) presents a detailed list of candidate transmission lines proposed for new installations and repowering within the EC-45 bus system. For each candidate line, its voltage, name, length, assigned geographical zone, and approximate elevation are specified. A notable candidate is the Chorrillos-Posorja 500 kV line. Although this line is not explicitly part of Ecuador's Electricity Master Plan, it has been identified as a viable option to meet the growing energy demand in Posorja (Busbar B49), based on studies such as that conducted by Jacho et al. [24]. This highlights the importance of considering both officially planned projects and technically feasible alternatives in TEP.

Furthermore, existing National Interconnected System (NIS) lines that currently utilize the ACSR (Aluminum Conductor, Steel Reinforced) Bluejay 1113 conductor are being considered as candidates for repowering. To enhance their performance and increase capacity, it is proposed to replace these conductors with ACSS (Aluminum Conductor, Steel Supported) Bluejay 1113. ACSS conductors offer an ampacity (current-carrying capacity) approximately 22% higher than the original ACSR conductors and can operate at higher temperatures, thereby improving the overall efficiency and capacity of these specific lines without requiring the construction of new corridors.

In the context of the transmission expansion problem, accurately considering long-term demand growth is critical. For the EC-45 bus system, the projected demand outlined in Ecuador's EMP is adopted. Table 3 (from the original PDF, detailing demand growth rates) provides details on the corresponding growth percentages for short, medium, and high scenarios, offering insight into how the total demand (5965 MW) is expected to change and how it will be distributed among the various busbars over the planning horizon. This demand forecasting is a fundamental input for determining the necessary expansion of the transmission network.

3.2 Investment Costs for New Transmission Lines Considering Elevation

To adequately address the problem of transmission grid expansion, it is crucial to have accurate and context-specific information on the costs associated with the construction of new transmission lines and the repowering of existing ones. While general information on the cost per kilometer of transmission line construction is available from various sources, such as reports from AEMO (Australia) [26], Miranda et al. (Alaska) [27], and the Agency for the Cooperation of Energy Regulators (European Union) [29], the reported data are often limited to regions whose geographical and socio-economic conditions differ significantly from those of the Andean region. These differences include variations in terrain, labor costs, material availability, regulatory environments, and logistical challenges.

Given the limited availability of specific, publicly accessible cost datasets for Andean countries that precisely reflect their unique conditions, this study adopts values reported in the "Plan de Expansion del Sistema Interconectado Nacional 2019-2033" of Panama [30]. Panama is considered a suitable reference due to its relatively similar developing country context and an average elevation below 1500 m.a.s.l., offering a more relevant baseline than data from highly developed economies or vastly different geographies.

Table 4 (from the original PDF, showing estimated investment costs) provides a detailed estimate of transmission line construction costs per unit length (MUSD/km), taking into account the voltage level (e.g., 230 kV, 500 kV) and the number of circuits (e.g., dual conductor, single circuit). These costs are comprehensive, including various components such as:

- Right-of-Way (ROW) Acquisition: Costs associated with acquiring land or easements for the transmission corridor.
- Installation: Expenses related to the physical erection of towers, stringing of conductors, and civil works.
- Compensation: Payments for environmental or social impacts, or to affected communities.
- Design and Engineering: Costs for planning, surveying, and detailed engineering designs.
- Inspection and Supervision: Expenses for quality control and project oversight.

It is important to note that construction costs can vary over time due to inflation, changes in material prices (e.g., world metal prices for copper and aluminum), labor costs, and the dynamics of the market for transmission equipment. To provide a reasonable approximation, the values adopted from the Panama plan have been updated to the year 2020 using appropriate inflation adjustment concepts.

However, the data from ETESA (Panama) [30], while valuable, does not provide sufficient information to precisely estimate the percentage increase in costs specifically related to infrastructure built above 1500 m.a.s.l. To address this critical gap and demonstrate that the elevation at which transmission towers are installed significantly affects construction costs, additional data was collected from various Andean countries. Construction costs per unit length of transmission lines were gathered for Bolivia [32], Ecuador [33], Colombia [34], and Peru [35]. These costs were meticulously classified by voltage level, circuit type, and crucially, by elevation zone.

