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A review on the short-term strategy for reducing the peak-valley difference and the long-term energy structure optimization strategy in cities based on the integration of “power generation - power grid - power load - Energy storage”

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Effectively alleviating the contradiction in load regulation brought about by the peak-valley difference of electricity is an important measure to promote the high-quality development of energy and electricity in the new era and realize the optimization of the energy structure. As a city entering a new stage of development as an ultra-large-scale urban economy, Shanghai has a strong external dependence on energy and a shortage of available resources within the city. Coupled with factors such as the connection of a high proportion of renewable energy sources, the uncertainty on the power supply side has increased, resulting in a shortage of short-term electricity power and obstruction to the optimization of the long-term energy structure. Therefore, in view of the characteristics and formation causes of the peak-valley difference in Shanghai, combined with the energy structure within the city and the situation of power supply connections from outside the city, the fundamental reasons for the continuous widening of the peak-valley difference in Shanghai's electricity and the bottleneck encountered in the adjustment of the energy structure are deeply explored. On this basis, the research status and development trends of technical measures on each side of “Source-Grid-Load-Storage” are sorted out, and a technical system applicable to reducing the peak-valley difference and realizing the optimization of the energy structure in Shanghai is refined and established. Further multi-time dimension and multi-index contribution degree evaluations are carried out to strengthen forward-looking strategic guidance and top-level layout planning.

KEYWORDS

reduce the peak valley difference, urban energy structure optimization, source-network-charge-storage integration, technical system, urban energy planning

1 Introduction

Since the commencement of the “14th Five-Year Plan” period, the maximum power peak-valley difference in Shanghai has exhibited a progressively increasing annual volatility and pronounced seasonal fluctuation tendencies, concomitant with the persistent augmentation of electricity consumption and the abrupt escalation of peak loads. The details regarding the highest and lowest loads on the days when the maximum peak-valley differences occurred over the years, along with the corresponding trends of these maximum peak-valley differences, are illustrated in [Figure 1a](#). In 2022, the maximum peak-valley difference within the power grid of Shanghai reached 16.159 million kilowatts, signifying a year-on-year growth rate of 9.3% and attaining a record high. Concurrently, the maximum peak-valley difference rate was recorded as 45.67%, denoting an increment of 0.12 percentage points in comparison to the preceding year. An examination of the historical growth patterns reveals that the trend of the continuous expansion of the maximum peak-valley difference has become increasingly conspicuous, with an average annual growth rate of 6.36% over the past 5 years, thereby exacerbating the issue of excessive peak-valley difference. The electricity consumption and load profiles of typical metropolises, both domestically and internationally, are presented in [Table 1](#).

From a vertical perspective, the urban power peak-valley difference is characterized by a prominent short-term peak manifestation in power load. This phenomenon is influenced by a multitude of factors, including alterations in the power demand structure and the transformations in the income levels and electricity consumption patterns of residents. The residential electricity consumption load is typified by substantial seasonal oscillations, pronounced randomness, and formidable challenges in decentralized load management, all of which constitute crucial hurdles in addressing the power peak-valley difference. The proportions of peak loads and electricity consumption across various industries within the electricity consumption structure of Shanghai in 2022 are depicted in [Figures 1b,c](#). As large cities progress from the industrialization phase to the post-industrialization era, the share of electricity consumption in the secondary industry has declined, while the proportions in the tertiary industry and residential electricity consumption have experienced a gradual ascendancy. Compounded by the elevation in income levels and the widespread adoption of high-load electrical appliances such as air conditioners, the peak load during summer has witnessed a rapid surge.

From a horizontal vantage point, the urban peak-valley difference is marked by conspicuous seasonal oscillations and a high degree of sensitivity to extreme weather conditions, manifesting a pattern of “two peaks (summer and winter) and two valleys (spring and autumn)” in accordance with the seasonal climatic variations. Under the impact of the summer heat wave in 2022, the national peak value of electricity consumption load peaked at 1.26 billion kilowatts, with Shanghai registering 38.07 million kilowatts, both of which established new historical benchmarks. Projections suggest that by 2030, under the extreme scenario of global warming, the peak load is anticipated to escalate by approximately 40%–50%.

The increasingly prominent contradiction between supply and demand in Shanghai is the fundamental reason for the increasingly severe problem of peak-valley difference and the bottleneck encountered in the adjustment of the energy structure, which is mainly manifested in the following two aspects.

Firstly, the growth of electricity demand within the city has exceeded expectations, the proportion of load has been increasing year by year, and renewable energy resources are in short supply. On the one hand, the intra-day peak-valley difference has been continuously widening with the increase in the proportion of household energy consumption. Meanwhile, along with the frequent occurrence of extreme climates, the seasonal electricity load fluctuates significantly. In 2022, in the summer and winter peak loads of the Shanghai power grid, the proportions of cooling and heating loads were 48.6% and 34.4% respectively. With the global climate change, extreme weather such as heat waves and extreme cold is occurring more and more frequently, and the problem of power load peaks will be further highlighted. According to research ([Yang et al., 2025](#)). There is a nonlinear relationship between electricity demand, electricity load and air temperature. The impact of the variation of the daily maximum air temperature in summer in Shanghai on the cooling load is shown in [Figure 2](#). For every one-degree increase in the average air temperature in the urban energy consumption environment, the electricity consumption will increase by 9.2%, and the increase in the summer peak load will reach 36.1%. Meanwhile, it is also worth noting that the growth momentum of new types of loads such as electric vehicle charging is rapid. The new energy vehicles in Shanghai have been growing at a high speed year after year. The city has a total of 945,000 new energy vehicles, ranking first in the world, with a penetration rate exceeding 45%. In the summer and winter of 2022, the peak charging loads within the day were approximately 300,000 kilowatts and 400,000 kilowatts respectively. The peak charging load is concentrated from 22:00 to 24:00, but there is still a charging load of about 100,000 kilowatts during the noon peak in summer and the evening peaks in winter and summer.

On the other hand, Shanghai has a high dependence on external energy sources and a shortage of local renewable resources. In 2022, the local renewable energy was 8.1 billion kilowatt-hours, accounting for 4.7% of the total electricity consumption of the whole society, still having a large gap compared with the imported renewable energy of 43.9 billion kilowatt-hours, accounting for 29.8%.

Secondly, the uncertainties of imported green electricity are increasing, and the implementation of increments falls short of expectations. On the one hand, there is uncertainty about the stable supply of the existing imported green electricity ([Yan, 2023](#)). Affected by various factors such as the supply and demand situation at the sending end and the water inflow situation, the electricity imported into Shanghai from the Three Gorges, Xiangjiaba and other places has decreased sharply in the past 2 years. Coupled with the unexpected growth of Shanghai's electricity and power in 2022, the uncertainty of the planned hydropower supply has a great impact on Shanghai's energy supply guarantee and low-carbon transformation, forcing Shanghai's local coal-fired power plants to bear more of the heavy responsibility of ensuring the bottom-line supply. On the other hand, it is difficult to strive for incremental low-carbon imported electricity. At present, there are

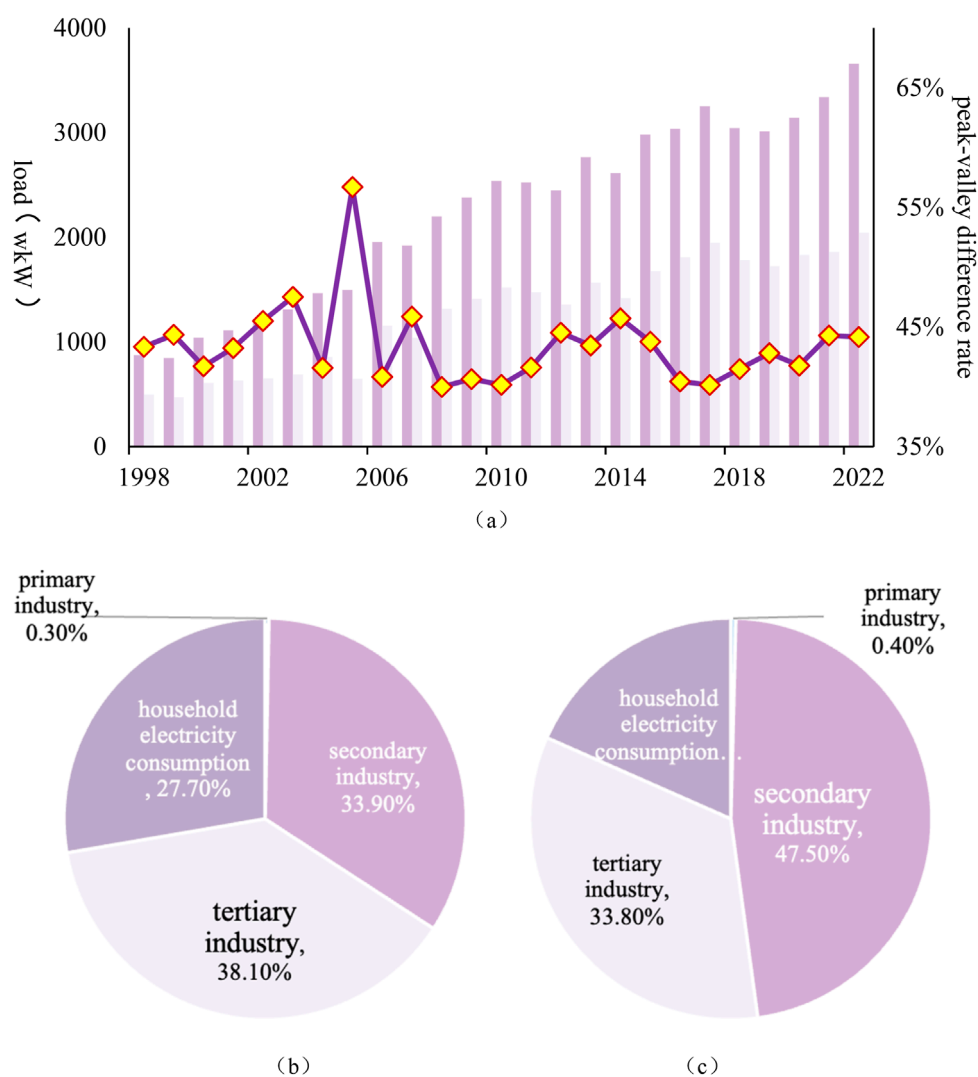


FIGURE 1
The graph of the maximum peak-valley differences and their growth trends over the years (a) and the proportions of peak loads (b) and electricity consumption of various industries (c) in the electricity consumption structure of Shanghai in 2022.

problems such as the tendency of reluctant selling at the sending end and the tightness of the receiving end channels, resulting in fierce competition for purchasing renewable energy across provinces and regions.

