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Challenges Ahead in Transmission Network Expansion Planning in The Presence of Renewable Energy Sources; An Updated Review

Abdollah Rastgou

Highlights

- **Transmission network expansion planning (TNEP) is vital for reliability in restructured power systems.**
- **Effective TNEP integrates renewable energy sources, supporting sustainability and reducing emissions.**
- **Proper transmission planning minimizes congestion, optimizing infrastructure for future demand and generation.**
- **A robust transmission network fosters competition, resilience, and public trust in the energy sector's evolution.**

Graphical Abstract

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Challenges Ahead in Transmission Network Expansion Planning in The Presence of Renewable Energy Sources; An Updated Review

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ABSTRACT

The significance of transmission network expansion planning (TNEP) in a restructured power system is underscored by the urgent need to integrate renewable energy sources. As the world shifts towards sustainability, effective transmission planning becomes critical for accommodating diverse energy sources, particularly wind and solar, which are frequently situated far from consumption centers. This integration is not only essential for achieving sustainability goals and reducing greenhouse gas emissions but also for ensuring a reliable and efficient power supply. Moreover, strategic transmission planning plays a vital role in minimizing congestion within the network, which can escalate costs and compromise reliability. By anticipating future demand and generation patterns especially the intermittent nature of renewables planners can optimize the placement of transmission lines and substations to mitigate potential bottlenecks. In a competitive market, a resilient transmission infrastructure is crucial for providing equitable access to all market participants, thereby fostering innovation and competition. Additionally, effective planning must address regulatory requirements and stakeholder interests, promoting transparency and collaboration among various entities in the power sector. This comprehensive approach not only ensures compliance but also builds public trust in the energy system. In summary, developing an efficient transmission network is imperative for supporting a reliable, competitive, and sustainable power system that prioritizes renewable energy sources. This paper aims to provide an overview of the challenges ahead in TNEP while proposing necessary solutions to effectively address these challenges.

1. Introduction

Energy planning refers to a set of activities that are carried out on a macro level to study the interrelationship between the energy sector and other economic sectors with an emphasis on environmental considerations to create coordination between supply and demand. In every country, one of the important issues in government policy is energy planning and management. Large-scale energy planning depends on many factors, including economic development prospects, political approaches, macro-management issues, economic situation, etc. According to Figure 1, one of the basic branches of energy planning is power system planning, which can be done even in a 50-year period. This planning includes generation expansion planning, transmission network expansion planning, and finally distribution network expansion planning (DNEP). After determining the share of electrical energy in meeting a country's energy needs, long-term production planning is conducted for a horizon of 30 to 40 years, during which the required capacities and types of power plants are specified. The TNEP is part of a broader process that begins with energy planning and concludes with operational planning. Once the expansion plan for generation is established, TNEP is carried out over a long-term horizon (up to 30 years), with updates occurring at shorter intervals. These updates and modifications to the expansion plans can even occur within horizons of 2 to 3 years depending on unforeseen events during the planning phase. After the TNEP is defined, reactive power planning is conducted in shorter intervals of 2 to 3 years. The goal here is to determine the type, capacity, and location of reactive power compensators needed to properly operate the network and to reduce losses. Finally, the operational planning process begins, covering a horizon from one year prior to one day before operation [1]. This phase addresses issues such as scheduling maintenance for power plants and lines, necessary switching operations in the transmission network, and establishing the production patterns for the units.

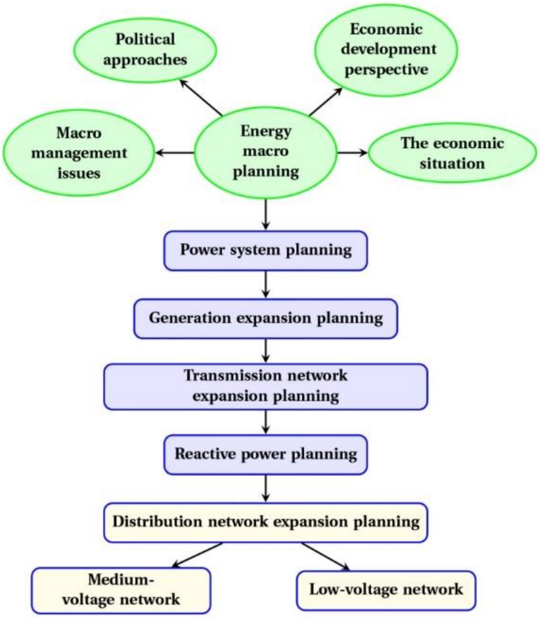

Figure 1. Energy planning procedure.

The significance of renewable energy sources (RESs) has become increasingly paramount in the face of climate change and the depletion of fossil fuels. As nations strive to reduce their carbon footprints and transition towards sustainable energy systems, harnessing the power of RESs such as solar, wind, hydro, and biomass is essential. These energy sources not only contribute to a cleaner environment but also enhance energy security by diversifying the energy mix. Furthermore, the adoption of renewables can stimulate economic growth by creating jobs in manufacturing, installation, and maintenance sectors, thus driving innovation and technological advancements. However, the effective integration of renewable energy into existing power grids necessitates comprehensive planning and expansion of transmission networks. As renewable energy generation is often decentralized and variable, a robust transmission infrastructure is crucial for transporting electricity from remote generation sites to urban centers where demand is highest. Strategic planning of these networks must consider factors such as geographical distribution, grid stability, and the incorporation of energy storage solutions. By investing in advanced transmission technologies and smart grid systems, countries can enhance their capacity to accommodate fluctuating renewable energy supplies, ultimately leading to a more resilient and sustainable energy future.

The TNEP is carried out in practice for four reasons, as illustrated in Figure 2, The primary goal of The TNEP is to develop a plan that ensures the economical supply of power while maintaining or improving the reliability of the network. Economical power supply means that, first, the investment costs for new lines and substations are minimized, and second, the transmission network does not impose any limitations on the economic operation of the power system. In the past, economic operation of the power system was synonymous with minimizing production costs; in restructured networks, it refers to the ability to create a competitive market for trading electrical energy. One of the reasons for expanding the transmission network is to connect newly constructed power plants to the grid. Naturally, the generated power must be transmitted to consumption points through the transmission system. Therefore, the expansion of the transmission network is inevitable, especially when considering the expansion and construction of new power plants.

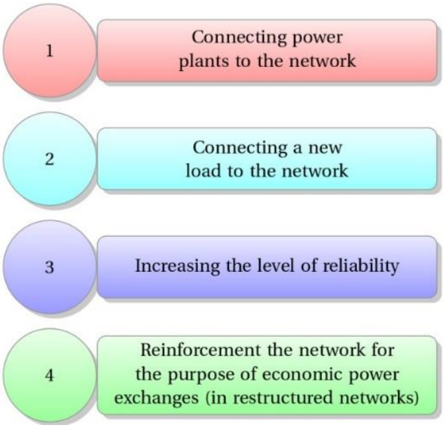

Figure 2. The main reasons for the TNEP.

Another reason for expanding the transmission system is to connect new load points to the grid. This connection primarily occurs at the sub-transmission level, and its impact is modeled as an increase in the load on transmission substations and a change in their loading patterns. In cases such as supplying large industries, their power needs can be met directly from the transmission network [2]. Maintaining and enhancing network reliability is also a key reason for network expansion. The most commonly used criterion for assessing the reliability of transmission networks is the *N-1* security criterion. According to this criterion, the power network must meet consumer needs without experiencing overload, unacceptable voltage drops, or load shedding, not only under normal conditions but also when one of its components is lost. Plans aimed at increasing reliability in power system planning can be categorized into two types:

- Expansion plans
- Reinforcement plans

In expansion plans, planners select new routes or locations for constructing new lines or substations while considering environmental constraints. This approach effectively adds new power transmission paths to the network [3]. In reinforcement plans, certain paths within the network are typically strengthened. Examples include converting an existing line into a double-circuit line, increasing the number of transformers at substations, or raising the transmission voltage level. Another reason for developing the transmission system is the economic exchanges of power, which becomes increasingly important in restructured power systems. In practice, since not all forecasts will be realized exactly, expansion plans are reviewed periodically (for example, every five years). Over time, some ambiguous information becomes clearer, allowing for more accurate predictions of the future. Additionally, the impacts of generation and the expansion of the distribution network must always be considered in the planning of the transmission network. This necessitates a feedback process between these optimization issues. The bar chart provided in Figure 3 illustrates the growth in transmission planning studies from 2016 to 2024.