According to the data presented in Figure 6 (from the original PDF, a bar chart comparing transmission costs across Andean countries by zone), a clear trend emerges: the construction costs of a transmission line in Zone 2 (Andean Highlands, >1000 m.a.s.l.) in Ecuador are estimated to be approximately 5% more expensive than in Zone 1 (Coastal Lowlands/Amazon, <1000 m.a.s.l.). For facilities constructed in Zone 3, which cross both low and high elevation areas, the cost increase is approximately 2.5%. This quantitative evidence underscores the direct financial impact of geographical elevation on transmission infrastructure development in the Andean region.

In addition to the challenges of estimating local transmission network construction costs, the implementation of non-conventional strategies like reconfiguring and repowering transmission lines faces unique obstacles that extend beyond purely financial considerations. These barriers include:

- Technical Complexities: Repowering, for instance, requires careful assessment of the compatibility of new, higher-capacity conductors with existing tower structures, foundations, and insulators. Modifications to network components may be necessary to adapt to new operating conditions, including increased current, higher temperatures, and altered sag characteristics.

- Regulatory Issues: Obtaining permits for reconfigurations or repowering projects, even if they utilize existing corridors, can still be subject to complex regulatory processes, environmental impact assessments, and public consultations.

- Environmental Impacts: While generally lower than new construction, repowering and reconfiguration can still have environmental implications, such as increased electromagnetic fields or the need for temporary access roads in sensitive areas.

- Operational Factors: Environmental and operational factors, such as extreme temperature fluctuations, heavy rainfall, high humidity, and air pollution (e.g., from industrial activities or volcanic ash), can significantly impact the efficiency, durability, and long-term performance of conductors and other infrastructure components. These factors can accelerate corrosion, lead to reliability issues, and increase maintenance costs. Therefore, a detailed assessment of conductor strength, capacity, and material resilience is often necessary, particularly in regions with extreme climates.

- Accurate Network Assessment: Accurately identifying existing lines that are prime candidates for repowering or reconfiguration is another crucial challenge. This requires a thorough analysis of the current state of the network, including its load capacity, operational bottlenecks, aging infrastructure, and future demand projections. This involves detailed power flow studies and asset condition assessments.

These factors, combined with the physical and regulatory limitations for the construction of entirely new lines, highlight the importance of developing expansion strategies—including both conventional and non-conventional approaches—that are not only technically feasible and economically efficient but also adaptable to the specific local technical, social, and environmental conditions of the Andean region. The MILP model employed in this study, implemented in AMPL and solved using Gurobi 10.0.3, accounts for these zonal factors and costs, with data preprocessing and postprocessing tasks handled in Python, as illustrated in Figure 3 (from the original PDF, showing the optimization process flowchart). The objective function (Eq. 1 in the original PDF) explicitly minimizes total cost, incorporating the construction costs of new lines, repowering costs, and the costs of new lines with identical characteristics to repowered ones, all weighted by the elevation-related zone factor (zfij). The model is subject to various constraints covering power balance, power flow limits, generation and angle limits, and rules for sequential line additions and reconfiguration logic (Eqs. 2-21 in the original PDF).

RESULTS

The application of a comprehensive Transmission Expansion Planning (TEP) framework, integrating geospatial considerations and non-conventional strategies, yields distinct outcomes when applied to the EC-45 bus system, a representative model for Andean electrical grids. This section presents the results derived from various scenarios, beginning with the traditional Linear Disjunctive model and progressing to scenarios incorporating reconfiguration, repowering, and a combination of both, providing a quantitative analysis of the benefits achieved.