In 2022, geopolitical conflicts and extreme climates led to a global energy crisis. Both at home and abroad, especially in European countries, a variety of energy-saving and consumption-reduction measures were introduced, aiming to reduce peak loads and optimize the energy structure. Some of these measures have achieved certain effects and can provide references for Shanghai's measures to reduce the peak-valley difference and optimize the energy structure. These technical measures are mainly divided into four sides: the power system supply side, the power grid side, the load side, and the energy storage side. Now, an overview of the current research status and development trends at home and abroad will be presented, and the framework of the technical system is shown in Figure 3.

On this basis, against the backdrop of the integrated development of the Yangtze River Delta region, in line with the energy consumption characteristics and power development trends of Shanghai, and based on the resources inside and outside the city, a technical system applicable to reducing the peak-valley difference and realizing the optimization of the energy structure in Shanghai is refined and summarized. From a multi-dimensional perspective of the near, medium, and long terms, with the end of the "14th Five-Year Plan," the end of the "15th Five-Year Plan," 2030, and 2060 as the time nodes respectively, a contribution assessment will be further conducted on the performance of this measure system in terms of adjusting and reducing the peak-valley difference in the near and medium terms and optimizing the energy structure in the medium and long terms.

This review categorizes the strategies for addressing urban power peak-valley differences and energy structure optimization into two complementary timelines: Short-term strategies (Within

TABLE 1 The situations of electricity consumption and loads in typical metropolises at home and abroad.

City	Year	Population	Electricity quantity	Maximum load	Per capita electricity quantity	Per capita load	Load density	Hours of maximum load utilization
		Ten thousand people	Hundred million kilowatt-hours	Ten thousand kilowatts	Kilowatt-hours per person	Kilowatts per person	Kilowatts per kilometer ²	
New York	2019	834	520	1002	6,238	1.2	12677	5,193
Greater Tokyo	2015	4,503	2,471	4,957	5,487	1.1	1,253	4,985
Hong Kong	2019	752	448	960	5,957	1.28	8,648	4,666
Singapore	2019	570	517	740	9,068	1.3	10211	6,985
Shanghai	2022	2,489	1,746	3,807	7,013	1.53	6,004	4,585
Beijing	2022	2,189	1,281	2,564	5,852	1.17	1,562	4,995

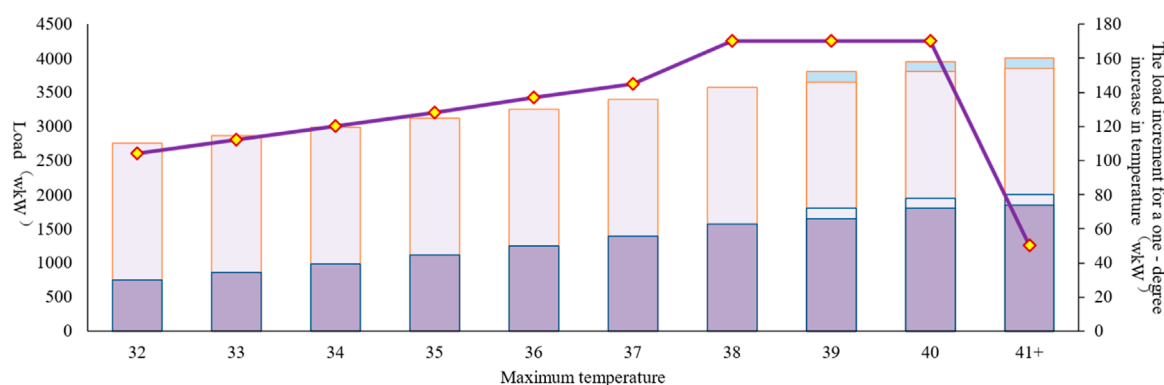


FIGURE 2

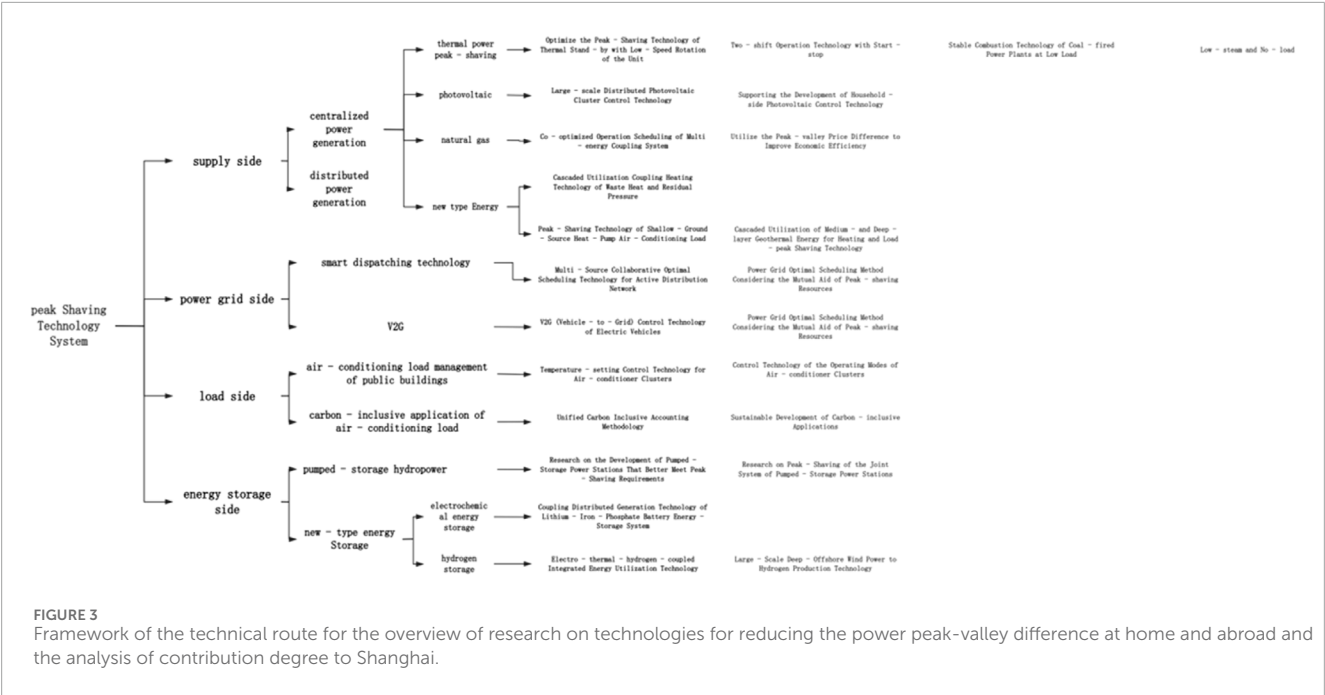
The impact of the variation of the daily maximum air temperature in summer on the cooling load.

5–10 years): Focus on rapid deployment of demand-side management, flexible operation of existing assets, and distributed energy resources to immediately alleviate the peak-valley contradiction. Key measures include orderly charging of electric vehicles, air-conditioning load management, demand response, and deployment of electrochemical energy storage. Long-term strategies (Beyond 10 years): Focus on fundamental transformation of the energy supply structure, large-scale integration of renewable energy, and investment in large-capacity, long-duration storage infrastructure. Key measures include high-percentage renewable penetration, regional green electricity import, development of pumped hydro storage and hydrogen energy systems. The following sections will review technical measures across the “Source-Grid-Load-Storage” spectrum under this strategic framing.

2 Research review on technical measures for reducing the power peak - valley difference on the supply side and analysis of the contribution degree to Shanghai

2.1 Simultaneous implementation of three - pronged retrofits for thermal power units (including energy - Saving and carbon - Reduction retrofit, flexibility retrofit, and heating retrofit)

As the role of thermal power in energy supply gradually shifts from being a supporting and conventional energy source



to a basic peak - shaving and standby energy source, the proportion of ancillary service revenue in the revenue of thermal power enterprises is continuously increasing. The “Simultaneous Implementation of Three - pronged Retrofits” including energy - saving and consumption - reduction retrofit, flexibility retrofit, and heating retrofit has become an important issue faced by current thermal power enterprises. Coal - fired power units generally have relatively high flexibility, with an average minimum output rate of about 0.4, an average peak - shaving capacity of 60%, and a peak - topping capacity of 100%.

Based on the current situation of thermal power units in Shanghai and the peak - shaving requirements, this paper summarizes the research trends of the existing thermal power units’ “Simultaneous Implementation of Three - pronged Retrofits” participating in system peak - shaving. The modeling approaches underpinning these strategies include AGC (Automatic Generation Control) optimization models for load coordination, economic dispatch models considering carbon capture, and thermal stress analysis models for variable pressure operation. We analyzes the five - dimensional comparison of the safety, economy, peak - shaving speed, peak - shaving range, and accident probability of the four formed peak - shaving modes, as shown in Table 2.

In summary, the four thermal power peak-shaving modes each possess distinct characteristics: the low-load steady-burning mode offers rapid response but inferior economics, making it suitable for frequent intraday peak-shaving; the two-shift start-stop mode provides a wide peak-shaving range with superior economics, ideal for extended off-peak periods during weekends or public holidays; the low-steam no-load and low-speed rotating hot standby modes strike a balance between safety and economics, serving as appropriate supplements to conventional peak-shaving. Given the Shanghai grid’s emphasis on daily peak regulation and significant seasonal peak pressure, it is recommended to prioritise the combined application of low-load steady-burning and two-shift

start-stop operations. Further more, new units should incorporate provisions for future conversion to low-speed rotating hot standby, thereby enhancing the system’s overall peak regulation flexibility and economic efficiency.

According to the “14th Five - Year Plan for Energy Development in Shanghai” and its mid - term evaluation, the “Shanghai Energy White Paper,” relevant documents of the Municipal Development and Reform Commission, statistical reports of the State Grid Shanghai Municipal Electric Power Company and other statistical documents within the industry (the same applies to subsequent statistical analysis documents): By the end of 2022, the total installed capacity of coal - fired power was 14.994 million kilowatts, accounting for 32% of the total installed capacity of all power sources in Shanghai (46.298 million kilowatts, the same hereinafter). The overall flexibility of coal - fired power units is relatively high, with an average minimum output rate of about 0.4, an average peak - shaving capacity of 60%, and a peak - topping capacity of 100%. The peak - shaving capacity of coal - fired power will be affected to a certain extent by the way of dispatching and starting up. Under the small starting - up mode, the releasable peak - shaving capacity of coal - fired power will be somewhat reduced. The adopted technical transformation route is to guide and promote the existing thermal power units of Caojing Power Plant, Caojing Cogeneration Power Plant, Lingang Gas Turbine Power Plant, Huadian Fengxian Cogeneration Power Plant and Huadian Minhang Gas Turbine Power Plant to implement heating transformation according to the distribution of urban heat load demand, so as to achieve peak - shaving. The contribution degree analysis is as follows: ① In terms of forming the incremental peak - shaving and valley - filling capacity, by the end of the “14th Five - Year Plan,” about 5.95 million kilowatts of high - efficiency coal - fired power units can be retrofitted and newly built, with an additional heating capacity of about 600 t/h, forming a peak - shaving capacity of 42,000 kilowatts for summer and winter peak loads; by the end of the “15th Five - Year Plan,”

TABLE 2 Comparison of four peak - shaving modes of coal - fired units.

