frontiers | Frontiers in Energy Research

TYPE Review
PUBLISHED 04 December 2024
DOI 10.3389/fenrg.2024.1501450

Check for updates

OPEN ACCESS

EDITED BY
Zhong Ge,
Yunnan University, China

REVIEWED BY
Bai Xiaoxia,
Yunnan University, China
Songyuan Zhang,
Kunming Metallurgy College, China

*CORRESPONDENCE
Liting Zhang,
✉ 2079478684@qq.com

RECEIVED 25 September 2024
ACCEPTED 19 November 2024
PUBLISHED 04 December 2024

CITATION
Zhou H, Zhang L, Yang Y, Li Q and Qian F (2024) Review of spatial layout planning methods for regional multi-station integration.
Front. Energy Res. 12:1501450.
doi: 10.3389/fenrg.2024.1501450

COPYRIGHT
© 2024 Zhou, Zhang, Yang, Li and Qian. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Review of spatial layout planning methods for regional multi-station integration

Huiying Zhou, Liting Zhang*, Yongwen Yang, Qifen Li and Fanyue Qian

College of Energy and Mechanical Engineering, Shanghai University of Electric Power, Shanghai, China

In order to accelerate the high-quality development of China's infrastructure, it is not only necessary to ensure the continuation and efficiency improvement of the original infrastructure, but also to promote the layout, implementation, improvement and quality improvement of new infrastructure. As an important part of the energy Internet and new power system, "multi-station integration" plays a role in strengthening digital transformation, intelligent upgrading, integration and innovation support, achieving the nearby integration of resources and the coordination and complementarity of operation, reducing redundant design, so that users, enterprises and industries in the region can reduce costs, energy saving and emission reduction, improve quality and efficiency. By combing the spatial layout planning methods, models and influencing factors of traditional single function station and multi-station integration in the region, the influences of the function station itself and other surrounding infrastructure on the function station are analyzed. Combined with the application scenario, load demand and integration mode of multi-station integration, it is proposed to combine common factors and characteristic factors. The objective evaluation method is introduced to improve the practicability and suitability of the layout location. Finally, the three-layer theoretical framework is proposed to improve and supplement the existing layout principles and methods, so as to provide reference suggestions for the scientific location selection and optimization of regional multi-station integration.

KEYWORDS
multi-station integration, spatial arrangement, influencing factors, infrastructure, data center (DC)

1 Introduction

As an important part of the energy Internet and new power system, "multi-station integration" plays a role in strengthening digital transformation, intelligent upgrading, and integration and innovation support, effectively promoting the layout and construction of infrastructure and integration and innovation, and promoting the bilateral collaborative development of power computing power (Liu et al., 2020; Tan and Zhang, 2023).

"Multi-station fusion" is mainly to realize the synergistic effect of multi-function stations in the aspects of energy flow, service flow and data flow. On the one hand, the construction mode can integrate infrastructure such as various functional stations, integrate and layout key infrastructure resources in different ways according to scene requirements, and create a new infrastructure integrating multiple load supplies such as cold, heat, and electricity, as well as a number of comprehensive energy sources such as cloud computing, 5G network, charge and discharge. The green upgrade of data centers and 5G base stations is driven by electricity, and at the same time, the flexible adjustment characteristics of new infrastructure are fully utilized to enable the digital transformation of power systems, so as to achieve a virtuous cycle of nearby resource integration and coordination and complementarity (Tan and Zhang, 2023; Pei and Yan, 2022; Tang et al., 2022).

In terms of improving the energy supply system construction of China's new power system, the important role of "multi-station integration" has also become increasingly prominent. Experts and scholars have studied the spatial layout planning method of "multi-station integration", improved the resource allocation scheme, and considered the joint scheduling problem of computing power and electricity. To a large extent, it provides solutions to solve the problems of uneven energy distribution, low-taste waste heat in data centers, and new energy load fluctuations, improves the economy, efficiency and practicability of the overall system, and promotes the effective interaction and cooperative supply of surrounding power suppliers, equipment suppliers and users, which is an important layout and strategy for the win-win cooperation between national energy and information technology.

2 Research significance and scientific contribution

In order to accelerate the high-quality development of China's infrastructure, it is not only necessary to ensure the continuation and efficiency improvement of the original infrastructure, but also to promote the layout, implementation, improvement and quality improvement of new infrastructure. At present, the layout planning and site selection of traditional infrastructure have been studied and discussed in depth, but for the collaborative integration of traditional infrastructure and new infrastructure, the research on its spatial layout and fusion effect is still in the initial stage, and the relevant spatial layout principles, application scenarios, construction modes and influencing factors are relatively lacking. Therefore, it is of great significance to study the regional "multi-station integration" spatial layout planning method. This paper will analyze the influence factors of the traditional single function station in the region, analyze the influence of the function station itself and other surrounding infrastructure on the function station, summarize the research methods of experts and scholars, and summarize the common factors affecting the spatial layout, characteristic factors of the function station, application scenarios and load demands. This paper concludes the shortcomings of the existing research and provides reference suggestions for the scientific site selection and optimal layout of "multi-station integration".

The scientific contributions of this paper can be summarized as follows:

1) By summarizing the current research status of domestic and foreign experts and scholars on the spatial layout planning method of single function station, sorting out the advantages and disadvantages of common research methods, it puts forward the shortcomings of existing research at home and abroad: experts and scholars rarely consider land use planning, functional station construction standards and the landing of later planning, and lack some objective evaluation indicators and evaluation methods to evaluate the practicability of spatial layout schemes.
2) By summarizing the application scenario, load demand and research status of construction mode of regional multi-station fusion, it analyzes how different construction modes achieve the integration and optimization of energy flow, data flow and service flow in multi-station fusion scenario, thus verifying the advantages of multi-station fusion compared with traditional single function station in terms of load demand, land use and system configuration. To provide a more efficient and perfect spatial layout scheme for infrastructure construction and urban industrial layout.
3) Based on the analysis of existing studies on the influencing factors of spatial layout and location planning of single functional stations in the region, it is concluded that experts and scholars still have deficiencies in the selection of influencing factors for the integration of multiple stations in the region, and only focus on the common influencing factors, ignoring the characteristic factors of some functional stations. In the follow-up study, the characteristics of the functional station should be taken into account while considering the common influencing factors of the functional station, so as to further improve the overall operation efficiency and operation economy of the fusion station.

3 Research status of spatial layout planning method of single function station

For different functional stations, their spatial layout methods and influencing factors will be greatly different, which not only involves a wide range of areas, but also makes the situation more complex after mutual integration. Therefore, there are still many problems to be studied in the study of spatial layout method and spatial effect of "multi-station integration", and attention to the spatial layout principles and influencing factors of new infrastructure is relatively lacking. However, many experts and scholars have deeply discussed the characteristics of single infrastructure layout, and have relatively mature research on its layout location and model. The research mainly focuses on two aspects: on the one hand, the spatial layout and development of infrastructure; On the other hand, it is to summarize the direct and indirect factors and layout principles that affect the spatial layout of the infrastructure. The following is a detailed analysis of the layout and location research methods and influencing factors of each typical functional station.

3.1 Current status of domestic research

3.1.1 Analysis of research methods and models

By summarizing the research methods and optimization models of the layout location of each function station (Wang et al., 2023; Wang, 2018; WU et al., 2021; Wang, 2020; Liang and Li, 2021;

TABLE 1 Research methods of spatial layout planning.

Research methods/models		Data center	5G communication base station	Substation	Charging Station	Photovoltaic power station	Energy storage power station
Research methods based on influencing factors	Analytic Hierarchy Process (AHP)	√	√	√	√	√	√
	Clustering Algorithm	√		√	√	√	
	Fuzzy Comprehensive Evaluation (FCE)			√		√	
Multi-objective cooperative optimization model	Geographic Information System (GIS)		√	√	√	√	
	Particle Swarm Optimization (PSO)			√	√	√	√
	Tobit	√					
	Decision trial and Evaluation Experiment Method					√	
	Firefly Algorithm			√			
	Genetic Algorithm	√	√				√
	Robust Optimization Algorithm				√		√

Zhang, 2017; Li, 2017; Zhang Jiyang et al., 2020; Tang and Chen, 2022; Q/GWD383-2009, 2009; Gao and Zhang, 2006; Xiong, 2022; Baojun, 2011; Wu, 2019; Liu, 2022; Fu et al., 2017; Khalkhali et al., 2015; Wang, 2017; Liu L. et al., 2016; Zhang, 2021; Jia, 2020; Lei et al., 2023; Sun et al., 2024; Huang et al., 2024; Zhao et al., 2023; Liu Z. et al., 2016; Cao et al., 2022; Leou, 2008; Oudalov et al., 2007; Liu et al., 2017; Che et al., 2018; Tang et al., 2020; Wu et al., 2014; Ding et al., 2019; LI et al., 2017), the advantages and disadvantages of different methods and models as well as the scope of application are analyzed, as shown in Tables 1, 2.

As can be seen from the table, Analytic Hierarchy Process (AHP) is the most commonly used method for the layout and location of function stations among the research methods based on analysis of influencing factors of different function stations. This method analyzes the influencing factors of different function stations at multiple levels and combines the construction requirements and specifications of function stations. Realize the spatial layout optimization of functional station and the optimal site selection. In the spatial layout planning model of single function station considering multi-objective collaborative optimization, Geographic Information System (GIS) spatial analysis technology and Particle Swarm Optimization (PSO) are more commonly used and efficient algorithms. Different research methods and optimization models have their own advantages and disadvantages and scope of application. Experts and scholars should optimize the research methods and optimization models according to the construction needs, construction objectives and candidate sites, so as to make the spatial layout planning scheme of a single function station more valuable and practical.

3.1.2 Spatial layout planning method based on influencing factors

In terms of spatial layout planning of data centers, existing studies have provided great guidance for the scientific location and construction of data centers (Cai, 2021; Cao, 2023; Hu, 2021). For example, literature (Wang et al., 2023) constructs an index system that affects the macro layout of data centers by analyzing the four principles of macro layout. It is mentioned in literature (Wang, 2018) that in the past 30 years, factors such as natural environment, market demand, municipal conditions and policies and institutions have a great impact on the location of data centers. Literature (Wu et al., 2021) established a data center evaluation index system with six key elements as the core; Literature (Wang, 2020) classifies and models key factors affecting the location of data centers, and determines the location of data centers by combining qualitative and quantitative methods. To sum up, the existing literature establishes an evaluation index system based on the induction methods of different influencing factors, determines the index weights of each factor, and thus obtains the layout and location scheme suitable for different types and sizes of data centers, injecting fresh blood into the construction of digital infrastructure and the cultivation of new green industrial ecology.