4.1 Linear Disjunctive Model

The Linear Disjunctive model serves as a benchmark for evaluating the cost-effectiveness of alternative expansion strategies. This classical approach primarily focuses on the construction of new transmission lines to meet future demand and system reliability criteria. The solution obtained for the transmission expansion of the EC-45 bus system using the Linear Disjunctive model is detailed in Table 5 (from the original PDF, showing results of the disjunctive linear model).

Key findings from this scenario include:

- Number of New Lines: A total of 12 new transmission lines are selected for addition to the EC-45 bus system. These lines are strategically chosen to alleviate congestion, enhance power transfer capabilities, and ensure N-1 reliability (the ability of the system to withstand the outage of a single component).

- Total Investment Cost: The combined investment cost for these 12 new lines amounts to $447.90 MUSD. This figure represents the baseline cost for expanding the network using conventional construction methods, without explicitly considering the benefits of repowering or reconfiguration.

- Geographical Distribution of New Lines: The selected new lines span across both Zone 1 (low elevation) and Zone 2 (high elevation) areas, reflecting the geographical diversity of the Ecuadorian system. Examples include the Milagro [B24]-Zhoray [B44] line (Zone 2, 120.07 km, $41.06 MUSD) and the Chorrillos [B9]-Posorja [B49] line (Zone 1, 46.74 km, $46.74 MUSD). The costs for lines in Zone 2 are notably higher per kilometer due to the elevation factor (Zfij), as discussed in the Methods section.

The results from the Linear Disjunctive Model provide a crucial benchmark against which the economic viability and efficiency of the non-conventional strategies (reconfiguration and repowering) can be directly compared. This comparison highlights the potential for cost savings when leveraging existing infrastructure and adapting to geographical constraints.

4.2 Reconfiguration of Existing Lines

Reconfiguration is a non-conventional strategy that seeks to optimize the use of existing infrastructure by altering the network topology, often by redirecting existing line segments or creating new connections using parts of existing lines. To identify suitable candidates for reconfiguration, a power flow analysis was conducted on the EC-45 bus system using commercial software (DigSILENT PowerFactory). This analysis revealed that the existing transmission line connecting Milagro [B24] and Zhoray [B44] was operating at a particularly high load level, approximately 89.5% of its capacity, as depicted in Figure 7 (from the original PDF, showing line loadability). This high loadability indicates a bottleneck in the network, making this line an ideal candidate for a reconfiguration solution to redistribute power flow and reduce congestion without building entirely new circuits.

Figure 8 (from the original PDF, illustrating reconfiguration scenarios) illustrates two possible scenarios for reconfiguring the Milagro [B24]-Machala [B21] transmission line to alleviate the load on the [B24]-[B44] branch:

- Scenario (a): The objective is to change the network topology towards the Sinincay busbar [B40]. The results for this scenario are presented in Table 6 (from the original PDF). In this specific case, the model opted not to reconfigure the section. This suggests that, given the objective function (cost minimization) and constraints, reconfiguring towards Sinincay [B40] did not provide a more cost-effective solution compared to other expansion options in this scenario.
- Scenario (b): The objective is to change the network topology towards the Zhoray busbar [B44]. The results for this scenario are presented in Table 7 (from the original PDF). In contrast to scenario (a), the model did opt for reconfiguration in this case. Specifically, it chose to construct new transmission lines: Sopladora [B6]-Cardenillo [B51], Cardenillo [B51]-Taday [B41], and Chorrillos [B9]-Pasaje [B53]. Crucially, it also opted to reconfigure the Milagro [B24]-Machala [B21] line towards the Zhoray [B44] busbar, involving the creation of new reconfiguration nodes (B57 and B58) and associated line segments.

Comparing scenario (b) with the Linear Disjunctive model, the reconfiguration approach provided a solution that was $5.14 MUSD (1.14%) less costly than the $447.90 MUSD benchmark. This demonstrates that even a relatively modest reconfiguration can lead to tangible economic savings by optimizing the utilization of existing assets and reducing the need for extensive new construction. The reconfiguration effectively redistributes power flows, reducing the burden on congested lines and improving overall network efficiency.

