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Simulation and economic analysis of the high-temperature heat storage system of thermal power plants oriented to the smart grid

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With the continuous increase of the grid-connected proportion of intermittent renewable energy, in order to ensure the reliability of smart grid operation, it is urgent to improve the operational flexibility of thermal power plants. Electric heat storage technology has broad prospects in terms of in-depth peak shaving of power grids, improving new energy utilization rates and improving the environment. It is an important means to promote electric energy substitution. In this study, the economics of technical application scenarios are compared and analyzed, the principle of solid heat storage technology is discussed, and its application in heating fields such as industrial steam, district heating, and deep peak regulation of congeneration units is expounded. The results indicate that in the scenario where the peak shaving subsidy and the heat storage duration are the same, as the unit output increases, the investment recovery period increases. Moreover, the results also indicate that in the 0.3 yuan/kW power market peaking subsidy scenario, only when the unit output is 0 and the heat storage time is greater than 8 h, the investment can be recovered in 5 years, while in the 0.7 yuan/kW power market peaking subsidy scenario, except for the scenario where the unit output is 40% and the heat storage time is 7 h, the investment cannot be recovered; in other scenarios, the investment can be recovered within 5 years.

KEYWORDS

smart grid (SG), high temperature, thermal energy storage (TES), economic analysis (EA), thermal power plant (TPP)

1 Introduction

In 2000, a smart power system concept was established with the primary goal of integrating two-way communication into the infrastructure of a standard grid system (Riaz et al., 2020; Fu et al., 2020; National Energy Administration, 2021). In order to achieve the goal of carbon neutrality, clean, efficient, and flexible operation has become an important goal of the transformation and development of the thermal power industry, and more and more attention has been paid to the flexibility transformation technology of thermal power plants (Fu et al., 2015; Riaz et al., 2020). Among them, the cost of the flexible retrofit, operating costs, and peak shaving benefits under the market rules of electric auxiliary services are the keys to choosing the most suitable retrofit technology (State Grid Corporation, 2013).

The summarized literature overview is tabulated in Table 1Ahmad et al., 2020, Long et al., 2022, National energy administration, 2019, Pasta et al., 2012. This is explained in greater detail as follows. In the recently released "Northeast Electric Power Auxiliary Service Market Operating Rules (Interim)" (Yang et al., 2011; Pasta et al., 2012; National energy administration, 2019; Ahmad et al., 2020; Long et al., 2022), the market rules have been further improved and upgraded (Hughes, 2010; Singh et al., 2015). The new rules design a day-head bidding mechanism for the peak rotating reserve market to achieve full coverage of the auxiliary service market "trough lows and peak peaks" (Fu et al., 2017). Only the two-way peak shaving units that can "go up and down" can obtain all the benefits of auxiliary services (Chinese Government, 2020) and put forward a complete flexibility standard for thermal power units, which can motivate and guide thermal power plants to adopt appropriate flexibility transformation technologies and comprehensively improve the peak shaving capacity of units (Rong et al., 2008; Deng et al., 2016). Among many energy storage technologies, thermal energy storage is one of the most promising large-scale energy storage technologies (Singh et al., 2016). Compared with other energy storage technology routes such as electrochemical energy storage and electrical energy storage, thermal energy storage has obvious advantages in terms of installed capacity, energy storage density, technology cost, service life, etc., (Huang et al., 2021). Compared with these two mechanical energy storage technologies, thermal energy storage technology has many advantages, such as small footprint, low cost, high energy storage density, small impact on the environment, and is not restricted by geographical and environmental conditions; it has obvious scale effects (Desrues et al., 2010). According to the needs of users, it can realize the combined supply of cold, heat, electricity, and steam of various energy grades; it can realize peak shaving and valley filling, two-way adjustment, and absorb the installed output of intermittent new energy (wind power, photo voltaic, etc.,) for the regional power grid (Rodríguez et al., 2009). The best solution is to balance the peak-to-valley difference; a large number of cycles, long life, and the bidirectional regulation function of the energy storage power station will not lead to a decrease in efficiency with long-term heat storage cycles (Suárez et al., 2015); no chemical reaction in the storage and storage processes and technical parameters and processes can be controlled, with high system security (Wang et al., 2015). Thermal energy storage technology can be applied to the power supply side, the grid side, and the user side (Hall et al., 1979). On the user side, thermal energy storage technology can be applied to user cooling, heating, electricity-integrated energy services, seawater desalination, and other occasions; in the direct utilization of thermal energy, thermal energy storage technology has higher energy utilization efficiency than electricity storage technology (Yang et al., 2018a; Yang et al., 2018b; Zhang et al., 2020); thermal technology also includes the storage and utilization of thermal energy below ambient temperature, that is, cold storage technology has been maturely applied in cold chain-related fields, and the market size is also expanding (Tao and He, 2015). For the power supply and grid side, the current power system presents a "double-high" characteristic of a high proportion of renewable energy and a high proportion of power electronic equipment, the system's moment of inertia continues to decline, and the frequency and voltage regulation capabilities are insufficient, posing severe challenges to grid security; solar thermal energy storage power generation can effectively realize frequency