Over this period, there has been a noticeable upward trend, with the number of studies increasing significantly, particularly in the last few years. This surge indicates a heightened focus on enhancing transmission infrastructure, likely driven by the growing demand for reliable energy supply and the integration of RESs into the grid. The substantial rise in studies during 2020 and beyond may reflect a response to emerging challenges in energy transition, regulatory changes, and technological advancements. Overall, this trend underscores the importance of strategic planning in ensuring that transmission networks can meet future energy needs efficiently and sustainably. Here's a more detailed breakdown of the trends and implications:

- Overall Trend: The data shows a consistent increase in the number of transmission planning studies each year. This upward trajectory indicates that there is an increasing recognition of the importance of thorough planning in transmission systems.
- Significant Growth Post-2020: Notably, there is a marked spike in the number of studies starting in 2020. This could be attributed to several factors:
    1. Energy Transition: As more countries and regions commit to transitioning to RESs, there is a greater need for comprehensive planning to ensure that the transmission infrastructure can accommodate these changes.
    2. Regulatory Changes: New policies and regulations may have been implemented that require more rigorous planning and analysis of transmission networks.
    3. Technological Advancements: Improvements in technology, such as smart grid solutions and advanced forecasting methods, may have made it easier and more effective to conduct these studies.
- Implications for Energy Supply: The increase in transmission studies suggests that utilities and energy planners are proactively addressing potential challenges in energy supply and reliability. This is crucial as electricity demand continues to rise, driven by factors such as population growth, increased electrification of transportation, and a shift towards electric heating.
- Integration of RESs: With the growing penetration of RESs like wind and solar, there is a need for enhanced transmission planning to ensure that these resources can be effectively integrated into the grid. This requires careful consideration of geographic locations, capacity needs, and potential bottlenecks in the existing infrastructure.
- Future Outlook: The trend indicated by the chart may continue as the energy landscape evolves. Ongoing studies will likely focus on resilience against climate change impacts, cybersecurity for grid operations, and optimizing existing infrastructure to meet future demands.

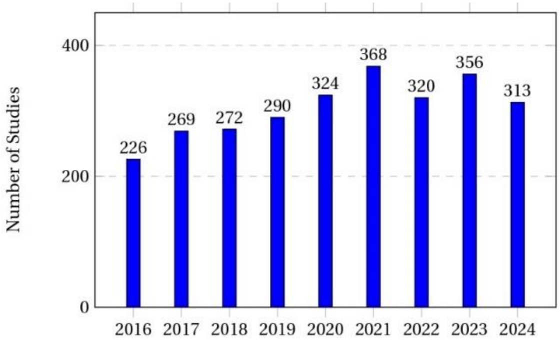

Figure 3. Number of studies on TNEP from 2016-2024 (adapted from Google Scholar).

Therefore, the bar chart reflects a vital aspect of energy management and planning, showcasing how stakeholders are increasingly prioritizing the expansion and enhancement of transmission networks to support a sustainable and reliable energy future. The following pie chart shown in Figure 4 represents the various components involved in the planning process, highlighting their relative contributions.

- Infrastructure Investment (40%): This segment represents the largest portion of the planning process, indicating that a significant amount of resources is allocated to upgrading and expanding physical infrastructure, such as substations and transmission lines.
- Regulatory Compliance (25%): A quarter of the planning effort goes into ensuring that all expansions comply with local, national, and international regulations. This includes environmental assessments and adherence to safety standards.
- Technological Innovation (15%): This portion signifies the investment in new technologies, such as smart grid solutions and renewable energy integration, which are essential for modernizing the network and improving efficiency.
- Stakeholder Engagement (10%): Engaging with stakeholders, including local communities, government bodies, and industry partners, is vital for gaining support and addressing concerns related to new projects.
- Risk Management (10%): This segment focuses on identifying and mitigating potential risks that could impact the transmission network's reliability and performance.

The Figure 4 clearly illustrates that infrastructure investment is the dominant factor in TNEP, reflecting the need for robust physical systems to support growing energy demands. Regulatory compliance is also a significant concern, emphasizing the importance of aligning projects with legal frameworks and environmental considerations. Technological innovation, while smaller in percentage, highlights a forward-looking approach to integrate advanced solutions that can enhance grid reliability and sustainability. Stakeholder engagement and risk management are equally important, ensuring that projects are socially acceptable and resilient against potential disruptions.

2. Problem formulation

The TNEP consists of two stages. In the first stage, various options for the expansion of the transmission network within the planning horizon are generated as a set of reinforcement and expansion plans using simplified models, such as the DC load flow model. In the second stage, the expansion options are evaluated through a more detailed analysis that includes maximum, average, and minimum load levels, short-circuit analysis, transient stability assessment, and reliability evaluation. In most studies, the TNEP primarily refers to the first stage mentioned above, although it can also incorporate more accurate load flow models and consider reliability in the planning process. The various methods used to generate transmission network expansion plans in the first planning stage typically focus solely on adequacy criteria in their models, while security aspects are deferred to the analyses conducted in the second planning stage.

3. TNEP challenges with RESs

The integration of RESs, such as solar and wind power, into the transmission network presents several challenges in the planning and expansion of electricity transmission systems. These challenges can significantly impact the reliability, efficiency, and overall effectiveness of the electrical grid [4-15]. Below are some of the key challenges associated with the installation of renewable energy plants in transmission network planning:

- Intermittency and Variability: RESs are inherently intermittent and variable, meaning their output can fluctuate based on weather conditions. This variability poses significant challenges for grid operators who must ensure a stable and reliable electricity supply. Planners need to develop strategies to accommodate these fluctuations, which may involve the integration of energy storage systems or demand response mechanisms.

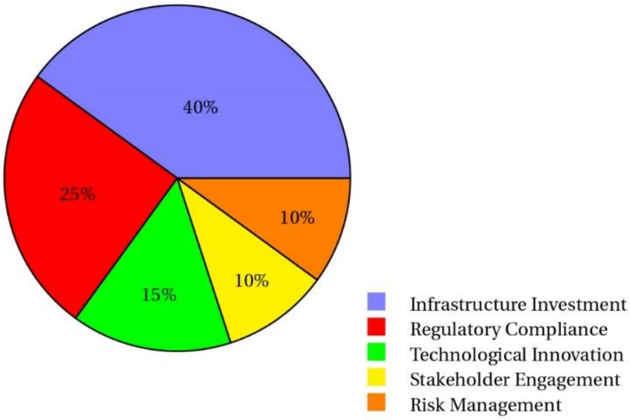

Figure 4. The various components involved in the planning process, highlighting their relative contributions.

- Grid Capacity and Infrastructure: The existing transmission infrastructure may not be adequately equipped to handle the additional load from renewable energy installations. Upgrading or expanding the grid may be necessary to accommodate new generation sources, which can be costly and time-consuming. Furthermore, planners must consider the location of renewable resources, as they are often situated far from existing transmission lines, necessitating new construction.
- Location and Resource Assessment: Identifying optimal locations for renewable energy plants is crucial for minimizing transmission losses and maximizing efficiency. However, suitable sites for wind and solar farms may not always align with existing transmission infrastructure. Comprehensive resource assessments and geographic analyses are required to determine the best locations while considering environmental impacts and land use.
- Regulatory and Policy Framework: The planning and installation of renewable energy projects are often subject to complex regulatory frameworks that can vary significantly by region. Navigating these regulations can be a challenge for developers and planners alike. Additionally, policies related to grid interconnection, permitting processes, and incentives for renewable energy can influence project timelines and feasibility.
- Technical Integration Challenges: Integrating renewable energy into the transmission network requires advanced technical solutions to manage issues such as voltage stability, frequency control, and power quality. Planners must consider the implementation of smart grid technologies, advanced forecasting tools, and real-time monitoring systems to effectively manage the integration of diverse energy sources.
- Economic Considerations: The economic viability of renewable energy projects is influenced by factors such as capital costs, operational expenses, and market prices for electricity. Planners must conduct thorough economic analyses to determine the cost-effectiveness of integrating renewables into the transmission network. This includes evaluating potential revenue streams from energy sales and considering the long-term impacts on electricity prices.
- Stakeholder Engagement: Successful planning for renewable energy integration requires collaboration among various stakeholders, including government agencies, utility companies, developers, and local communities. Engaging these stakeholders early in the planning process is essential to address concerns, gather input, and build support for renewable energy projects.
- Environmental Impact Assessments: The installation of renewable energy plants can have environmental implications that must be carefully evaluated. Conducting thorough environmental impact assessments is essential to understand potential effects on local ecosystems, wildlife habitats, and communities. Planners must balance the benefits of renewable energy with potential environmental trade-offs.

In summary, while the integration of RESs into the transmission network offers significant benefits in terms of sustainability and reducing greenhouse gas emissions, it also presents a range of challenges that must be addressed through careful planning and innovative solutions. By tackling these challenges head-on, planners can facilitate a smoother transition to a cleaner and more resilient energy future.

