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RESEARCH ARTICLE

Analysis of Electric Power Transmission Lines Through Graph Theory: Protecting Environmental Preservation Areas Through Strategic Planning

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Abstract: Electrical networks consist of generation plants, transmission, and distribution substations of electrical energy. Power is transmitted through towers and lines that span hundreds or even thousands of kilometers. To ensure the health, the stability of ecosystems, and our quality of life, we must protect the environmental areas where transmission lines intersect. Given the global challenges related to sustainability, the conservation of natural resources, and the mitigation of climate change, these studies are imperative. Through graph algorithms, especially vertex degree search and depth-first search, we identify alternative routes, avoiding sensitive regions such as conservation areas within the 440 kV transmission networks of São Paulo, Brazil. By reallocating energy transport, we can ensure network maintenance and reduce environmental impacts from potential accidents. The results highlight the sustainable planning of transmission lines, aligning energy needs with Brazilian environmental conservation efforts, including the Rio do Peixe State Park, Aguapeí State Park, Itapetinga State Park, and Itaberaba State Park. Combining existing environmental laws with the promotion of sustainable technologies and practices, can lead to the promotion of more efficient use of resources while protecting the environment and fostering economic growth.

Keywords: environmental preservation, power grids, transmission lines, graph theory, energy sustainability, search algorithms

1. Introduction

In the transmission of electrical energy, the composition reveals itself as an intricate arrangement, where the organization and strategic interconnection of components constitute the network infrastructure. This includes transmission towers, conductor cables, insulators, and support structures, forming an efficient line for transmitting electricity over long distances. The strategic arrangement of these elements aims to ensure operational efficiency and optimization of energy distribution. Taken together, energy sustainability refers to a balanced and environmentally responsible production system for the distribution and consumption of energy that meets present needs without compromising the ability of future generations to meet their own needs. This concern has become a consensual goal, and the National Electric Energy Agency (ANEEL) plays a fundamental role in this context. In Brazil, 84.8% of the energy consumed is generated by renewable sources, while in the world, it is only 23%. The fact that we have a cleaner matrix is due to the generation coming from hydroelectric plants, with 65.2%, followed by biomass (9.1%), wind (8.8%), and solar energy representing 1.7% of mines and energy [1].

Transmission circuits have specific voltages and currents, which are determined by several factors, including the amount of energy to be transmitted, the characteristics of the regional electrical system, and the distance between the energy generation point and consumption centers. These transmission lines are often called high voltage lines, a name derived from their operation at nominal voltages >69 kV. In Brazil, for example, these voltages can reach 765 kV, as documented in the study by Elias (2015). For this study, we will focus on the 440 kV range. These high voltage levels are essential for two main reasons. Firstly, they serve to minimize power losses during transmission, making the process more efficient. Secondly, they allow the transport of substantial amounts of electrical energy through a single transmission line, contributing to the robustness and reliability of the electrical grid.

After being transmitted, the electrical energy reaches the step-down substation. At this stage, the voltage of electrical energy is reduced, making it suitable for distribution to consumers at lower voltage levels. Furthermore, substations also play an important role in protecting the electrical system, monitoring the flow of energy, and acting quickly in the event of failures or overloads [3–7], minimizing damage caused by short circuits and preventing electrical accidents. One of the main functions of a substation is to change the voltage levels of electricity, transforming the high voltage generated in power plants into lower voltages suitable for distribution to consumers. The transformation is carried out through transformers [8–11]. Therefore, these installations must be designed, built, and maintained with strict quality and safety control, aiming to guarantee the continuous supply of quality electrical energy to society [12–17].

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One of the main problems that affect the supply of electricity to the population and the functioning of economic activities is the lack of investment and adequate maintenance in the transmission infrastructure [18], resulting in failures and interruptions in the supply of electricity [19]. The distance between generating plants and consumer centers is another challenge, requiring the construction of long transmission lines and passing through areas that are difficult to access and have environmental restrictions [20–22]. This results in delays in the construction of new transmission lines and the need to reinforce existing lines. The lack of integration between the different regions of the country is also a problem, with some regions experiencing excess electricity production, while others suffer from shortages, leading to the overloading of some transmission lines and difficulty balancing the supply and demand of electrical energy across the country [23, 24]. The vulnerability of the transmission system to weather events and the risk of failures resulting from cyberattacks are other threats to the security of the electrical system. Modernization and the adoption of advanced technologies are essential for the efficient management of electrical energy transmission in Brazil.

The process of electrical energy transmission poses one of the primary challenges in ensuring the availability of electrical power to consumer centers worldwide. In Brazil, electricity generation is predominantly derived from hydroelectric plants, necessitating the transportation of large quantities of energy from generation sites to load centers. To address this requirement, the country has established the National Interconnected System, which integrates various companies from the north to the south of the country, connecting different regions involved in both electricity production and consumption [25]. In the context of energy generation, significant challenges arise, including the need for expanding transmission lines, particularly in geographically challenging areas like the Amazon region, and ensuring the stability and safety of the electrical system. In this regard, the utilization of direct current transmission lines is noteworthy, as they enable the transportation of substantial amounts of electrical energy over long distances [26].

We will target the region of the state of São Paulo for analysis, which stands out as a fundamental piece in Brazil's energy mosaic. The state's electrical infrastructure covers an extensive variety of transmission bands, representing a dynamic and adaptable system to the region's diverse energy demands. The transmission bands of 230 kV, 345 kV, 440 kV, 500 kV, 600 kV, and 765 kV stand out, which constitute an interconnected network capable of serving both densely populated urban areas and extensive industrial regions. The 440 kV line in Brazil belonging to the state of São Paulo strategically runs through the metropolitan region, the interior of São Paulo, the Paraíba Valley, and the coast of the state. Its vital role in transmitting large volumes of energy stands out for powering urban centers, industrial areas, and diverse geographic regions. This strategic presence reinforces the resilience of the state's electrical system, contributing to the sustainable development of different locations in São Paulo.