TABLE 1 Comparative analysis of literature.

References	Heat storage medium	Maximum heat storage temperature/°C	Whether to consider peak shaving subsidies
Singh et al. (2015)	NaCl	800	No
Xu et al. (2013)	NaCl	600	No
Hughes. (2010)	$MgCl_2$	714	No
Fu et al. (2017)	$MgCl_2$	700	No
Tyagi and Buddhi. (2007)	LiF/CaF_2	767	No
Soprani et al. (2019)	Al/Si	577	No
Sowmy and Prado. (2008)	KNO_3, $LiNO_3$, Ca $(NO_3)_2$	500	No
Reboussin et al. (2005)	KNO_3, $LiNO_3$, Ca $(NO_3)_2$	600	No
Xu et al. (2015)	MgO	800	No
Qarnia. (2009)	MgO	700	No
Regin et al. (2006)	—	—	Yes
Fukahori et al. (2016)	—	—	Yes
Kandasamy et al. (2008)	—	—	Yes
Zhang and Liu. (2019)	—	—	No
Tian et al. (2021)	NaCl–$CaCl_2$	512.8	No
Our study	New composite materials	900	Yes

regulation through the rotational inertia of the steam turbine generator set; in the flexibility transformation of thermal power plants (Yaqub et al., 2016), the thermal energy storage power generation technology converts the excess steam heat that occurs when the unit operates with variable loads into a heat storage medium (Quan et al., 2013; Zhang et al., 2021b). The thermal energy is stored and released when needed, which can not only increase the peak shaving depth of the unit but can also increase the peak load capacity, with lower investment and operating costs, which has obvious advantages (Andersen, 2009). The Shapley value (SV) has been calculated to estimate the benefits of cooperative power suppliers (Tao et al., 2012). The presented case studies have verified that the proposed algorithm and the established bidding strategy exhibit higher effectiveness (Baños et al., 2011).

1.1 Motivation

From the aforementioned discussion, it is concluded that thermal energy storage already exists in a wide spectrum of applications. Sensible heat storage is used in pebble beds, packed beds, or molten salts for thermal solar power plants (Zhao and Wu, 2011; Li et al., 2017; Yin et al., 2020), in water heater storage (Denholm and Kulcinski, 2004; Denholm and Holloway, 2005; Sun et al., 2008; Zheng and Chen, 2008), and in blast or glass furnace regenerators (Carrasco et al., 2006), and it is the most used technology for heating and cooling of buildings Latent heat storage is used in buildings for passive storage systems such as phase change material walls, wall boards, and shutters (Bejan et al., 1996; Laing et al., 2006; Kuravi et al., 2013). As far as we know, solid heat storage devices with a thermal storage temperature of 900°C have not been considered for peak shaving in thermal power plants, and this study considers different peak shaving subsidy scenarios and peak shaving benefits of thermal power plants with high-temperature solid heat storage devices.

1.2 Contributions

The contributions of this study are summed up as follows.

1) A new type of high-temperature heat storage material is proposed, and its heat storage performance is compared with that of current main heat storage materials.
2) In the proposed model, according to the characteristics of the new heat storage material, THERMOFLEX simulation software was used to establish the deep peak-regulating model of the thermal power plant with a high-temperature heat storage device. The feasibility of applying the new heat storage material to deep peak regulation in thermal power plants is proved.
3) An economic analysis model is established considering the scenario of the peak-regulating subsidy, considering different load rates of units, heat storage duration, subsidies, and the corresponding capital recovery period. It provides a reference for the application of heat storage technology in practical projects.