Category	Stable combustion at low load	Two - shift start - stop system	Low - steam (Yang et al., 2022) and No - load (Huanhuan, 2024)	Low - speed rotating hot standby (Lei et al., 2023; Zhang, 2017)
Technical Route	Oxygen - enriched Combustion (Lu et al., 2021), Retrofit of the Central Storage Pulverizing System, Flexibility Retrofit of the Boiler Heating Surface and Steam - water Pipes (Lin et al., 2023)	Optimize the economic dispatch model of carbon capture power plants (Ma et al., 2023), Optimize the system configuration of carbon capture power plants (Peng et al., 2021)	Improve the low - cycle fatigue life of the high - pressure rotating shaft (Yan, 2020), Explore ways to mitigate the thermal shock caused by the steep drop in the temperature of the regulating stage (Jie et al., 2012)	Conduct configuration optimization on the coordinated control loop of the load section with AGC (Automatic Generation Control) input (Xiaoyan, 2017)
Peak - shaving Safety	When operating at constant pressure, the temperature change of the regulating stage of the steam turbine is small. When operating at variable pressure, the temperature remains basically unchanged, which is relatively safe. However, the thermal stress of the thick - walled components of the boiler is large	The temperature difference between the upper and lower walls of the thick - walled components of the boiler and the steam turbine cylinder is large, resulting in large thermal stress and being unsafe	The temperature after the regulating stage of the steam turbine is higher than that in the two - shift start - stop system, but there are safety issues with the last - stage blades	The temperature after the regulating stage of the steam turbine is higher than that in the two - shift system, but there are safety issues with the last - stage blades
Peak - shaving Economy	The economy is relatively poor, especially when the trough period is long	The economy is relatively good, especially when the trough period is long	Medium	Medium
Peak - shaving Speed	Relatively the best	The operation is complex and relatively poor	Relatively good	Relatively good
Peak - shaving Range	Smaller	The largest (100%)	The largest (100%)	The largest (100%)
Accident Probability	The lowest	High	Lower	Lower

the installed capacity of coal - fired power will not increase, and the peak - shaving capacity will remain unchanged. ② In terms of optimizing the energy structure, it is expected that in 2030 and 2060, the total installed capacity of coal - fired power will reach 16.32 million and 10.26 million kilowatts respectively, and the proportion of the installed capacity accounting for the total installed capacity of all power sources in Shanghai in that year (75.14 million and 11,300 kilowatts, the same hereinafter) will be reduced to 22% and 9% respectively.

2.2 Photovoltaic development

With the advancement of the “dual - carbon” goals, the development of renewable energy has been comprehensively accelerated, and the installed capacity is showing an explosive growth trend. Using renewable energy, represented by photovoltaics, as a peak - regulation means has become a global research hotspot (Peng et al., 2021). The photovoltaic market in Shanghai has also continued to maintain a high growth trend. By the end of 2022, the cumulative installed capacity of renewable energy in Shanghai was approximately 3.708 million kilowatts, among which the cumulative installed capacity of photovoltaics was approximately 1.948 million kilowatts, accounting for more than 50%. Photovoltaic

systems usually reach their output peaks at noon, which helps offset part of the summer peak loads. In recent years, New York State has installed over 3.2 GW of distributed photovoltaic capacity through the NY-Sun Initiative programme. Commercial and residential solar systems contributed approximately 12% of local electricity supply during summer midday peak periods, significantly alleviating grid strain. Tokyo, meanwhile, achieved over 1.5 GW of distributed PV capacity through its “Solar City Tokyo” scheme by 2023, with commercial building solar systems providing approximately 8% of peak power support during extreme heatwaves. Compared with centralized photovoltaics, the effect of reducing peak power loads is more significant. It can not only extend the output time of the energy storage system during peak hours but also smooth out the volatility of photovoltaics itself and reduce the impact on the power grid during normal times.

Therefore, based on the current situation of distributed photovoltaics in Shanghai and the peak - regulation requirements, this paper summarizes the current research trends of centralized peak - regulation management and power distribution of existing clustered distributed photovoltaics. Key modeling approaches include cluster control models for distributed PV systems, robust virtual synchronous control strategies, and optimal capacity allocation models minimizing distribution network losses. We analyzes the technical routes and effect

TABLE 3 Comparison of two peak - regulation modes of clustered distributed photovoltaic units.

Category	Large - scale distributed photovoltaic cluster control	Supporting the development of household - end photovoltaics
Research Trends	Model Framework, Operation Strategy, and Degree of Intelligent Management of Large - scale Distributed Photovoltaic Cluster Control (Fu, 2014)	Creating photovoltaic development and utilization in multiple scenarios and continuously carrying out optimal configuration and layout optimization (Zhang et al., 2020a)
Technical Route	A model framework that can address the grid - connected power generation and centralized peak - regulation management of centralized distributed photovoltaics (Luo, 2022), Enhancement of the measurable and controllable capabilities of distributed photovoltaics (Zhou et al., 2018), Robust virtual synchronous control strategy to make the peak - regulation control of clustered units more effective (Ying et al., 2018)	Taking the minimum loss of the distribution network as the optimization objective and implementing optimal configuration of the system capacity (Gernaat et al., 2020), Implementing integrated development and operation of distributed photovoltaic clusters after leasing the photovoltaic site of users (Qi et al., 2025)

presentations of the two formed peak - regulation modes, as shown in Table 3.

Centralised cluster control and household photovoltaic support exhibit significant differences in peak-shaving effectiveness: the former is better suited to concentrated settings such as industrial parks and large commercial complexes, enabling rapid response through unified dispatch; the latter is more appropriate for residential areas and distributed scenarios, offering slower response times but superior social acceptance and rooftop resource utilisation. It is recommended that Shanghai prioritise cluster control in scenarios such as “PV + Transport” and “PV + Industrial Parks,” while promoting the household PV + energy storage model in residential areas. This dual approach would achieve both peak shaving objectives and user benefits.

The current situation, technical transformation routes, and contribution degree analysis are as follows: By the end of 2022, the total installed capacity of photovoltaics was 1.07 million kilowatts, accounting for 2.3% of the total installed capacity of all power sources in Shanghai. The total developable photovoltaic resources within the city are approximately 10 million kilowatts. The adopted technical transformation route is to comprehensively promote the implementation of seven major solar energy projects such as “photovoltaic + residential, park, transportation” by refining the transformation plan for existing buildings and guide the development of demonstration projects such as building-integrated photovoltaics.

The contribution degree analysis is as follows: ① In terms of forming the incremental peak-shaving and valley-filling capacity, it is expected that by the end of the “14th Five-Year Plan,” the installed capacity of new photovoltaics can reach 2 million kilowatts, and by the end of the “15th Five-Year Plan,” the installed capacity of new photovoltaics can exceed 5 million kilowatts. Calculated according to a 50% simultaneity rate, by the end of the “14th Five-Year Plan,” the peak-shaving capacity for summer peak loads can be increased by approximately 1 million kilowatts, and by the end of the “15th Five-Year Plan,” the peak-shaving capacity for summer peak loads can be increased by approximately 2.5 million kilowatts. ② In terms of optimizing the energy structure, it is expected that in 2030 and 2060, the total installed capacity of coal-fired power will reach 7

million and 14 million kilowatts respectively, and the proportion of the installed capacity accounting for the total installed capacity of all power sources in Shanghai in that year will be increased to 9% and 12% respectively.

2.3 Natural - gas distributed energy supply

Natural - gas Distributed Energy Supply, as a new - type kinetic energy system and utilization method, is widely used due to its advantages such as rapid start - up and shutdown, high - efficiency, environmental - friendliness, and being closer to users (Sun et al., 2025), and it has entered a stage of rapid development. Taking Copenhagen, Denmark as an example, natural gas distributed energy accounts for over 40% of its district energy system. Through waste heat recovery and cold storage technologies, the system achieves an overall thermal efficiency exceeding 90%, successfully reducing peak grid load by approximately 15% during winter heating peaks. For gas turbine units, simple cycle gas turbines have almost no minimum technical output limitation. Technically, the peak - shaving depth is close to 100%, and the adjustment speed is fast. Natural gas distributed energy projects belong to the clean energy projects that are strongly supported and encouraged to develop by the state and this city. These projects achieve cascaded utilization of energy, and the comprehensive thermal efficiency can reach more than 70%. In regional natural gas distributed energy supply systems, the operation of prime movers such as internal combustion engines or gas turbines is relatively stable, and the amount of residual heat they generate is also stable. The cooling capacity prepared by hot water lithium bromide units using the residual heat is also relatively stable (Sun et al., 2022). The storage of surplus cooling capacity takes into account both energy utilization rate and economic benefits (Ma, 2023). Based on the current situation of gas - steam combined cycle gas turbines in Shanghai and the peak - shaving requirements, this paper summarizes the current research trends of improving the peak - shaving capacity of gas - steam combined cycle gas turbines and forms a comparison from research perspectives, as shown in Table 4.

Two optimisation strategies enhance the economic efficiency and flexibility of gas turbines for peak shaving from distinct

TABLE 4 Comparison of two peak - regulation modes of gas - steam combined cycle gas turbines.

Category	Optimize the operation strategy to reduce the peak - to - valley difference	Utilize the peak - valley electricity price difference to enhance economic efficiency
Research Trends	By means of optimizing the flue gas bypass configuration or start - stop peak - shaving, etc., make the thermal cycle efficiency close to that of a single - cycle gas turbine	Carry out beneficial discussions and (Sun, 2019) effectively improve the economic efficiency of the system by using the peak - valley electricity price difference, and jointly make efforts from the power supply side and the user side to reduce the peak - valley difference (Jinquan et al., 2019)
Technical Route	A combined cycle gas turbine with a flue gas bypass can utilize the flue gas bypass to achieve single - cycle start - up and operation of the gas turbine (Du, 2023), for a combined cycle gas turbine without a flue gas bypass (Lin et al., 2018), make the gas turbine, waste heat boiler, and steam turbine form an integral whole (Wu, 2020), For a combined cycle unit with a heating load (Yu et al., 2019), operate according to the principle of “determining power based on heat” (Zhu et al., 2017), Start - stop peak - shaving (Li et al., 2018)	Life cycle analysis (Zhang and Wang, 2019), determination of the optimal peak - shaving coefficient (Zhu, 2007), environmental and other influencing factors (Mu et al., 2008)

perspectives. ‘Leveraging peak-off-peak electricity price differentials’ constitutes a market-driven approach. By optimising operational modes—such as generating power during off-peak hours whenever feasible—it internalises the economic benefits of system peak shaving, thereby improving the project’s return on investment. This strategy is straightforward to implement, relying primarily on electricity price signals, though its peak-shaving effectiveness hinges on the incentive strength of the price differential. ‘Optimising operational strategies to reduce peak-to-off-peak differences’ constitutes a technology-driven approach. This involves modifying equipment (such as optimising flue gas bypasses) or refining dispatch algorithms to directly enhance the unit’s inherent flexibility and peak-shaving capability. While technically more demanding, it yields more direct and controllable peak-shaving outcomes.