The length of the 440 kV lines, extending across several areas of the state, assumes significant relevance when crossing conservation zones. To ensure the protection of these regions and preserve them, rules are established to be followed. To facilitate the standardization of rules and greater security, we rely on ANEEL, a Brazilian federal agency, linked to the Ministry of Mines and Energy, responsible for regulating, supervising, and controlling the generation, transmission, distribution, and commercialization of electrical energy in the country. ANEEL was the founder of the Electric Energy Transmission Service Regulation; these standards regulate the planning, construction, and operation of transmission lines, aiming to minimize environmental impacts and preserve the integrity of conservation areas [27].

The occurrence of sparks or short circuits in the vicinity of environmental preservation areas represents a significant risk to the environment. These incidents can trigger a series of problems and negative impacts, including forest fires, especially in regions covered by dry vegetation. These fires have the potential to spread quickly, causing severe damage to local flora, fauna, and ecosystems, increasing the carbon tax on the environment [13, 28]. Additionally, sparks and heat generated by a short circuit can destroy vegetation near transmission lines. This affects biodiversity and can harm plant and animal species that depend on this vegetation to survive. In addition to damaging the environment, forest fires can impact local communities, destroying properties, threatening lives, and harming economic activities.

In this context, the modeling of electrical energy transmission networks using graph theory and algorithms can aid in assessing infrastructure efficiency, environmental preservation control, and the quality of electrical energy transmission in Brazil, helping to pinpoint critical points in the network. For instance, the depth-first search (DFS) algorithm is a technique employed to traverse graph nodes until all possible nodes are visited or until a specific condition is met. This method determines the connectivity of a graph and facilitates topological ordering, which can be utilized for planning new lines and substations to address future electrical energy transmission requirements.

2. Literature Review

Planning the expansion of electrical energy transmission and distribution networks is a critical precursor to major investments in an energy distribution company [29]. These investments entail optimizing networks to enhance existing infrastructure and ensuring efficient, economical, and sustainable transmission and distribution of energy. An optimized network helps minimize energy losses during transmission, reduces operational costs, and enhances overall system efficiency. In Figure 1, we observe the electrical energy supply chain, commencing with energy generation and progressing through the step-up substation, which elevates electrical energy voltage to suitable transmission levels.

The energy is subsequently transmitted through transmission lines and finally reaches the step-down substation. At this stage, the voltage of electrical energy is reduced, making it suitable for distribution to consumers at lower voltage levels.

The search for more efficient, reliable, and sustainable electrical systems is fundamentally guided by the optimization of energy transmission and distribution networks. According to Marquesan et al. [30], there are three simplified models developed specifically to determine the nodal voltage in energy distribution networks. These models were tested in two networks, one composed of 18 bars and the other of 69 bars. In Figure 2, the graphical representation of the 18-bar system is presented, as prepared by Marquesan et al. [30] and reproduced in this work. The visualization highlights the specific structure of the bar arrangement.

In Figure 2, the system also represents a system of bars created by Marquesan et al. [30] but with 69 bars, providing a comprehensive and detailed view of this more complex configuration.

The results indicated that this approach is highly useful for issues related to operation planning, such as switching to relieve overloads, improving the voltage profile, and reducing losses, and highlights the usefulness of these simplified models when dealing with convergence problems and divergence compared to conventional models based on load flow equations. The ability to

Figure 1
Electric energy generation, transmission, and distribution system

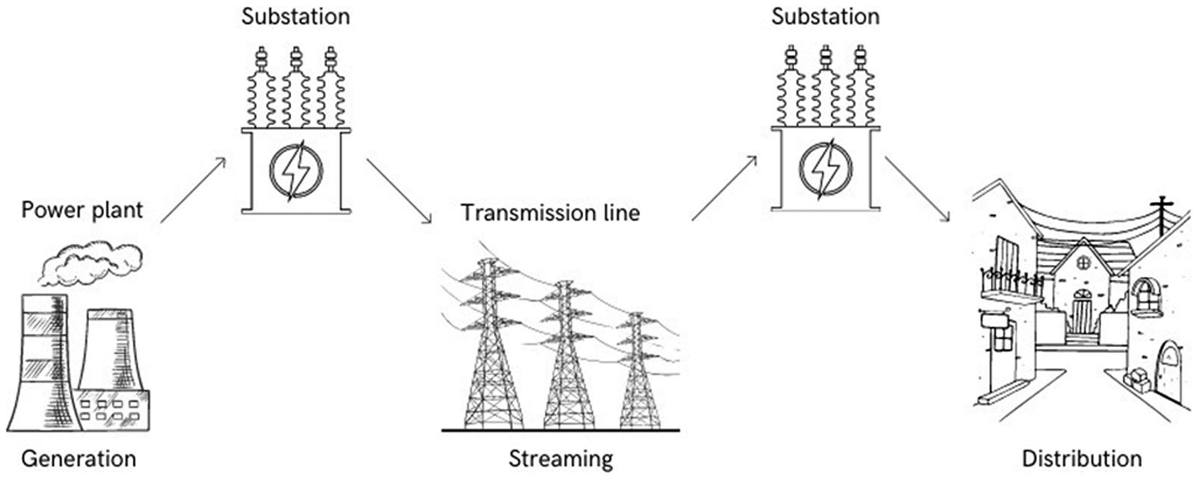
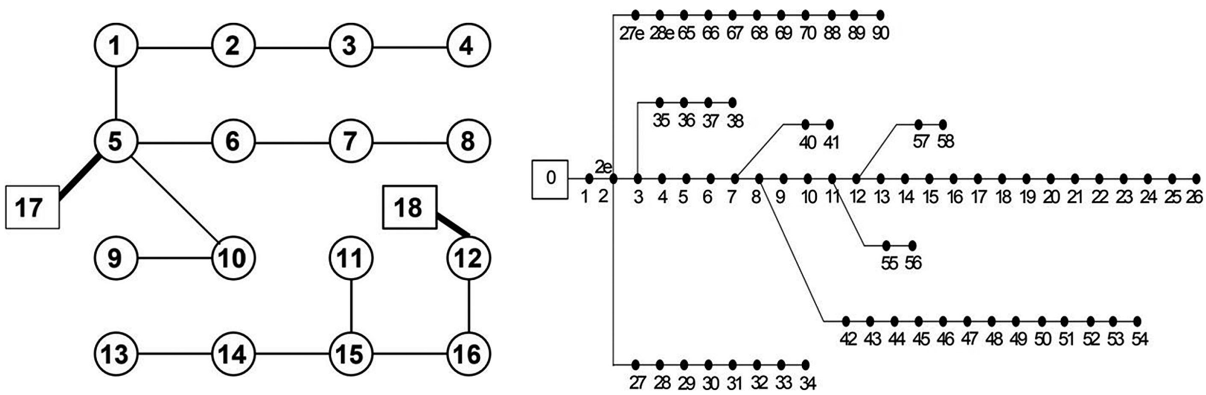