4. Restructuring power systems and its impact on TNEP

Restructuring power systems is a significant trend that has emerged in response to the challenges of traditional utility models. This transformation aims to enhance efficiency, promote competition, and improve service delivery in the electricity sector. One of the critical areas affected by this restructuring is the planning and expansion of transmission networks. The primary objective of restructuring is to separate generation, transmission, and distribution functions within the power sector. This unbundling allows for a more competitive market environment where multiple entities can participate in electricity generation. As a result, the transmission network must adapt to accommodate the new dynamics of competition among generators. In a restructured environment, independent system operators or regional transmission organizations often manage the transmission network. These organizations are responsible for ensuring reliable electricity delivery while facilitating market access for various generators. The planning process becomes more complex as it must consider not only technical constraints but also market signals and economic factors.

One significant impact of restructuring on transmission network expansion is the increased emphasis on interconnections. Enhanced interconnections between regions can facilitate electricity trading, improve reliability, and reduce costs. Planners must evaluate potential transmission upgrades or new lines that can connect regions with surplus generation to those with deficits. Moreover, the integration of RESs into the grid presents both challenges and opportunities for transmission planning. As more renewable generators enter the market, the need for flexible and robust transmission infrastructure becomes paramount. Planners must consider factors such as the geographical dispersion of renewable resources and their variability in generation. Another important aspect is the role of advanced technologies in transmission network expansion. Smart grid technologies enable better monitoring, control, and optimization of the transmission system. These innovations facilitate real-time data exchange and improve decision-making processes, which are crucial in a competitive market environment. Regulatory frameworks also play a vital role in shaping transmission expansion post-restructuring. Policies that promote investment in transmission infrastructure while ensuring fair access for all market participants are essential. Additionally, cost allocation methods must be transparent and equitable to encourage investment.

In summary, the restructuring of power systems significantly impacts transmission network expansion by introducing competition, enhancing interconnections, integrating RESs, and promoting technological advancements. Effective planning in this new paradigm requires a comprehensive understanding of market dynamics, regulatory frameworks, and technological innovations to ensure a reliable and efficient electricity supply for all consumers.

5. Congestion management and TNEP

Congestion management in the context of TNEP is a vital aspect of modern power system operations. As electricity demand grows and the integration of RESs accelerates, the need for effective congestion management strategies becomes increasingly important. Congestion refers to situations where the demand for electricity exceeds the available transmission capacity, leading to potential overloads, inefficiencies, and reliability issues within the power grid. As global electricity consumption continues to rise, driven by factors such as population growth, urbanization, and the proliferation of electric vehicles, the existing transmission infrastructure faces increasing pressure. This situation necessitates a proactive approach to managing congestion to prevent potential failures and maintain the stability of the power grid. Congestion occurs when the demand for electricity at certain points in the network exceeds the capacity of the transmission lines to deliver it. This imbalance can lead to several issues, including voltage fluctuations, thermal overloads, and, in extreme cases, blackouts. Such scenarios not only compromise the reliability of the power supply but also result in significant economic losses and risks to public safety. Therefore, effective congestion management is essential for safeguarding the integrity of the electrical system.

One of the primary challenges in congestion management is the integration of RESs, such as wind and solar power. While these sources are crucial for reducing greenhouse gas emissions and promoting sustainability, their intermittent nature can create additional complexities in power flow management. For instance, during periods of high generation from renewables and low demand, excess electricity may be produced, leading to potential congestion in certain areas of the grid. Conversely, during peak demand periods when renewable generation is low, traditional fossil-fuel-based plants may struggle to meet demand without causing congestion. To address these challenges, several strategies can be employed within TNEP. First, enhancing transmission infrastructure through the construction of new lines or upgrading existing ones can significantly alleviate congestion. This requires careful planning and investment to ensure that the network can accommodate future growth in electricity demand and renewable energy integration. Second, implementing advanced technologies such as Smart Grids and Flexible AC Transmission Systems (FACTS) can improve real-time monitoring and control of power flows. These technologies enable operators to respond dynamically to changing conditions on the grid, thereby optimizing the use of available capacity and reducing congestion risks. Demand response programs represent another effective strategy for managing congestion. By incentivizing consumers to adjust their energy usage during peak periods, utilities can flatten demand curves and reduce stress on the transmission system. This approach not only helps mitigate congestion but also promotes energy efficiency and cost savings for consumers.

Moreover, market-based mechanisms such as locational marginal pricing can provide economic signals that encourage efficient resource allocation across the grid. By reflecting the true cost of congestion in electricity prices, these mechanisms motivate generators and consumers to make decisions that align with system reliability and efficiency goals. Regulatory frameworks also play a crucial role in facilitating effective congestion management. Policymakers must create an environment that encourages investment in transmission infrastructure while ensuring equitable access for all market participants. This includes establishing clear guidelines for interconnection processes and addressing any barriers that may hinder new projects.

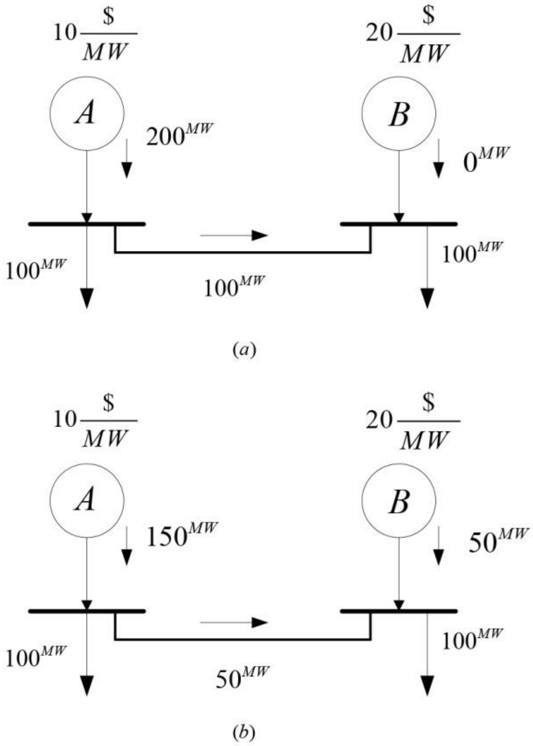

Figure 5. An example of the importance of congestion management in TNEP.

The occurrence of congestion in transmission lines is not a new issue and has also been present in traditional networks. However, in modern networks, this problem leads to complications, the most significant of which is a reduction in the competitiveness of the electricity market. Congestion in transmission lines causes the market to deviate from a perfectly competitive state, which in turn results in decreased social welfare and imposes additional costs on network users. To clarify this point, consider the following example. Figure 5 illustrates a two-area network connected by a transmission line. In scenario (*a*), the line between the two areas is considered to be without constraints. In this situation, based on the bids from the generating units, the loads in both areas prefer to purchase their required power from generator *A*, resulting in a flow of 100 megawatts across the line connecting the two areas. In this case, the total required power is purchased from the first generator at a price of 10 $ per megawatt, leading to a total supply cost of 2000 $ (calculated as 10 × 200).

In scenario (*b*), it is assumed that the transmission capacity of the line between the two areas is limited to 50 megawatts. In this case, the 100-megawatt load in area B must purchase at least 50 megawatts of its required power from the more expensive generator in its own area at a price of 20 $ per megawatt. Consequently, the total production cost for the loads in this network will be 2500 $, calculated as 20 × 50 + 10 × 150, which is 25% higher than the cost in the first scenario. It is assumed that both generators have submitted their bids based on their marginal costs, and generator *B* is unaware of the limitation on the interconnecting line and the behavior of generator *A*. It can be shown that in a perfect market, generators achieve maximum profit when they submit their bids based on their marginal costs. This example demonstrates that the increase in the cost of supplying electric energy is equal to the product of the flow through the congested line and the price differential of electric energy on either side of the line, which amounts to 500 $ (calculated as 50 × (20 - 10)), representing the congestion cost. This can serve as a suitable metric for assessing the overall congestion level in the network. Given the network conditions, generator *B* can be confident that the 100 megawatt load in area *B* is compelled to obtain 50 megawatts of its required power from this generator; thus, generator *B* can propose any higher price to participate in the market. In this scenario, generator *B* can set prices in area *B* according to its preferences.

It should be noted that the network may not necessarily have zero congestion costs regarding line congestion levels. Therefore, it is essential to establish a compromise between investment costs in the network and congestion costs. For instance, consumers may prefer to pay higher energy prices due to line congestion; however, they may not want transmission usage tariffs to increase. This is because congestion and the resulting price increases typically occur only during peak load hours, and depending on their duration and extent of price increases, these additional costs during peak times may be negligible compared to a permanent increase in transmission tariffs. To keep transmission tariffs low, which can account for up to 11% of the total cost of delivered energy, operators are increasingly focused on maximizing the utilization of the existing transmission network. This is a key factor contributing to the increased density of transmission lines. High loading on existing lines, aside from issues related to line congestion (such as reduced competition in the market and higher energy prices for certain consumers), leads to a decrease in the reliability of the network and raises the risk of local or widespread blackouts.

