Research on the Planning Strategy and Layout Pattern of Electricity Grids in Megacities from the Perspective of Urban Planning

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Abstract. In light of the advancement of urbanization and the development of digital and intelligent technologies, urban power consumption has shown a continuous and rapidly increasing trend, which makes power supply and its protection key issues in terms of further urban development. Given this context, the electric power system per se has likewise been undergoing continuous improvement and change, with many efforts directed toward AC-to-DC conversion for electricity transmission. As such, the new measures applied in urban areas inevitably face the challenge with regard to coexisting with the existing urban systems. On the one hand, electricity grids, as important infrastructure of urban power supply systems, play a key role in supporting modern urban life. On the other hand, the traditional planning methods, solely relying on electricity load forecasting and load nodes, results in a certain degree of inconsistency and conflict between the electricity grid planning and the Master Urban Plan, thereby leading to serious negative impacts of the electricity grid layout on urban space quality. Given this context, this article reflected on the limitations of the traditional electricity grid layout and planning methods by analyzing the current situation and the needs of urban space development. Subsequently, relevant planning theories were combined to explore strategies and models for the planning and layout of electricity grids and related facilities in megacities based on comprehensive consideration of power security, power safety, not-in-my-backyard mentality, urban development needs, and urban space quality, in order to achieve harmonious coexistence of electricity grid construction with urban-rural space.

1. Introduction: Development Trends and Dilemmas of Urban Electricity Grids

With the continuous rise of urbanization and the increasing popularity of informatization and digitalization, the urban electricity load has shown a rapidly increasing trend, thereby increasing demands on efficient, reliable, safe, and stable power supply in cities. Given this context, the construction of electricity grids in megacities has drawn increasing attention [1]. The construction and rapid development of electricity grids are, to a certain extent, inevitable needs because of the increase in power generation capacity and load as well as the extension of transmission distances. However,
while the rapid construction and improvement of power transmission lines ensure power transmission, these also result in the so-called not-in-my-backyard mentality and a conflict between urban development and social life, even affecting the values of corresponding rural and urban real estate [2]. In the meantime, the security requirements for electricity grids also split the overhead power transmission lines and limit the expansion of urban construction to some extent, which is especially true for ultra-high-voltage (UHV) power transmission lines with a voltage above 550 kV [3]. As a result, a contradiction between grid construction and urban construction emerges (i.e., it is difficult to construct a power corridor in urban built areas on the one hand; and it is difficult to construct urban areas wherein a power corridor runs through on the other hand). This contradiction is mainly manifested through two aspects: (1) the two types of construction are not adapted to each other (i.e., urban roads are constructed much earlier in urban development than electricity transmission corridors in urban electricity grid planning, resulting in the possibility that the original urban electricity grid planning necessitates updating or possibly becoming obsolete) [4]; (2) the two types of construction have mutual conflict, a common problem in cities. As an example, the installation infrastructure of electricity transmission corridors (e.g., electric poles and electric towers) stands in the middle of roads, thereby seriously affecting the normal road traffic and causing potential safety hazards to traffic and electricity (Fig. 1). In addition, the strong electromagnetic radiation of an electricity grid will not only cause panic among nearby residents but will likewise restrict the use of the land that the corridor runs through [5].

![Figure 1. Electricity transmission corridors and facilities occupy the road, destroy the landscape, and affect the living conditions. Source: Author Collected](image)

These problems are caused mainly by the lack of effective coordination between the planning of electricity transmission corridors and facilities and the urban-rural planning. The planning of electricity grids, especially high-voltage, extra-high-voltage (EHV), and UHV electricity transmission lines, is usually conducted within the electric power system with consideration given to the convenience and economy of electricity transmission corridors while attempting to meet the prescribed safety and reliability requirements. The planning and construction of electricity transmission corridors usually adhere to a direct-connection rule to ensure that the electricity transmission corridors have the shortest routes. This approach disregards coordination with urban-rural planning and ignores the complexities of urban-rural space and life, thereby making it vulnerable to experiencing conflicts. Unfortunately, there are relatively few studies on the analysis of coordination between urban electricity grids and urban development and planning [6]. To date, studies on electricity grids of megacities have mostly been focused on power engineering, with research efforts directed toward wiring modes, capacitances, resistances, and transmission line relay protection [7, 8]. Existing research efforts are likewise focused on exploring how to improve the safety of electricity transmission corridors and how to avoid low-voltage issues [9, 10]. Such studies simply address electricity grid-related technical issues but fail to address problems regarding the coordination between electricity grids and urban development or
planning. Other major aspects of electricity grid research which need to be addressed are the planning, layout, and construction of electricity grids based on urban electricity load [11] with focus on the forecasting of urban electricity load and the power supply-side reform [12]. Although existing studies consider the relationship between the demand for urban power and the planning and layout of electricity grids, these are mostly limited to the field of power engineering. As such, there is still no in-depth exploration of how urban construction and development and the planning and layout of electricity grids can be coordinated. Nowadays, China's urbanization rate has exceeded 50%, indicative of middle and late stage of urbanization. Thus, concerns regarding the manner of improving the quality of urban-rural life and space have become core issues to address. Accordingly, it is necessary to better harmonize the relationship of power infrastructure construction with urban development and minimize the conflicts regarding electricity grid planning and construction with urban-rural space, various systems, and social life, for the purpose of achieving comprehensive development.