Figure 2
Representation of 18-bar system (left) and 69-bar system (right)



derive solutions regardless of network topology (such as islanding) and load is highlighted as a significant advantage.

Furthermore, the optimization of electrical networks is closely linked to the incorporation of renewable energy sources and the promotion of sustainability. Efficient integration of sources such as solar and wind requires infrastructure adaptations to accommodate the variability inherent in these sources. By optimizing networks to support the diversification of energy sources, it is possible to create more sustainable systems, reducing dependence on fossil fuels and mitigating associated environmental impacts.

3. Materials and Methods

The main data source used is available on the Energy Research Company (EPE) website 1[1]. One of the company's areas of activity is the development and carrying out of studies necessary to carry out short- and medium-term expansion plans for the national electricity transmission system. Through this platform, we were able to access the "Interactive Energy Map," where we work with descriptive statistical techniques to evaluate the geographic distribution of electricity transmission lines in Brazil. This work is a case study, where Table 1 [31] serves as a comprehensive repository of data about a variety of electrical substations. Each line corresponds to a specific substation, providing vital information such as a unique identification number, the name of the substation, geographic coordinates (longitude and latitude), rated voltage levels, the supervisory entity (agent), and the year in which the substation operations started. This table facilitates access to critical substation data, assisting in research, planning, and analysis of power transmission lines. It highlights differences in location, voltage, agents, and start years, showing the country's complex electrical infrastructure.

The substations listed vary in terms of responsible agent and year of entry into operation. These data provide an overview of the geographic distribution of substations in the state of São Paulo, allowing a preliminary analysis of the electricity transmission infrastructure in the region. It allows electrical sector professionals, researchers, and decision-makers to access relevant information about substations, capacities, and geographic locations, facilitating informed decisions and strategic planning. This data is essential to plan, operate, and maintain the electrical grid in an efficient, sustainable, and safe way. Furthermore, the table can be used for analyses, such as identifying areas that may require expansion of

[1]Webmap Energy Research Company (EPE), accessed on July 3, 2023, https://gisepeprd2.epe.gov.br/WebMapEPE/

Table 1
Information about various substations, including ID, name, location (longitude and latitude), voltage level, responsible agent, and year of operation Webmap

ID	Substation name	Longitude	Latitude	Voltage agent	Year	Operation
1	SE Nova Porto Primavera	−52,965	−22,4878	440/230	Porto Primavera	2006
2	SE Taquaruçu	−52,0009	−22,5386	440/138	Duke Energy	1992
3	SE Capivara	−51,3603	−22,6577	440/138/14,4	Duke Energy	1977
4	SE Assis	−50,3507	−22,6687	500/440/230	CTEEP	–
5	SE Oeste	−47,4122	−23,4472	440/88	CTEEP	–
6	SE CBA 2	−47,2964	−23,5408	440–230	CTEEP	2006
7	SE Embu-Guaçu	−46,7998	−23,8447	440/235/138/16/13,8	CTEEP	–
8	SE Solvay	−46,3746	−23,769	440/88	CTEEP	2011
9	SE Santo Angelo	−46,2539	−23,5861	440/345/138	CTEEP	–
10	SE Água Azul	−46,4014	−23,375	440/138	Água Azul	2019
11	SE Fernão Dias	−46,5147	−23,0579	500/440	MSGT	2020
12	SE Mogi Mirim 3	−47,0656	−22,4199	440/138	CTEEP	–
13	SE Araras	−47,4619	−22,3957	440/138	IEP	2010
14	SE Ribeirão Preto	−47,688	−21,202	500/440/137	CTEEP	–
15	SE Água Vermelha	−50,3489	−19,8609	500/440/138	AES	1978
16	SE UHE Ilha Solteira	−51,3704	−20,3813	440/138/14,4/13,8	RPE	1973
17	SE Ilha Solteira 2	−51,4172	−20,3198	440/230	ITATIM	2011
18	SE Três Irmãos	−51,3026	−20,6741	440/138	TIJOA	1993
19	SE Jupiá	−51,6331	−20,7831	440/138	RPE	1969
20	SE Marechal Rondon	−51,6388	−20,7963	440/138	MRTE	2016
21	SE Alta Paulista	−51,1605	−21,6413	440	IE	2021
22	SE Getulina	−49,8383	−21,8556	440/138	IEP	2011
23	SE Bauru	−49,096	−22,2828	440/138	CTEEP	–
24	SE Bracell	−48,8085	−22,5388	440	–	2021
25	SE Salto	−47,2406	−23,1789	440/88	IESJ	2012
26	SE Cabreuva	−47,1162	−23,2775	440/230/138/13,8	CTEEP	–
27	SE Gerdau SP	−47,085	−23,4382	440/33/13,8	CTEEP	2005
28	SE Jandira	−46,9066	−23,563	440/88	IESJ	2012
29	SE Bom Jardim	−46,9902	−23,1518	440/138/88/13,8	CTEEP	–
30	SE Sumaré	−47,2867	−22,8669	440/138/13,8	CTEEP	–
31	SE Santa Bárbara d'Oeste	−47,4182	−22,7259	440/138/13,8	CTEEP	–
32	SE Araraquara CTP	−48,2639	−21,7827	440/138	CTEEP	–
33	SE Araraquara 2	−48,3497	−21,8336	500/440	Araraquara	2012
34	SE Taubaté	−45,5864	−23,0632	500/440/230/138	–	–
35	SE Replan	−47,1125	−22,735	440/138	CTEEP	2016
36	SE Piracicaba	−47,5712	−22,6344	440/138	CPFL Piracicaba	2015
37	SE Mirassol 2	−49,5022	−20,867	440/138	IEP	2011
38	SE Baguaçu	−50,2811	−21,1456	440	IE Aguapei	2021