6. New frameworks for the TNEP

TNEP often employs a two-level optimization framework, which consists of a main optimization problem and a sub-problem as shown in Figure 6. This dual-level approach allows for a systematic evaluation of both network development and generation patterns, ensuring that decisions made at one level are consistent with the operational realities at the other.

At the main level, the TNEP problem focuses on determining the optimal expansion plan for the transmission network. This involves identifying which new transmission lines should be built, where they should be located, and when they should be constructed.

The objective is typically to minimize the overall cost of the network while ensuring that it meets reliability standards and can accommodate future demand growth. Various constraints, such as budget limits, environmental regulations, and technical specifications of the network, must be considered in this optimization process. The sub-problem, on the other hand, deals with the generation patterns of power plants. It is essential to determine how much electricity each power plant should generate to meet the demand while minimizing operational costs. This is often formulated as an economic load dispatch problem, which seeks to allocate generation resources in a way that minimizes total generation costs while satisfying demand and operational constraints.

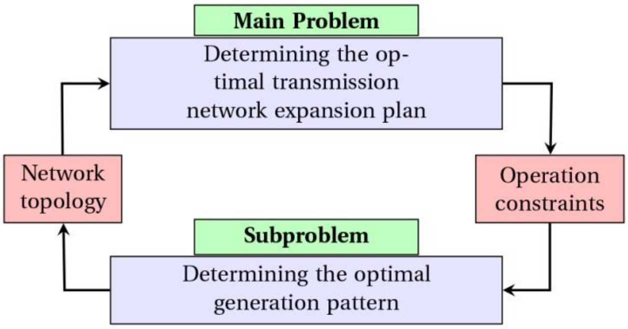

Figure 6. Model the TNEP problem as a main problem and a sub-problem.

The interaction between the two levels is critical. The main optimization problem relies on accurate generation patterns from the sub-problem to assess the flow capacities of existing and new transmission lines. Conversely, the results from the main problem can influence the operational decisions in the sub-problem by altering the available transmission capacity for power flows. This interdependence necessitates an iterative approach, where solutions from one level inform adjustments in the other until a satisfactory equilibrium is reached. Moreover, incorporating uncertainties such as fluctuations in demand or variations in renewable energy generation into this two-level optimization framework can enhance its robustness. Stochastic optimization techniques can be utilized to account for these uncertainties, allowing for more resilient planning outcomes that can adapt to changing conditions.

In summary, the two-level optimization framework in TNEP serves as a powerful tool for integrating network expansion decisions with generation dispatch strategies. By systematically addressing both aspects, engineers can develop comprehensive plans that not only enhance the transmission infrastructure but also ensure efficient and reliable electricity generation. This holistic approach is essential for meeting the evolving energy needs of society while maintaining economic and environmental considerations.

Considering generation costs in the objective function complicates the problem, and one of the common tools used in such cases is Benders Decomposition. Benders Decomposition is a powerful optimization technique that is particularly useful in TNEP due to its ability to manage complex problems [1-7]. One of the primary reasons for using this method is its capacity to reduce complexity by breaking down large-scale problems into smaller, more manageable sub-problems. This decomposition allows planners to focus on specific aspects of the network without being overwhelmed by the entire system's intricacies. Moreover, Benders Decomposition is highly scalable, making it suitable for large transmission networks that involve numerous decision variables and constraints. As a result, it enables the effective handling of extensive instances that would otherwise be computationally prohibitive with traditional optimization approaches. By solving these smaller sub-problems iteratively, the technique significantly improves solution times, which is essential for real-time decision-making in dynamic environments.

Another key advantage of benders decomposition is its flexibility in accommodating various types of constraints typical in transmission network planning, such as flow conservation and capacity limits. This flexibility allows for a more comprehensive optimization framework that can integrate multiple objectives, such as minimizing costs while enhancing reliability. Additionally, the method can be adapted to address uncertainty by incorporating stochastic elements, enabling planners to develop robust strategies that account for variations in demand and generation.

In summary, Benders Decomposition offers a structured and efficient approach to optimizing TNEP, effectively managing complexity, enhancing scalability, and facilitating robust decision-making under uncertainty.

6.1. Bi-level model

The increasing complexity of electricity markets and the growing demand for reliable and sustainable energy have necessitated advanced methodologies in the TNEP. Among these methodologies, bi-level programming has emerged as a particularly effective framework. A general structure of a bi-level problem in TNEP, represented in a textual format along with a description of the diagram the reader can visualize in Figure 7. The diagram illustrates a bi-level model used in TNEP. At the upper level, the "Upper-Level Problem" node represents strategic investment decisions that influence the overall network expansion. This level is connected to the "Investment Decisions" node, which highlights the decision-making process regarding investments in infrastructure. Below, the "Lower-Level Problem" node captures the operational aspects of the network, where the "Operational Decisions" node focuses on real-time operational strategies. The feedback loop between the lower and upper levels signifies the iterative nature of the planning process, where insights gained from operational decisions can inform and refine investment strategies, thereby creating a dynamic interplay between long-term planning and short-term operations. The rationale for employing bi-level models in TNEP can be understood through several key philosophical and practical considerations.

6.1.1. ierarchical Decision-Making

At the core of bi-level programming is the concept of hierarchical decision-making, where two distinct entities with different objectives interact. In TNEP, this typically involves a transmission planner (the upper level) and power generation companies (GENCOs) (the lower level). The upper-level planner aims to optimize the expansion of the transmission network, while the lower-level entities seek to minimize their operational costs in response to the network configuration. This dual perspective allows for a more realistic representation of the interactions between network infrastructure and generation strategies.

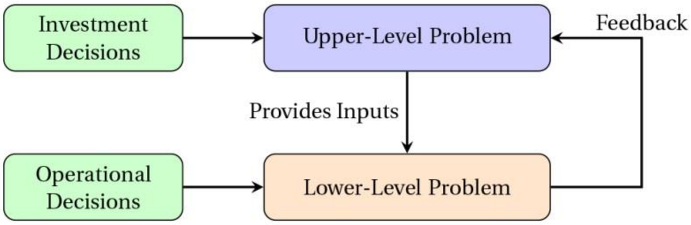

Figure 7. Bi-level model diagram in TNEP.

6.1.2. Capturing Strategic Interactions

Bi-level models effectively capture the strategic interactions between planners and generators. The decisions made by the transmission planner directly impact the operational landscape for GENCOs, influencing their generation dispatch and investment decisions. Conversely, the operational responses of GENCOs can affect the feasibility and cost-effectiveness of proposed expansions. By modeling these interactions, bi-level programming provides insights into how changes at one level affect outcomes at another, enabling better-informed decision-making.

6.1.3. Incorporating Uncertainty

Electricity markets are inherently uncertain due to fluctuations in demand, variable renewable generation, and regulatory changes. Bi-level models can incorporate stochastic elements, allowing planners to evaluate potential scenarios and their impacts on both network expansion and generation strategies. This capability is crucial for developing robust plans that can withstand unexpected changes in market conditions, enhancing the resilience of the power system.

6.1.4. Balancing Economic and Environmental Goals

Modern TNEP must balance economic efficiency with environmental sustainability. Bi-level programming allows planners to incorporate environmental objectives into their expansion decisions. For instance, planners can consider emissions reduction targets or renewable energy integration when determining network configurations. This holistic approach aligns with global efforts to transition to greener energy systems and ensures that expansion plans contribute positively to environmental goals.

6.1.5. Facilitating Regulatory Compliance

Regulatory frameworks often impose constraints on both transmission planning and generation operations. Bi-level models enable planners to account for these regulatory requirements systematically. By integrating compliance considerations into the optimization process, bi-level programming helps ensure that expansion plans meet legal standards while also being economically viable.

6.1.6. Enhancing Computational Efficiency

Bi-level programming can improve computational efficiency by decomposing complex problems into manageable sub-problems. The upper-level problem focuses on strategic planning, while the lower-level problem handles operational optimization. This separation allows for the application of specialized algorithms tailored to each level's unique characteristics, leading to faster convergence towards optimal solutions.

6.1.7. Supporting Multi-Objective Optimization

In practice, TNEP often involves multiple conflicting objectives, such as minimizing costs, maximizing reliability, and reducing environmental impact. Bi-level models can be extended to multi-objective frameworks, allowing planners to explore trade-offs between different goals. This flexibility is essential for stakeholders who must navigate competing priorities in a complex energy landscape.