In terms of spatial layout planning and location selection of 5G communication base stations, many domestic experts and scholars have made great progress through theoretical research, data analysis and mathematical modeling (Liang and Li, 2021; Zhang, 2017; Li, 2017). For example, literature (Zhang Jiyang et al., 2020) takes user density, regional land use nature, development intensity and other factors as consideration indicators, and puts forward corresponding measures and planning schemes for its spatial layout planning.

TABLE 2 The advantages and disadvantages of the research methods and applicable scope.

Research methods/models		Advantages/disadvantages	Scope of application
Research methods based on influencing factors	Analytic Hierarchy Process (AHP)	Advantages: wide applicability, strong consideration, high flexibility Disadvantages: strong subjectivity, complex calculation	It is suitable for multi-criteria and multi-objective decision problems, and can be used in decision analysis of multi-fields and multi-industries.
	Clustering Algorithm	Advantages: strong balance, batch processing data Disadvantages: The number of clusters is difficult to determine and the result is uncertain	It is suitable for data mining, machine learning, pattern recognition, image processing and other fields.
	Fuzzy Comprehensive Evaluation (FCE)	Advantages: Dealing with uncertainty, comprehensive consideration, intuitive results Disadvantages: strong subjectivity, complex calculation, uncertain evaluation criteria	It is suitable for the evaluation and decision-making of some fields which are difficult to be measured by precise values and various non-deterministic problems.
Multi-objective cooperative optimization model	Geographic Information System (GIS)	Advantages: high data accuracy, strong analysis function, high visualization Disadvantages: technical complexity, spatial data update is not timely	It is used in geographic information system, urban planning, land management, environmental protection, transportation, water conservancy and hydropower and other fields.
	Particle Swarm Optimization (PSO)	Advantages: wide applicability, simple algorithm and good parallelism Disadvantages: easy to fall into local optimal, lack of theoretical basis	It is suitable for a class of high-dimensional optimization problems with multiple local extremum points without the need to obtain very high precision solutions.
	Tobit	Advantages: Considering sample selection bias, processing limited data Disadvantages: High data requirements and complex results	It is applicable to the research of economics, sociology, medicine, energy and other fields.
	Decision trial and Evaluation Experiment Method	Advantages: strong controllability, timely feedback Disadvantages: High experiment cost and long time	It is suitable for some situations where the effect and feasibility of the decision plan are required and in-depth analysis and evaluation are needed.
	Firefly Algorithm	Advantages: Strong adaptability, strong global search ability, simple parameter setting Disadvantages: easy to fall into local optimal, lack of theoretical basis	It is suitable for function optimization, combinatorial optimization and other fields, such as path planning, image recognition, data clustering and so on.
	Genetic Algorithm	Advantages: wide applicability, good parallelism, strong global search ability Disadvantages: low optimization efficiency, complex coding and decoding	It is widely used in optimization problems in engineering design, production scheduling, resource allocation and other fields.
	Robust Optimization Algorithm	Advantages: Strong anti-interference ability, strong reliability Disadvantages: the calculation is complicated and the reliability of the results is greatly affected by parameter uncertainty	It can be used in supply chain management, financial risk management, power system scheduling and other fields.

Literature (Tang and Chen, 2022) combines the business development needs of the three application scenarios of 5G, and satisfies the business development needs of the three application scenarios by making special layout and planning layout of 5G mobile communication base stations and supporting facilities such as offices, pipelines and electric power. By considering the influence of multiple factors, it can realize the coordinated development and deep integration of various functions of the base station and the city on the basis of ensuring the smooth operation of the base station and good network condition.

In terms of substation spatial layout planning and site selection, problems such as the expansion of modern complex power grids and the improvement of renewable energy utilization rate have become important challenges for traditional substations (Gao and Zhang, 2006), so the location, capacity determination and intelligent upgrading of substations (Q/GWD383-2009, 2009) have become particularly important. There are two existing spatial layout site selection and planning methods in China. One is to make substation site selection planning by considering the number, capacity and power supply range of substations in distribution network planning, and evaluate its feasibility (Xiong, 2022; Baojun, 2011). The other is to select influencing factors (Wu, 2019; Liu, 2022) as characteristic indicators, including substation load, safety, benefit, etc., to establish an evaluation index system, so as to evaluate and screen candidate sites. The researchers found that the second planning method can consider the influencing factors as comprehensively as possible, so as to significantly optimize the distribution network of the substation, and achieve the effect of emission reduction and cost reduction while increasing the benefit.

In terms of spatial layout planning and site selection of charging stations, the existing charging facilities for new energy vehicles mainly involve three types: charging pile, charging station and changing station (Fu et al., 2017; Khalkhali et al., 2015; Wang, 2017). As the influencing factors for charging stations are mainly on the user side, at present, most domestic researchers analyze the influencing factors of charging infrastructure for new energy vehicles. This paper mainly analyzes the single factors such as user demand, economic cost, traffic density and power grid reliability. In addition, some scholars combined the actual situation to consider the coordination of multiple elements of the layout location method, such as literature (Liu L. et al., 2016) combined with a variety of factors and the surrounding conditions of facilities proposed a new comprehensive evaluation system. Literature (Zhang, 2021) summarized various factors affecting the spatial layout of charging infrastructure for new energy vehicles, and conducted in-depth analysis to obtain a spatial layout model. It can be seen that the planning and location of charging infrastructure combined with multiple factors will provide feasible solutions in terms of facility utilization, convenience of use, cost savings and land resources.

In terms of PV power generation layout planning and site selection research, China is still in the initial stage. Literature (Lei et al., 2023) not only considers the basic resource conditions such as slope, slope direction, shadow and catchment area, but also takes into account the impact of catchment area and environmental sensitive area on the development of PV power stations. Literature (Sun et al., 2024) discusses the relationship between photovoltaic module layout and power generation, as well as the influence of building factors such as roof bearing capacity. Literature (Zhao et al., 2023) preprocessed the obtained data, weighted the influencing factors in the evaluation indicators, and based on this, drew a spatial suitability distribution map for the construction of large-scale photovoltaic power stations. Most researchers carry out theoretical or modeling analysis by analyzing the conditions that affect the macro layout, so as to effectively solve the contradiction between the current "dual carbon" goal and the "land difficulty" of photovoltaic system construction (Jia, 2020; Huang et al., 2024).

In terms of layout planning and site selection of energy storage power stations, domestic experts and scholars mainly select different index factors to determine the optimal location and capacity of energy storage after adding energy storage to the power grid, and focus on the shift from the user side to the new energy generation side and the transmission side (Liu Z. et al., 2016), including transmission line interface effectiveness, spatial suitability and safety (Cao et al., 2022). For example, literature (Che et al., 2018) analyzed the influencing factors involving energy storage system in a certain area, and then used AHP to analyze the influence of various factors on location selection. In addition, some scholars have adopted the optimization model for several iterations in the research of integrated planning of constant capacity and location, and obtained the optimal solution (Tang et al., 2020; Wu et al., 2014; Ding et al., 2019; Li et al., 2017). Literature (Tang et al., 2020) comprehensively considers energy storage peak cutting and valley filling, voltage quality and active support capability. Literature (Wu et al., 2014) proposed an improved PSO algorithm to solve the model from the aspects of system voltage quality and load fluctuation. To sum up, in the fixed-capacity location planning of energy storage power stations, besides economic issues, the safety of the energy storage system itself and the situation of charge and discharge (Leou, 2008; Oudalov et al., 2007; Liu et al., 2017) should also be included in the layout planning index system for analysis, so as to optimize the economy of the entire system and improve the stability and security of the system.

3.2 Current status of foreign research

Recent research status of different countries is shown in Table 3 (Covas et al., 2013; Ramos Cáceres et al., 2024; Siamak et al., 2020; Elbasheir et al., 2021; Kezunovic et al., 2010; Zambrano-Asanza et al., 2021; Mohammad et al., 2022; Wilson et al., 2024; Choi et al., 2024; Krystyna et al., 2022; Hassan et al., 2017; Sayyed et al., 2020; Ali et al., 2023). As can be seen in the table, in terms of research methods and models, in addition to theoretical research, foreign experts and scholars mainly use GIS and a variety of comprehensive evaluation methods based on influencing factors, such as AHP, ANP, BWM, fuzzy evaluation, etc. In addition, in terms of influencing factors, foreign experts and scholars have fully considered the reliability of energy supply, geographical environment, economic cost, social factors, etc., and established an evaluation system based on the energy use characteristics and hard demands of different functional stations. Finally, the feasibility of spatial layout method and the suitability of location selection were evaluated through actual cases. It can be seen that foreign studies mainly consider the construction economy, reliability and impact on surrounding users for subjective evaluation and scoring, but rarely consider the land use planning, functional station construction standards and the landing of later planning, and lack some objective evaluation indicators to evaluate the practicability of spatial layout schemes, such as land intensification rate and energy self-supply ratio.

4 Research status of regional multi-station integrated spatial layout planning method

4.1 Research status of application scenario, load demand and construction mode

In recent years, many experts and scholars have carried out research on the scenario and mode of "multi-station integration", but the main direction of research is around the business model and operation model of "multi-station integration" and the economic and energy-saving benefits after putting into use. There is also a lack of generalization of multi-station fusion scenarios, load requirements and architecture models with the objectives of land intensification, function station modularization and system configuration coordination (Zhang et al., 2023), as well as research on the advantages of different fusion modes, so as to propose suitable multi-station fusion spatial layout planning methods and fusion construction models based on different application scenarios and load requirements. The following is a detailed analysis of the application scenarios, load requirements and construction modes of multi-station integration.

4.1.1 Application scenarios

In terms of technology, multi-station integration takes smart grid as the backbone, and realizes extensive access to clean energy through technologies such as new energy, energy storage, intelligent

TABLE 3 Research methods and influencing factors of spatial layout planning of single function stations in different countries.