transmission capacity, evaluating the average age of substations in a region, or identifying substations operated by specific agents. This table is a valuable tool for managing and improving electrical infrastructure.

Furthermore, information on substation voltages indicates the diversity of transmission capabilities of state networks, from higher voltages, such as 500 kV, to lower voltages, such as 88 kV. These data are relevant for planning and expanding the transmission network, allowing the identification of areas that may require reinforcement or additional investments. The table also highlights the presence of different agents responsible for substations, which may indicate the participation of several companies in the electrical sector in the state of São Paulo.

For environmental analysis, the website provides a section related to the environment, where we have the location of preservation units, separated into areas of integral preservation and sustainable use, where we work with the territorial description and greater protection measures for the regions. Figure 3 presents the map generated by the EPE website, where we can visualize the region of the 440 kV transmission line that was selected as the object of study in this research.

Electrical power transmission lines are typically overseen by power transmission companies who have responsibility for building, operating, and maintaining these critical infrastructure elements. In our analysis, we transformed the data represented in Figure 3 into the areas designated for investigation. We delimited the regions highlighted in green as fully protected, characterizing them as state parks. By identifying these areas, we transfer them to a graph, as shown in Figure 4. This graph represents the 440 kV transmission lines located in Brazilian territory. Each edge of the graph is weighted with the value 440, meaning the voltage of the corresponding transmission line, while the vertices of the graph represent the various substations. This transformation was carried out using an online graph visualization tool, where nodes symbolize substations and edges denote transmission lines. These transmission lines are located exclusively in the territory of the state of São Paulo and are managed by several entities, including Porto

Figure 3
Step by step to choose the transmission line to be worked on

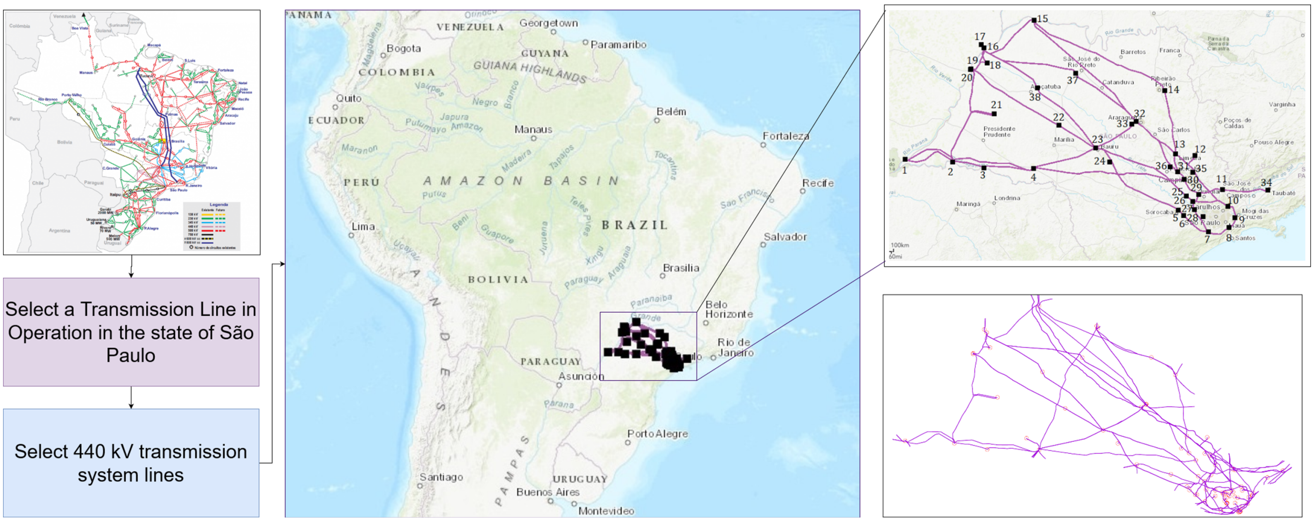


Figure 4
Transmission lines with 440 kV in Brazilian territory, belonging only to the state of São Paulo