6.1.8. Real-World Applicability

The real-world applicability of bi-level models is evident in their successful implementation in various case studies across different regions. These models have been used to analyze the impacts of new transmission lines, assess renewable energy integration, and evaluate the effects of policy changes on network expansion strategies. Their proven effectiveness enhances confidence in their use for future TNEP challenges.

In summary, the rationale for using bi-level programming in TNEP lies in its ability to model hierarchical decision-making processes, capture strategic interactions between planners and generators, and incorporate uncertainties and regulatory constraints. By balancing economic and environmental objectives while enhancing computational efficiency, bi-level models provide a robust framework for addressing the complexities of modern electricity markets. As the energy landscape continues to evolve, these models will play a crucial role in guiding sustainable and efficient transmission network development.

In [8], a bi-level TNEP model considering short-circuit current constraints is proposed. Refs. [9,10] present a new framework for addressing the expansion planning of distributed generation (DG) in sub-transmission substations, taking into account the capacity expansions of transmission substations and available incentives. The proposed model incorporates both firm contracts and capacity payments as incentive options and a bi-level model is developed for this problem, where the upper level focuses on the investor's optimal decision aimed at maximizing profit, while the lower-level addresses market clearing and substation expansion. Reference [11] presents a practical application of bi-level evolutionary optimization aimed at improving the electricity industry infrastructure. It provides a coordinated approach to generation and transmission expansion planning from the viewpoint of an independent system operator. The primary goal of this study is to demonstrate how optimizing generator capacity and location can reduce transmission investments while enhancing the reliability of the network. Reference [12] introduces a bi-level proactive transmission expansion framework where a centralized transmission system operator operates at the upper level, while decentralized generation companies participating in the market function at the lower level. Reference [13] presents a novel dual-based bi-level approach for robust AC TNEP that accounts for uncertainties in RESs generation and load. The method employs convex relaxation and is solved using Benders Decomposition, with the master problem focused on determining the robust AC expansion plan. To effectively incorporate the impact of the electricity market, Reference [14] proposes a bi-level model for transmission expansion planning aimed at ensuring market fairness and investment efficiency. Reference [15] presents a bi-level model for TNEP that takes into account financial transmission right trading, along with a proposed comprehensive evaluation index for assessing TNEP schemes. Reference [16] proposes a bi-level optimization model for TNEP aimed at enhancing the network of an energy-exporting power grid with a hybrid AC/DC interface.

In [17], a bi-level transmission and generation expansion planning model that takes into account the correlation of wind power using mixed integer linear programming is proposed. Reference [18] introduces a bi-level proactive transmission expansion framework where a centralized Transmission System Operator operates at the upper level, while decentralized generation companies participating in the market represent the lower level. Reference [19] introduces a bi-level TNEP model that incorporates both prohibited operating zones and multi-fuel units.

6.2. *Multi-Stage Methods in TNEP*

Multi-stage methods provide valuable tools for optimizing TNEP in restructured power systems by enabling scenario analysis, investment timing, risk management, renewable integration, and comprehensive cost-benefit assessments. However, challenges such as model complexity, data availability, computational burdens, stakeholder coordination, dynamic market conditions, and regulatory hurdles must be addressed to fully leverage these methods. Overcoming these challenges is essential for ensuring that transmission networks are developed efficiently and effectively to meet future energy demands while supporting a sustainable energy transition [20-24].

6.2.1. *Key applications of multi-stage methods in TNEP*

- Scenario Analysis: Multi-stage methods enable the assessment of different future scenarios, such as varying demand levels, technological advancements, and regulatory changes. By evaluating multiple scenarios, planners can identify potential risks and opportunities in transmission network development.
- Investment Timing and Sequencing: These methods facilitate the strategic timing and sequencing of investments in transmission infrastructure. By analyzing costs and benefits over different stages, planners can determine the optimal schedule for upgrades and expansions, ensuring that investments align with market needs.
- Risk Management: Multi-stage approaches help in identifying and managing risks associated with uncertain factors, such as fluctuating energy prices or changes in policy. By incorporating risk assessments into the planning process, decision-makers can develop strategies to mitigate potential negative impacts on investments.
- Integration of Renewable Energy: As renewable energy sources become more prevalent, multi-stage methods can assist in planning for their integration into the transmission network. This includes evaluating the impact of variable generation on grid stability and determining the necessary infrastructure to accommodate future renewable projects.
- Cost-Benefit Analysis: Multi-stage methods allow for comprehensive cost-benefit analyses over time, considering both capital and operational expenditures. This helps stakeholders make informed decisions regarding the economic viability of transmission projects.

6.2.2. *Challenges arise in applying multi-stage methods for TNEP*

Despite their advantages, several challenges arise in applying multi-stage methods for TNEP:

- Complexity of Models: The complexity inherent in multi-stage models can make them difficult to develop and implement. Creating accurate models that capture all relevant variables and uncertainties requires significant expertise and resources.
- Data Availability and Quality: Reliable data is essential for effective multi-stage planning. However, obtaining high-quality data on demand forecasts, generation profiles, and regulatory environments can be challenging, leading to uncertainties in model outcomes.
- Computational Burden: Multi-stage optimization problems can be computationally intensive, especially when dealing with large networks and numerous scenarios. This can result in longer processing times and may require advanced computational tools.
- Stakeholder Coordination: In restructured power systems, multiple stakeholders (e.g., utilities, regulators, investors) are involved in transmission planning. Coordinating among these diverse entities can be challenging, particularly when interests and priorities differ.
- Dynamic Market Conditions: The rapidly changing nature of energy markets poses a challenge for multi-stage planning. Factors such as technological advancements, policy shifts, and economic fluctuations can render initial plans obsolete or less relevant over time.
- Regulatory Hurdles: Regulatory frameworks may not fully support or accommodate multi-stage planning approaches. Inflexible regulations can limit the ability of planners to adapt their strategies based on evolving circumstances.

6.3. Multi-criteria decision making

Multi-criteria decision making (MCDM) has become increasingly important in various fields, including the planning and development of electrical transmission networks. As the demand for electricity grows and the push for RESs intensifies, decision-makers must evaluate multiple conflicting criteria to ensure a sustainable and efficient energy transmission system. MCDM encompasses a range of methods designed to help decision-makers evaluate alternatives based on multiple criteria. Some popular MCDM techniques include:

- Analytic Hierarchy Process (AHP): This method decomposes a complex decision problem into a hierarchy of simpler sub-problems, allowing for pairwise comparisons among different criteria and alternatives. AHP is widely used in energy planning due to its structured approach [25-28].
- Technique for Order Preference by Similarity to Ideal Solution (TOPSIS): TOPSIS identifies solutions from a finite set of alternatives based on their geometric distance from an ideal solution. This method is particularly useful in energy transmission planning, where it helps prioritize projects that minimize costs while maximizing efficiency and sustainability.
- Weighted Sum Model (WSM): In this straightforward approach, each criterion is assigned a weight based on its importance, and alternatives are scored accordingly. WSM is easy to implement but may oversimplify complex decisions.
- Fuzzy MCDM: This approach incorporates fuzzy logic to handle uncertainty and imprecision in the decision-making process. Fuzzy MCDM is particularly beneficial in energy planning, where data may be uncertain or incomplete.

The TNEP involves numerous factors, including cost, reliability, environmental impact, and social acceptance. MCDM methods facilitate a comprehensive analysis of these factors:

- Cost-Benefit Analysis: MCDM allows for a detailed comparison of the economic viability of different transmission projects, helping stakeholders choose the most cost-effective solution.
- Environmental Considerations: As RESs gain prominence, MCDM can evaluate the environmental impacts of various transmission routes, ensuring that the least harmful options are selected.
- Social Impact Assessment: Public acceptance is crucial in energy projects. MCDM can incorporate social criteria, such as community impact and stakeholder preferences, into the decision-making process.
- Reliability and Resilience: MCDM methods can assess the reliability of different transmission configurations, ensuring that the chosen network can withstand disruptions and meet future demand.

Therefore, MCDM provides a robust framework for evaluating multiple criteria in the planning and TNEP. By employing various MCDM techniques, decision-makers can navigate the complexities of energy systems, balancing economic, environmental, and social considerations to achieve sustainable development goals. As the energy landscape continues to evolve, the integration of MCDM into transmission planning will be essential for optimizing resource allocation and ensuring reliable energy delivery.

7. Uncertainty

The restructuring of power systems and the integration of RESs have introduced significant uncertainties that pose challenges to the planning and development of electrical transmission networks. These uncertainties stem from various factors, including the variability of renewable energy generation, regulatory changes, technological advancements, and market dynamics.