The current situation, technical transformation routes, and contribution degree analysis are as follows: By the end of 2022, the total installed capacity of gas - fired power was 8.12 million kilowatts, accounting for 18% of the total installed capacity of all power sources in Shanghai. The peak - shaving gas turbines have relatively strong peak - shaving capabilities and can perform start - stop peak - shaving with an equivalent peak - shaving capacity of approximately 100%. However, due to factors such as gas sources, gas prices, and the start - up of other various power sources, the regulating performance of peak - shaving gas turbines has not been fully utilized.

The adopted technical transformation route is to focus on areas with relatively rapid load growth and difficulties in power capacity expansion, such as the Five New Towns, newly built industrial parks, and areas with concentrated construction of new infrastructure. Select projects with relatively concentrated cooling, heating, and power loads to promote natural gas distributed energy supply. It is expected that by the end of the “14th Five - Year Plan,” the installed capacity of new natural gas distributed energy supply projects can reach 150,000 kilowatts, and by the end of

the “15th Five - Year Plan,” the cumulative installed capacity of new natural gas distributed energy supply projects can reach 300,000 kilowatts.

The contribution degree analysis is as follows: ① In terms of forming the incremental peak - shaving and valley - filling capacity, by the end of the “14th Five - Year Plan,” in cooperation with energy storage facilities, the peak - shaving capabilities for summer and winter peak loads will be increased by 210,000 and 150,000 kilowatts respectively, and the valley - filling capacity will be 50,000 kilowatts. By the end of the “15th Five - Year Plan,” the peak - shaving capabilities for summer and winter peak loads will be increased by 370,000 and 290,000 kilowatts respectively, and the valley - filling capacity will be 100,000 kilowatts. ② In terms of optimizing the energy structure, it is expected that in 2030 and 2060, the total installed capacity of gas - fired power will reach 13.04 million and 10.07 million kilowatts respectively, and the proportion of the installed capacity accounting for the total installed capacity of all power sources in Shanghai in that year will be reduced to 17% and 9% respectively.

2.4 Geothermal energy development

Geothermal energy is a type of renewable energy. Through ground - source heat pump technology, it is used for building cooling and heating. Compared with conventional cooling and heating systems, it can effectively reduce the electricity load for building cooling and heating (Yang, 2013). According to research (Zhang, 2022), the full utilization of low - grade energy such as geothermal energy is expected to increase the regional electrification level by about 20% and reduce the regional load peak - to - valley difference rate by more than 5%. Based on the current development status of geothermal energy in Shanghai and the peak - regulation requirements, this paper summarizes the current research trends of improving the peak - regulation capacity of geothermal energy

TABLE 5 Comparison of two peak - regulation methods for geothermal energy development.

Category	Shallow - soil ground - source heat pump air - conditioning load - peak - regulation technology	Medium - and deep - layer geothermal energy cascade utilization for heating and load - peak - regulation technology
Research Trends	The shallow - layer geothermal resources near the earth's surface are used as the cold/heat source for energy conversion. And relying on the amount of heat extraction/release from the soil throughout the year and different environmental factors, multi - objective optimization of the auxiliary cold/heat sources and various parameters is carried out to achieve efficient peak - regulation	The geothermal resources in the medium - and deep - layers of the earth's surface are used to extract heat in stages to meet different heating requirements
Technical Route	Compare and optimize the electricity load of ground - source heat pump technology used for building cooling (Li, 2021) and heating and that of conventional cooling and heating systems (Islam et al., 2016), various normal - temperature operating conditions (Yin et al., 2019), energy - saving and emission - reduction environmental benefits (Jinhua, 2021) and social - environmental factors (Zhou et al., 2022)	Well - type Structures (Saleh et al., 2020; Sun et al., 2018), circulating heat - transfer modes (Chen et al., 2022; Ni et al., 2011), heat - transfer Areas (Wei et al., 2022; Shi et al., 2019)

development and forms a comparison from subdivided research perspectives, as shown in Table 5.

Shallow and medium-to-deep geothermal energy exhibit significant differences in technical principles, applicable scale, and peak-shaving characteristics. Shallow ground source heat pump technology is mature, primarily utilising heat from the near-surface constant-temperature zone to provide cooling and heating for buildings via heat pumps. Its peak-shaving capability manifests in directly replacing traditional electric cooling and heating loads. However, its performance is considerably constrained by surface area and geological conditions, and carries risks of soil thermal imbalance, making it more suitable for distributed, small-to-medium-scale building clusters. Medium-to-deep geothermal energy, conversely, draws heat directly from the Earth's deeper layers, offering higher temperatures and greater energy density. This makes it viable for district heating and even power generation, with substantial peak-shaving potential. Nevertheless, it presents greater technical challenges, incurs costly drilling expenses, and carries significant geological uncertainty risks in sedimentary basin regions such as Shanghai. Shanghai's geothermal development should prioritise shallow ground source heat pumps as its primary focus.

The current situation, technical transformation routes, and contribution degree analysis are as follows: By the end of 2022, the application area of shallow geothermal energy in buildings in this city was approximately 19.4 million square meters. The total installed capacity of other power generation from waste heat and residual pressure was 1.48 million kilowatts, accounting for 3% of the total installed capacity of all power sources in Shanghai.

The adopted technical transformation route is to focus on the Five New Towns, green ecological urban areas, and new buildings, comprehensively explore the geothermal energy in soil, surface water, and urban sewage, and create a number of high - quality development demonstration areas and pilot projects of shallow geothermal energy.

The contribution degree analysis is as follows: ① In terms of forming the incremental peak - shaving and valley - filling capacity, it is expected that by the end of the "14th Five - Year Plan," the utilization area of shallow geothermal energy can be increased by more than 5 million square meters, and the new installed capacity can be 855,000 kilowatts. By the end of the "15th Five - Year Plan," the cumulative increase in the building area of shallow geothermal energy can be more than 10 million square meters, and the new installed capacity can be 1.71 million kilowatts. By the end of the "14th Five - Year Plan," the peak - shaving capacity for summer and winter peak loads can be increased by 90,000 and 60,000 kilowatts respectively. By the end of the "15th Five - Year Plan," the peak - shaving capacity for summer and winter peak loads can be increased by 180,000 and 120,000 kilowatts respectively. ② In terms of optimizing the energy structure, it is expected that in 2030 and 2060, the total installed capacity of other power generation will reach 3.82 million and 7.64 million kilowatts respectively, and the proportion of the installed capacity accounting for the total installed capacity of all power sources in Shanghai in that year will be increased to 5% and 7% respectively.

2.5 Comprehensive utilization of waste heat and residual pressure

The industrial sector is the area with the richest low - grade thermal energy resources in the city. According to statistics from foreign research institutions, during the utilization of fossil energy in the industrial sector, only 40% of the energy is effectively utilized, and the remaining 60% is ultimately converted into waste heat. Generating electricity from waste heat (cold) and residual pressure is not only an effective way to save energy and reduce carbon emissions, but also can bear a certain power load during peak electricity consumption periods, playing a certain role in reducing the peak - to - valley difference of the power grid.

TABLE 6 Comparison of two peak - regulation modes for comprehensive cascade utilization of waste heat and residual pressure.

Category	Traditional steam turbine power - generation technology with water as the working fluid	Peak - shaving technology of organic working fluid power - generation technology with low - boiling - point working fluid
Research Trends	Research on the low - temperature steam turbine power - generation system composed of a waste - heat boiler + steam turbine or expander with water as the working fluid	Parameters such as power - generation capacity, thermal efficiency, exergy efficiency, and the amount of peak - load - bearing are used as performance indicators and optimization targets to better achieve cascade utilization of waste heat and residual pressure and couple with heat - supply
Technical Route	Research on the waste - heat boiler + steam turbine (Fan et al., 2021) and research on the low - temperature steam turbine power - generation system composed of expanders (Jankowski et al., 2021)	Working - Fluid Characteristics (Cai et al., 2021), cycle Improvement (Sanchez et al., 2018), Thermodynamic - Performance Analysis (Geng et al., 2021)

Improving the grade of waste heat using thermal - work conversion technology is an important technology for recovering industrial waste heat. Based on the current situation of comprehensive utilization of waste heat and residual pressure in Shanghai and the peak - regulation requirements, this paper summarizes the current research trends of improving the peak - regulation capacity of comprehensive utilization of waste heat and residual pressure and forms a comparison from subdivided research perspectives, as shown in Table 6.

Traditional water-cooled steam turbines and organic Rankine cycle (ORC) power generation represent two mainstream approaches for waste heat utilisation, with selection primarily determined by the quality of the heat source and economic considerations. Steam turbine technology is more mature and suited to stable, high-grade heat sources at elevated temperatures and pressures (typically above 300 °C), such as blast furnace gas from steel and chemical industries or residual heat from catalytic cracking. While these systems are complex and require substantial investment, they offer high efficiency and reliable operation. ORC technology, conversely, is suited to medium-to-low temperature (80 °C–300 °C) low-grade heat sources, such as industrial wastewater or low-temperature flue gas. Its systems are simpler, feature higher automation levels, and demonstrate greater adaptability to fluctuations in heat source quality, though its thermal-to-electrical conversion efficiency is comparatively lower. As a megacity with a comprehensive industrial base, Shanghai possesses substantial industrial waste heat resources of varying grades. Consequently, the approach should not be confined to a single technology; rather, differentiated technical pathways should be adopted based on the specific characteristics of the heat available.

The current situation, technical transformation routes, and contribution degree analysis are as follows: By the end of 2022, the total installed capacity of power generation from other energy sources composed of the comprehensive utilization of waste heat and residual pressure and shallow geothermal energy was 1.48 million kilowatts, accounting for 3% of the total installed capacity of all power sources in Shanghai. The adopted technical transformation route is to combine with the industrial layout, give full play to the aggregation advantages of various types of energy in industries such as steel, electricity, and petrochemicals, promote the work of the

“Hundred and One” Action for energy conservation and carbon reduction, and comprehensively develop and utilize the waste heat, cold energy, and differential pressure resources in areas such as Baosteel Base, Chemical Industry Zone, Gaoqiao Petrochemical, and Yangshan LNG Receiving Station. Through utilization methods such as waste heat (cold) and residual pressure power generation, waste heat refrigeration, waste heat external heating supply, and waste heat recovery, the comprehensive application of diversified energy is realized.