4.3 Repowering of Existing Lines

Repowering is a strategic option for enhancing the capacity of existing transmission lines by upgrading their conductors, thereby increasing their ampacity and improving power transfer capabilities without building new corridors. Candidate lines for repowering within the EC-45 bus system were selected based on the type of conductor currently in use, specifically those using ACSR Bluejay 1113. The repowering process involves replacing these with ACSS Bluejay 1113 conductors, which offer higher ampacity (approximately 22% more) and can operate at higher temperatures, making them more efficient and durable.

The solution obtained from the repowering scenario is presented in Table 8 (from the original PDF, showing results of repowering scenario).

- Selected Repowering Projects: The model opted for repowering only one specific section: the Riobamba [B24] - Totoras [B42] line. This decision indicates that, among all candidate lines for repowering, this particular section offered the most significant cost-benefit in terms of capacity enhancement versus investment.
- New Line Constructions: In addition to the repowering, the model also selected several new lines for construction, similar to the Linear Disjunctive model, but adjusted based on the capacity improvements from repowering.
- Total Investment Cost and Savings: The total cost of expansion in the repowering scenario was $423.70 MUSD. This represents a significant cost saving of $24.20 MUSD (5.40%) compared to the Linear Disjunctive model's cost of $447.90 MUSD. Furthermore, the repowering scenario resulted in a reduction of $19.06 MUSD (4.30%) compared to scenario (b) of the reconfiguration model ($442.76 MUSD).

These findings strongly demonstrate that repowering is a highly viable and cost-effective option for reducing the expenses associated with transmission expansion. By leveraging existing infrastructure and upgrading components, utilities can achieve substantial capacity increases and improve network performance at a fraction of the cost of building entirely new lines, especially in geographically challenging regions where new construction is inherently expensive.

4.4 Combined Reconfiguration and Repowering of Existing Lines

This scenario represents the most comprehensive approach, considering all candidate lines for both reconfiguration and repowering, alongside potential new constructions, as listed in Table 2 (from the original PDF). The primary objective is to optimize the combination of these non-conventional strategies to achieve the maximum possible cost reduction while ensuring system reliability and meeting future demand.

The results for the combined repowering and reconfiguration scenario are presented in Table 9 (from the original PDF, showing results for combined scenario).

- Optimal Strategy: The model successfully identified an optimal combination of strategies.
  - Repowering: The lines Zhoray [B44] - Molino [B27] and Riobamba [B24] - Totoras [B42] were selected for repowering. This indicates that upgrading the conductors on these existing lines provided significant capacity benefits.
  - Reconfiguration: The Milagro [B24] - Machala [B21] line underwent reconfiguration, redirecting it towards the Zhoray [B44] busbar, similar to scenario (b) of the individual reconfiguration analysis. This topological change helped in redistributing power flow and alleviating congestion.
  - New Lines: A reduced number of new lines were also constructed, strategically placed to complement the capacity enhancements from repowering and reconfiguration.
- Total Investment Cost and Maximum Savings: The total cost of expansion for this combined scenario was $310.84 MUSD. This outcome represents the most significant savings across all tested scenarios, achieving a remarkable cost reduction of $137.06 MUSD (30.60%) compared to the baseline cost obtained from the Linear Disjunctive model ($447.90 MUSD).
- Visual Representation: Figure 9 (from the original PDF, showing combined results) visually depicts the results for the combined scenario, illustrating the locations of new lines, repowered lines, and reconfigured lines within the EC-45 bus system. This visual aid clearly shows how a hybrid approach optimizes the network's physical expansion.

This compelling outcome demonstrates that a holistic approach, which integrates both reconfiguration and repowering into the TEP framework, can lead to substantial economic benefits. By prioritizing the optimization and enhancement of existing infrastructure before resorting to new construction, utilities in regions with complex geographies like the Andes can achieve more efficient resource management, reduce overall investment costs, and minimize environmental impact. These findings validate the premise that non-conventional solutions are not merely alternatives but can be superior strategies for transmission network expansion, especially in contexts where geographical constraints and limited budgets are significant considerations.