7.1. Variability of renewable energy generation

One of the primary challenges in integrating RES, such as wind and solar power, is their inherent intermittency. Unlike conventional power plants that can provide a steady output, renewable sources are subject to fluctuations due to weather conditions and time of day. This variability complicates the planning of transmission networks, as operators must ensure that the infrastructure can accommodate sudden changes in generation levels. As a result, planners need to develop strategies that enhance grid flexibility and reliability, such as incorporating energy storage systems and demand response mechanisms.

7.2. Regulatory and policy uncertainties

The restructuring of power markets often involves changes in regulations and policies aimed at promoting renewable energy adoption. These changes can create uncertainties regarding financial incentives, grid access, and interconnection standards. For instance, shifts in government policies may affect the economic viability of certain renewable projects, leading to fluctuations in investment levels. Planners must stay abreast of regulatory developments and incorporate potential policy scenarios into their planning models to mitigate risks associated with these uncertainties.

7.3. Technological advancements

Rapid advancements in technology can also introduce uncertainty into transmission network planning. Innovations in energy storage, smart grid technologies, and demand-side management can significantly alter the landscape of energy generation and consumption. While these technologies offer opportunities for enhancing grid resilience and efficiency, they also require planners to adapt their strategies continuously. The challenge lies in accurately forecasting the impact of these technologies on future energy demand and supply patterns.

7.4. Market dynamics

The restructuring of power systems has led to the emergence of competitive electricity markets, which can introduce additional uncertainties. Market prices for electricity can fluctuate based on supply-demand dynamics, leading to unpredictability in revenue streams for renewable energy projects. Planners must consider these market variations when designing transmission networks to ensure that they remain economically viable under different scenarios.

7.5. Strategies for addressing uncertainties

To effectively manage these uncertainties in TNEP, several strategies can be employed:

- Scenario Analysis: Planners can use scenario analysis to evaluate a range of possible futures, considering different levels of renewable energy penetration, regulatory changes, and technological advancements. This approach helps identify robust solutions that can withstand various uncertainties.
- Stochastic Modeling: Incorporating stochastic modeling techniques allows planners to account for the probabilistic nature of renewable generation and demand patterns. By simulating multiple scenarios, planners can develop more resilient transmission strategies.
- Flexible Infrastructure: Designing transmission networks with flexibility in mind is crucial. This includes investing in modular components that can be easily upgraded or expanded as new technologies emerge or demand patterns change
- Stakeholder Engagement: Collaborating with stakeholders, including regulators, utility companies, and community representatives, is essential for understanding diverse perspectives and addressing concerns related to uncertainty in transmission planning.

In summary, the challenges posed by uncertainties in restructured power systems and RESs significantly impact the planning and development of electrical transmission networks. By employing strategic approaches such as scenario analysis, stochastic modeling, and stakeholder engagement, planners can better navigate these complexities and create resilient transmission systems that support a sustainable energy future. As the energy landscape continues to evolve, addressing these uncertainties will be critical for ensuring reliable and efficient electricity delivery.

7.6. Scenario analysis

Scenario analysis is a strategic planning method used to make flexible long-term plans. It is particularly useful for analyzing uncertainties and understanding the potential impacts of different future conditions on an organization or project. Here, I will provide a detailed explanation of scenario analysis, its benefits, and how it compares to other methods of uncertainty analysis. Scenario analysis involves developing a set of plausible future scenarios based on varying assumptions about key drivers that affect outcomes. These scenarios are not predictions but rather narratives that help organizations visualize how different factors might interact and influence future events [21,29,30]. The process typically involves:

- Identifying Key Drivers: Recognizing the critical uncertainties that could impact the organization, such as economic trends, technological advancements, regulatory changes, and social dynamics.
- Developing Scenarios: Crafting distinct scenarios based on different combinations of these drivers. Each scenario represents a unique view of the future.
- Analyzing Impacts: Evaluating how each scenario would affect the organization's objectives, strategies, and operations.
- Strategic Planning: Using insights from the scenarios to inform decision-making, risk management, and strategic planning.

Advantages of scenario analysis are as follows:

- Comprehensive Understanding of Uncertainties: Unlike traditional forecasting methods that often rely on a single predicted outcome, scenario analysis embraces uncertainty by exploring multiple possible futures. This helps organizations prepare for various contingencies.
- Enhanced Strategic Flexibility: By considering a range of scenarios, organizations can develop more adaptable strategies that are resilient to changes in the external environment.
- Improved Risk Management: Scenario analysis allows organizations to identify potential risks associated with different futures and devise strategies to mitigate these risks effectively.
- Encourages Creative Thinking: The process of developing scenarios fosters creative thinking and innovation among team members, leading to more robust and diverse strategic options.
- Stakeholder Engagement: Scenario analysis can be a collaborative process that engages stakeholders across the organization, fostering a shared understanding of uncertainties and potential responses.

Scenario analysis is a powerful tool for navigating uncertainty, and it offers several advantages over other methods of uncertainty analysis. Below, I will explain these advantages in detail, comparing scenario analysis with other common techniques.

1. Holistic Perspective on Uncertainties

    - Scenario Analysis: This method considers a wide range of uncertainties by developing multiple plausible scenarios based on various assumptions. Each scenario provides a narrative that captures different potential futures, allowing organizations to explore diverse outcomes and their implications.

- Other Methods (e.g., Sensitivity Analysis): Techniques like sensitivity analysis typically focus on how changes in individual variables affect outcomes, often in isolation. This can lead to an incomplete understanding of the complex interactions among multiple factors.
- Advantage: Scenario analysis provides a more comprehensive view of uncertainties by integrating multiple variables and their interdependencies.

2. Flexibility and Adaptability
    - Scenario Analysis: By generating various scenarios, organizations can develop flexible strategies that can be adjusted as conditions change. This adaptability is crucial in dynamic environments where unexpected events can occur.
    - Other Methods (e.g., Forecasting): Traditional forecasting methods often rely on historical data to predict future outcomes, assuming that past trends will continue. This can limit an organization's ability to respond effectively to sudden changes or disruptions.
    - Advantage: Scenario analysis encourages strategic flexibility, allowing organizations to pivot their plans based on emerging trends or shifts in the environment.
3. Encouragement of Creative Thinking
    - Scenario Analysis: The process of creating scenarios fosters creative thinking and innovation. It encourages teams to think outside the box and consider unconventional possibilities, which can lead to novel solutions and strategies.
    - Other Methods (e.g., Quantitative Risk Analysis): Quantitative methods often focus on statistical models and data-driven predictions, which can stifle creativity and limit exploration of alternative futures.
    - Advantage: Scenario analysis promotes a culture of innovation by challenging conventional thinking and encouraging diverse perspectives.
4. Enhanced Risk Management
    - Scenario Analysis: By exploring different potential futures, organizations can identify risks associated with each scenario and develop targeted mitigation strategies. This proactive approach helps prepare for adverse events before they occur.
    - Other Methods (e.g., Monte Carlo Simulation): While Monte Carlo simulations provide valuable insights into the probability of various outcomes, they may not capture qualitative risks or extreme events that are not easily quantifiable.
    - Advantage: Scenario analysis allows for a more nuanced understanding of risks, including those that are difficult to quantify, thereby enhancing overall risk management efforts.
5. Stakeholder Engagement and Collaboration
    - Scenario Analysis: The development of scenarios often involves collaboration across different teams and stakeholders, fostering a shared understanding of uncertainties and encouraging collective problem-solving.
    - Other Methods (e.g., Traditional Forecasting): Many quantitative methods are conducted in isolation by analysts or modelers, which can lead to a disconnect between the analysis and the broader organizational context.
    - Advantage: Scenario analysis promotes engagement and collaboration, ensuring that diverse viewpoints are considered in the decision-making process.

Therefore, scenario analysis offers significant advantages over other methods of uncertainty analysis by providing a holistic perspective, enhancing flexibility, encouraging creative thinking, improving risk management, and fostering stakeholder engagement. These strengths make scenario analysis an invaluable tool for organizations seeking to navigate complex and uncertain environments effectively. By incorporating scenario analysis into their strategic planning processes, organizations can better prepare for a range of potential futures and make more informed decisions.

8. Challenges of reliability assessment with TNEP

The restructuring of power systems, aimed at enhancing competition and integrating RESs, has introduced significant challenges in assessing the reliability of electricity supply. Reliability assessment is crucial for ensuring that the transmission network can meet demand consistently and effectively, especially as the energy landscape evolves. Below are some key challenges associated with this process:

- Increased Complexity of the Grid: The integration of diverse RESs, such as wind and solar, adds complexity to the power grid. These resources are inherently variable and uncertain, making it difficult to predict their output. This variability can lead to challenges in maintaining system reliability, particularly during peak demand periods or adverse weather conditions.
- Market-Driven Operations: In restructured power systems, market mechanisms dictate generation and transmission operations. This market-driven approach can lead to short-term decision-making that may not prioritize long-term reliability. The focus on cost minimization can result in underinvestment in critical infrastructure necessary for maintaining reliability.
- Regulatory Uncertainties: Frequent changes in regulatory frameworks can create uncertainties regarding reliability standards and requirements. This inconsistency can hinder effective planning and investment in transmission networks, as stakeholders may be unsure about future regulations impacting system reliability.