The contribution degree analysis is as follows:① In terms of forming the incremental peak - shaving and valley - filling capacity, by the end of the “14th Five - Year Plan,” the newly added waste heat (cold) and residual pressure projects in the whole city will increase the peak - shaving capacity for summer and winter peak loads by 60,000 and 40,000 kilowatts respectively. By the end of the “15th Five - Year Plan,” the peak - shaving capacity for summer and winter peak loads will be increased by 130,000 and 80,000 kilowatts respectively.② In terms of optimizing the energy structure, it is expected that in 2030 and 2060, the total installed capacity of power generation from other energy sources will reach 3.82 million and 7.64 million kilowatts respectively, and the proportion of the installed capacity accounting for the total installed capacity of all power sources in Shanghai in that year will be increased to 5% and 7% respectively.

3 Research review on technical measures for reducing the power peak - valley difference on the grid side and analysis of the contribution degree to Shanghai

In the power grid system, the grid security during peak hours has become the main contradiction in grid peak regulation. The unbalanced peak load will lead to energy supply interruption and cause huge losses. To ensure the safe operation of the power grid in each period, relevant peak regulation technologies and equipment in the power grid system are crucial. In view of the energy consumption characteristics and power development trend in Shanghai, the

TABLE 7 Comparison of two peak regulation modes of intelligent and orderly charging and discharging of electric vehicles.

Category	Algorithm optimization	Control strategy improvement
Research Trends	To reduce the adverse effects of disordered charging of electric vehicles on the power system, guide their orderly charging, reduce the peak-to-valley difference at the grid end, and thus improve the operational reliability of the power system	
Technical Route	Genetic algorithm (Leemput et al., 2012), particle swarm algorithm (Han et al., 2011)	Taking reducing the system peak-to-valley difference (Chen et al., 2021) and charging cost as multi-objective optimization (Zhang et al., 2022)
Both	The impact of electric vehicles on the distribution network in the next decade has been predicted and analyzed, and the charging and discharging characteristics during non-peak load periods are adjusted according to the demand response of V2G (Cheng and Wu, 2008), combining with the accommodation of renewable energy, using wind power for charging to reduce the peak load (Shin et al., 2014)	

grid - side peak regulation technology mainly outlines the intelligent and orderly charging measures for electric vehicles.

3.1 Intelligent and orderly charging and discharging of electric vehicles

Electric vehicles equipped with distributed mobile energy storage units have the advantages of being complementary to the large power grid, alleviating the power supply shortage of the power grid and improving the reliability of the power grid. As a new type of vehicle driven by storage batteries, an electric vehicle is not only a new type of load but also can supply power reversely to the power grid as a mobile power source. It can assist the power grid in accommodating new energy and participating in the ancillary services of the power market. California has implemented intelligent charging and discharging management for over 5,000 electric vehicles through its “V2G Pilot Programme”. During the summer heatwave of 2022, the orderly discharge of these vehicles provided approximately 50 MW of temporary power support, effectively alleviating peak pressure on the local grid. The interaction with the power grid is an inevitable trend for future development. Based on the current development status of electric vehicles in Shanghai and the peak regulation requirements, this paper summarizes the current research trends of improving the peak regulation capacity of the electric vehicle system. Modeling approaches include ordered charging optimization models based on improved particle swarm algorithms, V2G scheduling models considering user behavior, and game-theoretic models for ancillary service participation. We form a comparison from subdivided research perspectives, as shown in Table 7. Overall, compared with other developed countries, the development speed of V2G technology in China is relatively slow, and it is mostly based on theory, but it has great development prospects. Recent research on microgrid optimization also supports the potential of V2G systems in enhancing urban energy resilience and peak load management (Kar et al., 2024).

Ordered Charging (V1G) and Vehicle-to-Grid (V2G) represent two distinct developmental stages for electric vehicles’ participation in grid dispatch, differing markedly in technical complexity and value creation potential. Ordered Charging (V1G) involves unidirectional control of charging timing and power to achieve ‘peak shaving and valley filling’. It boasts high technical maturity,

minimal impact on battery degradation, and low user acceptance barriers, making it the most practical and scalable model for current implementation. Its core value lies in shifting EV load from peak to off-peak periods, thereby optimising load curves. Vehicle-to-Grid (V2G), conversely, enables bidirectional energy flow. EVs function as mobile energy storage units, discharging power back to the grid to provide multiple ancillary services such as peak shaving, frequency regulation, and reserve capacity. While offering greater value creation potential, V2G demands exceptionally high standards in battery technology, communication protocols, power electronics, and market mechanisms, remaining largely in the demonstration and exploratory phase. Shanghai’s implementation strategy should proceed in phases. In the short term (through the end of the 15th Five-Year Plan), prioritise the widespread adoption of orderly charging (V1G). In the medium to long term, as battery technology advances and V2G costs decrease, focus should shift to piloting V2G within dedicated vehicle sectors such as public transport and logistics. This will explore viable business models for V2G’s participation in the electricity market.

The current situation, technical transformation routes, and contribution degree analysis are as follows: By the end of 2022, there were 285 charging facility operation enterprises connected to the municipal-level platform in this city, and approximately 146,000 public charging piles were connected. Actively promote the construction of charging demonstration stations in old residential areas in the central urban area and taxi demonstration stations across the city. 68 residential area demonstration stations and 55 taxi demonstration stations have been completed. The adopted technical transformation route is to support the comprehensive implementation of intelligent replacement of 240,000 existing non-intelligent charging piles in the city that meet the conditions before 2026 through government procurement. Steadily promote the demonstration of intelligent vehicle-to-grid discharging in public charging stations and residential areas, and construct “ten stations and one hundred piles” pilot projects every year. By the end of the “15th Five-Year Plan”, a storage and discharging regulation capacity of tens of thousands of kilowatts of electric vehicles will be formed.

The contribution degree analysis is as follows: It is expected that by the end of the “14th Five-Year Plan”, 500,000 intelligent charging piles can be incorporated into the intelligent and orderly charging management system. By the end of the “15th Five-Year Plan”, 880,000 intelligent charging piles will be incorporated into the intelligent and

orderly charging management system. By the end of the “14th Five-Year Plan”, the peak shaving capacity for summer and winter peak loads will be no less than 150,000 kilowatts and 450,000 kilowatts respectively, and the valley filling capacity will be no less than 750,000 kilowatts. By the end of the “15th Five-Year Plan”, the peak shaving capacity for summer and winter peak loads will be no less than 220,000 kilowatts and 660,000 kilowatts respectively, and the valley filling capacity will be no less than 1,100,000 kilowatts.

3.2 Grid-side intelligent dispatching technology

In line with the trend of the global energy structure transformation and the rapid development of digital technology, power grid dispatching operation is at a critical moment of technological change. The traditional centralized control method has gradually become difficult to meet the needs of complex and dynamic power grid systems. Especially with the wide deployment of distributed energy resources, electric vehicles and energy storage technologies, in order to meet the multi-dimensional nature of source-grid-load-storage variables, it is more necessary to integrate technologies such as smart grid, big data and artificial intelligence to provide technical support for the deployment of the above facilities, and present the technical effects and update the technological iteration. Based on the current situation of grid-side intelligent dispatching technology in Shanghai and the peak regulation requirements, this paper summarizes the current research trends of improving the peak regulation capacity of grid-side intelligent dispatching technology and forms a multi-dimensional analysis including comparison of subdivided research perspectives, effect evaluation, improvement measures and development directions, as shown in Table 8.

4 Research review on technical measures for reducing the power peak - valley difference on the load side and analysis of the contribution degree to Shanghai

The peak regulation demand brought by the load side is quite significant. Therefore, the technology for reducing the power peak-to-valley difference on the load side is particularly important. In view of the energy consumption characteristics and power development trend in Shanghai, the load-side peak regulation technology mainly outlines the measures for the management of air-conditioning loads in public buildings and the “carbon inclusive” application of air-conditioning loads in households and enterprises.

4.1 Management of air - conditioning loads in public buildings

The air-conditioning load management of public buildings is an important means of load-side peak regulation, which is mainly divided into rigid control and flexible control. Rigid control mainly manages the air-conditioning load through operations such as shutting down the main unit, shutting down the circulating

system, or shutting down the terminal fan coil unit. Flexible control obtains the regulatory capacity that is nonlinear and volatile, that is, the regulated load. By superimposing the basic load and the regulated load, the target virtual peak regulation load is obtained. The PJM grid in the United States successfully coordinated the air conditioning systems of over 10,000 commercial buildings through its demand response programme during the summer peak period of 2021, achieving a peak load reduction of approximately 1.2 GW. Air conditioning load regulation contributed over 30% to this reduction. Based on the current development status of air-conditioning load management in public buildings in Shanghai and the peak regulation requirements, this paper summarizes the current research trends of improving the peak regulation capacity of air-conditioning load management in public buildings and forms a comparison of subdivided research perspectives and a summary of cases, as shown in Table 9.

‘Setpoint temperature control’ and ‘altering operating modes’ represent two distinct technical philosophies in air conditioning load management. “Setpoint temperature control” constitutes flexible regulation, offering advantages such as being “imperceptible” or “barely perceptible” to users, high societal acceptance, and ease of large-scale deployment. However, its single-point control capability is limited, requiring aggregation of substantial loads to achieve significant effects. “Changing operating modes,” exemplified by ice storage cooling, constitutes rigid or semi-rigid control. It delivers highly effective peak shaving but necessitates retrofitting or constructing dedicated cold storage facilities, entailing high initial investment. This approach is better suited to new large-scale public buildings. Shanghai should adopt a strategy combining both rigid and flexible approaches. For the tens of thousands of existing public buildings across the city, flexible control technologies should be prioritised. Integrating these into load management systems can generate substantial aggregated peak-shaving capacity. For new large-scale landmark buildings, airports, railway stations, and similar facilities, rigid control technologies such as ice storage cooling should be mandatorily incorporated during the design phase. These should be leveraged as critical localised peak-shaving resources.

The current situation, technical transformation route and contribution degree analysis are as follows: Strengthen the temperature management of air conditioners in public buildings, advocate the air-conditioning temperature control requirements of no lower than 26 °C in summer and no higher than 20 °C in winter, and strengthen the monitoring, inspection and supervision of air-conditioning temperature control. According to the principle of “from large to small, easy first and difficult later”, focusing on public institutions and commercial buildings, promote users to install air-conditioning load regulation and environmental monitoring devices and connect to the load management system of the new power system. During the city’s load peak, respond to the grid temperature regulation instructions in the mode of “no perception in half an hour and slight perception in 1 hour” to achieve precise regulation of air-conditioning loads.

Contribution degree analysis: It is expected that by the end of the “14th Five-Year Plan,” 1,000 users will be connected, and the air-conditioning management scale will reach 1 million kilowatts. By the end of the “15th Five-Year Plan,” a cumulative total of 3,000 users will be connected, and the air-conditioning management scale will reach 2 million kilowatts. By the end of the “14th Five-Year Plan,” the peak shaving capacity for summer and winter peak loads will be

TABLE 8 Comparison of grid-side intelligent scheduling modes.