Function station	Influencing factors of spatial layout planning of single function station	Research method	Location	No.
Data center	The literature is based on four main assessment dimensions: geological risk, social, economic and environmental. Each dimension contains multiple sub-criteria and is elaborated.	ELECTRE TRI	Portugal	Ref. (Covas et al., 2013)
	The literature suggests that effective Internet infrastructure, political stability, high power capacity, renewable energy, low taxation and cold climate are more competitive in the siting and construction process of data centers.	Theoretical research	Sweden	Ref. (Ramos Cáceres et al., 2024)
	The literature proposes a multi-dimensional evaluation method that includes social, economic and environmental factors to evaluate the suitability of data center location in Iran.	BWM	Iran	Ref. (Siamak et al., 2020)
5G communication base station	The literature takes the electromagnetic radiation of 5G base stations as the main influencing factor of location selection for simulation evaluation and measurement analysis.	Modeling research	Sudan	Ref. (Elbasheir et al., 2021)
Substation	According to the literature, the design and location of substation should meet these criteria: reliability, safety, interoperability, reconfigurability, controllability, maintainability, flexibility, cost reduction and environmental impact reduction.	Theoretical research	United States	Ref. (Kezunovic et al., 2010)
	The literature defines power load growth as a key factor in the capacity and siting of new substations, and considers environmental factors, soil characteristics, geo-climatic risks, social factors and site management standards as important factors affecting the final location.	GIS-MCDA	Brazil	Ref. (Zambrano-Asanza et al., 2021)
Charging station	The factors and evaluation criteria for selecting the best site of charging station are analyzed, and the evaluation indexes are divided into traffic feasibility index, user proximity index and technical index.	GIS; AHP	Iran	Ref. (Mohammad et al., 2022)
	The literature considers 12 influencing factors such as energy distribution, economic cost, transportation portability, population density and environmental pollution to develop the suitability analysis of EV charging stations.	Fuzzy TOPSIS	Brazil	Ref. (Wilson et al., 2024)
	The literature optimizes the location and distribution of charging stations and charging piles by considering various factors such as transportation convenience, human flow, site location, employment and the number of electric vehicles around.	AHP	Republic of Korea	Ref. (Choi et al., 2024)
Photovoltaic power station	The literature points out that the factors that need to be considered in the planning stage of photovoltaic power stations are: geographical location, light intensity, regional area, surrounding infrastructure, and soil type.	Theoretical research	Poland	Ref. (Krystyna et al., 2022)
	The paper calculated and scored the weights of factors such as solar irradiance, average temperature, land slope, proximity (including roads, power grids, residential areas) and economy, and verified the feasibility of the research method based on numerical examples.	AHP	Canada	Ref. (Hassan et al., 2017)
Energy storage power station	There are four main indicators in the literature, each containing several secondary indicators, including wind farm area, power production and storage capacity, and reservoir area and its geographical location.	Fuzzy-ANP、Fuzzy-VIKOR	Iran	Ref. (Sayyed et al., 2020)
	The literature mainly considers the impact of environmental factors on the construction of functional stations, including land slope, water resources, traffic, transmission and distribution lines, wind resources, annual precipitation, photovoltaic output, etc.	GIS; AHP	Austrlia	Ref. (Ali et al., 2023)

regulation and multi-energy conversion, and interconnects with terminal energy supply networks to build a greener and more efficient energy system. With advanced information networks as the link, digital information technologies such as digital twins, 5G mobile communication, and supercomputing are used to intelligently empower traditional energy systems and achieve accurate allocation and efficient utilization of energy. In the long run, multi-station integration will deeply integrate into and penetrate the pillar industries of the national economy such as energy and information communication, promote the intensive construction of edge computing nodes, and realize the lean utilization of power stations and communication resources, which can effectively promote the development of digital products and service markets such as 5G commercial use and intelligent manufacturing, and help China's industrial upgrading and economic development (Zhang and Wen, 2017). Tian et al. (2017) and Lu (2018) studied the edge computing technology and edge computing platform of 5G network, and expounded the application of edge computing nodes for 5G network in delay-sensitive services and large-bandwidth service scenarios.

In terms of functions, multi-station integration has a strong resource allocation ability, and realizes the vertical flexible interaction between the supply side and the demand side of power through intelligent scheduling. Through the innovative application of integrated energy services of electricity, gas, heat and cold, the horizontal dynamic complementarity and optimal allocation between different energy categories are realized. On this basis, many places actively explore the deep integration of key infrastructure such as data centers and substations, as an important support point for the construction of smart cities. Chen Y. et al. (2023) proposed to combine modular data centers and photovoltaics and apply them in engineering practice, and to build a technical theoretical framework for digital circular agriculture by enriching the agricultural scene case base. Yin (2023) and Tian (2021) analyzed the special data types and operation safety requirements of the steel and metallurgical industries, and proposed to combine the data center with 5G base stations or energy storage stations in this scenario to promote the deep integration of digital technology and the steel industry. Li (2023) introduced various new energy storage technologies applied in the current urban rail transit industry, combined with the characteristics of industrial power load, and realized the consumption of renewable energy and the charging of new energy vehicles through the data transmission and distribution of data centers and the integration of photovoltaic and charging stations. He and Feng, (2021) proposed five typical scenario design schemes for different areas of the city, and the scheme of building underground substations in urban land shortage areas is an effective solution to the current land shortage problem.

4.1.2 Load demand

According to the analysis of the construction location of "multi-station integration", the current load demand can be divided into the following three types according to the regional area (Zhou et al., 2023):

(1) Central City fusion Station

Most substations with voltage levels of 110 kV and below are densely populated and occupy a small area in central urban areas (Dong et al., 2020). In this scenario, energy consumption density is high, energy consumption behavior is relatively regular, and load demand is concentrated, with obvious peak and valley characteristics. At present, the typical fusion method is "substation + small energy storage power station + small data center", "substation + small data center" and so on.

(2) Small industrial park fusion station

In this scenario, the goal should be to maximize the utilization and supply of energy in the park, meet the demand for energy conservation and consumption reduction while ensuring the power quality of equipment, and carry out the optimization plan and construction of energy utilization in the park and local areas. At present, the typical integration methods are "substation + energy storage power station", "substation + renewable energy (photovoltaic power generation/wind power generation)" and so on.

(3) Regional centralized smart energy station

As an innovative energy management and service system, it can be used to build a regional energy regulation and information service center, which has higher requirements for data storage, communication services and car charging. Through the use of advanced technologies such as energy storage, it actively participates in the peak regulation and optimal operation of the power grid, so as to achieve the optimal regulation of energy in the region and ensure the safe and stable operation of the power grid. At present, the typical integration methods are "substation + energy storage power station + data center station + electric vehicle charging station +5G network base station", "substation + data center station + energy storage power station" and so on. In addition, in order to improve the absorption capacity of renewable energy, large-scale substations are connected in the construction process of photovoltaic power stations and wind power stations, and energy storage power stations are built to improve the carrying capacity. At present, the typical integration mode is "renewable energy (photovoltaic power generation/wind power generation) + substation + energy storage power station".

4.1.3 Construction mode and function analysis

(1) Integration of the two stations

The combination of substation and energy storage station is one of the most typical construction modes in the integration of the two stations. The substation mainly provides power to the energy storage station, while the energy storage station plays an important role in this scenario, which not only contributes to the peak and frequency regulation of the power system but also provides emergency support for the power grid, and also promotes the absorption capacity of renewable energy to a certain extent. It improves the efficiency of new energy power generation, and finally achieves multiple advantages of coordination and complementarity of functional requirements, improvement of economic benefits and reduction of energy consumption (Wang D. et al., 2019; Wang, 2019).

In terms of peak regulation and frequency regulation of the power system (Chen et al., 2022; Wang Y. et al., 2022; Li D. et al., 2021), due to its fast response characteristics and load regulation ability, the energy storage system can store electric energy in the off-peak period and release it in the peak period, so as to achieve a series of functions such as power generation and electrolytic coupling, peak cutting and valley filling, load control and transfer. For the power grid, under the premise of ensuring the smooth and stable voltage, the operation efficiency of the system can be improved and the loss of the transmission and distribution network of the system can be reduced.

In terms of power grid emergency support (Wang X. et al., 2022; Quan et al., 2022), energy storage power stations can quickly absorb and supplement electric energy to provide active power support and realize active or reactive power compensation. Therefore, when the power grid produces voltage fluctuations, it can play an emergency support role, which is conducive to reducing the line loss and improving the system power factor.

In terms of renewable energy consumption (Olabi, 2017; Paul and Mai, 2019), the energy storage station can store excess electricity when the scenery resources are sufficient, and output it when the