1.2 Study organization

This study is organized as follows: Section 1 introduces the smart power system, its elements, and related research contribution, while Section 2 covers the architecture and flexible peak shaving technology for typical thermal power plants. The mathematical model and economic analysis of the high-temperature solid heat storage system are discussed in Section 3. The rest of the study is organized as follows. Simulation results are discussed in Section 4. Section 5 provides a brief summary of the whole article with concluding remarks.

2 Flexible peak-shaving technology for typical thermal power plants

At present, the flexibility of thermal power plants is mainly limited by the operation flexibility of "determining electricity by heat." Therefore, improving the peak-shaving capacity of the heating unit is the main content of flexibility transformation. The flexibility transformation of the heating unit is mainly divided into three categories (Bai et al., 2019). One is to increase the heating capacity of the unit, reduce the boiler output, and reduce the forced output of the unit under the condition of meeting the heating load (Verda and Colella, 2011). Second is the electric heating peak regulation technology, which converts the electric energy generated by the unit into heat energy for external heating, such as the electrode boiler technology and electric boiler solid heat energy storage technology; third is the thermal energy storage peak shaving technology, which converts excess steam thermal energy in steam turbines into thermal energy of energy storage medium for storage, such as the hot water tank energy storage technology, phase change thermal energy storage technology, concrete thermal energy storage technology, and molten salt thermal energy storage technology (Tyagi and Buddhi, 2007; Morisson et al., 2008; Cao et al., 2019; Wang et al., 2019; Xing et al., 2019; Ling et al., 2020).

2.1 Increasing the unit heat supply peak regulation technology

The peak-shaving technology to increase the heating capacity of the unit is mainly to reduce the work share of the steam inside the steam turbine and convert it into heat energy for external heating, which can reduce the forced output of the steam turbine unit and show a strong peak-shaving capacity (Kocak and Paksoy, 2020). The steam turbine bypass heat supply extracts the high-temperature and high-pressure steam with a strong performance for heating and shows great potential for peak shaving, but there is a lot of thermal economic loss and higher operating cost. Used for heating, the loss of cold source is eliminated, and the operating cost is low; however, they generally need to replace the special low-pressure cylinder rotor, and the cost of transformation is high (Sowmy and Prado, 2008).

2.2 Electric heating peak regulation technology

Electric heating peak regulating technology mainly includes the electrode boiler and electric boiler solid thermal energy storage technology, which does not involve the transformation of the main equipment of the thermal power plant and has little influence on the normal operation of the thermal power plant (Lizarraga-Garcia and Mitsos, 2014). The solid electrode boiler and electric boiler thermal energy storage lead to electric consumption directly, external power supply, reduce the thermal power plant to increase the load capacity, low load with a load, and the large depth operation flexibility, which are good advantages, but the disadvantages are the high investment cost, operation cost is high, and suit the market early gains' high load of the depth of the market demand, with the addition of more and more power plant auxiliary service markets (Miao et al., 2019). The demand for deep peak shaving is becoming less and less (Yin et al., 2020). In the market competition of cost sharing, it will be difficult for the heat supply peak-shaving technology with electric energy as the heat source to gain a competitive advantage (Laing et al., 2006).

2.3 Thermal energy storage peak regulation technology

The thermal energy storage peak-shaving technology is a peak-shaving technology that converts the excess steam heat that occurs when the unit is running at variable loads into thermal energy of the thermal energy storage medium and releases the heat energy when needed, thereby increasing the flexibility of the unit (Reboussin et al., 2005; Wu et al., 2015; Hao et al., 2019). For example, when there is an excess of heating steam in the heating season, the excess heat energy is stored in the thermal energy storage equipment (Jian et al., 2015). When the power load is at a low valley, the boiler load and steam turbine output are reduced to meet the low-load peak regulation requirements of the unit (Zhang et al., 2021a). Part of it is supplemented by thermal energy storage equipment; when the power load is at its peak, the boiler load is increased, the external heat supply of the steam turbine is reduced, the peak load capacity of the unit is enhanced, and the insufficient heat supply is supplemented by thermal energy storage equipment (Igreen, 2019).

To sum up, there is no high-temperature thermal energy storage technology that uses the deep peak-shaving period of thermal power plants to combine the high-temperature steam of the system with valley electricity for cascade storage and utilization.