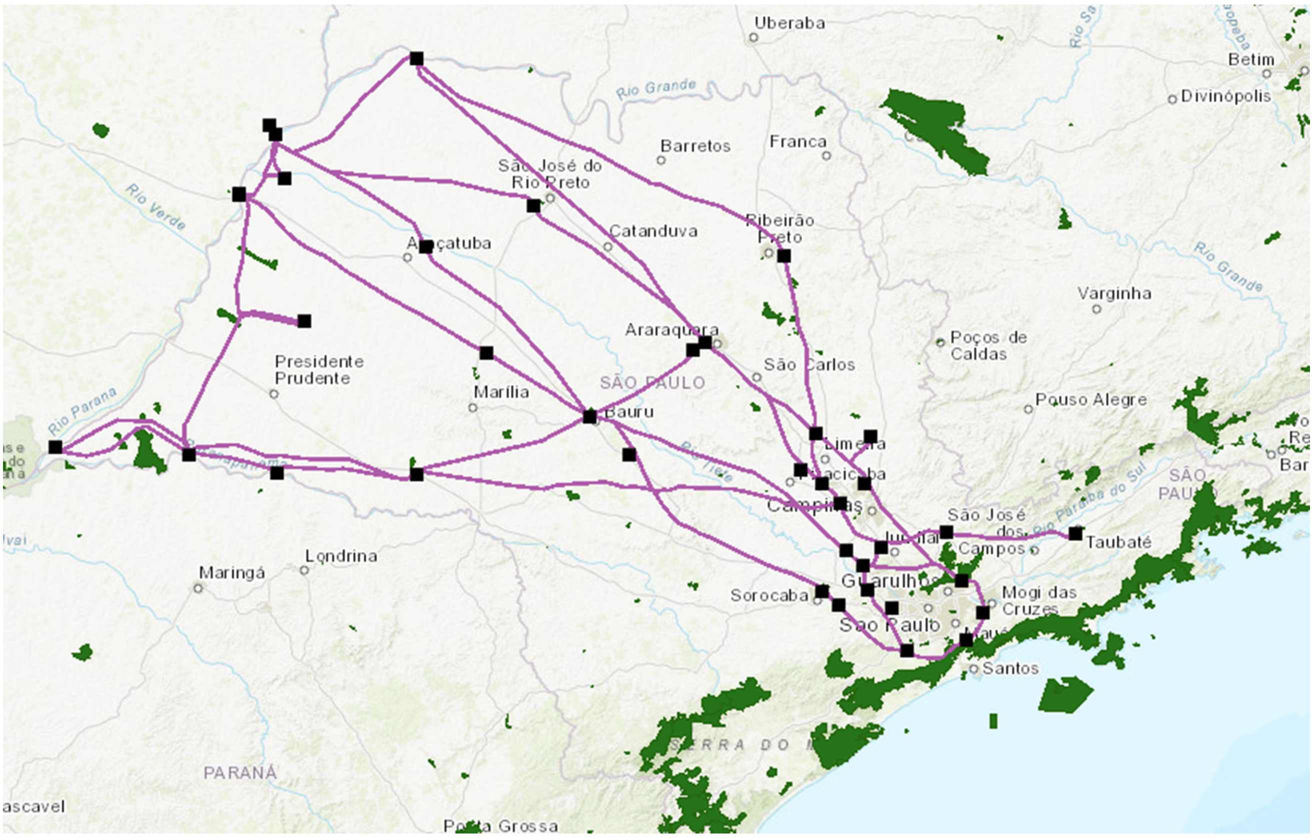
Primavera, Duke Energy, CTEEP, Água Azul, MSGT, AES, RPE, ITATIM, TIJOA, MRTE, IE, IEP, IESJ, CPFL Piracicaba, and Araraquara. These entities are actively involved in the electrical energy sector, where they perform crucial functions of operation, maintenance, and expansion of the electrical energy transmission system in different regions of the state of São Paulo. Its main objective is to guarantee a safe and reliable supply of electricity to end consumers. Furthermore, these entities operate following the regulations established by ANEEL, the National Electric Energy Agency, and other relevant standards that govern the electricity sector.

The state of São Paulo, occupying 248,222.8 km^2, accounts for approximately 2.91% of Brazil's total territory, as reported in a recent study [32]. Positioned in the southeast region of Brazil, São Paulo has notable geographic diversity in terms of topography, climate, ecosystems, and economic activities. The state's topography varies from low-lying coastal regions to high plateaus and mountains. São Paulo predominantly experiences a tropical climate characterized by hot, humid summers, and milder winters. However, coastal areas have a hotter and more humid climate, while southern regions have a subtropical climate with colder temperatures. Economically, São Paulo stands out as Brazil's leading financial and industrial center, home to a wide range of thriving industries, including automotive, technology, textiles, and agriculture.

In terms of its environment, the State of São Paulo boasts a diverse ecosystem. Along its coastline, one encounters picturesque beaches, mangroves, sandbanks, and idyllic islands, which harbor a rich array of marine and coastal species. Further inland, the landscape undergoes a transformation, revealing expanses of savannah, Atlantic forest, open fields, and meandering rivers that provide habitat for a wide spectrum of wildlife and flora [33]. Amidst this wealth of biodiversity, certain regions are designated for environmental preservation. These areas are delineated and protected by legal mandates to ensure the conservation of biodiversity, natural ecosystems, and valuable resources found within the region.

Besides that, the state of São Paulo presents a plethora of outdoor recreational opportunities, offering an array of natural amenities such as pristine air, verdant landscapes, avian biodiversity, hiking trails, and designated ecological reserves. Positioned within a geographically advantageous locale, São Paulo boasts an extensive coverage of approximately 30% of its total land area by the illustrious Atlantic Forest. The intricate interplay among its diverse fauna, flora, water bodies, and marine ecosystems renders São Paulo's natural

Figure 5
Map depicting the environmental conservation areas in the state of São Paulo



landscape exceptionally rich, abundant, and perpetually captivating. Presently, São Paulo hosts in excess of 30 state ecological reserves, encompassing a combined area exceeding 700,000 hectares, devoted to the comprehensive conservation of the environment. These reserves are specifically designated for the preservation of biodiversity, scientific research endeavors, and ecotourism activities.

With an emphasis on conservation units, we will analyze the areas established by the Brazilian Ministry of the Environment[2] (MMA), environmental preservation regions can be of different types and categories, such as national parks, biological reserves, ecological stations, and environmental protection areas, as possible to see in Figure 5.