- Technological Integration: Emerging technologies, such as energy storage systems and demand response programs, can enhance reliability but also introduce new complexities. Understanding how these technologies interact with existing infrastructure is essential for accurate reliability assessments.
- Interconnectedness of Systems: As power systems become more interconnected, reliability assessments must account for the impacts of outages or failures in one region on neighboring areas. This interconnectedness complicates the analysis, as it requires a comprehensive understanding of the entire grid's dynamics.

To effectively address the challenges of reliability assessment in restructured power systems, several strategies can be implemented:

- Enhanced Modeling Techniques: Utilizing advanced modeling techniques, such as probabilistic load flow analysis and Monte Carlo simulations, can help assess the impact of renewable energy variability on system reliability. These models can incorporate a range of scenarios, providing a more comprehensive view of potential reliability issues.
- Robust Planning Frameworks: Developing robust planning frameworks that prioritize long-term reliability over short-term cost savings is essential. This includes establishing clear guidelines for investment in transmission infrastructure that considers future demand growth and renewable energy integration.
- Stakeholder Collaboration: Engaging stakeholders including regulators, utilities, and consumers in the planning process can ensure that diverse perspectives are considered. Collaborative efforts can lead to more informed decision-making regarding reliability standards and investment priorities.
- Regular Reliability Assessments: Conducting regular reliability assessments using updated data and models is crucial for adapting to changing conditions in the power system. Continuous monitoring allows for timely identification of potential reliability issues and facilitates proactive measures.
- Incorporation of Technological Innovations: Leveraging technological innovations, such as smart grid technologies and advanced energy management systems, can enhance real-time monitoring and control of the grid. These tools can improve operational flexibility and help mitigate reliability risks associated with variable RESs.
- Policy Stability: Advocating for stable regulatory frameworks can help reduce uncertainty related to reliability standards. Clear policies that support investment in reliable infrastructure are essential for maintaining system integrity in a restructured environment.

The assessment of reliability in restructured power systems with integrated RESs presents significant challenges due to increased complexity, market dynamics, regulatory uncertainties, technological advancements, and interconnectedness. By employing enhanced modeling techniques, robust planning frameworks, stakeholder collaboration, regular assessments, technological innovations, and advocating for policy stability, stakeholders can effectively navigate these challenges and ensure a reliable electricity supply for the future. Addressing these issues is vital for creating resilient power systems capable of meeting the demands of a sustainable energy landscape.

9. Challenges of Private Investment in TNEP

The restructuring of power systems has led to the emergence of competitive markets aimed at improving efficiency and integrating RESs. However, private investment in transmission network development faces several challenges that can hinder the effective planning and expansion of these critical infrastructures. Below are some of the key challenges associated with attracting private investment, along with strategies to enhance investment opportunities.

The main Challenges in this regard are:

- Item Regulatory Uncertainty: The regulatory environment in restructured power systems can be volatile, with frequent changes in policies and standards. This uncertainty can deter private investors who seek stable and predictable returns on their investments. Inconsistent regulations may also lead to confusion regarding the rights and responsibilities of private entities in the transmission sector.
- Long-Term Investment Horizon: Transmission projects typically require significant capital investment and have long payback periods. Private investors may be hesitant to commit to long-term projects without assurances of stable revenues and guaranteed returns. The mismatch between the short-term focus of many private investors and the long-term nature of transmission investments can create barriers to entry.
- Market Competition and Pricing: In competitive markets, the pricing mechanisms for transmission services may not adequately reflect the costs of infrastructure development. If transmission prices are kept artificially low due to market competition, it may not provide sufficient incentives for private investors to fund new projects.
- Risk Allocation: Investors are often concerned about the allocation of risks associated with transmission projects, including construction risks, operational risks, and demand risks. If the regulatory framework does not clearly define how these risks are shared between public and private entities, it can deter investment.
- Integration of RESs: The integration of variable RESs into the transmission network adds complexity to planning and investment decisions. Investors may perceive the uncertainties associated with RES output as a risk factor that complicates their financial models.
- Public Opposition and Environmental Concerns: Transmission projects often face opposition from local communities due to concerns about environmental impact, land use, and aesthetic issues. This public opposition can delay projects and increase costs, making them less attractive to private investors.

To address these challenges and enhance private investment in transmission network development, several strategies can be implemented:

- Stable Regulatory Frameworks: Establishing clear and stable regulatory frameworks is crucial for attracting private investment. Governments should work towards creating consistent policies that provide long-term visibility for investors regarding tariffs, revenue models, and regulatory requirements.
- Incentive Structures: Implementing incentive structures, such as tax breaks or guaranteed returns on investment, can make transmission projects more appealing to private investors. These incentives can help mitigate perceived risks and improve the overall investment climate.
- Public-Private Partnerships (PPPs): Developing public-private partnerships can facilitate collaboration between government entities and private investors. By sharing risks and responsibilities, PPPs can create a more favorable environment for investment while ensuring that public interests are met.
- Transparent Planning Processes: Ensuring transparency in planning processes can build investor confidence. Engaging stakeholders early in the planning phase and providing clear information on project timelines, costs, and expected returns can help attract private capital.
- Risk Mitigation Mechanisms: Implementing risk mitigation mechanisms, such as insurance schemes or government guarantees, can help reduce the financial risks associated with transmission projects. By providing a safety net for investors, these mechanisms can encourage greater participation.
- Facilitating Community Engagement: Actively engaging with local communities and addressing their concerns can help mitigate opposition to transmission projects. By incorporating community feedback into project planning and demonstrating commitment to environmental stewardship, developers can build trust and support.
- Promoting Technological Innovation: Encouraging the adoption of innovative technologies in transmission infrastructure can enhance efficiency and reduce costs. Public funding for research and development in smart grid technologies, energy storage solutions, and demand response programs can create a more attractive investment landscape.

Attracting private investment in transmission network development within restructured power systems is fraught with challenges, including regulatory uncertainty, long-term investment horizons, market competition, risk allocation, integration of RESs, and public opposition. However, by implementing strategies such as establishing stable regulatory frameworks, creating incentive structures, fostering public-private partnerships, ensuring transparency, mitigating risks, engaging communities, and promoting technological innovation, stakeholders can enhance the attractiveness of transmission projects for private investors. A collaborative approach that balances public interests with private investment objectives is essential for developing a resilient and efficient transmission network capable of supporting a sustainable energy future.

10. The effect of electrical energy storage devices and electric vehicles on TNEP

The integration of energy storage systems and electric vehicles (EVs) into TNEP presents a transformative opportunity for enhancing grid reliability, efficiency, and sustainability. Energy storage systems, such as batteries, can effectively balance supply and demand by storing excess energy during periods of low demand and releasing it during peak times. This capability is particularly beneficial in accommodating the variable nature of RESs like solar and wind. Moreover, electric vehicles can act as mobile energy storage units, offering the potential for vehicle-to-grid (V2G) technology, where EVs discharge stored energy back into the grid during high-demand periods. Consequently, when developing transmission networks, planners must consider the dual role of EVs as both loads and potential sources of energy. By strategically incorporating these technologies into transmission planning, utilities can reduce the need for costly infrastructure upgrades, improve grid resilience against outages, and facilitate a smoother transition to a low-carbon energy future. The synergy between energy storage and electric vehicles not only optimizes resource utilization but also enhances the overall stability of the electrical grid, paving the way for a more integrated and sustainable energy ecosystem [4,7,18] and [42-81]

The integration of energy storage systems and EVs into TNEP presents several significant challenges that need to be addressed. Energy storage systems must be carefully sized and strategically located to effectively mitigate these fluctuations, requiring advanced forecasting and modeling techniques. Additionally, the increasing penetration of EVs introduces new load patterns that can strain existing infrastructure, particularly during peak charging times. This necessitates a reevaluation of grid capacity and the potential for congestion in certain areas, demanding enhanced demand response strategies and dynamic pricing models to manage load effectively. Moreover, the interoperability of different technologies poses another challenge, as various energy storage systems and EVs may not seamlessly integrate with existing grid infrastructure or communication protocols. Regulatory frameworks also need to evolve to accommodate these technologies, ensuring that market structures incentivize investment in energy storage and EV charging infrastructure. Finally, there are concerns related to the lifecycle impacts of battery production and disposal, which must be considered in the broader context of sustainability. Addressing these challenges requires a collaborative approach involving utilities, policymakers, technology developers, and consumers to create a resilient and efficient transmission network that can support the growing role of energy storage and electric vehicles in the energy landscape.