2. Main Influencing Factors and Conflicts Regarding Urban Electricity Grids

2.1. Main Influencing Factors of Electricity Grid Construction

A city is a massive, complex system, comprised of dimensions related to spatial quality, landscape environment, and other physical elements as well as dimensions related to economy, society, and other non-physical elements. Urban electricity grids are considered as complex engineering systems, which include physical facilities (e.g., lines and stations) and elements not visible to the naked eye (e.g., electromagnetic radiation during the operation of electricity grids). Accordingly, in the construction of urban electricity grids, the main influence between urban space and urban electricity grids is comprised of four parts [13].

| Indicators Category | Influence Indicators |
|---------------------|----------------------|
| Economic            | Direct Costs: Power infrastructure construction costs |
|                     | Indirect Costs: Urban environment repair or other costs |
|                     | Landscape: Urban skyline and environment |
|                     | Urban Scenery: Urban view corridor and sense |
|                     | Land Use: The function of urban land use |
|                     | Public Health: Short-term or long-term health influence |
|                     | Resource Waste: The scale of power infrastructure |
|                     | Urban Ecology: Urban physical environment |
| Environment         | Cultural Resources: Artificial or urban heritage |
|                     | Natural Resources: Plants or biodiversity |
|                     | Public Safety: The impact of power infrastructure on safety |
|                     | Functionality: The degree of coincidence with urban industrial formats distribution |
|                     | Aesthetic Value: The impact of power infrastructure on vision |
| Social              | Coordination: The interoperability between power network and integrated urban space |
| Quality             | Source: Author Made |

2.2. Main Conflicts Between Current Electricity Grids and Urban Development

(1) Conflict between the rapid growth of electricity load and the shortage of urban land.

With the sustained and stable development of China's economy, the electricity load has been rising. In recent years, electricity loads in the Pearl River Delta and Yangtze River Delta have been increasing by more than 10%. Furthermore, in some places the annual growth rate has exceeded 20% (Fig. 2).
However, with the increase in electricity load, the scope of infrastructure construction in cities is also expanding. The development of urban land requires the provision of a large amount of residential land to accommodate the population moving into the cities and a large amount of commercial land to satisfy the daily living and work-related needs of people. However, the construction of electricity grid infrastructure only in response to the growth of electricity load often results in a scenario wherein the planning and construction of electricity grid infrastructure is absent until electricity load begins to increase in some urban areas. This makes it practically impossible to implement the conditions that are designed for facility layout and electricity grid construction in accordance with electricity load. The reason is that the surrounding land of an electricity load center is often under construction and planning and, therefore, unable to provide space for the necessary electricity transmission corridors and relevant facilities, thereby forcing power infrastructure to be constructed at outer areas. However, after power infrastructure is constructed at outer areas, the construction of overhead power transmission lines presents a serious negative impact on the urban landscape.

![Total national electricity consumption from 2006 to 2019.](source: Author Made)

(2) Conflicts between urban electricity grid construction and other urban infrastructure construction.