Category	Multi-source collaborative optimal scheduling technology for active distribution network		Research on optimal scheduling method of power grid considering mutual aid of peak regulation resources	
Research Trends	The optimization direction is from single power supply radial distribution network to multi-source optimal scheduling (Mazidi et al., 2016)		Make full use of peak regulation resources to improve the absorption capacity of clean energy and reduce the system peak regulation cost at the same time (Pilo and Soma, 2011)	
Technical Route	Enhance the handling of various uncertainties on the source-load side	Improve the active-reactive power collaborative scheduling optimization of active distribution network	Research and Optimization of Unit Peak Regulation Characteristics	Mutual Aid of Peak Regulation across Regional Power Grids
	Latin hypercube is used to generate a large number of random scenarios to simulate and reduce the risk situations in the operation process of new energy resources such as wind and solar (Yunlong et al., 2020), the confidence level is used to describe and reduce risk and uncertainty (Shuqiang et al., 2021)	Reduce active power network loss (Liu et al., 2021) and reactive power network loss (Liu et al., 2022a),construct an active-reactive power collaborative optimal scheduling model for active distribution network, and set up multiple partitions (Guo et al., 2021), multiple stages to achieve multi-objective optimization (Yan et al., 2019)	Deep peak regulation operation cost model of coal-fired units (Ying et al., 2020), electricity quantity plan execution model (Yanchun et al., 2018), ancillary service undertaking model (Yang et al., 2020)	Operation mechanism of inter-provincial peak regulation trading market (Haiyu et al., 2020), peak regulation demand assessment model of provincial power grid (Lu et al., 2015)
Effect Evaluation	The experimental results lack universality due to high requirements for probability level	All have proved the active-reactive power collaborative optimal operation among adjustable resources	Effectively improve the economic benefits of the peak regulation operation range of respective units	The future research direction is to continuously optimize from provincial level to regional level and from single objective to multi-objective
Improvement Measures	The modeling analysis using the robust optimization model is feasible for the whole interval but is rather conservative and worthy of in-depth research (Zhou and Qian, 2020)	Improving the security of distribution network and solving key problems such as voltage limit violation and line loss need to attract research attention		

no less than 300,000 and 200,000 kilowatts respectively. By the end of the “15th Five-Year Plan,” the peak shaving capacity for summer and winter peak loads will be no less than 600,000 and 400,000 kilowatts respectively.

4.2 “Carbon inclusive” application of air - conditioning loads in households and enterprises

As one of the important carbon emission sources in load-side management, the potential for emission reduction in the consumption fields of residents and enterprises is quite significant. For this reason, various regions around the world have successively formulated relevant systems and supporting policies to promote the process of users’ low-carbon lifestyles. “Carbon Inclusive” is one of the initiatives that have been explored for a relatively long time and have initially shown certain effectiveness. Shenzhen has registered over two million users through its “Carbon Benefits” platform. In 2023, incentive measures targeting air conditioning temperature settings enabled load adjustment of approximately 50 MW during

summer peak periods. Beijing, meanwhile, has employed a “Green Living Points” mechanism to encourage residents’ participation in air conditioning load regulation, cumulatively reducing peak loads by around 30 MW. Based on the current development status of the “Carbon Inclusive” application of air-conditioning loads in households and enterprises in Shanghai and the peak regulation requirements, this paper summarizes the current research trends of the “Carbon Inclusive” application of air-conditioning loads in households and enterprises and forms a comparison of subdivided research perspectives as well as a summary of pain points and difficulties, as shown in Table 10.

The current situation, technical transformation route and contribution degree analysis are as follows: By the end of 2022, Shanghai has not yet formed a “carbon inclusive” methodological system that can be promoted to the whole society. In the research on user energy consumption behavior, the air-conditioning load in the city’s maximum load accounts for about 48%, and the proportion of air-conditioning loads of residents and enterprises in the total load has exceeded 40%. The adopted technical transformation route is to research and establish a “carbon inclusive” methodology with the active control of air-conditioning load as the

TABLE 9 Comparison of two peak - regulation modes of air - conditioning load management in public buildings.

Category	Air-conditioning set temperature control		Changing the operating mode of the air-conditioning system
Research Trends	By changing the operating parameters of the air-conditioning system, such as frequency conversion and adjusting the chilled water temperature, on the important basis of ensuring the users' thermal comfort, the power peak-to-valley difference is minimized, and the performance is continuously optimized		By changing the operating mode of the air-conditioning system, such as global temperature control and ice storage cooling, existing cases have achieved the same effect of reducing the peak-to-valley difference as large energy storage power stations, showing good development potential
Technical Route	Minimum enthalpy value estimation (Tran-Quoc et al., 2009), load feedback control (Lei et al., 2014), individual control separation (Duncan and Hiskens, 2011), cluster air-conditioning load frequency modulation (Li and Wang, 2015)		Different media (Hu et al., 2016), different numbers of units (Fankang et al., 2018), different start-stop strategies (Xu et al., 2016)
Case	United States (Deng et al., 2014)	Japan	Huangpu District, Shanghai (Anonymous, 2014)
	The central air-conditioning alternate shutdown technology realizes the batch grouping of users and alternate shutdown by batch	The preferential tariff strategy in the valley period is used to cut peaks and fill valleys	Through the instructions of the operation and dispatching platform, the reasonable control of users' electrical equipment such as air-conditioners is realized in a flexible adjustment manner (Xu, 2023)

TABLE 10 Comparison of two peak - regulation modes of “carbon - inclusive” application of air - conditioning loads for households and enterprises.

Category	Algorithm optimization	Control strategy improvement
Research Trends	Unify the carbon inclusive accounting methodology and connect related application scenarios	To continuously develop the carbon inclusive application, institutional and mechanism suggestions are put forward. While effectively connecting relevant national and local policies, it provides innovative ideas and long-term guarantees for the long-term development of the carbon inclusive application in the future. Some of them have been promoted for trial use and received effective feedback
Technical Route	In different regions (Liu et al., 2022b), different supporting policy systems (Pan and Du, 2021), by creating multiple entities (Gao, 2022), the future models and work processes that can be adopted in different application scenarios (Liu and Fang, 2022)	Starting from dimensions such as laws and regulations (Hou et al., 2023), framework formulation (Liu and Liu, 2023), and system construction (Wang, 2022) involving the digital RMB and market incentive mechanism sectors
Problem	The problems like the absence of top-level design, imperfect standard system, imperfect platform technical system, and insufficient publicity are gradually resolved, endowing carbon inclusive with the power to assist low-carbon development (Zhang, 2021) and energy structure transformation (He, 2023)	

key application scenario, carry out “carbon inclusive” demonstration applications for multiple entities such as relevant enterprises and resident users, and guide users to actively participate in “carbon inclusive” applications and voluntarily adjust air-conditioning loads. Contribution degree analysis: By the end of the “14th Five-Year Plan”, the peak shaving capacity for summer and winter peak loads will be no less than 150,000 and 100,000 kilowatts respectively. By the end of the “15th Five-Year Plan”, the peak shaving capacity for summer and winter peak loads will be no less than 200,000 and 150,000 kilowatts respectively.

5 Research review on technical measures for reducing the power peak - valley difference by energy storage methods and analysis of the contribution degree to Shanghai

Using energy storage devices to achieve peak shaving and valley filling is a crucial measure to balance power supply and demand, stabilize fluctuations on both sides of supply and demand, and deal with and reduce peak loads. Recent reviews have emphasized

the integration of renewable energy with storage systems as a key strategy for enhancing grid flexibility and reliability (Kumar et al., 2023). According to different application links, energy storage includes power source side energy storage, which, by coupling with renewable energy, stabilizes output fluctuations; grid side energy storage, which realizes peak shaving, valley filling, peak regulation and frequency modulation through coordinated dispatching; and user side energy storage, which affects user behavior through a tiered peak-valley electricity price system and realizes cross-time optimization of demand. Regardless of which energy storage technology it is, through market mechanisms and coordinated dispatching, it can further improve the comprehensive utilization efficiency of energy, optimize electricity consumption plans, reduce enterprise energy consumption costs, and thereby reduce the pressure on the grid load. It can be seen that energy storage integrates and plays an important role in the three-side applications. Therefore, a separate chapter is set to summarize the technical measures for achieving peak shaving and valley filling using energy storage devices, which are mainly divided into pumped storage and new energy storage.

5.1 Pumped storage

Pumped storage power stations in physical energy storage have a relatively wide range of capacity provision thresholds (with installed capacity mostly between 300,000 and 2 million kilowatts), possess relatively complete functions (including peak regulation, frequency modulation, voltage regulation, reserve capacity, black start, peak shaving and valley filling, etc.), have excellent regulation characteristics (in terms of regulation speed, they can reach full output operation from a static state within hundreds of seconds; in terms of peak regulation ability, they can provide deep peak regulation ranging from 0% to 220%), enjoy superior environmental protection benefits (as they do not directly generate carbon emissions), have a high level of technological maturity (having achieved commercial applications long ago), and good economic benefits (with a capacity cost of about 100 yuan/kWh, which has an absolute advantage among energy storage methods and a cost per kilowatt-hour reduced due to the scale effect to 0.3 yuan/kWh). They are widely used. The Anji Pumped Storage Power Station in Zhejiang, China, boasts an installed capacity of 1.8 million kilowatts. During the peak period of the East China Power Grid in summer 2022, through rapid response dispatch, it successfully reduced peak load by approximately 1.5 million kilowatts, effectively lowering the grid's peak-to-valley difference ratio by about 5%. Based on the current development status of pumped storage in Shanghai and the peak regulation requirements, this paper summarizes the current research trends of pumped storage for peak regulation applications. Modeling approaches include dynamic economic dispatch models integrating pumped storage with renewable energy, chaotic fast convergence algorithms for multi-region scheduling, and environmental cost-inclusive optimization models. We form a comparison of subdivided research perspectives and a summary of the technical transformation routes for optimized development, as shown in Table 11.

The current situation, technical route and contribution degree analysis are as follows: By the end of 2022, there is currently

no pumped storage power station site resource in Shanghai, and electricity distribution needs to be obtained through investment. The adopted technical route is to take investment as a link and focus on Zhejiang and Anhui, actively strive for the pumped storage resources under construction and in planning in the East China region. It is expected that by the end of the "15th Five-Year Plan", 2 - 3 pumped storage power stations will be built, and more than 3.6 million kilowatts of pumped storage installed capacity will be added. Contribution degree analysis: ① In terms of forming incremental peak shaving and valley filling capacity, by the end of the "15th Five-Year Plan", the peak shaving capacity for summer and winter peak loads will be increased by 3.6 million kilowatts, and the valley filling capacity will be 3.6 million kilowatts. ② In terms of optimizing the energy structure, it is expected that in 2030 and 2060, the total installed capacity of pumped storage will remain at 3.6 million kilowatts, and the proportion of the installed capacity in the total installed capacity of all power sources in Shanghai in that year will be 5% and 3% respectively.