3 Modeling and economic analysis of the high-temperature solid heat storage system

3.1 System model composition

A subcritical intermediate reheating self-heating cycle drum furnace is used, and the furnace type is HG1025/17.4-YM28. The steam turbine has a capacity of 300MW, is of subcritical intermediate reheat type, possesses a high- and medium-pressure cylinder, and is of double-cylinder double-exhaust steam single-shaft condensing type (Igreen, 2019; Zhang et al., 2021a; Thermoflow, 2021). The unit model is N300-16.7/538/538. The external supply of industrial steam by the unit is mainly divided into two specifications, namely, 1) 4.2 MPa, 420°C, 60–70 t/h; and 2) 1.8MPa, 320°C, 240 t/h.

3.2 Thermal storage system materials and performance

In this study, carbon-based high-temperature heat storage materials are used, which have the following characteristics (Soprani et al., 2019; Zhang et al., 2020; Fu, 2022; Zhang et al., 2022): 1) good heat storage and thermal conductivity (as shown in Table 2); 2) excellent high-temperature resistance characteristics, can be used under oxygen-free conditions, and the temperature can be up to 3,000°C; also, it has thermal shock resistance at high temperature and good mechanical strength; and 4) good self-lubricating performance (Duan et al., 2018; Liu et al., 2018).

3.3 System simulation and economic analysis model

3.3.1 Simulation model

THERMOFLEX software is a process simulation software application, especially developed for thermodynamics (Carrasco et al., 2006; Soprani et al., 2019; Zhang et al., 2020; Zhang et al., 2022). In terms of simulating steam balance, THERMOFLEX can complete the basic material and energy balance, and set up

TABLE 2 Performance comparison of typical heat storage materials.

Heat storage medium	Specific heat kJ/(kg·K)	Heat storage density kJ/kg	Thermal conductivity W/(m·K)	Heat storage temperature °C
Water-atmospheric pressure	4.2	105	0.6	70–95
Water-pressurized	4.2	252	0.6	70–130
Heat transfer oil	2.0	300	0.11	200–350
Concrete	0.85	425	1.5	100–600
Solid magnesia brick	1.2	480	2	200–600
Molten salt	1.6	528	0.52	220–550
New heat storage material	1.3	910	70–100	200–900

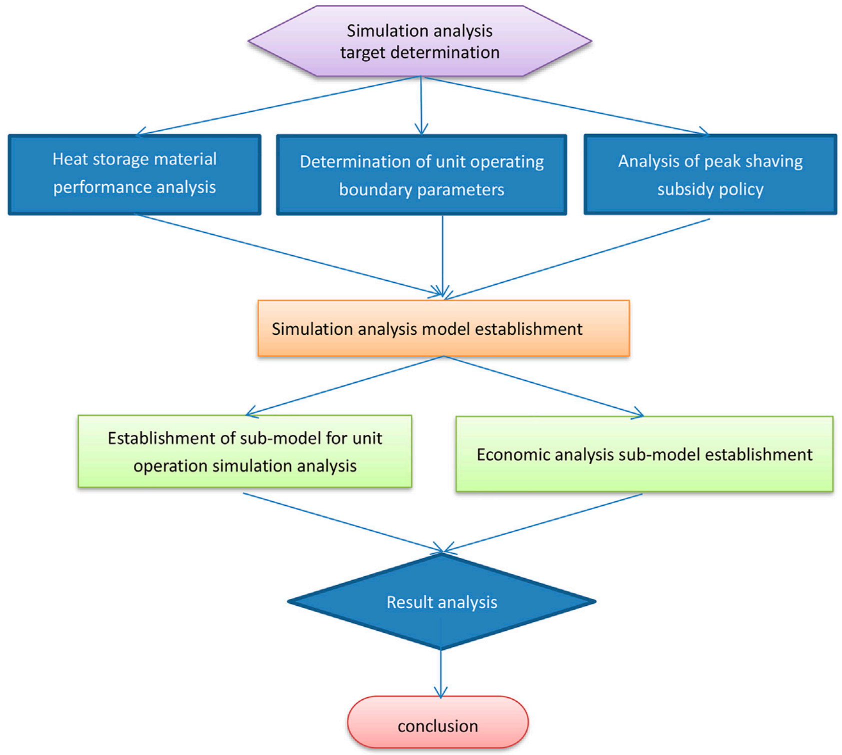

FIGURE 1
Proposed flow chart.

various logic controls integrated into the steam balance model usually.