The most prominent conflicts between urban electricity grid construction and urban infrastructure construction is concentrated in urban road reconstruction and expansion. Due to current situational constraints, the construction of electricity transmission corridors and of urban roads, including reconstruction and expansion, cannot be performed simultaneously. As a result, the construction of new urban roads or the expansion of old urban roads will often be conducted on existing electricity transmission corridors. Otherwise, new electricity transmission corridors (usually in the form of cable trenches, drainage pipes or direct burial) have to be added on existing roads. Due to the lack of comprehensive coordination, in the first scenario, the power supply department often requests the road expansion department to be responsible for all the relocation costs of power transmission lines. The reason is that if the relocation plan will change the overhead power transmission lines into underground power cables, it will cause high construction costs, which the municipal department usually refuses to shoulder. In the second scenario, the municipal department requires the power supply department to pay three to five times the road excavation fee as compensation, which is even greater than the investment of the power supply department in the power-line corridor construction and cable materials. The two scenarios will eventually lead to conflicts and stalemates between electricity grid construction and urban municipal construction or make both parties refuse to take responsibility, resulting to spatial disorder in the urban areas in general. In addition, the repeated excavation of urban roads will also have a certain negative impact on urban landscape quality and urban traffic.
(3) Conflicts between the construction of urban electricity grids and the quality of urban spatial environment.

At present, the planning of urban electricity grids is not integrated with the Master Urban Plan, which results in considerable impacts of urban electricity grids on the environment, considering that electricity transmission corridors and outdoor transformer substations will have large negative impacts on urban environmental quality, landscape, and public health. These negative impacts are concentrated in the following aspects: (1) the overhead power transmission lines frequently cross urban areas, causing serious negative effects on urban public safety and landscape; (2) the electromagnetic radiation and noise during the operation of electricity grids have certain impacts on the life and health of residents, especially when outdoor transformer substations are close to residential buildings.

Given the abovementioned conflicts and problems between urban electricity grids and urban spatial environment, Nanjing City, one of the megacities of China, was selected as a subject in this study to address the issues on electricity grids in the main urban zone of Nanjing based on statistical data and analysis. As a result, proposals on corresponding optimization strategies were formulated.

3. Current State of Electricity Grids in the Main Urban Zone of Nanjing

3.1. Electricity Load and Forecasting in Nanjing

(1) Overview of current electricity consumption in Nanjing.

Nanjing, the capital of the Jiangsu Province, is a sub-provincial city, a mega city, and a core city in the Nanjing metropolitan area. It is an important central city in eastern China, as determined by the State Council. Nanjing has 11 districts and a total area of 6,587 km², including a built-up area of 971.62 km². It is home to a resident population of 8.4362 million, including an urban population of 6.9599 million, with an urbanization rate of 82.5%. Nanjing is the load center of the East China Electricity Grid. The electricity grids in the main urban zone are operated and managed by the Southern Nanjing Power Supply Company, the Northern Nanjing Power Supply Company, the Qixia Power Supply Company, and the Yuhua Power Supply Company, all under the jurisdiction of the Nanjing Power Supply Company. In 2019, the maximum power supply load of the electricity grids in Nanjing was 11.7 million kWh, showing an approximate yearly increase of 9.2% to 13.7%.

(2) Forecasting of Nanjing electricity load.

Electricity load forecasting constitutes a basic and integral part of special urban electric power planning since it provides fundamental support for the determination of the proper size and layout of urban power sources and grids. Special urban power planning pertains to reserving the necessary power infrastructure for urban development, relying on the land-use and population data provided by the urban plan. Therefore, the electricity load of Nanjing was predicted using the load density method, with the following formula for computation:

\[ P = K_p \sum_{i=1}^{N} P_i \times S_i \]

In the foregoing formula, \( P \) pertains to the forecasted load, \( K_p \) refers to the simultaneity usage coefficient, \( P_i \) is the load density indicator of the \( i \)-th land-use type in the city, and \( S_i \) is the area of the \( i \)-th land-use type.

According to the statistics released by the National Energy Administration as well as the Nanjing electricity consumption data released by the Nanjing Statistics Bureau and the Nanjing Municipal Government, the whole electricity load in Nanjing was 19.96 billion kWh in 2005, 33.85 billion kWh in 2010, and 49.516 billion kWh in 2015. Based on the foregoing electricity load changes from 2005 to 2015, combined with the areas of various land-use types in Nanjing’s Master Urban Plan and a simultaneity usage coefficient of 0.8, the total annual electricity load of Nanjing is projected to be 75.912 billion kWh in 2020.
3.2. Current State of Electricity Grids in the Main Urban Zone

The current state and the corresponding problems of electricity grids in the main urban zone of Nanjing are in line with the aforementioned conflicts between electricity grids and urban space. However, due to the high spatial density and mixing in the main urban zone, the current state and the corresponding problems of the electricity grids have some unique characteristics. Based on the forecasted electricity load of Nanjing and the planning of electricity grids (Fig. 3), the existing problems with regard to the electricity grids of Nanjing are as follows.