DISCUSSION

The findings from this study unequivocally underscore the paramount importance of integrating geospatial considerations into Transmission Expansion Planning (TEP) for regions characterized by complex geographies, such as the Andean countries. This approach transcends traditional economic and purely technical optimization, embracing crucial environmental, social, and resilience dimensions that are critical for the sustainable development of electrical infrastructure. The insights gained from the EC-45 bus system case study, representative of the Ecuadorian electrical system, provide a robust foundation for generalizing these conclusions to other Andean nations facing similar challenges.

Synthesis of Findings

The comprehensive analysis reveals that geographical features are not merely obstacles to be overcome but fundamental determinants of TEP outcomes in the Andean region. The rugged terrain, with its significant elevation differences and varied topographies, directly dictates higher construction costs and necessitates more complex engineering solutions. This influences the choice of technology, as evidenced by the potential for underground HVDC lines in specific Ecuadorian contexts where overhead lines might be prohibitively expensive or environmentally disruptive [24]. The study's quantitative results, showing a 5% cost increase for lines in high-elevation Zone 2 compared to Zone 1, directly validate the impact of elevation on investment.

Furthermore, the region's inherent susceptibility to seismic activity, landslides, and other natural hazards necessitates a proactive approach to resilience planning. The studies on the Ecuadorian system's resilience to seismic events [15] highlight the critical need for integrating geological and hazard data into TEP models. This ensures that infrastructure is designed and placed to withstand such events, minimizing downtime and recovery costs.

Strategic cross-border interconnections, such as those between Ecuador and Peru [16] or within Colombia [14], are not only economically beneficial for energy exchange and market integration but also crucial for enhancing regional energy security and flexibility. Their optimal placement and design are heavily reliant on meticulous geospatial analysis to navigate physical constraints and political boundaries effectively. These interconnections enable optimal dynamic reactive power compensation and enhance overall system stability, as demonstrated by the Ecuador-Peru interconnection case.

The adoption of advanced AC models, incorporating Flexible AC Transmission Systems (FACTS) devices and Voltage Source Converter-based Multi-Terminal DC (VSC-MTDC) systems [7], becomes essential for managing the intricate power flows and maintaining stability across long, geographically challenging transmission corridors. These technologies provide the necessary control and flexibility to operate complex networks efficiently.

Crucially, the study's most compelling finding is the significant economic viability of non-conventional expansion strategies—reconfiguration and repowering—

especially when combined. The combined scenario yielded a remarkable 30.60% cost reduction compared to the traditional Linear Disjunctive model. This substantial saving is achieved by leveraging existing infrastructure, upgrading components (repowering), and optimizing network topology (reconfiguration) before resorting to expensive new line construction. This holistic view, which prioritizes the optimization of existing assets, is increasingly reflected in national energy balances [18] and master plans [21], [25] across the region, signaling a shift towards more efficient and sustainable grid development. The economic benefits are not just about lower initial investment but also about reduced environmental impact and potentially faster project deployment.

Challenges and Limitations

Despite the clear benefits, integrating geospatial considerations into TEP for complex regions like the Andes presents several inherent challenges and limitations that must be acknowledged and addressed in future research and implementation:

● Data Availability, Resolution, and Standardization: High-resolution, accurate, and up-to-date geospatial data (e.g., detailed topography, precise geological surveys, comprehensive environmental impact assessments, land ownership information) can be costly and difficult to acquire, especially in remote, inaccessible, or politically sensitive areas. Furthermore, data from different sources may lack standardization, making integration challenging. For instance, detailed seismic maps might exist at varying resolutions across national borders, complicating regional planning.

● Modeling Complexity and Computational Burden: Incorporating diverse and high-resolution geospatial datasets into complex optimization models significantly increases the computational burden. Balancing model fidelity (detail and accuracy) with computational tractability (solvability within reasonable timeframes) remains a significant challenge, particularly for large-scale, multi-stage TEP problems. The non-linearities introduced by AC models and the discrete nature of expansion decisions further exacerbate this complexity.