5.2 New energy storage

To further balance the problem of power supply and demand mismatch, more auxiliary service providers with sufficient capacity and response capabilities are required to enter the power market. Therefore, new energy storage methods have gradually emerged. The Hornsdale Energy Storage Project in South Australia (capacity 150 MW/194 MWh) delivered over 200 GWh of flexible power support to the grid through frequency regulation and peak shaving services between 2019 and 2022, successfully reducing the regional peak-to-off-peak ratio from 45% to 38%. Based on the current development status of new energy storage in Shanghai and the peak regulation requirements, this paper summarizes the current research trends of new energy storage for peak regulation applications and forms a comparison of subdivided research perspectives and a summary of the technical transformation routes for optimized development, as shown in Table 12.

Electrochemical energy storage and hydrogen storage represent key technologies for addressing challenges across different timescales. Electrochemical storage (primarily represented by lithium-ion batteries) exhibits linear cost increases over extended periods, rendering it economically unviable for solving multi-day, multi-week, or even seasonal energy storage requirements. Hydrogen storage systems suffer from relatively low efficiency (with an electrolyser-to-fuel cell cycle efficiency of approximately 40%), currently high costs, and inadequate infrastructure. Shanghai must clearly define the positioning and development sequencing for both technologies. In the near term (up to 2030), focus should be placed on electrochemical storage. Accelerate the deployment of demonstration projects on both the grid side and the consumer side (e.g., data centres, industrial parks) to rapidly establish peak-shaving capacity. In the medium to long term (2030–2060), strategic deployment of hydrogen storage should be pursued. This should integrate with offshore wind power and wind-solar bases outside the city, conducting 'electricity-hydrogen-electricity' or 'electricity-hydrogen-fuel' demonstrations. Key technologies must be mastered and costs reduced to build technical reserves

TABLE 11 Comparison of two peak regulation modes of pumped storage.

Category	Research on the development of pumped storage power stations that better meet peak regulation requirements		Research on peak regulation of a combined system considering pumped storage power stations	
Research Trends	High head, large capacity, high speed	Underground pumped storage to achieve the effect of “resource reuse” (Zheng et al., 2023)	Improve peak regulation economy	Optimization of dispatch model and solution algorithm
Technical Route	Process optimization such as rotor assembly and ball valve installation (Peng et al., 2023)	Different development methods (He et al., 2023), safety monitoring mechanism (Liu, 2018), stress field (Fan et al., 2018), rock mass structure (Lin et al., 2021)	Pumped storage-assisted conventional units participate in power system peak regulation (Mel and ikoglu, 2017) and based on suppressing the uncertainty of wind and solar power, joint optimization of pumped storage and new energy units (Zhang et al., 2020b)	Consideration of environmental costs (Peng, 2018), consideration of complementary operation characteristics of the combined system (Cao et al., 2021), multi-region dynamic solution method of chaotic fast convergence evolutionary programming (Basu, 2019)
Optimized development	Realize adjustable speed pumped storage power stations with better dynamic regulation performance (Junhui et al., 2019)			

TABLE 12 Comparison of two peak regulation modes of new energy storage.

Category	Electrochemical energy storage		Hydrogen energy storage	
Advantages	Electrochemical energy storage features a rapid response speed to dynamic changes. The storage and release of electric quantity enable a two-way regulation of electric energy, and it is less affected by environmental conditions. Therefore, it has unique advantages in the auxiliary service market such as peak regulation		As a relatively emerging power-to-hydrogen technology for long-duration energy storage, provides new ideas for solving the problem of wind and solar curtailment	
Research Trends	Lithium-ion batteries, with a rated power reaching the gigawatt level (Pei, 2022), comply with the current development trend of large-capacity energy storage power stations. They provide an alternative power source for power stations, which can be used for frequency control, suppressing fluctuations and so on		Solving the problem of wind and solar curtailment	Research on hydrogen energy in the integrated energy system
Technical Route	It can be combined with distributed power generation systems (Shi and Yongqi, 2010)	It perfectly combines the two properties of large capacity and portability (Peng, 2018)	The construction idea of the electricity-hydrogen integrated station (Gu et al., 2022)	Power to X model, multi-source energy storage system of electricity, heat and hydrogen (Hu et al., 2023)
Comprehensive evaluation	For a fairly long period of time, it is the secondary electrochemical energy storage battery with the best market prospects and the fastest development. It is an important direction for large-scale energy storage technologies in modern power systems to reduce the peak-to-valley difference		It effectively improves the ability of the power grid to shave peaks and fill valleys as well as the absorption ability of renewable energy	Effectively reduces the cost of deep-sea offshore wind power

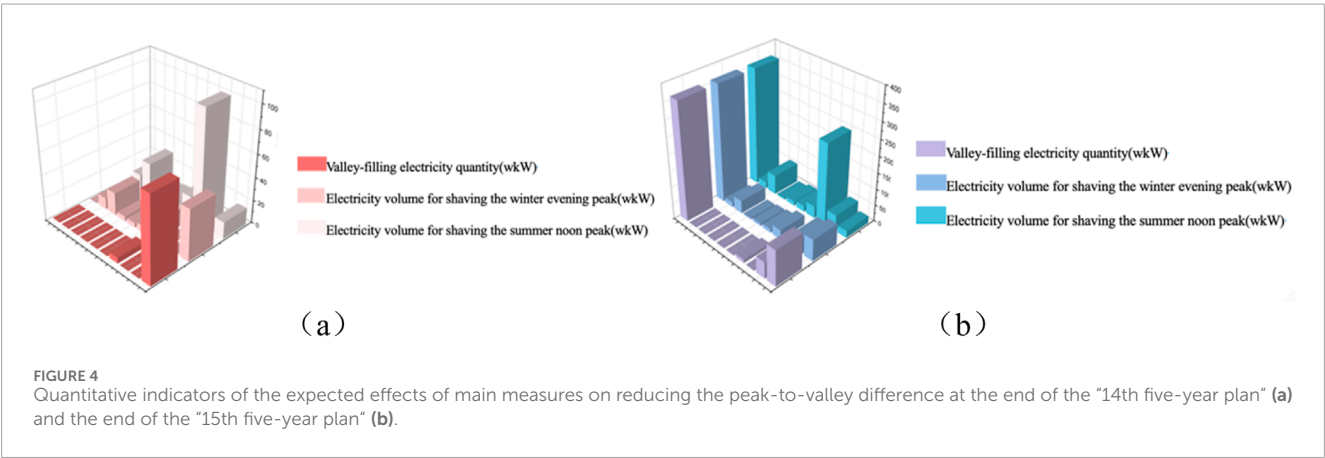
and industrial readiness for ultimately resolving seasonal energy balancing challenges.

The adopted technical transformation route is to focus on end-users such as big data centers, 5G base stations, and industrial parks, promote the construction of integrated joint-regulation and joint-transportation demonstration projects with new energy storage as the core, and provide subsidies. At the same time, closely monitor the development of the entire hydrogen energy industry chain, including renewable energy hydrogen production, hydrogen storage and transportation technologies, and hydrogen-based fuels. Timely layout hydrogen energy bases around the access of large-scale non-fossil energy such as external power into Shanghai, deep-sea offshore wind power, island nuclear power, and hydropower, so as to support hydrogen energy in playing a regulatory role in both the supply and

demand sides of the power grid and balancing the long-cycle peak-to-valley difference of the future new power system. Contribution degree analysis: ① In terms of forming incremental peak shaving and valley filling capacity, it is expected that by the end of the “15th Five-Year Plan”, 500,000 kilowatts of new energy storage facilities will be newly built, increasing the peak shaving capacity for summer and winter peak loads by 500,000 kilowatts and the valley filling capacity by 500,000 kilowatts. ② In terms of optimizing the energy structure, it is expected that by 2060, the total installed capacity of nuclear power will reach 4.5 million kilowatts, and the proportion of the installed capacity in the total installed capacity of all power sources in Shanghai (11,300 kilowatts) in that year will increase to 4%. It is expected that by 2030 and 2060, the total installed capacity of wind power will reach 5 million and 28 million kilowatts respectively, and

TABLE 13 Comparative analysis of peak-shaving strategies under different urban contexts.

Strategy	Strengths	Weaknesses	Suitable city scales	Suitable energy mixes
Thermal Retrofit	High reliability, fast response	High carbon, fossil-dependent	Megacities	Coal-dominated, hybrid
Distributed PV	Peak shaving, rooftop utilization	Intermittency, storage needed	Medium to large cities	Solar-rich, high renewable target
Gas Distributed Energy	High efficiency, rapid deployment	Gas dependency, not zero-carbon	Growing urban areas	Gas-available, mixed energy
Geothermal	Stable base load, low emission	High upfront cost, site-specific	Cities with geothermal resources	Diversified, low-carbon
Pumped Storage	Large capacity, long duration	Geographic constraints	Regions with topography	High renewable penetration
EV Ordered Charging	Utilizes existing infrastructure	Requires smart grid support	All scales	Electrified transport system



the proportion of the installed capacity in the total installed capacity of all power sources in Shanghai in that year will decrease to 7% and 25% respectively.

6 Summary of technical measures for reducing the power peak-to-valley difference in Shanghai Based on the "source-grid-load-storage" integration and analysis of their utility in optimizing the energy structure

6.1 Form the ability of incremental peak shaving and valley filling

A comparative analysis of peak-shaving strategies across different urban contexts in relation to the aforementioned strategy is presented in Table 13.

Overall, Shanghai needs to fully implement the strategic deployment of "dual carbon", accurately grasp the characteristics of urban energy consumption and the trend of power development, combine short-term and long-term considerations, make scientific plans, and coordinate the efforts of the four aspects of "source, grid, load, and storage" to strive to control and reduce the power peak-to-valley difference. These strategies are supported

by integrated modeling frameworks such as multi-time-scale scheduling models, source-load-storage coordination models, and multi-objective optimization models considering both economic and environmental objectives. While safeguarding the bottom line of energy security, it should continuously enhance the regulation and guarantee capabilities and the level of clean energy of the Shanghai power system, and accelerate the construction of a new energy system featuring safety, high efficiency, flexibility, and resilience and meeting the needs of low-carbon transformation. The development goals for different periods are as follows, and the quantitative indicators are shown in Figure 4.