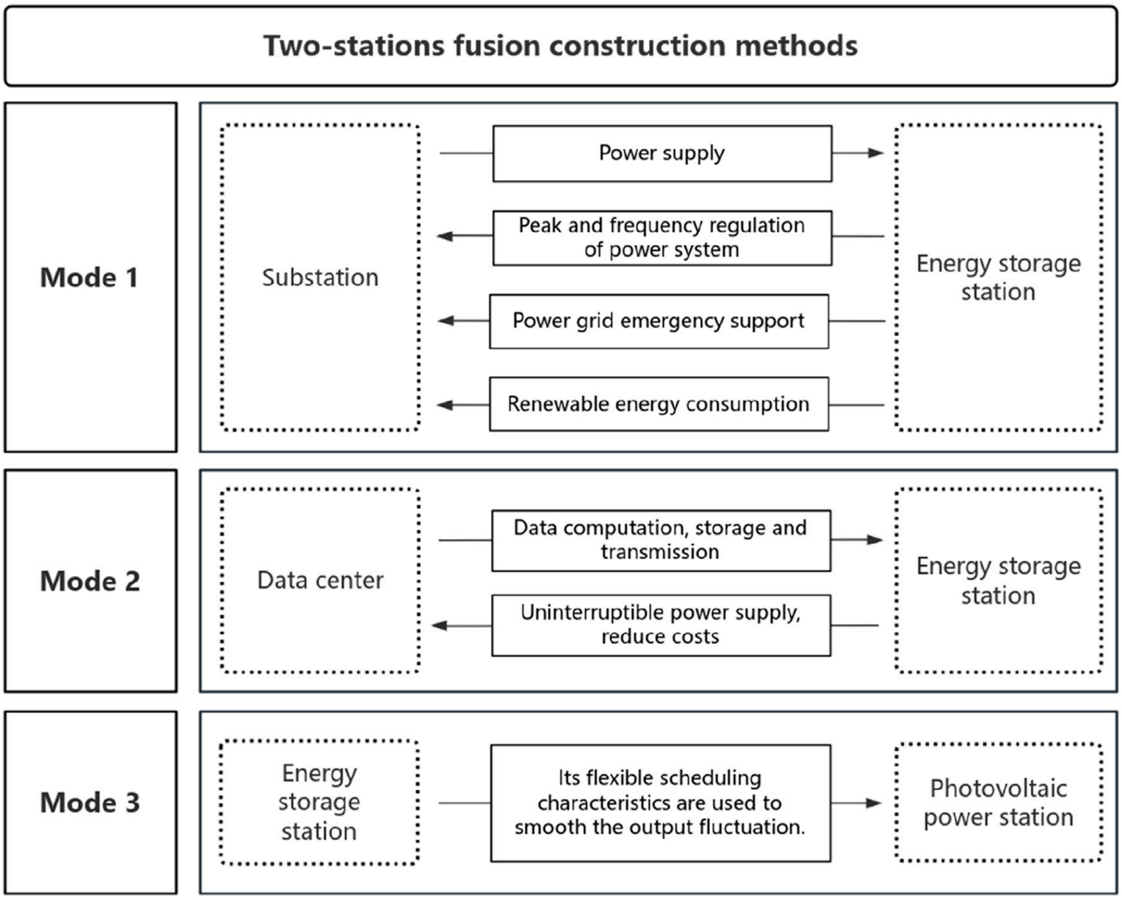

FIGURE 1
The fusion construction mode of the two stations.

resources are insufficient, effectively alleviate the phenomenon of wind and light abandonment, and improve the consumption and utilization efficiency of clean energy.

In terms of economic benefits (Chacra et al., 2005; Leng et al., 2022), the combination of substation and energy storage station gives full play to the huge advantages of energy storage station in the power system. By balancing the power load and reducing the peak-valley difference, the problem of peak power consumption in some areas is solved, and the configuration requirements of multi-energy complementarities are enriched. In order to ensure the efficient and safe operation of the power grid, the high capacity cost and power saving cost caused by the peak load are reduced.

In addition to "substation + energy storage power station", there are many different fusion modes of two stations to meet the diversified functional needs of the power system, among which the integration with energy storage power station is the most common, such as: 1) data center and energy storage station integration; 2) Fusion of energy storage station and photovoltaic power station, as shown in Figure 1 (Ma et al., 2021; Qi et al., 2019).

(2) Three-station integration

Compared with the integration of two functional stations, the three-station integration has more possibilities and can also meet more scene and functional requirements. A typical construction mode of three-station integration is to integrate the data center on the basis of "substation + energy storage power station" (Zou et al., 2023). In this fusion scenario, information technology is used to closely combine information flow, energy flow and business flow to achieve "three-flow integration", and the co-construction and sharing of energy and data are promoted through interconnection, bringing a new profit model of leasing service to power grid enterprises. To achieve the optimization of overall efficiency.

In addition to the existing advantages and functions after the integration of the two stations, the model on the one hand is to use the advantages of the substation close to the user, extensive coverage, power security, etc., to meet the user's power, computing power, storage, connection and other aspects of service needs, and provide IT infrastructure resources for the digitalization, intelligence, and precision of the power grid. On the other hand, the data center uses the energy storage station as a backup power supply, thereby reducing the hidden danger of large-scale power interruption in the data center and improving the reliability of its operation. In addition, the electricity bill of the data center accounts for half of the total operating cost and the energy consumption is very high. This fusion method can use the peak-valley electricity price policy to transfer the power consumption of the data center during the peak period to the trough period to improve its economic efficiency.

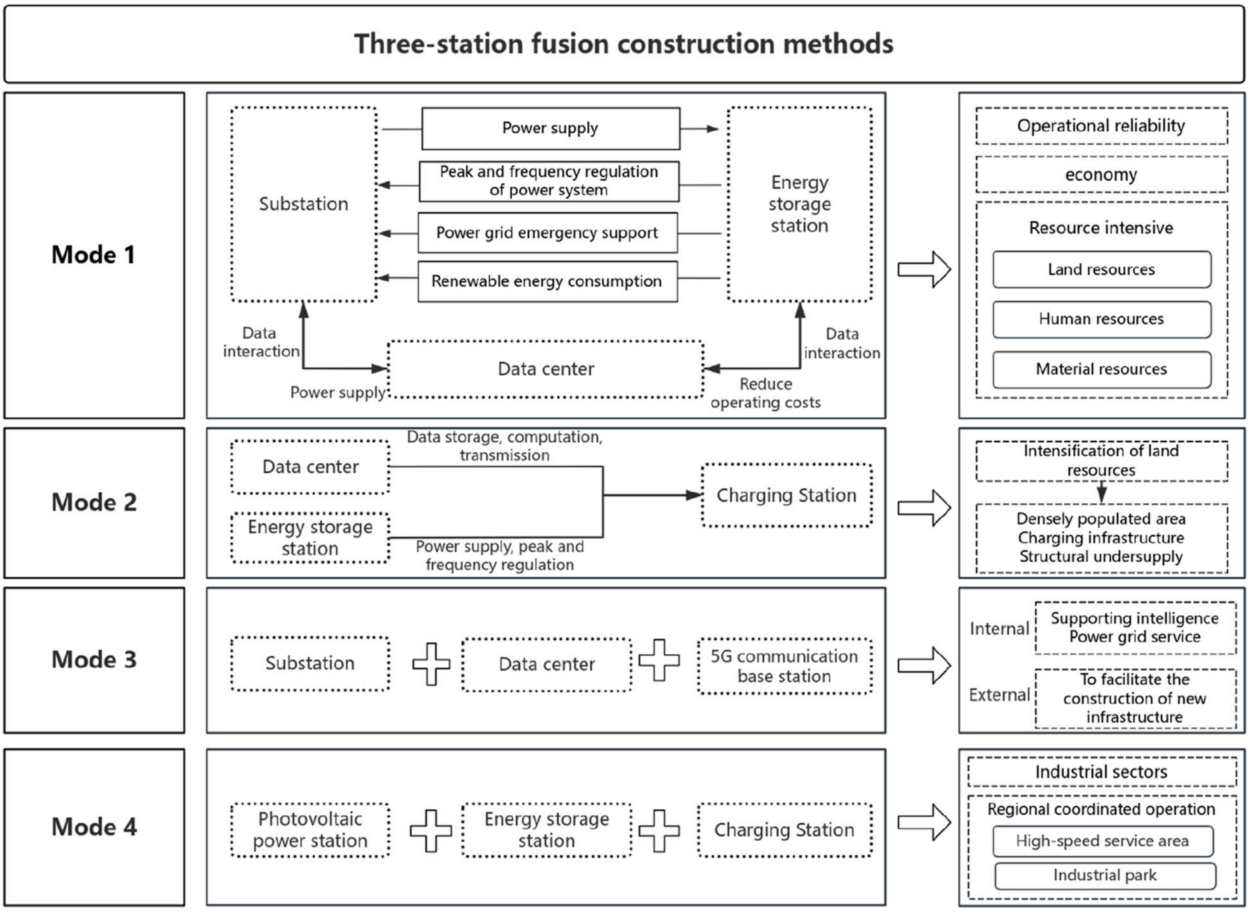

FIGURE 2
The fusion construction mode of the three stations.

The core value of this integration mode is to save social resources. In view of the shortage of urban land resources caused by the surge of data storage and computing demand in the future, the "three-station in one" strategy not only fully excavates the land resource value of substations, effectively solves the site problems such as the digital nodes of the power grid, but also can solve the problems through unified layout, planning, operation and maintenance. Significant savings in manpower, material resources and operating costs (Li Y. et al., 2021).

In addition to the typical construction mode of "substation + energy storage power station + data center", a variety of construction modes have been applied in practice, as shown in Figure 2 (Shan et al., 2020; Jiang and Yang, 2018).

(3) Multi-station integration

According to different scenarios and functional requirements, the fusion mode between function stations is becoming more and more diversified, and multiple function stations are integrated to achieve "three-stream integration", which covers the integration and optimization of energy flow, business flow and data flow (Jiang and Yang, 2018; Qian et al., 2022; Li et al., 2023; Zhou et al., 2023) to meet the multiple functions and business needs of power grid, society and enterprises (energy and industrial fields) (Yang et al., 2020). First of all, the fusion method simplifies the collection process of power grid companies in energy regulation, power transformation and electricity consumption data, and realizes the intelligent regulation of energy supply and demand with the help of edge computing for data analysis, providing strong support for comprehensive energy services, power inspection, distribution Internet of things and other businesses. Secondly, the integration can simultaneously meet the various needs of users at all levels of society, including electric vehicle charging, resource sharing, and base station communication services; Finally, it can be applied to the energy consumption analysis of enterprise production and environmental protection governance, provide energy consumption optimization schemes, and provide advisory services for government decision-making.

In terms of energy flow, through the physical and logical integration of substation, energy storage, photovoltaic, charging station and other facilities, traditional substation nodes have been reshaped into an energy hub with the characteristics of source, network, load and storage, to achieve the two-way orderly flow of energy, coordinate the flow direction of the whole network, implement power flow control, and achieve a dynamic balance between supply and demand between power generation and users, thereby supporting the safe operation of regional power grids. In terms of information flow, the construction of green

TABLE 4 Function analysis in multi-station fusion scenario.