● Multi-objective Optimization and Trade-offs: TEP is inherently a multi-objective problem, requiring a balance among often conflicting objectives: economic efficiency (minimizing costs), reliability (ensuring uninterrupted supply), environmental impact (minimizing ecological disruption), social acceptance (avoiding conflicts with local communities), and resilience (withstanding and recovering from disruptions). Quantifying and integrating all these factors, especially those related to geographical constraints and their socio-environmental consequences, into a single optimization framework is complex. Decision-makers often face difficult trade-offs, such as choosing between a shorter, cheaper route that impacts a sensitive ecosystem and a longer, more expensive route that avoids it.

● Uncertainty in Geospatial and Future Data: Geospatial data, particularly related to future climate change impacts (e.g., altered hydrological cycles affecting hydropower potential, increased frequency of extreme weather events) or long-term seismic activity, carries inherent uncertainties. Managing these uncertainties within the planning process requires advanced stochastic or robust optimization techniques, which add another layer of complexity. Similarly, long-term load forecasting and renewable energy generation forecasts are subject to significant uncertainties.

● Inter-agency Coordination and Stakeholder Engagement: Effective geospatial TEP requires robust coordination and collaboration among various governmental agencies (energy ministries, environmental agencies, land-use planning bodies), local communities, indigenous groups, and utility companies. This inter-agency and multi-stakeholder coordination can be challenging in practice due to differing mandates, priorities, data silos, and potential conflicts of interest. Lack of early and meaningful stakeholder engagement can lead to project delays, legal challenges, and social opposition.

● Regulatory and Policy Frameworks: Existing regulatory and policy frameworks in some Andean countries may not fully support or incentivize the adoption of advanced TEP methodologies that account for geographical complexities or promote non-conventional solutions. Outdated regulations can hinder the implementation of innovative technologies or flexible grid solutions.

● Technical Constraints of Non-Conventional Strategies: While highly beneficial, repowering and reconfiguration have their own technical constraints. Repowering existing lines with higher-capacity conductors requires careful assessment of the structural integrity of existing towers, foundations, and insulators to ensure they can withstand increased loads and different sag characteristics. Reconfiguration might be limited by the existing network topology and the availability of suitable connection points. In some cases, existing systems may already use high-capacity conductors, limiting the scope for further repowering and necessitating a hybrid strategy that combines new construction with non-conventional methods.

Future Directions

To further enhance the robustness, sustainability, and adaptability of electrical grids in the Andean region, future research and practical implementation should focus on several key areas:

● Advanced AI/ML for Dynamic and Adaptive TEP: Further exploration and development of AI/ML techniques, beyond current DQN and DDQN applications

[9], [10], [11], are crucial. This includes:

○ Reinforcement Learning for Real-time Adaptation: Developing reinforcement learning agents that can learn optimal expansion and operational strategies in real-time, responding dynamically to changing geographical conditions, environmental shifts (e.g., landslides, floods), and real-time data from remote sensing and IoT devices.

○ Predictive Analytics for Geospatial Risks: Utilizing machine learning for more accurate prediction of geospatial risks (e.g., seismic activity, extreme weather patterns, vegetation growth impacting lines) to inform proactive planning and mitigation measures.

○ Generative AI for Scenario Generation: Exploring generative adversarial networks (GANs) or other generative AI models to create diverse and realistic future scenarios for load growth, renewable energy penetration, and climate impacts, providing a richer input for stochastic TEP.

● Integrated Multi-Criteria Decision Making (MCDM) Frameworks: Developing more sophisticated and transparent MCDM frameworks that explicitly weigh economic, technical, environmental, and social factors, with a strong emphasis on quantifiable geospatial impacts. This could involve:

○ Spatial Multi-Criteria Analysis (SMCA): Integrating SMCA with TEP optimization models to systematically evaluate alternative routes and technologies based on a comprehensive set of spatial criteria (e.g., ecological sensitivity, cultural heritage sites, social equity).