- During the "14th Five-Year Plan" period, in terms of development goals, it is necessary to accelerate the improvement of the peak-to-valley difference regulation capacity and actively plan the layout of energy storage. First, mainly on the user side, research and explore countermeasures such as intelligent and orderly charging of electric vehicles, optimized layout of distributed photovoltaic and energy supply systems, development and utilization of low-grade energy, and regulation of air-conditioning loads. Cooperate with the transformation of thermal power units to quickly form the capacity to reduce peak loads on the basis of the original demand-side response capacity, focusing on alleviating the contradiction of daily peak-to-valley regulation. Second, actively plan the layout of energy storage, conduct

resource surveys, and complete the preliminary work for the construction of large-capacity energy storage devices. In terms of total indicators, it is expected that by 2025, on the basis of 2022, the capacity to reduce summer and winter peak loads will be about 2 million and 1 million kilowatts respectively, and the valley filling capacity will be about 800,000 kilowatts. The daily peak-to-valley difference and seasonal peak-to-valley difference will be controlled at about 17.7 million and 28 million kilowatts respectively. In terms of sub-item indicators, the capacity to reduce summer and winter peak loads and the incremental regulation capacity for valley filling formed by various measures at the end of the “14th Five-Year Plan” are shown in Figure 4A. In terms of shaving the summer noon peak, the incremental regulation capacity to shave the summer noon peak formed by photovoltaic development is the strongest, reaching 1 million kilowatts, followed by the management of air-conditioning loads in public buildings, which is 300,000 kilowatts. In terms of shaving the winter evening peak, the incremental regulation capacity to shave the winter evening peak formed by intelligent and orderly charging of electric vehicles is the strongest, reaching 450,000 kilowatts, followed by the management of air-conditioning loads in public buildings, which is 200,000 kilowatts. In terms of valley filling, the incremental regulation capacity to fill the valley formed by intelligent and orderly charging of electric vehicles is the strongest, reaching 750,000 kilowatts, followed by the distributed energy supply of natural gas, which is 50,000 kilowatts. The construction and utilization of pumped storage and the development of new energy storage demonstration applications have a relatively long time cycle, and their incremental regulation capacities for peak shaving and valley filling are not considered during the “14th Five-Year Plan” period.

- During the “15th Five-Year Plan” period, in terms of development goals, focus on resources inside and outside the city to fully enhance the regulation potential of large-capacity energy storage. First, further tap the potential of load management measures in key fields, combine with the continuous improvement of the regulation capacity of thermal power units, continuously enhance the application scale and output effect of various measures to reduce the peak-to-valley difference, and promote the demonstration of pumped storage and new energy storage. Second, strengthen the construction of power grid supporting facilities and the power spot market, continuously form incremental regulation capacities, and simultaneously control the daily peak-to-valley difference and seasonal peak-to-valley difference. In terms of total indicators, it is expected that by 2030, on the basis of 2022, the capacity to actively reduce summer and winter peak loads will be about 8.3 million and 5.8 million kilowatts respectively, and the valley filling capacity will be about 5.3 million kilowatts. The daily peak-to-valley difference and seasonal peak-to-valley difference will be the same as those at the end of the “14th Five-Year Plan”. In terms of sub-item indicators, the capacity to reduce summer and winter peak loads and the incremental regulation capacity for valley filling formed by various measures at the end of the “15th Five-Year Plan” are shown in Figure 4B. The capacities to shave the summer

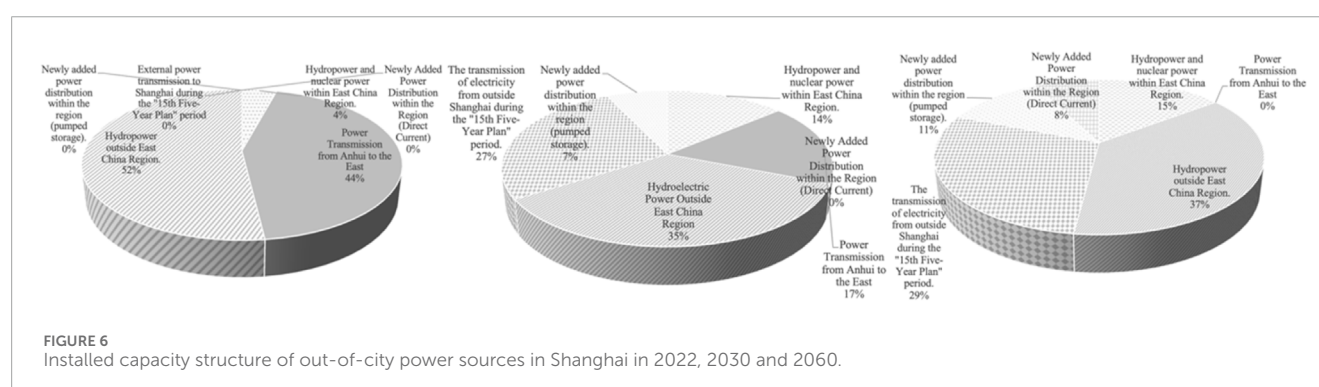
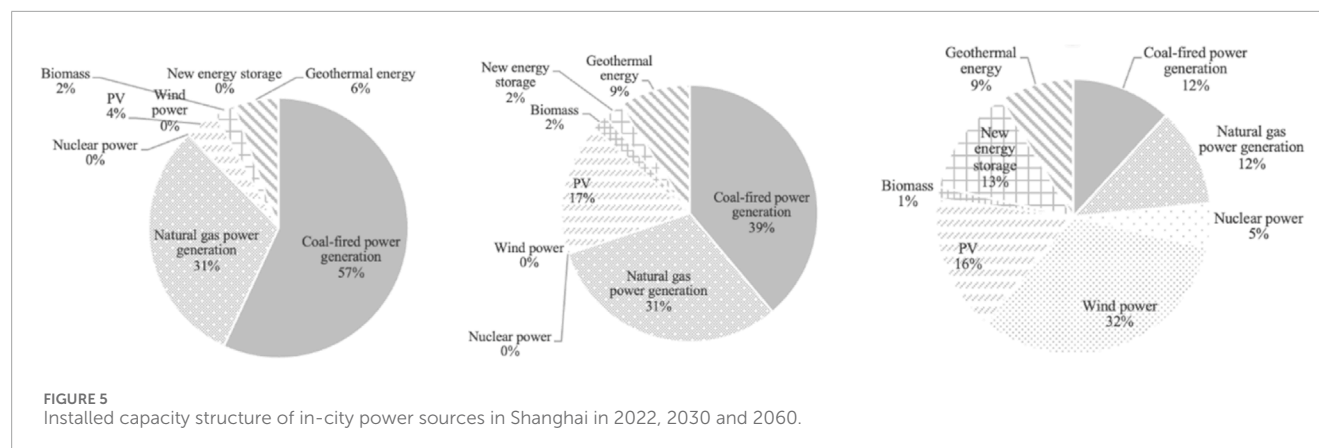
noon peak, shave the winter evening peak and fill the valley through the construction and utilization of pumped storage are all the strongest, and each can regulate 3.6 million kilowatts. At the same time, the incremental regulation capacity to shave the summer noon peak formed by photovoltaic development is the second strongest, reaching 2.5 million kilowatts, and the incremental regulation capacity to shave the winter evening peak and fill the valley formed by intelligent and orderly charging of electric vehicles is the second strongest, reaching 660,000 kilowatts and 110,000 kilowatts respectively.

- During the “16th Five-Year Plan” and in the long term, in terms of development goals, break through the bottleneck of seasonal difference regulation through long-term energy storage, and gradually promote the transformation of the energy structure. By breaking through the bottlenecks of long-term energy storage technologies such as hydrogen energy and hydrogen-based fuels, timely layout hydrogen energy bases around the access of large-scale non-fossil energy such as external power into Shanghai, deep-sea offshore wind power, and island nuclear power, providing strong support for hydrogen energy to play a regulatory role at both the supply and demand ends of the power grid and balance the long-period peak-to-valley difference of the future new power system.

6.2 Promote the optimization of the long-term energy structure

Against the backdrop of the continuous growth of total consumption in Shanghai, based on the analysis of the current situation, development goals, and implementation measures in Chapters 2 and 3, on the one hand, the total amount of carbon emissions from electricity and the emission factor of electricity consumption for the whole society will develop with a trend of a slight decline from the peak value in the medium to long term and a continuous significant decrease, from 0.78 billion tons and 4.0 tons/10,000 kWh in 2025 respectively. On the other hand, the energy structure will continue to be optimized, mainly manifested in the continuous reduction of coal consumption and the increase in the proportion of non-fossil and renewable power generation, as shown in Figures 5, 6.

- From the perspective of the in-city power source structure, the proportion of coal-fired power in the total in-city power source installed capacity will decrease from 53% in 2022 to 34.7% in 2030, and further to 11.8% in 2060. The proportion of renewable energy composed of wind power, photovoltaic power, biomass, new energy storage, and shallow geothermal energy in the total in-city power source installed capacity will increase from 18.3% in 2022 to 37.6% in 2030, and further to 71.4% in 2060. The proportion of non-fossil energy power generation, including nuclear power, will also increase from 18.3% in 2022 to 37.6% in 2030, and further increase significantly to 76.6% in 2060.
- From the perspective of the out-of-city power source structure, the proportion of Anhui Electricity Transmitted to the East, which is mainly thermal power, in the total out-of-city power source installed capacity will decrease from 43.9% in 2022 to



17.2% in 2030, and the transmission will stop in 2060. In terms of the proportion of non-fossil energy power generation, the proportion of hydropower, nuclear power inside and outside East China, hydropower within the region, and newly added pumped storage power distribution within the region in the total out-of-city power source installed capacity will change from 56.1% in 2022 to 55.8% in 2030, and then increase to 63.4% in 2060. The newly added power source base for external electricity entering Shanghai is preliminarily designated as the Kubuqi Desert in Inner Mongolia. The transmission capacity is 8 million kilowatts, the annual electricity transmission volume exceeds 40 billion kilowatt-hours, and the proportion of renewable energy power exceeds 50%.

plans, adaptive control systems, and recovery mechanisms. Thirdly, electric vehicles as flexible energy storage units. Whilst orderly charging of electric vehicles has been discussed, their potential as distributed mobile energy storage units (V2G) supporting the grid—particularly in peak shaving, frequency regulation, and emergency backup—requires deeper analysis. This should encompass market mechanisms, battery degradation modelling, and user behaviour modelling. Addressing these research gaps is crucial for advancing the integrated ‘generation-grid-load-storage’ framework and building more resilient, flexible, and sustainable urban energy systems.

Author contributions

YS: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. LZ: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft. YY: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft. QL: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software,

6.3 Research gaps and future directions

Although this paper proposes a comprehensive strategy, several research gaps remain to be explored: firstly, the integration of urban microgrids. The integration of urban microgrids with mainstream power systems, particularly their role in enhancing local energy autonomy and resilience, has not been sufficiently investigated. Future research should focus on microgrid control strategies, interoperability with the main grid, and economic viability. Secondly, resilience under extreme events. This study has not systematically examined the resilience of Shanghai's power system during extreme weather events or cyber-physical attacks. There is an urgent need to develop robust contingency

Supervision, Validation, Visualization, Writing – original draft. HZ: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft.

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Conflict of interest

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