Function station	Solvable problems
Data Center	The data center provides data storage, calculation and transmission services for substations, energy storage stations and electric vehicle charging stations, transforming and upgrading traditional functional stations to smart microgrids and regional integrated energy systems.
Charging Station	In terms of economy, the energy storage station provides UPS service for the data center/5G communication base station/charging station to improve the reliability of power supply, and the remaining capacity reduces the operating cost based on the peak valley electricity price difference to reduce the electricity cost of the data center/5G communication base station, and at the same time, the shallow charging and shallow discharge of the battery can be realized in this scenario, so as to extend the battery life. In terms of technology, energy storage stations contribute to the peak regulation and frequency regulation of the power system and also provide emergency support for the grid and promote the absorption capacity of renewable energy.
Energy storage power station	It can provide charging service, and as an adjustable power load, can achieve peak cutting and valley filling; as a distributed power supply, it supports the efficient operation of the power grid.
Photovoltaic power station	Combined with the energy storage power station, the distributed optical storage system is formed to ensure the stability of the power supply of the data center and the electric vehicle charging station.
5G communication base station	Using 5G base stations to remotely control data in substations and realize unmanned management can save a lot of manpower and material resources for inspection.

data centers provides the necessary infrastructure for the coordination of the energy Internet, and realizes the information interconnection of the whole network of generation, transformation, distribution and use. Using the ultra-low delay and ultra-high reliability of 5G technology, it can quickly locate, isolate and restore grid line faults, significantly shorten the power outage time to the second or even millisecond level, and give rise to new applications such as substation operation monitoring, grid situation awareness, and 5G base station peak filling power supply. In terms of business flow, through the interconnection of multi-energy flow, the sharing of big data and the application of blockchain technology, it carries out a number of businesses such as the coordination of cold, hot and power system of regional energy stations, the operation of charging and replacing power, and the management and control of energy use in the station, so as to realize the penetration and integration of operation, regulation, distribution, use and other functions, and then build an integrated operation mode of comprehensive energy (Yang et al., 2020; Wang Bi et al., 2019; Huang et al., 2020).

Based on the functional positioning analysis of the multi-station fusion scenario, Table 4 analyzes the functions and advantages of each station after fusion from two aspects of economy and energy-saving technology. It can be seen from the table that data center and energy storage station play a key role as an important functional station of multi-station fusion.

In addition to the “three-stream integration”, multi-station integration has also shown great advantages in terms of economic benefits and energy conservation and environmental protection (Zhao et al., 2015; Zhang et al., 2019; Xie et al., 2021).

In terms of economic benefits, the first is to save costs, that is, the land resources, labor costs, capital costs and electricity costs saved by the construction of multiple stations compared with the construction of a single station. In the initial stage of operation, the main characteristics of the areas that can carry out the multi-station integration pilot are low investment cost, quick effect, and mature municipal conditions, and most of them give priority to the construction of new infrastructure such as modular data centers, charging stations, energy storage stations and 5G communication base stations based on the renovation or transformation needs of original substations. Provide diversified and intensive construction services for government, power grid and various enterprise users. After the overall integration enters a mature stage, the multi-station integration strategy will be comprehensively promoted and applied regionally. Based on the powerful functions of data centers and 5G base stations, data value-added services satisfying various businesses will be provided to different users to support the construction and application of smart cities, industrial Internet and smart microgrids (Xie et al., 2021; Wang Bi et al., 2019).

In terms of energy conservation and environmental protection, multi-station integration helps to solve the problem of sustainable development of clean energy, alleviate wind and light abandonment, reduce energy consumption, and reduce carbon emissions. It is mainly reflected in three aspects: First, make full use of data analysis, edge computing, 5G and other advanced technologies, through data sharing, resource sharing and other services, improve the accuracy of power generation and power consumption forecast, develop flexible scheduling plans for substations, and promote the consumption of renewable energy; Second, as the transmission of energy from a one-way side to a two-way, multi-station integration needs to collect data has also increased dramatically, and data centers, 5G base stations and other functional stations can serve the power grid’s own energy distribution and control, but also as the infrastructure of the digital economy to achieve data services in other industries, so as to improve the utilization rate of equipment, to achieve synergies of multiple functional stations. Third, based on the step utilization of energy, the data center and 5G base station are regarded as functional stations with dual identities of energy production and consumption, and the heat pump technology is applied to recover a large number of low-grade heat source waste heat in the data center, which is used for heating and domestic hot water of the surrounding buildings, so as to reduce the heat dissipation of the data center while saving the heating cost of the building.

4.2 Current research methods of regional multi-station integration spatial layout planning

From the above, the layout selection of “multi-station integration” should not only consider the needs and objectives of

TABLE 5 Common factors and characteristic factors affecting regional multi-station integration.

	Primary index	Secondary index (constraint)
Common factor	Distance of load center	Distance from the user, transmission and distribution lines, power loss, etc
	Situation of land parcels	Land use status, land use planning, etc
	Situation of businesses	Number of users, service volume, etc
	Municipal conditions	Grid capacity, power supply status (distribution system, power quality), etc
	Environmental protection	Water resources pollution, noise pollution and other impacts on the surrounding users
	External environment	Spatial location, geographical conditions, etc
	The economic costs	Construction cost, operating cost, power supply cost, etc
Characteristic factor	Facility Resources (Data Center)	Reliable power supply and efficient communication node
	Solar resources (photovoltaic power Station)	Total solar radiation, illumination time
	Communication resources (5G base station)	Signal interference, signal coverage

a single functional station, but should investigate the layout planning and site selection from an overall perspective, take into account the constraints of the influencing factors of each station in the multi-station, and select the construction mode and layout scheme according to different application scenarios to meet the diversified functional and load requirements in the region. Therefore, it is necessary to fully and comprehensively consider before construction to form a perfect spatial layout planning method.

At present, the research methods of regional multi-station integration spatial layout planning mainly focus on two aspects: on the one hand, quantitative evaluation is carried out based on comprehensive evaluation methods based on influencing factors (Xincong et al., 2020; Mingze and Xincong, 2020; Sun et al., 2021); on the other hand, research is carried out based on different optimization objectives (Yang et al., 2021; Miao et al., 2023; Chen et al., 2021), so as to provide theoretical suggestions and technical support for the site selection and spatial layout of multi-station integration.

4.2.1 Comprehensive evaluation methods based on influencing factors

By analyzing the research status of the spatial layout location method of each single function station summarized above, and combining with the existing research, it can be concluded that there are many common factors (Lu et al., 2023; Zhang C. et al., 2020) that have a great impact on the spatial layout and planning site selection. At the same time, there are also some influencing factors of the characteristics of single-function stations in multi-stations (Zhang XL. et al., 2022)' which also need to be taken into consideration, so as to make the layout planning method more referential and universal. The summarized influencing factors are shown in Table 5. Based on the coordination mechanism between functional stations in energy supply, information exchange, equipment operation, etc., power supply reliability, grid capacity, and economic cost are common factors in the layout of most functional stations, while user density and business volume mainly affect the operating efficiency of data centers, 5G base stations, and charging stations, and indirectly affect the load fluctuation of fusion stations. In addition, in terms of characteristic factors, the ambient temperature greatly affects the indoor temperature, cooling efficiency and the use time of air conditioning equipment in the data center, which directly affects the electricity consumption of the data center. The intensity of solar radiation and the total duration of light will affect the power generation efficiency of distributed photovoltaic equipment. Reliable communication nodes and anti-signal interference capabilities mainly affect the use experience of surrounding enterprises and residents, as well as the operating efficiency of the function station itself.

As for the comprehensive evaluation of spatial layout and site selection planning of functional stations in the region, Zhang XL. et al. (2022) comprehensively considered the influencing factors of site selection evaluation of each single station, and proposed a comprehensive evaluation method combining analytic hierarchy process (AHP) and fuzzy comprehensive evaluation, involving the calculation of index weights and the scoring of alternative stations. Hu et al. (2022) and Zhang et al. (2021) used analytic hierarchy process (AHP) in index weights and comprehensive scoring. Zhu et al. (2022) combined analytic hierarchy process (AHP) and risk entropy weight method to calculate the weights of subjective and objective factors respectively, and then obtained the comprehensive evaluation results. Based on the analytic hierarchy process, Gao (2019) used the fuzzy comprehensive evaluation method to build a location selection model, which improved the accuracy and persuasiveness of location selection. These applications all reflect the important application of analytic hierarchy process in the evaluation of multi-station fusion location.

Combined with the research methods of single-function station location planning, it can be seen that the main evaluation methods used by scholars in the current research in this area include: Analytic hierarchy Process (AHP), which divides the evaluation problems into several levels, compares the importance degree and determines the weight and results in turn; The characteristic of fuzzy evaluation method is that it can deal with and evaluate the data whose information contains fuzziness. The evaluation results obtained by this method are rich in information and can be used to evaluate the evaluation objects scientifically, reasonably and practically.

TABLE 6 Summary of comprehensive evaluation methods.

Research methods/models		Advantages/ disadvantages	Scope of application	Applicability analysis	
				Load demand	Construction pattern
Subjective evaluation method	Analytic Hierarchy Process (AHP)	Advantages: wide applicability, strong consideration, high flexibility Disadvantages: strong subjectivity, complex calculation	It is suitable for multi-criteria and multi-objective decision problems, and can be used in decision analysis of multi-fields and multi-industries	It is suitable for small and medium-sized load scenarios in central urban areas and parks	In view of the strong consideration of the method, it can be used for the construction of more than 3 stations. However, the fusion building model of 6 stations or more may be computatively too complex.
	Clustering Algorithm	Advantages: strong balance, batch processing data Disadvantages: The number of clusters is difficult to determine and the result is uncertain	It is suitable for data mining, machine learning, pattern recognition, image processing and other fields	It is suitable for the scene of load concentration and obvious fluctuation in the central city	Because the clustering number of the method is difficult to determine and the result is not accurate, it is not recommended for the fusion of too many sites.
	Fuzzy Comprehensive Evaluation (FCE)	Advantages: Dealing with uncertainty, comprehensive consideration, intuitive results Disadvantages: strong subjectivity, complex calculation, uncertain evaluation criteria	It is suitable for the evaluation and decision-making of some fields which are difficult to be measured by precise values and various non-deterministic problems	It is suitable for small and medium-sized load scenarios in central urban areas and parks	Because the method can fully consider the factors affecting the collaboration of multifunctional stations, it can be used in the construction mode of three or more stations. However, due to strong subjectivity and lack of evaluation criteria, its layout scheme may not be suitable for practical application.
Objective evaluation method	Entropy weight method	Advantages: objectivity, easy to operate Disadvantages: lack of consideration of the actual meaning of indicators, weight volatility	It is suitable for comprehensive evaluation of multiple indicators in scenarios that require decision analysis based on data characteristics	It is suitable for medium and high load scenarios in parks and regional large energy stations	Because the method is objective and easy to operate, it can be applied to the construction mode of 3 stations or more. However, due to the lack of consideration of the practical significance of the index and the large fluctuation of the weight, the layout should be combined with the subjective evaluation method.
	CRITIC Evaluation method	Advantages: Comprehensive consideration, reliable results Disadvantages: complex calculation and high data quality requirements	It is suitable for comprehensive evaluation of complex system and large area data	It is suitable for medium and high load scenarios in parks and regional large energy stations	Considering that this method can fully consider the influencing factors of multifunctional station collaboration, it can be used in the construction mode of 3 or more stations. However, the fusion building model of 6 stations or more may be computatively too complex.