11. Discussion

The restructuring of power networks has led to significant changes in the concepts of operation and planning due to various reasons. The requirement for open access for producers and consumers to the transmission network, the involvement of private investors in the generation and transmission sectors, the separation of generation and transmission sectors, and consequently the potential for achieving full coordination in the planning of these two sectors, as well as the increasing emphasis on investment profitability in network development due to the presence of private investors, have all contributed to the diminishing effectiveness of conventional network planning approaches.

Network planning algorithms in a restructured environment must possess the following characteristics:

- Consider the diverse and often conflicting objectives of market players and investors
- Since the transmission network serves as a platform for power exchange and a more competitive market benefits all participants (as societal welfare), aim to eliminate barriers to competition within the market
- Model reliability in such a way that economic analysis can be performed, allowing for the determination of an optimal technical-economic level of reliability
- Model input uncertainties, which are significantly greater and more impactful than in the past, and effectively interact with the planning of other sectors, especially the generation sector
- Utilize a cost-benefit analysis approach instead of a cost-minimization approach to enable a thorough technical-economic evaluation of investments
- Facilitate the presence of private capital by shifting away from a fully centralized traditional approach

Since the introduction of transmission network planning models based on optimization with a single objective function in the 1970s, nearly all research efforts have focused on developing this model. Over the past three decades, research studies have been based on two main approaches:

- The introduction of new and more efficient methods for solving problems, including mathematical, intelligent, or hybrid methods
- Modifying the objective function of the initial model by incorporating factors such as operational costs and network losses

These approaches have not changed even with the restructuring of the network, such that most new planning models continue to follow the original single-objective structure, considering objectives such as minimizing congestion costs or maximizing overall welfare as their primary objective function. A suitable algorithm for TNEP in the new structure should possess the following capabilities and features:

- Pursue facilitating competition in the market as a goal
- Consider the interests of various stakeholders, including investors
- Take uncertainties in different sectors into account during the planning process
- Enable cost-benefit analysis

Figure 8 shows a bar chart that illustrates the trends in research studies related to transmission network development from 2016 to 2024. The horizontal axis represents the years, while the vertical axis indicates the number of studies conducted. The chart categorizes studies into five distinct types, each represented by a different color in the legend: Bi-level, Benders decomposition, Wind effect, Energy storage, and Multi-stage.

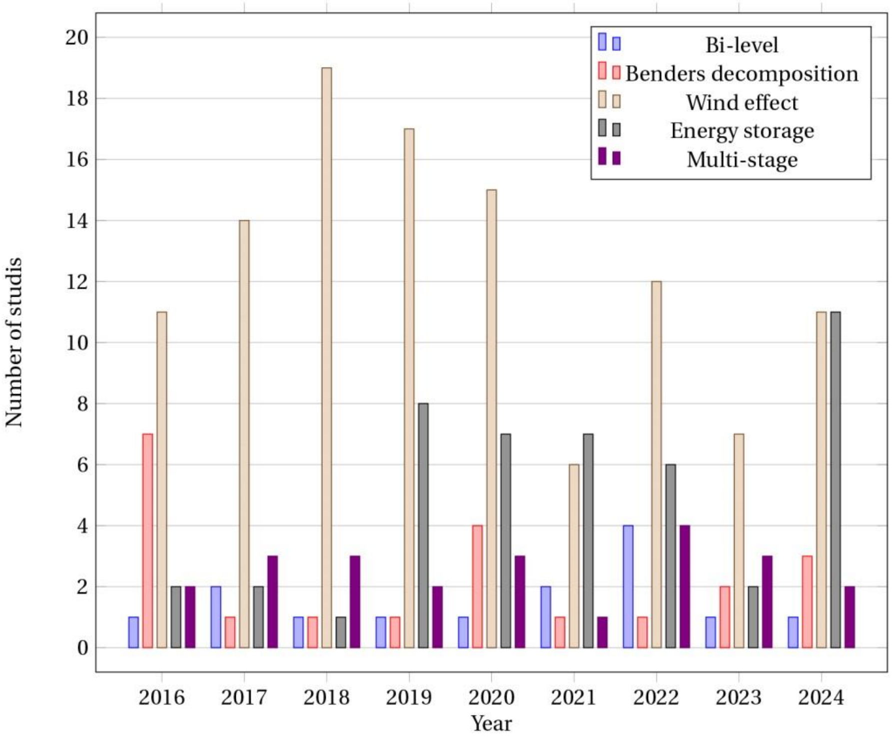

Figure 8. Trends in research studies related to transmission network development from 2016 to 2024.

The data shows that the Bi-level studies have shown significant variability, peaking in 2022 with four studies, indicating a growing interest in this approach for optimizing network planning. In contrast, Benders decomposition reached its highest point in 2018 with 19 studies but has since declined, suggesting a possible shift in focus towards other methodologies. The Wind effect category has gained traction, particularly in recent years, reflecting an increasing acknowledgment of renewable energy integration into transmission planning. Energy storage studies have fluctuated but saw a notable increase in 2024, highlighting the rising importance of energy storage solutions in managing grid stability and reliability. Lastly, multi-stage studies have remained relatively low but consistent, emphasizing their niche role in the broader context of transmission network research. Overall, this chart provides valuable insights into the evolving landscape of transmission network development research, showcasing how different topics have gained or lost relevance over time and guiding future research directions.

The optimization of TNEP faces several significant challenges that stem from the complexity of modern energy systems. As electricity demand continues to grow and the integration of RESs becomes more prevalent, traditional optimization methods may fall short in addressing the multifaceted nature of these challenges. One of the primary challenges is the inherent uncertainty associated with load forecasting and renewable generation. The variability of RESs, such as solar and wind, can lead to fluctuations in supply, making it difficult to ensure that the transmission network can reliably meet demand. This uncertainty necessitates the use of stochastic optimization techniques that can account for a range of possible scenarios, rather than relying solely on deterministic models.

Another challenge is the multi-objective nature of transmission planning. Planners must balance various competing objectives, including minimizing costs, maximizing reliability, and minimizing environmental impacts. Traditional optimization approaches often focus on a single objective, which may lead to suboptimal solutions when considering the broader implications of network development. Therefore, adopting multi-objective optimization frameworks is essential for finding solutions that satisfy diverse stakeholder interests. Additionally, regulatory and market uncertainties pose significant challenges to effective transmission planning. The evolving landscape of energy markets and regulations can affect investment decisions, making it crucial for planners to incorporate flexibility into their optimization models. This flexibility allows for adjustments in response to changing policies and market dynamics, ultimately leading to more resilient network designs.

In conclusion, addressing the challenges of optimization in transmission network development planning requires innovative approaches that incorporate uncertainty, multi-objectivity, and flexibility. By leveraging advanced optimization techniques and engaging with various stakeholders, planners can develop robust strategies that meet the demands of a rapidly changing energy landscape.

12. Conclusion

In conclusion, the importance of transmission network expansion planning (TNEP) in a restructured power system cannot be overstated. As we face the challenges of integrating diverse energy sources and meeting growing electricity demands, TNEP serves as a crucial framework for ensuring that the transmission infrastructure is capable of supporting a reliable and efficient energy supply. The transition to a more decentralized energy landscape, characterized by increased reliance on renewable resources, necessitates a forward-thinking approach to planning and investment in transmission networks. Effective TNEP not only facilitates the integration of renewable energy but also addresses issues related to network congestion and reliability. By strategically identifying areas where expansion or reinforcement is needed, TNEP helps to optimize the flow of electricity, reduce transmission losses, and enhance overall system performance. Furthermore, it plays a vital role in fostering competition among market participants by ensuring that all stakeholders have equitable access to the transmission network. Engaging with stakeholders including regulators, utility companies, and the public—is essential for successful TNEP implementation. Transparent communication and collaboration can help build trust and ensure that the planning process considers the diverse needs and concerns of all parties involved. Additionally, aligning TNEP with regulatory frameworks and policy objectives can facilitate smoother project approvals and encourage investment in necessary infrastructure. As we look to the future, it is clear that TNEP must adapt to evolving technologies and market dynamics. Innovations such as smart grid technologies, energy storage solutions, and demand response strategies offer new opportunities for enhancing transmission network efficiency and reliability. By embracing these advancements, we can create a more resilient power system capable of meeting the challenges of climate change and energy security. Ultimately, the successful implementation of TNEP will be instrumental in achieving not only economic growth but also environmental sustainability. A well-planned transmission network is essential for supporting clean energy transitions and ensuring that future generations have access to reliable and affordable electricity. As such, TNEP should be prioritized as a key component of energy policy and investment strategies moving forward.

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Declaration of competing interest

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