3.3 2 System economic analysis model

$$Y = M - C. \tag{1}$$

Here, Y is the net income, yuan/y;M is the income, yuan/y; and C is the cost, yuan/y.

$$M = M1 + M2 + M3. \tag{2}$$

Here, M1 is the peak-shaving subsidy, yuan/y;M2 is the heat sales revenue, yuan/y; andM3 is the peak electricity revenue increase, yuan/y.

$$C = C1 + C2 + C3. \tag{3}$$

Here, C1 is the electricity cost, yuan/y;C2 is the financing charges, yuan/y; andC3 is the operation and maintenance cost, yuan/y.

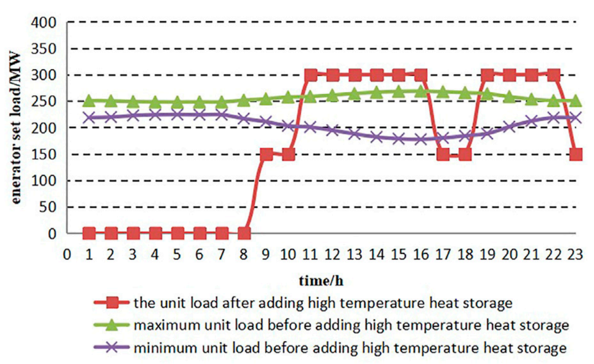

FIGURE 2
Output curves of units before and after adding high-temperature thermal energy storage devices.

4 Results and discussion

In the proposed framework, the overall framework is presented in Figure 1.

According to the new high-temperature solid heat storage system designed in this study, it can be seen from the following Figure 2 that the minimum load of the unit is effectively reduced under the condition of the constant heating load. It can increase the low-load peak load capacity of the unit but cannot increase the peak load capacity of the unit during peak load, and even the high back pressure circulating water heating transformation will reduce the unit's peak load capacity. According to the latest auxiliary service market rules, it belongs to the flexible transformation technology of “can go down but not go up” that cannot bring comprehensive peak-shaving benefits. High-temperature thermal energy storage enables thermal power plants to have “two-way” peak-shaving capabilities, which can increase the low-load operation capacity of thermal power plants and increase the top-load capacity during peak periods and can obtain complete peak-shaving benefits. Light (valley electricity) as a heat source and thermal energy storage have a good thermal economy and low operating costs. Therefore, the thermal energy storage peak-shaving technology has the best technical and economic competitive advantage.

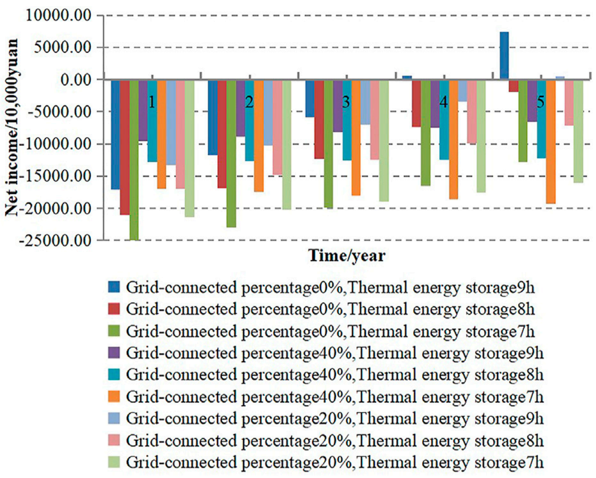

FIGURE 3
Comparison of investment returns under different outputs and heat storage duration of units (the peak-shaving subsidy is calculated at 0.3 yuan/kW).

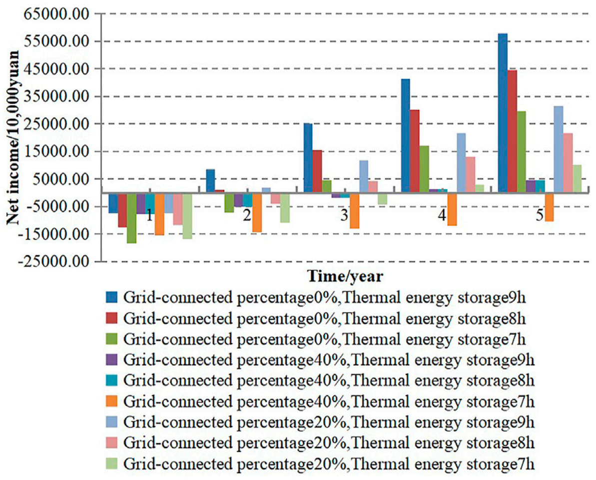

FIGURE 4
Comparison of investment returns under different outputs and heat storage duration of units (the peak-shaving subsidy is calculated at 0.7 yuan/kW).