To sum up, the main evaluation methods in most studies are subjective evaluation methods, and appropriate objective evaluation methods should be added, such as entropy weight method and CRITIC evaluation method, so as to verify the land intensification degree and economy of multi-station integration through the combination of subjective evaluation indicators and objective evaluation indicators. However, the comprehensive evaluation method has advantages, disadvantages and scope of application, as shown in Table 6. In the following research, the combination of subjective evaluation method and objective evaluation method should be considered, so as to evaluate different construction modes while meeting the load demand, and obtain the most suitable multi-station integrated spatial layout planning scheme for construction requirements.

4.2.2 Multi-objective collaborative optimization

In terms of spatial layout and location planning of regional multi-station fusion involving multi-objective optimization Zhang et al. (2023), Liang (2021) proposed a method of optimal configuration and fault current characteristics analysis for the distribution network with joint access of optical storage, and used the PSO algorithm to optimize the double objective function, and the simulation results proved the effectiveness of the method. Xu et al. (2022) put forward a number of optimization suggestions based on the characteristics of conventional power distribution schemes for data centers at different levels, and discussed the feasibility of using flywheel energy storage instead of backup batteries, finally forming an optimized power distribution scheme for data centers in multi-station fusion scenarios. Chen X. et al. (2023) comprehensively considered multiple factors such as power supply reliability of data centers, charge and discharge power limitation of energy storage systems and loss cost in the process, aiming to build an optimized operation model, which aims to minimize comprehensive operation cost and optimize the effect of peak cutting and valley filling. In contrast, Zhang Z. et al. (2022) conducted an in-depth analysis of different energy supply structures and construction modes of multi-station fusion data centers based on carbon emission and investment return as evaluation indicators. Lu et al. (2021) realized data migration in the data center with the goal of minimizing the comprehensive cost and data processing delay constraints, and reduced the configured capacity of the energy storage power station on the premise of meeting the load demand of the data center, so as to save the electricity cost and the construction cost of the power grid. Pan et al. (2023) and Zhang X. et al. (2022) built a multi-station fusion optimization scheduling model with cost as the objective function and multiple constraints to realize the full absorption of capacity PV in the fusion station and the transfer of high-load period to low-price period respectively.

It can be seen that experts and scholars have respectively optimized the economic cost, configuration capacity, transmission and distribution scheme, power supply reliability, load scheduling and other aspects, providing theoretical basis and technical support for the construction, operation and layout planning of regional multi-station integration, so as to better play the role of each functional station and help regional development.

5 Conclusion and prospect

By analyzing the research status of application scenario, load demand, construction mode, influencing factors and other aspects, the main conclusions of the existing research are as follows:

(1) In terms of influencing factors, at this stage, there are still deficiencies in the selection of influencing factors for multi-station integration in the region. Only common influencing factors are considered, while the characteristic factors of some functional stations are ignored. In addition, the spatial layout planning of multi-station integration should be carried out based on the actual land use situation and the construction standards of different functional stations, so that the planning method has more practical application value under the premise of providing theoretical basis. In terms of evaluation methods, analytic hierarchy Process (AHP) and fuzzy evaluation are both subjective evaluation methods, and appropriate objective evaluation methods should be added, so as to verify the land intensive degree and economy of multi-station integration through objective evaluation indicators. In terms of multi-objective collaborative optimization, most of the existing researches have optimized the system operation based on economic cost, capacity allocation, transmission and distribution scheme, and power supply reliability, while the optimization of multi-station fusion load scheduling based on economy and functionality is still lacking. Subsequent research in this direction will provide theoretical basis and technical support for the construction, operation and layout planning of regional multi-station integration, so as to better play the role of each functional station and help regional development.

(2) Aiming at the shortcomings of existing studies, in order to summarize a more perfect and universal spatial layout planning method, a three-layer theoretical framework is proposed to improve and supplement the existing layout principles and methods: The first layer is to realize the intensification of resources, mainly including land resources, human resources, energy consumption, etc., which has been deeply studied by many researchers. The second layer is the cascade utilization of energy in the fusion station, including the optimization of power, cold and heat load scheduling and waste heat utilization in the data center. The third layer is the value and function of multi-station integrated spatial layout planning, such as: New energy consumption, electric energy complementary and mutual benefit, economic efficiency improvement, help the construction of new infrastructure, etc. It is hoped that the architecture can provide reference suggestions for the future regional multi-station integration spatial layout planning method research, so as to realize the integration of new infrastructure and traditional infrastructure construction, and promote the industrial layout and booming development of new power system.

Author contributions

HZ: Writing–original draft. LZ: Writing–review and editing. YY: Writing–review and editing. QL: Writing–review and editing. FQ: Writing–review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was supported and funded by Shanghai Science and Technology Commission research project (No.22DZ1206900).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Ali, S., Stewart, R. A., Sahin, Oz, and Vieira, A. S. (2023). Integrated GIS-AHP-based approach for off-river pumped hydro energy storage site selection. *Appl. Energy* 337, 120914. ISSN 0306-2619. doi:10.1016/j.apenergy.2023.120914

Baojun, W. (2011). Research on substation spatial layout planning based on GIS spatial analysis: a case study of Beijing. *Eng. Plan.* (06), 121–126.

Cai, X. (2021). *Analysis of influencing factors and location selection of medium and large data centers*. Shanghai University of Finance and Economics. doi:10.27296/d.cnki.gshcu.2021.001113

Cao, X., Che, Y., Si, Z., Kai, S., Zhou, Z., Yuan, T., et al. (2022). Yuan Tiejiang. Integrated capacity-location planning for wide-area energy storage power Station. *Power China* 55 (7), 110–120.

Cao, Y. (2023). Location analysis of disaster recovery data center in existing buildings. *Ind. Build.* 53 (201), 803–805.

Chacra, F. A., Bastard, P., and Fleury, G. (2005). Impact of energy storage costs on economical performance in a distribution substation. *Trans. Power Syst.* 02 (20), 684–691. doi:10.1109/TPWRS.2005.846091

Che, Y., Xia, X., Song, X., Yu, Z., and Guan, H. (2018). Research on site selection of Energy storage System engineering based on Analytic Hierarchy Process and comprehensive evaluation method. *Electr. Appliances Energy Effic. Manag. Technol.* (11), 52–55. doi:10.16628/j.cnki.2095-8188.2018.11.008

Chen, Z., Yin, Y., Lin, X., and Yang, S. (2021). Research on the method of multi-station integrated data center module location based on fuzzy analytic hierarchy process. *J. Phys. Conf. Ser.* 03, 1871. doi:10.1088/1742-6596/1871/1/012057

Chen, C., Li, X., Zhang, B., and Yang, T. (2022). Collaborative control strategy of energy storage for peak and frequency modulation based on multi-time scale. *Power Syst. Prot. Control* 50 (5), 94–105. doi:10.19783/j.cnki.pspc.210857

Chen, Y., Li, Y., Li, C. J., and Li, Q. (2023a). Research on digital circular agriculture based on green data centers: theory, architecture and prospect. *Ecol. Econ.* 39 (2), 108–116.

Chen, X., Wang, Y., and Xue, H. (2023b). Optimal operation method of Data center energy storage system based on MDP-ADMM. *Energy Storage Sci. Technol.* 12 (6), 1890–1900. doi:10.19799/j.cnki.2095-4239.2023.0018

Choi, M., Van Fan, Y., Lee, D., Kim, S., and Lee, S. (2024). Location and capacity optimization of EV charging stations using genetic algorithms and fuzzy analytic hierarchy process. *Clean Technol. Environ. Policy*. doi:10.1007/s10098-024-02986-w

Covas, M. T., Silva, C. A., and Dias, L. C. (2013). Multicriteria decision analysis for sustainable data centers location. *Int. Trans. Operational Res.* 20, 269–299. doi:10.1111/j.1475-3995.2012.00874.x

Ding, M., Fang, H., Bi, R., Liu, X., Pan, J., Zhang, J., et al. (2019). Capacity planning of distributed photovoltaic and energy storage location in distribution network based on cluster division. *Proc. CSEE* 39 (8), 2187–2201. doi:10.13334/j.0258-8013.pcsee.180757

Dong, M., Qian, X., Yin, Y., and Chen, Y. (2020). Application Scenarios of "multi-station integration" to facilitate new digital infrastructure. *Rural. electrification* 11, 5–7. doi:10.13882/j.cnki.ncdqh.2020.11.001

Elbasheir, M. S., Saeed, R. A., and Edam, S. (2021). "5G base station deployment review for RF radiation," in *2021 international symposium on Networks,Computers and communications (ISNCC)* (Dubai.United Arab Emirates), 1–5. doi:10.1109/ISNCC52172.2021.9615689

Fu, D., Guo, Z., Zhu, Yu X., and Tan, X. (2017). Research on location Optimization of urban new energy vehicle charging pile. *Industry and Technol. Forum* 16 (11), 69–70.

Gao, X., and Zhang, P. (2006). Main features and key technologies of digital substation. *Power Syst. Technol.* 30 (23), 67–71.

Gao, Z. (2019). *Research on substation location selection based on Fuzzy Comprehensive evaluation*. Shandong University of Science and Technology.

Hassan, Z., Al, G., and Anjali, A. (2017). Solar PV power plant site selection using a GIS-AHP based approach with application in Saudi Arabia. *Appl. Energy* 206, 1225–1240. ISSN 0306-2619. doi:10.1016/j.apenergy.2017.10.024

He, X., and Feng, X. (2021). "State Grid Hebei Electric Power Co.LTD. Construction department," in *Typical scenario design of urban Substation Multi-station integration* (Beijing: Scientific and Technical Literature Press).