3.1. Environmental rules for implementing transmission lines

To guarantee the efficiency, quality, and safety of energy transmission, the structure of the Transmission Rules was approved by Normative Resolution No. 905/2020 with a normative character that consolidates the regulation of the electrical energy transmission segment by the ANEEL[3]. Module 4 of the document specifies the rules for transmission lines and a topic that regulates the inspection of regions containing transmission lines. This topic regulates the verification of vegetation near the power transmission line that puts the operation of the transmission line at risk in the event of fire.

One way to avoid blackouts and wiring accidents is to prune vegetation close to the transmission line path. Fires can cause irreversible damage to the population, fauna, and flora of a given region [33]. An accident that occurred in 2012 shows the need for special care in these regions, reports found the lack of plant suppression on the Salobo Transmission Line[4], the company did not cut or prune the vegetation close to the company's power transmission lines that cross the Carajás National Forest, which caused a short circuit that caused a fire that lasted 55 days and devastated an area of approximately a thousand football fields.

Another case in Canada illustrates the danger of failures in transmission lines. In 2018, at the Camp Fire, a failure caused a fire that killed 84 people. Although electrical wildfire ignitions represent only 8% of events in California, the severity of potential accidents highlights the extensive damage and the need for analysis, study, and improvement.

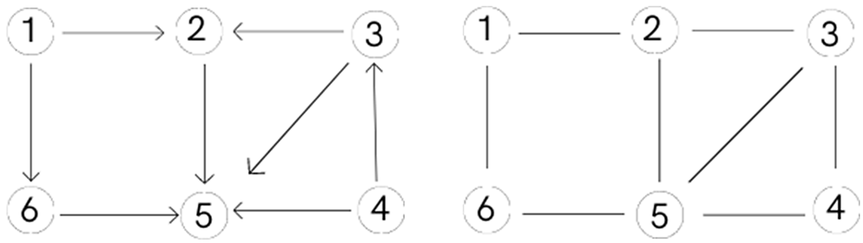
To avoid accidents like this, one way to protect vegetation is to create alternative energy transport routes, which in addition to protecting parks is an important approach to ensuring safety and efficiency in energy supply.

[2] Ministry of the Environment (MMA) in Brazil, accessed on July 3, 2023, https://cnuc.mma.gov.br/

[3] Electric Energy Transmission Service Rules established by ANEEL, accessed on July 3, 2023, https://www.gov.br/aneel/pt-br/centrais-de-conteudos/procedimentos-regulatorios/prodist

[4] Petition: 3618 - Crimes Against the Environment and Genetic Heritage, Process No. 0003219-65.2015.4.01 .3901 - 2nd Court - Marabá, Judgment date June 22, 2015, https://processual.trf1.jus.br/consultaProcessual/processo.php?proc=0003219-65.2015.4.01.3901&secao=MBA

Figure 6
Representation of graphs with six vertices considered oriented (left) and unoriented (right)



3.2. Theory of graphs

Graph theory began in the city of Königsberg in 1736 by the mathematician Leonhard Euler (1707–1783), he began his studies to show the community in his city a viable route to leave their homes and return through two different bridges that were connected to the city [34], and he used vertices and edges to represent the route to be taken but concluded that it would become impossible to take a route following the rules imposed by the residents.

After this idea of connection created by Euler, graph theory became an area of study for several scientists and mathematicians. According to mathematical language, a graph is a set of objects $X = \{x_1, x_2, x_3, \ldots, x_n\}$ called vertices and another set $U = \{u_1, u_2, u_3, \ldots, u_m\}$ such that u_i is called an edge, related to each other through a relationship that constitutes the graph $G = (X, U)$. The edge of a graph is defined by $u_r = (x_i, x_j)$, where x_i is called the initial vertex and x_j is the final vertex. In this case, the vertices x_i, x_j are said to be adjacent, and the vertices x_i, x_j are said to be incident on the edge u_r [35].

The edges used in a graph can be directed or not, and it may or may not be permissible to connect a vertex to itself. Furthermore, both vertices and edges can have an associated weight, generally expressed numerically. This mathematical structure is widely used in the description of networks, providing an approach for analyzing transport planning properties and human resource optimization.

To represent graphs, we have two different ways of showing the relationships between elements in a structure. We have oriented and unoriented graphs; in the oriented graph also known as symmetric, the edges have a direction. Each edge is represented by an arrow that indicates the direction between the vertices. It is a unidirectional representation, showing the source and destination graph. It is used to represent data flow in a computer system, reporting relationships in an organizational hierarchy [36].

We have the unoriented graph, known as asymmetric; it is an approach used to represent a set of vertices connected by edges that do not have a direction associated with them, which means that the connection between the vertices is bidirectional. In Figure 6, we have the representation of two graph models, and both have six vertices and eight edges, but in the first, the edges have a direction associated with a vertex, and in the other graph, the edges have no associated direction, concluding that we have a unidirectional graph (see left Figure 6) and another bidirectional (see right Figure 6).

Graph theory is fundamental in mathematics and computer science [37], graphs are versatile mathematical structures that consist of vertices interconnected by edges, and their application extends from computer networks and transportation systems to social network analysis and route optimization. Algorithms such as Breadth-First Search and DFS are essential for exploring and searching for information in graphs, while Dijkstra's algorithm is widely used in routing problems, demonstrating its relevance and practical applicability of graph theory in various domains.

4. Results

Using data obtained from maps, we generated graphs using the website Graph Online[5]. This site offers an interface for creating different types of graphs, allowing you to customize colors, sizes, and shapes of nodes and edges. Focusing on the state parks of Rio do Peixe, Aguapeí, Itaberaba, and Itapetinga, which have 440 kV transmission lines passing through their territory, we will provide alternative routes for possible maintenance on sections of the lines and shut down to mitigate accidents.

4.1. Vertex degree algorithm: Analysis and application

The vertex degree algorithm is a metric utilized in graph theory to signify the number of edges connected to a particular vertex of a graph. It can be determined by counting the edges linked to that vertex [38]. In the context of an undirected graph, the degree of a vertex refers to the total number of edges connected to it, irrespective of direction. As illustrated in Figure 7, the maximum number of edges linked to a vertex is seven, which corresponds to the Bauru substation identified as vertex 23.