The relative economic analysis is carried out using the static investment income. It calculated the return on investment years under the different outputs and heat storage time of the unit under the peak-shaving subsidy scenarios of 0.3 yuan/kW and 0.7 yuan/kW. It can be seen from Figure 3 that when the scenario of the peak-shaving subsidy in the power market is of 0.3 yuan/kW, all scenarios have static benefit years over 5 years, except that the output of the unit is 0 and the heat storage time is greater than 9 h. In addition, as shown in Figure 4, when the scenario of the peak-shaving subsidy in the power market is of 0.7 yuan/kW, all scenarios have static benefit years of less than 5 years, except that the output of the unit is 40% and the heat storage time is 7 h. Comparing Tables 3, 4, it can be seen that under the scenario of the peak-shaving subsidy in the power market of 0.3 yuan/kW, the investment can be recovered in 5 years only when the output of the unit is 0 and the heat storage time is greater than 8 h. In the scenario of the peak-shaving subsidy in the/kW power market, except for the scenario where the unit output is 40% and the heat storage

TABLE 3 Investment recovery period under different outputs and heat storage time of the unit (the peak-shaving subsidy is calculated at 0.3 yuan).

Unit load rate	Unit load rate before consumption	Heat storage time/h		
		9	8	7
40%	73.87%	>10	>10	>10
20%		4~5	7~8	>10
0%		3~4	5~6	7~8

TABLE 4 Investment recovery period under different outputs and heat storage time of the unit (the peak-shaving subsidy is calculated at 0.7 yuan).

Unit load rate	Unit load rate before consumption	Heat storage time/h		
		9	8	7
40%	73.87%	3~4	3~4	>10
20%		1~2	2~3	3~4
0%		1~2	1~2	2~3

time is 7 h, the investment cannot be recovered, and the investment can be recovered within 5 years in the other scenarios. Subsidies have a great impact on the payback period. In addition, in the scenario where the peak-shaving subsidy and the heat storage duration are the same, as the unit output increases, the investment recovery period increases.

5 Conclusion

In this work, we have presented a mathematical model for simulation and economic analysis of a new high-temperature heat storage system for thermal power plants oriented to the smart grid.

1) In the flexible transformation technology of thermal power plants, the methods of increasing the heating capacity of the unit can effectively reduce the forced output of the unit and improve the power plant low-load operation flexibility, but it will reduce the peak load capacity of the unit during the peak load and face the loss of peak-shaving revenue under the new ancillary service rules. The thermal power plant adopts thermal energy storage peak regulation technology, which can not only increase the low-load operation capacity of the unit but can also increase the peak load capacity when the load is at its peak.

2) Simulation and comparison of actual data based on a thermal power plant is determined by THERMOFLEX thermal simulation software. The preliminary results show that in the model where the peak-shaving subsidy and the heat storage duration are the same, as the unit output increases, the investment recovery period increases.

3) The power market peak-shaving subsidy has a great impact on the investment recovery period. In the 0.3 yuan/kW power market peaking subsidy scenario, only when the unit output is 0 and the heat storage time is greater than 8 h, the investment can be recovered in 5 years, while in the 0.7 yuan/kW power market peaking subsidy scenario, except for the scenario where the unit output is 40% and the heat storage time is 7 h, the investment cannot be recovered; in other scenarios, the investment can be recovered within 5 years.

4) From the aforementioned discussion, we can conclude that there are still certain research gaps that need to be filled in the future. The proposed scheme is based on the simulation method. In the future, this work can be extended to integrated energy, such as cold, hot, and compressed air. More comprehensive power consumption is considered, and the proposed scheme was implemented to contribute to grid stability and better utilization of the grid energy. Similarly, in the proposed mathematical model, we did not consider the cold and compressed air; therefore, the addition of them is another research direction. Moreover, our proposed peak-shaving subsidy is based on data given for 0.3 Y/kWh and 0.7 Y/kWh; however, it can be extended for real-time scenarios.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

HZ organized case studies and wrote the manuscript. JL contributed to the theoretical research of this study. All authors contributed to the manuscript and approved the submitted version.

Conflict of interest

MZ and YL were employed by the company CHN Energy Jinjie Energy Co. Ltd.

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

Publisher's note

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