Hu, Q., Zhou, Q., Chen, Q., Shen, B., and Xiang, J. (2022). Multi-station fusion location evaluation method based on Analytic Hierarchy Process. *Electrotech. Eng.* (5), 89–95. doi:10.19768/j.cnki.dgjs.2022.05.023

Hu, W. (2021). The salary increase of scientific and technological talents in the new infrastructure boom is as high as 50. *China Foreign Trade* (5), 72–74.

Huang, Y., Zhang, C., and Liu, T. (2020). Research on the "three-station in one" mode of ubiquitous Power Internet of Things. *Internet Things Technol.* 10 (1), 44–47. doi:10.16667/j.issn.2095-1302.2020.01.012

Huang, Z., Lin, B., Lu, Y., Liu, D., and Wang, M. (2024). Capacity determination method for charging station location for multi-objective optimization. *J. Fujian Normal Univ. Nat. Sci. Ed.* 40 (2), 23–35.

Jia, L. U. (2020). Design of distributed photovoltaic power generation control system. *Appl. Automation* (10), 100–101,104. doi:10.19769/j.zdhy.2020.10.035

Jiang, D., and Yang, Z. (2018). Analysis on practice and application prospect of optical storage and charging Station in Xuguantun Service Area. *China Energy* 40 (5).

Kezunovic, M., Guan, Y., Guo, C., and Ghavami, M. (2010). "The 21st century substation design: vision of the future," in *2010 IREP symposium bulk power system dynamics and control - VIII (irep)* (Brazil: Rio de Janeiro), 1–8. doi:10.1109/IREP.2010.5563267

Khalkhali, K., Abapour, S., Moghaddas-Tafreshi, S. M., and Abapour, M. (2015). Application of data envelopment analysis theorem in plug-in hybrid electric vehicle charging station planning. *Gener. Transmission and Distribution Iet* 9 (7), 666–676. doi:10.1049/iet-gtd.2014.0554

Krystyna, K., Hubert, K., and Stanisław, B. (2022). Location and technical requirements for photovoltaic power stations in Poland. *Energies* 15 (7), 2701. doi:10.3390/en15072701

Lei, M., Wei, G., and Zhao, Q. (2023). Research on macroscopic location scheme of large-scale photovoltaic power station based on GIS technology. *Sol. Energy* (1), 43–48. doi:10.19911/j.1003-0417.tyn20221010.01

Leng, Z., Zhao, J., Gong, C., Zhang, Z., and Lu, W. (2022). Research on operation optimization strategy of agricultural grid station area for source-grid-load storage and charging. *Electromechanical Inf.* (24), 11–14.

Leou, R. (2008). "An economic analysis model for the energy storage systems in a deregulated market," in 2008 IEEE International Conference on Sustainable Energy Technologies, 24-27 Nov. 2008 (IEEE), 744–749.

Li, Z., Chen, S., Fu, Y., Dong, C., and Zhang, J. (2017). Optimal allocation of energy storage in active distribution network based on time-series voltage sensitivity. *Proc. CSEE* 37 (16), 4630–4640,4888.

Li, D., Tian, C., Lyu, X., Zhang, H., Wang, F., Han, X., et al. (2021a). Planning of Power grid energy storage system with peak and frequency modulation based on AHP and CRITIC. *J. Power Sources* 19 (2), 136–141. doi:10.13234/j.issn.2095-2805.2021.2.136

Li, Y., Ye, Y., Li, H., Liang, H., Zhang, Q., Wang, Q., et al. (2021b). "Scenarios analysis and energy supply optimization configuration for multi-station integration," in *Asia conference on power and electrical engineering* (ACPEE), 1367–1371. doi:10.1109/acpee51499.2021.9436840

Li, X., Luo, Z., Ding, X., Sun, Z., Lu, X., Tang, P., et al. (2023). Research on distribution scheme of multi-station integrated planning. *Electr. Appliances Energy Effic. Manag. Technol.* (6), 51–57. doi:10.16628/j.cnki.2095-8188.2023.06.008

Li, L., Li, L., Li, L., Li, L., and Li, L. (2017). Application of new technology in mobile communication location. *China New Commun.* (1), 110–111.

Li, J. (2023). Application and prospect of new energy storage technology in urban rail transit industry. *Mech. Electr. Inf.* 22, 86–88.

Liang, C., and Li, X. (2021). Discussion on spatial layout planning of 5G communication base stations in Qingdao. *Planner* (7), 51–55.

Liang, F. (2021). *Study on location and capacity of distributed/centralized optical storage taking into account loss and voltage fluctuation of distribution network*. Nanjing University of Science and Technology.

Liu, L., Zhou, Y., Zhou, W., Jin, Q., Luo, Y., Qiu, Q., et al. (2016a). Research on evaluation system of EV charging station location planning. *Electr. Meas. and Instrum.* 53 (18), 1–5.

Liu, Z., Zhao, Y., and Liu, L. (2016b). Prediction and analysis of large-scale energy storage technology development in China. *China High-Tech Enterp.* (19), 79–80. doi:10.13535/j.cnki.11-4406/n.2016.28.040

Liu, W., Niu, S., and Xu, H. (2017). Optimal planning of battery energy storage considering reliability benefit and operation strategy in active distribution system. *J. Mod. Power Syst. Clean Energy* 5 (2), 177–186. doi:10.1007/s40565-016-0197-4

Liu, Y., Huang, X., and Shi, B. (2020). China's "new infrastructure": concept, current situation and problems. *J. Beijing Univ. Technol. Soc. Sci. Ed.* 20 (6), 1–12.

Liu, Y. (2022). *Research on intelligent site selection and line selection planning management of substation engineering under the digital background*. North China Electric Power University.

Lu, G., Zhang, W., and Liu, M. (2023). *Design of data center of multi-station fusion smart energy station based on convolutional neural network, IoT and industrial informatics (ICMIII)*, 611–615.

Lu, X., Zhang, M., Ji, W., Wang, L., Tao, Y., and Chen, J. (2021). *An optimization method and system for multi-station fusion data center based on data migration*. China Patent: CN113285523A.

Lu, L. (2018). Research on edge computing technology for 5G networks. *Ict Policy* (11), 1–6.

Ma, H., Li, X., and Jia, X. (2021). System configuration and coordinated operation strategy in multi-station fusion scenario. *China Electr. Power Constr.* 42 (1), 96–104.

Miao, A., Yuan, Y., Wu, H., and Zhu, J. (2023). Planning method and coordinated operation strategy for multi-station integration system. *CSEE J. Power Energy Syst.* 09 (6), 2394–2408. doi:10.17775/CSEEJPES.2022.02920

Mingze, Z., and Xincong, L. (2020). "Location evaluation of multi-station integration based on AHP-entropy weight method," in *2020 IEEE sustainable power and energy conference (iSPEC)*, 1887–1892.

Mohammad, H. G., Younes, N., and Rahim, Z. (2022). Optimal site selection and sizing of solar EV charge stations. *J. Energy Storage* 56, 105904. 2352-152X. doi:10.1016/j.est.2022.105904

Olabi, A. G. (2017). Renewable energy and energy storage systems. *Energy* 136 (136), 1–6. doi:10.1016/j.energy.2017.07.054

Oudalov, A., Chartouni, D., and Ohler, C. (2007). Optimizing a battery energy storage system for primary frequency control. *IEEE Trans. Power Syst.* 22 (3), 1259–1266. doi:10.1109/tpwrs.2007.901459

Pan, B., Wang, Y., Lei, X., Wang, X., Che, W., and Wu, X. (2023). *A multi-station fusion optimization scheduling method and system*. China Pat. CN116739261A (09.12).

Paul, D., and Mai, T. (2019). Timescales of energy storage needed for reducing renewable energy curtailment. *Renew. Energy* 130, 388–399. doi:10.1016/j.renene.2018.06.079

Pei, C., and Yan, C. (2022). Logic and suggestions of new infrastructure to promote the realization of "dual carbon" goal. *Price Theory Pract.* (4), 5–8,52. doi:10.19851/j.cnki.cn11-1010/f.2022.04.109

Q/GWD383-2009 (2009). Technical guide for smart substation. *State Grid Coop. China*.

Qi, M., Zhang, Y., and Yu, X. (2019). Operation optimization measures of optical storage power generation system based on energy storage power station scheduling. *China Sci. Technol. Inf.* (24), 80–81.

Qian, K., Miao, A., Zhou, J., He, M., Zhu, J., Yuan, Y., et al. (2022). Research on multi-station fusion scheme and key technologies under the background of "dual carbon". *Electr. Power Supply* 39 (9), 11–17,34. doi:10.19421/j.cnki.1006-6357.2022.09.003

Quan, H., Li, X., Jia, X., Zhnag, Y., Wang, S., Li, B., et al. (2022). Energy storage system model and control strategy for improving the interaction ability of fast charging station and distribution network. *Automation Electr. Power Syst.* 46 (19), 23–30.

Ramos Cáceres, C., Sandberg, M., and Sotoca, A.,Planning data center locations in Swedish municipalities:A comparative case study of Luleå and Stockholm, *Cities*Volume 150,2024,105063,ISSN 0264-2751,doi:10.1016/j.cities.2024.105063

Sayyed, H. R., Younes, N., Sasan, G., Ebrahimi, M., Hosseini, H., Foroozani, A., et al. (2020). Hybrid fuzzy decision making approach for wind-powered pumped storage power plant site selection: a case study. *Sustain. Energy Technol. Assessments* 42, 100838. ISSN 2213-1388. doi:10.1016/j.seta.2020.100838

Shan, D., Liu, X., Xu, L., and Wang, C. (2020). Application research of User Side light storage and Charge integrated intelligent microgrid system. *Electr. Appliances Energy Effic. Manag. Technol.* (2), 41–46. doi:10.16628/j.cnki.2095-8188.2020.02.007

Siamak, K., Mansoor, D. M., Hadis, F., and Rezaei, J. (2020). Sustainable location selection of data centers: developing a multi-criteria set-covering decision-making methodology. *Int. J. Inf. Technol. and Decis. Mak.* 19 (3), 741–773. doi:10.1142/s0219622020500157

Sun, Z., Chen, M., Ai, Q., Jiang, C., Ou, Q., and Wu, Z. (2021). "Multi-station integration scenario planning and economic benefit analysis based on dynamic adjustment of capacity-load ratio," in *2021 IEEE sustainable power and energy conference (iSPEC)*, 1256–1261.