![Figure 3](Source: Author Made)

(1) There is a huge demand for electricity grid infrastructure but the available urban land area is insufficient.

At present, there are only at least 30 220-kV transformer substations in Nanjing and at least 60 110-kV transformer substations. According to the capacities of transformer substations and the aforementioned increase of electricity load, the current electricity grid infrastructure is far from sufficient in meeting the current and future needs of Nanjing. Considering the standard capacity of a transformer substation, approximately 10 to 13 more 220-kV transformer stations and 20 to 22 more 110-kV transformer stations should be constructed in Nanjing to meet the increased demand for electricity load. However, the high-density development in the core area of the main urban zone of Nanjing has resulted in the inability to provide land and space around the electricity load centers for the layout of overhead power transmission lines and facilities, gradually aggravating the conflicts between electricity grid construction and urban space.

(2) Electricity grid planning and construction is not included in the Master Urban Plan, resulting in waste of resources.

The planning and construction of electricity grids in a city is always independent of the overall planning and construction of the city. As a result, the power transmission lines that could have been included in the comprehensive urban pipeline corridor of Nanjing can only be constructed separately. Considering the foregoing, the roads need to be re-excavated and underground power pipelines should be laid out for burying underground power cables, which results in a waste of resources and serious effects on the daily traffic and life in the city.

(3) Inconsistency between the electricity grid plan and the urban plan leads to inconsistency between electricity development and urban development.

As specified in the content and framework of Nanjing’s Master Urban Plan, the urban power supply plan is only carried out as a special plan under the former and does not involve the detailed planning of electricity grids. On the one hand, the special plan for urban power supply is basically made either by
Jiangsu Electric Power Design Institute or Nanjing Electric Power Design Institute, with most of the planners having a background in electrical engineering. As a result, the prepared special plan for power supply cannot be well-integrated with the urban master plan. On the other hand, the special plan for urban power supply is mostly based on the existing electricity load, thereby failing to be dynamically adjusted in response to the complexities of the Regulatory Detailed Plan of the city. As a result, the power supply plan cannot be implemented in practice.

4. Planning Strategy for Electricity Grids Under a Comprehensive Development Plan

4.1. Harmonious and Comprehensive Layout

Given that electricity grids have large impacts on urban morphology, landscape, and citizen life, their layout should be integrated into the overall urban framework and harmonized with various urban systems. At the overall urban level, as long as the planning of electricity grids ensures the reliability of power supply, it should not be limited to the electric power system. Instead, the planning should be based on the performance optimization of the entire urban system, its core objective, to re-examine the layout of electricity grids in order to achieve a consistent situation of comprehensive development in relation to electricity grid construction and urban-rural development.

A situation of comprehensive development refers to a scenario in which both electricity grids and urban-rural development can generate good benefits. It is a situation wherein ensuring urban-rural development benefits from the power supply capacity of electricity grids does not negate the possibility of reducing or even avoiding the negative effects of electricity transmission corridors on landscape and safety (e.g., radiation threat). Furthermore, it entertains the possibility of constructing electricity transmission corridors in a more efficient and convenient manner by leveraging existing urban-rural corridor space while reducing the use of urban-rural construction land and highlighting the structural and spatial characteristics of the city. In short, it is possible to simultaneously achieve electricity transmission corridor construction and urban-rural development in a joint, efficient manner in order to integrate the economic, environmental, constructional, and social benefits in a harmonious manner.

4.2. Key Issues to be Addressed in Electricity Grid Layout in a Situation of Comprehensive Development

The comprehensive development concept necessitates that the layout of electricity transmission corridors should be based on the overall development needs of the electric power system in a coordinated urban-rural development framework. In practice, the layout should adhere to the following rules:

1. Uniform implementation of spatial layout.

   According to the established scope and the delineation of powers and responsibilities among the administrative departments and execution departments, it is necessary to specify the quantitative and positioning requirements on electricity transmission corridors in a comprehensive, coordinated manner. For quantitative requirements, the municipal administrative departments should specify the necessary maximum and minimum control indicators at a municipal scale according to the urban-rural plan. For positioning requirements, municipal administrative departments should propose clear locations and land-use areas, which shall be approved by the planning administrative departments. Proposals meeting relevant planning and construction standards should be included in the urban plan and implemented in practice. If there are proposals that are not permitted by current conditions, the planning department should make suggestions for changes after coordination between various departments. After adhering to the foregoing measures, the spatial layout will be implemented at various planning levels.