Through this algorithm, we were able to realize that most substations have more than one connection, concluding that we have more than one route to reach the desired substation; thus, we were able to provide an optional route for maintenance periods and dry periods that are more prone to accidents involving local vegetation, so as not to harm the receipt of energy from nearby regions.

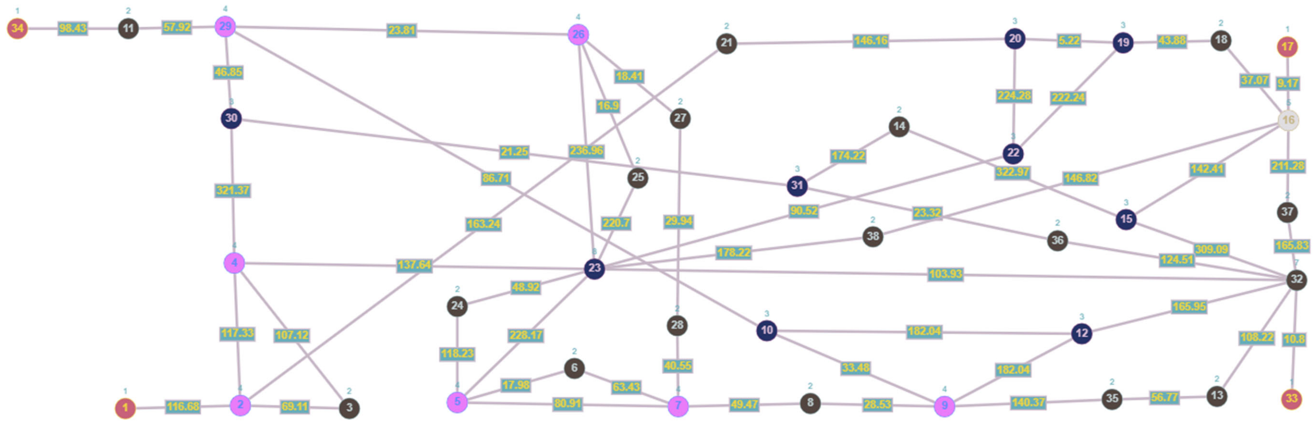
4.2. Analyzing the depth-first search algorithm

DFS is an algorithm used to explore graphs. It starts from a selected vertex and continues visiting neighboring vertices. The fundamental concept is to explore unvisited vertices and investigate their unvisited neighbors before backtracking. This procedure persists until all vertices of the graph have been traversed. DFS is useful in several applications, such as recognizing connected components, identifying cycles, and determining paths in graphs, making it an essential tool for analyzing and traversing them.

One approach to mitigating fire risk is to explore routes to substations that bypass environmentally protected areas. The search for alternative paths through state parks requires a thorough assessment of current infrastructure, focusing on the use of pre-existing routes. Given the environmental fragility of these regions, it is necessary to avoid any actions that could have adverse effects on

[5]Graph Online, accessed on July 3, 2023 https://graphonline.ru/

Figure 7
Graph that represents the number of edges connected to each vertex



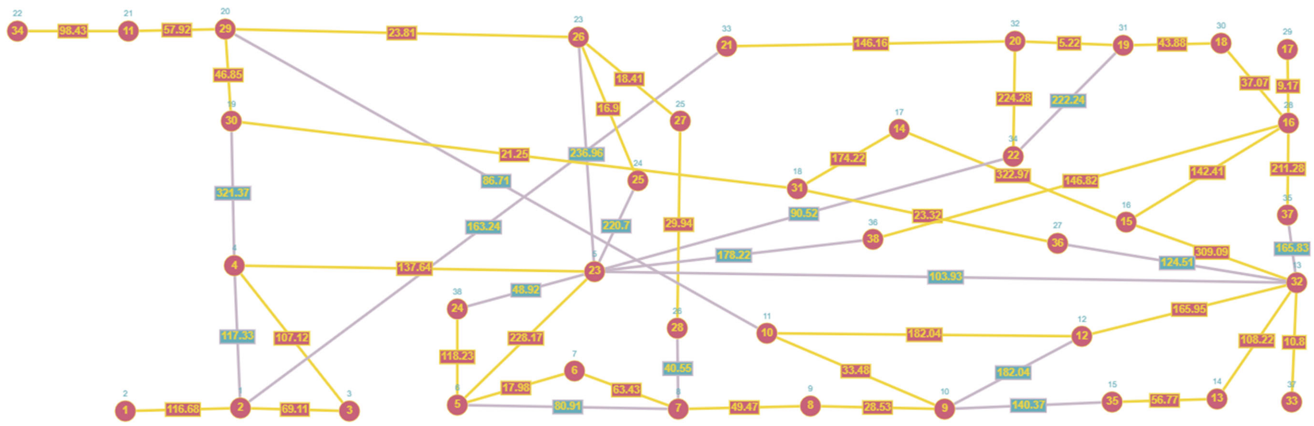
biodiversity and local habitats. This strategy not only reduces the risk of fires in these delicate ecosystems but also reinforces dedication, preservation, and environmental conservation, contributing to the preservation of our natural resources and biodiversity.

The Rio do Peixe and Rio Aguapeí State Parks were created as compensation for the construction of the Engenheiro Sérgio Motta Hydroelectric Plant in 2002 and 1998, respectively, by Companhia Energética de São Paulo, to protect Rio do Peixe's floodplain ecosystems, a tributary of the Paraná River, and floodplains of the Aguapeí River.