○ Stakeholder-Weighted Objectives: Incorporating mechanisms to weight objectives based on stakeholder preferences, ensuring that the planning process is inclusive and reflects the values of affected communities.

● Enhanced Climate Change Resilience Modeling: Deeper integration of climate change projections and impact assessments into TEP models is essential to design infrastructure that is inherently resilient to future climatic conditions. This includes:

○ Probabilistic Risk Assessment: Developing probabilistic models to assess the risk of extreme weather events (e.g., intense rainfall leading to landslides, prolonged droughts impacting hydropower) and their potential impact on grid components.

○ Adaptive Capacity Planning: Planning for adaptive capacity, such as modular grid components, flexible interconnection points, and pre-positioned emergency response resources, to enhance the grid's ability to recover from climate-related disruptions.

○ Nature-Based Solutions: Investigating the role of nature-based solutions (e.g., reforestation for slope stabilization, wetland restoration for flood mitigation) in enhancing the resilience of transmission corridors.

● Optimal Integration of Distributed Energy Resources (DERs) and Microgrids: Investigating the optimal placement and operation of DERs and microgrids, especially hybrid systems in remote Andean communities [17], to potentially reduce the need for extensive and costly transmission line extensions into challenging terrains. This includes:

○ Grid-Edge Intelligence: Developing smart grid technologies and control systems that enable seamless integration and coordinated operation of DERs with the main transmission network.

○ Energy Access Solutions: Focusing on how DERs and microgrids can provide reliable and affordable energy access to underserved populations in remote Andean areas, reducing energy poverty and fostering local economic development.

● Supportive Policy and Regulatory Frameworks: Developing and implementing supportive policy and regulatory frameworks that incentivize geospatial data collection, inter-agency data sharing, and the adoption of advanced TEP methodologies that explicitly account for geographical complexities and promote cross-border cooperation [29], [20]. This could involve:

○ Incentive Mechanisms: Creating financial and regulatory incentives for utilities to invest in non-conventional expansion strategies and resilience-enhancing technologies.

○ Streamlined Permitting Processes: Developing more efficient and transparent permitting processes for transmission projects, while ensuring robust environmental and social safeguards.

○ Regional Energy Market Integration: Fostering policies that promote greater regional energy market integration and cross-border infrastructure development, leveraging the diverse energy resources of Andean nations.

● Regional Collaboration and Data Sharing Platforms: Fostering greater regional collaboration among Andean nations, potentially facilitated by organizations like OLADE [20], to share best practices, standardized geospatial data, and coordinated planning efforts for cross-border infrastructure. This could involve:

○ Shared Geospatial Databases: Establishing regional platforms for sharing high-resolution geospatial data relevant to TEP, ensuring data consistency and accessibility.

○ Joint Planning Initiatives: Launching joint TEP initiatives for regional interconnections, ensuring that projects are optimized from a regional perspective rather than solely a national one.

○ Knowledge Exchange: Facilitating knowledge exchange and capacity building among TEP practitioners and researchers across the Andean region, drawing insights from experiences in other complex geographies like Alaska [27].

- Blockchain for Energy Trading and Grid Management: Exploring the potential of blockchain technology for secure and transparent energy trading across cross-border interconnections, and for decentralized grid management, enhancing efficiency and trust in regional energy markets.

- Advanced Sensor Networks and IoT: Deploying advanced sensor networks and Internet of Things (IoT) devices along transmission corridors to collect real-time data on environmental conditions, line performance, and potential threats (e.g., vegetation encroachment, structural integrity issues). This data can feed into AI/ML models for predictive maintenance and dynamic grid operation.

By addressing these challenges and vigorously pursuing these future directions, TEP in the Andean region can continue to evolve, ensuring the development of robust, resilient, and sustainable electrical grids that effectively serve the growing energy needs of its diverse populations and economies, while respecting the unique geographical and environmental characteristics of the region.

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