2. Comprehensive utilization of corridor space.

   As a subsystem in the overall urban-rural system, the electric power system should fully consider its relationship with other subsystems. Considering China's actual situation and the characteristics of electricity transmission corridors, full harmonization between the layout of electricity transmission corridors with the layout of road systems and protective green belt systems and share space is recommended by fully utilizing existing surface corridors and implementing comprehensive corridors...
in areas where such conditions permit the same. The corridor space necessary for an orderly layout of electricity transmission corridors should be based on ecological corridors (e.g., protective forest belts and river systems) and traffic corridors (e.g., highways, railways, and expressways).

(3) Strengthening of urban-rural spatial structure.

As important infrastructures for urban-rural development, electricity transmission corridors are also essential parts of the urban-rural system. In addition, due to their important effects on urban-rural space and landscape, electricity transmission corridors should be consistent with the urban-rural spatial structure (i.e., in line with the layouts and directions of important urban structural axes and corridors) in order to achieve greater operating efficiency, improve electricity grid efficiency, reduce conflicts, and strengthen the urban-rural spatial structure and characteristics.

(4) Adapting to urban planning and landscape requirements.

In fulfilling electricity load needs and ensuring electricity transmission safety, the construction of urban electricity grids should involve as little land as possible. For electricity transmission facilities located near or within urban residential areas, the use of switchgear substations should be replaced by the use of ring main units, as much as possible. Single-box substations should be avoided and replaced with double-box substations to save the use of urban land. In the meantime, in selecting locations for power transmission facilities, preference should be given to the urban corner areas and fragmented spaces (e.g., large viaduct arches) in order to ensure the integrity of urban-rural construction land and leave room for old city reconstruction. In addition, in constructing electricity transmission lines and facilities, it is necessary to harmonize the relationship between the main projects and the urban landscape to meet the requirements of the master urban plan and street landscape. In the meantime, for transmission lines and facilities passing through national parks or scenic spots, it is necessary to find a proper balance between the protection of scenic spots and cultural relics and the construction of infrastructure. The planning and site selection of electricity transmission lines must comply with relevant national laws and regulations on the protection of scenic spots and cultural relics.

4.3. **Technical Framework for the Layout of Electricity Transmission Corridors**

![Figure 4. Technology framework for corridor layout optimization](Source: Author Made)
In practice, electric power planning and urban-rural planning are separately made by different professional departments and institutions. Electric power serves as an important foundation and supporting condition for urban-rural construction and development. Accordingly, electricity load forecasting should also fully take into account the expectations and demands for urban-rural planning and development. Given this context, the urban-rural spatial structure and functional layout formed by urban-rural planning represent an integration of multiple systems including transportation, industry, functions, ecology, and municipality; while the layout of electricity transmission corridors in an electric power system is based on the consideration of the reliability, stability, safety, and economy of the electric power system.

As shown in Figure 4, in planning to construct electricity transmission corridors in an electric power system, it is necessary to propose specific space needs to the urban-rural planning administrative department, which is tasked with providing coordinated urban-rural planning within the bounds of comprehensive development and, moreover, bringing forward corridor optimization proposals based on layout coordination in response to the electric power administrative department. After multiple rounds of coordination and feedback, a comprehensive layout scheme for electricity transmission corridors can be formed for both parties.

5. Conclusion
There are obvious inconsistencies related to the planning and implementation of urban electricity grids. The inconsistency between the planning of urban electricity grids and the planning of urban and municipal development as well as that between the planning and actual construction of electricity grids have made the conflicts between urban electricity grids and urban construction increasingly prominent. This study, considering the main conflicts between current urban electricity grids and urban spatial environment, has selected Nanjing as a case city in order to analyze the actual problems relating to urban electricity grids. Thus, layout optimization strategies for urban electricity grids and facilities are proposed. The strategies are expected to reduce the damage to urban space and environment during the construction of urban electricity grids. In the meantime, the strategies will be conducive to the optimization of the overall urban space benefits so that electricity grid planning can effectively meet the needs of urban development and, moreover, be more feasible and effective in guiding further implementation planning.

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