Sun, J., Song, M. X., Qiu, G., and Liu, Z. (2024). Research on location selection and service capability of multi-level Charging Station based on Big Data of electric vehicles. *China J. Highw. Transp.* 37 (4), 48–60. doi:10.19721/j.cnki.1001-7372.2024.04.005

Tan, H., and Zhang, S. (2023). Digital new infrastructure, financial resource allocation and high-quality economic development. *J. Yunnan Minzu Univ. (Philosophy Soc. Sci. Ed.)* 40 (1), 134–142. doi:10.13727/j.cnki.53-1191/c.20221228.003

Tang, S., and Chen, C. (2022). Research on 5G Communication infrastructure planning method based on territorial spatial layout. *Commun. Inf. Technol.* (6), 100–104. (in Chinese). doi:10.19753/j.issn1001-1390.2022.06.016

Tang, Y., Guo, W., and Cui, Y. (2020). Research on frequency control strategy of hydro-thermal power units. *Electr. Power China* 53 (6), 153–160,178.

Tang, D., Zhong, W., Mu, X., Dai, F., Zhao, J., Zhu, Y., et al. (2022). Global low-carbon strategy of integrated energy system under multi-station fusion scenario based on robust model. *Electr. Meas. Instrum.* 59 (6), 113–121,180.

Tian, H., Fan, S., Lv, X., Zhao, P., and He, S. (2017). Mobile edge computing for 5G. *J. Beijing Univ. Posts Telecommun.* 40 (02), 1–10. doi:10.13190/j.jbupt.2017.02.001

Tian, Z. (2021). Analysis on planning, construction and Management of Data center in large metallurgical enterprises. *China Metal. Bull.* (3).

Wang, D., Xue, J., Ye, J., Xu, Q., and Fei, J. (2019a). Economic optimal scheduling strategy for energy storage power station based on particle swarm optimization. *J. Renew. Energy* 37 (5), 714–719. doi:10.13941/j.cnki.21-1469/tk.2019.05.014

Wang, B., Zhang, Y., Liu, M., and Er, X. (2019b). Exploration and research of "multi-station integration" operation model. *Electr. Power Inf. Commun. Technol.* 17 (7), 41–45. doi:10.16543/j.2095-641x.electric.power.ict.2019.07.008

Wang, Y., Ye, Z., Huang, J., Wei, W., Dai, S., and Zhang, B. (2022a). Research on energy storage peaking and frequency modulation economic scheduling based on dynamic peaking and valley division. *Electr. Power China* 55 (8), 64–72.

Wang, X., He, Y., Ma, H., Liu, X., and Zhang, H. (2022b). Voltage distributed control of distribution network considering large-scale energy storage. *Electr. Power Autom. Equip.* 42 (2), 25–30, 55. doi:10.16081/j.epae.202111012

Wang, J., Du, F., and Xiao, F. (2023). Spatial layout model of new infrastructure: a case study of large data centers. *Acta Geogr. Sin.* (2), 259–272.

Wang, M. (2017). *Research on network layout and operation of electric vehicle charging and replacing power stations*. Beijing Jiaotong University.

Wang, C. (2018). Research on location development of Chinese Data centers—taking the location layout of domestic data centers in the past 30 years as an example. *Plan. Des.* (12), 75–76.

Wang, Y. (2019). *Research on Operation optimization and storage capacity Allocation of power generation and storage community power station*. Wuhan: Huazhong University of Science and Technology.

Wang, Y. (2020). *Research on data center location based on analytic hierarchy process – A case study of T company*. University of International Business and Economics.

Wilson, E. C., Roger, M. M., Sergio, Z. A., Leite, J. B., and Franco, J. F. (2024). Suitable site selection of public charging stations: a fuzzy topsis mcda framework on capacity substation assessment. *Energies* 17 (14), 3452. doi:10.3390/en17143452

Wu, X., Liu, Z., Tian, L., Ding, D., and Yang, S. (2014). Location and capacity determination of energy storage in distribution network based on improved multi-objective particle swarm optimization. *Power Grid Technol.* 38 (12), 3405–3411. doi:10.13335/j.1000-3673.pst.2014.12.021

Wu, Z., Zhang, X., and Wang, X. (2021). Research on location factors and evaluation model of data center layout. *Telecommun. Eng. Technol. Stand.* (8), 16–20. doi:10.13992/j.cnki.tetas.2021.08.005

Wu, L. (2019). Application of GIS in substation location planning. *Hous. Real Estate* (08), 254.

Xie, Z., Tang, H., Han, X., Zhang, C., and Sun, Y. (2021). Research on power grid technology based on stackelberg multi-station fusion duopoly profit distribution mechanism. *Int. J. Electr. Power and Energy Syst.* 45 (10), 4009–4015.

Xincong, L., Mingze, Z., and Cheng, Q. (2020). "Location evaluation of multi-station integration based on AHP-fuzzy comprehensive evaluation method," in *IEEE PES asia-pacific power and energy engineering conference (APPEEC)*, 1–5. doi:10.1109/appeec48164.2020.9220407

Xiong, X. (2022). *Research on location capacity determination and optimization of intelligent substation based on GIS system and load forecasting model*. Zhengzhou University.

Xu, L., Zhu, Y., Zhang, Z., Jiang, X., and Xia, L. (2022). Optimization of data center power distribution scheme in multi-station fusion project. *Electr. Technol.* 23 (8), 17–22.

Yang, P., Gu, Y., and Zhou, X. (2020). Research on application scenario and construction operation mode of multi-station convergence. *Data Commun.* (3), 1–3,6.

Yang, X., Zhao, H., and Ren, H. (2021). Research on multi-scene and multi-station fusion mode based on layered theory of energy Internet. *J. Phys. Conf. Ser.* 12, 2148. doi:10.1088/1742-6596/2148/1/012006

Yin, W. (2023). *Discussion on the construction scheme of industrial data center in metallurgical industry*. Nonferrous Equipment.

Zambrano-Asanza, S., Chumbi, W. E., Franco, J. F., and Padilha-Feltrin, A. (2021). Multicriteria decision analysis in geographic information systems for identifying ideal locations for new substations. *J. Control, Automation Electr. Syst.* 32, 1305–1316. doi:10.1007/s40313-021-00738-5

Zhang, M., and Wen, J. (2017). *Research on green data center development: technology and practice [M]*. Beijing: Science Press, 46–49.

Zhang, Y., Wang, B., Li, R., and Er, X. (2019). Research on business model and development Path of multi-station Integration. *Power Supply Electr.* 36 (6), 62–66. doi:10.19421/j.cnki.1006-6357.2019.06.011

Zhang, J., Sun, W., and Ruijun, X. (2020a). Discussion on Spatial layout planning of the fifth generation Mobile Communication network infrastructure. *Internet + Commun.* (22), 25–26.

Zhang, C., Zhang, Y., Chen, J., and Sun, L. (2020b). "Research on combination modes and adaptability analysis of multi-station integration," in *2020 5th international conference on power and renewable energy (ICPRE)*, 538–542.

Zhang, J., Liu, S., Dai, Z., Wang, Q., Wei, X., Yin, J., et al. (2021). *A "Multi-station fusion" Data center station location method*. China Patent: CN112231923A (01.15).

Zhang, X., Li, H., Hu, Q., Zhou, Q., Shen, B., Xiang, J., et al. (2022a). Research on comprehensive evaluation of multi-station fusion site selection. *Electr. Power Eng. Technol.* 41 (2), 53–59.

Zhang, Z., Yao, Y., Chen, J., Peng, T., and Lin, S. (2022b). Energy Supply structure analysis of multi-station fusion data center under dual-carbon target. *Guangdong Electr. Power* 35 (12), 46–55.

Zhang, X., Guo, X., Jin, G., Yin, K., Gao, Y., Zhou, Y., et al. (2022c). Multi-station fusion cooperative optimal scheduling based on affine robust optimization. *Mod. Electr. Power* 39 (4), 379–388. doi:10.19725/j.cnki.1007-2322.2021.0139

Zhang, X., Zhou, J., Ma, Y., Ma, W., Zhang, Z., Wu, K., et al. (2023). Review of multi-station fusion architecture design and strategy optimization under dual-carbon target. *Power Demand Side Manag.* 25 (2), 1–7.

Zhang, F. (2017). Location selection and network optimization of wireless communication base Station based on GIS. *Commun. World* (7), 41–42.

Zhang, C. (2021). *Spatial layout of charging infrastructure for new energy vehicles: a case study of Tianjin*. Tianjin University of Commerce.

Zhao, F., Zhang, C., Sun, B., and Wei, D. (2015). Three-level collaborative overall optimization design method for cooling, heating and power supply system. *Proc. CSEE* 35 (15), 3785–3793. doi:10.13334/j.0258-8013.pcsee.2015.15.006

Zhao, Z., Zhang, S., and Ge, X. (2023). Construction of regional large-scale photovoltaic power station location index system based on geographic information technology and Fuzzy Hierarchical Analysis - fuzzy Decision Trial and Evaluation Experimental method (AHP-DEMATEL): a case study of Inner Mongolia. *Sci. Technol. Manag. Res.* 43 (6), 78–87.

Zhou, Z., Wang, P., Xu, C., and Deng, P. (2023). Research on general layout optimization of multi-station integrated smart energy station. *Autom. Appl.* 64 (18), 149–151.

Zhu, Y., Liu, X., Mu, X., Dai, F., Xyu, W., Qian, W., et al. (2022). Multi-index comprehensive evaluation of multi-station integrated energy system based on AHP and risk entropy weight. *Electr. Meas. Instrum.* 59 (4), 128–136,143. doi:10.19753/j.issn1001-1390.2022.04.019

Zou, Q., Chen, H., and Wu, Y. (2023). Research on three-station integration construction scheme. *Civ. Eng. Urban Res.* (2), 5.