The region is often called "Pantaninho Paulista" due to its vast alluvial plains, which are very similar to the Pantanal. Located between substations 2 (SE Taquaruçu) and 21 (SE Alta Paulista) is the Rio do Peixe State Park. The Itapetinga State Park is close to substation 10 (SE Água Azul), with more than 10 thousand hectares of preserved area; it is part of the protection of forest remnants of the Serra do Itapetinga, which is home to numerous species threatened with extinction in the state of São Paulo [39]. The Itaberaba State Park, also close to substation 10, is an important ecological corridor between Serra da Cantareira and Serra da Mantiqueira, covering an area of more than 15 thousand hectares, preserving important remnants of the Atlantic Forest and several endangered species of animals of extinction. Together they protect springs from important river basins that supply the Cantareira System.

Passing through the territory of the parks, we have three transmission lines, one route from substation 9 (Santo Ângelo) to substation 12 (Mogi Mirim 3), another from substation 9 (Santo Ângelo) to substation 35 (Replan), and from substation 10 (Água Azul) to substation 29 (Bom Jardim). To fully preserve the conservation area between the highlighted substations, we proposed an alternative route, moving away from the route that passes through substations 2 and 21. In another preservation region, we carefully avoided the sections between substations 9 and 12, 9 and 35, as well as 35 and 10. Figure 8 visualizes this second route, showing an alternative route for the transmission lines that avoids crossing the areas of the State Parks of Rio do Peixe, Aguapeí, Itapetinga, and Itaberaba. This strategic rerouting was designed to minimize environmental disruption to these delicate ecosystems. Through a single simulation, we were able to obtain alternative routes for the protection of four environmental preservation parks, offering efficient solutions. Using the algorithm, we identify routes that bypass sensitive areas and minimize environmental impacts, ensuring the preservation of the natural ecosystems present in the parks in parks and their surroundings.

Figure 8
Depth-first search graph without the connection that passes through the territory of the Rio do Peixe State Park and the Aguapeí State Park



5. Environmental Preservation Strategies

The expansion of electrical transmission networks, although essential to meet growing demands, often confronts areas of environmental preservation, where biodiversity conservation is a priority. This topic explores the critical need to adopt strategies that minimize environmental impact when implementing transmission lines in sensitive regions.

Currently, the implementation of the proposed optimization strategies significantly reflects the improvement of the environmental situation compared to conventional approaches to expanding transmission networks. By adopting alternative routes and avoiding conservation regions, as illustrated in Figure 8, we observed a substantial reduction in the environmental impact associated with the installation of transmission lines. This innovative approach not only preserves sensitive ecosystems, such as the Rio do Peixe, Aguapeí, Itapetinga, and Itaberaba State Parks, but also minimizes potential damage to biodiversity.

The identification and prevention of critical stretches, such as those between substations 2 and 21, 9 and 12, 9 and 35, and 35 and 10, are crucial to mitigate negative impacts on sensitive natural habitats. Proactive strategies in the implementation of transmission lines strengthen the commitment to environmental preservation, providing a balance between the development of electrical infrastructure and the conservation of ecosystems. The continuous search for alternative routes and the promotion of sustainability demonstrate the importance of a responsible and integrated approach to the expansion of electrical transmission networks, contributing to a more efficient and ecologically conscious energy future.

6. Future Perspectives

Exploring future prospects for expanding transmission networks presents opportunities for novel alternatives and significant advancements in energy efficiency. In an era marked by continuous technological evolution, there emerges a chance to redefine the landscape of energy transmission, aiming not only to meet escalating demands but also to foster sustainable and efficient practices.

There exist research avenues that encompass the integration of renewable technologies, seeking to investigate the effective assimilation of renewable energy sources into transmission networks. This approach aims to leverage distributed generation to diminish reliance on nonrenewable sources. Concurrently, evolution intertwines with the development of smart networks, constituting an investment in transmission infrastructures that integrate advanced communication and automation technologies. These smart networks facilitate dynamic and adaptive infrastructure management, thereby contributing to the operational efficiency and sustainability of the electrical system.

Within the realm of resource allocation optimization, the exploration of advanced algorithms emerges as an initiative to allocate resources efficiently. This optimization takes into account network topology, energy demand, and environmental impacts. Simultaneously, while contemplating innovations in materials and transmission line design, research endeavors to identify more efficient and sustainable materials. Moreover, it seeks to devise innovative designs for transmission lines aimed at minimizing energy losses and mitigating environmental impact, thus fostering a more conscientious and effective approach to expanding electrical transmission networks.

7. Conclusions

During this study, we conducted an analysis highlighting the imperative need for environmental protection, considering the diverse ecosystems found in each region. Our examination revealed concerning trends; for instance, the Serra do Mar State Park, where only 12.4% of its original state remains, faces ongoing deforestation driven by agricultural expansion for banana and vegetable cultivation, leading to the proliferation of informal settlements [40]. Similarly, the Municipal Natural Park of Cratera da Colônia has been encroached upon by clandestine land allotments since 1990. Meanwhile, the Aguapeí and Rio do Peixe State Parks are engaged in preserving the last remnants of floodplain ecosystems, while the Itapetinga and Itaberaba State Parks grapple with deforestation and unauthorized construction.

Both regions are plagued by unbridled deforestation, compounded by the escalating incidence of wildfires, a global phenomenon wreaking havoc on biodiversity and air quality. Our research delves into the origins of fires, whether natural, human-induced, or caused by faults in transmission line wiring. Considering the dire consequences of these fires, we advocate for proactive measures to address or alleviate the issue.

Our study identified one such approach to mitigate the impacts in these areas: the reconfiguration of transmission line routes. This strategy not only serves the interests of conservation areas but also enhances the quality of energy supplied to consumers. By rerouting transmission lines, we mitigate the risks of power outages during dry season fires in regions served by these lines. Moreover, it helps prevent potential short circuits in the wiring, averting sparks that could ignite fires, often challenging to control due to the remote accessibility of these areas, resulting in protracted firefighting efforts.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

The data that support the findings of this study are openly available in Webmap Energy Research Company (EPE) at https://gisepeprd2.epe.gov.br/WebMapEPE/.

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