

Article

Peak Load Shifting Control for a Rural Home Hotel Cluster Based on Power Load Characteristic Analysis

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Abstract: The large-scale rural home hotel clusters have brought huge pressure to the rural power grid. However, the load of rural home hotels not only has the inherent characteristics of rural residential buildings but is also greatly impacted by the occupancy rate, which is very different from conventional buildings. Therefore, the existing peak shifting strategies are difficult to apply to rural home hotels. In view of the above problems, this study took a typical visitor village in Zhejiang Province as the research object, which had more than 470 rural home hotels. First, through a basic information survey and power load data collection, the characteristics of its power load for heating, cooling and transition months were studied, and a “No Visitors Day” model was proposed, which was split to obtain the seasonal load curve for air conditioning. Then, combined with the characteristics of the air conditioning power load and the natural conditions of the rural house, a cluster control peak-load-shifting system using phase change energy storage was proposed, and the system control logic was determined and established. Finally, the collected power load data was brought into the model for actual case analysis to verify its feasibility and the effect of peak-load shifting. The results showed that due to the influence of the number of tourists, the electricity loads on weekends and holidays were higher, especially the electricity load of air conditioning equipment in the heating and cooling seasons. An actual case was simulated to verify the peak-shifting effect of the proposed regulation strategy; it was found that the maximum peak load of the cluster was reduced by 61.6%, and the peak–valley difference was 28.6% of that before peak shifting.

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Keywords: load data analysis; demand side management (DSM); rural home hotels; cluster control strategy; PCM storage

1. Introduction

Developing rural home hotels is an important measure to promote rural economic development in China. However, the expansion speed of the rural power grid is having trouble matching the rapid development of the rural home hotel industry. Rural roads are relatively backward [1], and thus, the transportation of construction material is difficult and the construction costs are high [2]; furthermore, equipment construction and upgrade periods are long [3], thus leading to insufficient power supply capacity [4]. Especially for the rapidly developing rural home hotels industry, the existing power grid cannot meet the increasing electricity load. Therefore, the peak-load shifting strategy of the demand side plays a crucial role in balancing the difference between supply and demand of the rural power grid [5,6].

Rural home hotels are usually clustered together, and thus, load fluctuations and load peaks caused by the change in the number of visitors are prominent. Furthermore, due to the large visitor number during winter and summer holidays, indoor thermal comfort is very important [7], and thus, the air conditioning load is the main cause of power

supply tension in summer [8] and the problem is also prominent in winter for non-centrally heated villages. Therefore, as a suitable technology for shifting the peak load of air conditioning, thermal energy storage is expected to reduce the pressure on a rural power grid and improve the stability of a rural power grid.

1.1. Thermal Energy Storage Technology

Thermal energy storage technology [9–11] uses thermal storage materials as media to store and release thermal energy to solve the problem caused by the mismatch between thermal energy supply and demand in time, space or intensity. Thermal storage technologies are divided into three main categories: sensible, latent and thermochemical thermal storage [12]. Among them, phase change energy storage is a promising technology, which takes advantage of the phase change process of new types of phase change materials (PCMs). PCMs are usually divided into four major types: liquid–gas [13], solid–liquid [14], solid–gas [15] and solid–solid [16]. PCMs have the advantages of high applicable energy storage density, wide temperature range, high crystallization rate and high thermal conductivity [17–19]. At present, phase change energy storage has been widely used in energy storage and construction [20], such as air conditioning systems in buildings [21].

The utilization of PCMs in building peak-load shifting received extensive attention. Sun et al. [22] proposed a phase change thermal storage electric heater that could meet the peak-shifting demand throughout the day with 8 h of thermal storage at night and 3 h of thermal storage during the daytime. Wang et al. [23] proposed a PCM tank for clean heating projects of intertemporal heating, which could transfer at least a 1309.2 kW peak load of an office building. Liu et al. [24] analyzed the effect of the addition of a phase change thermal storage device on a solar heating system with a valley filling rate of 66.67% and a peak shaving rate of 11.9%. Riahi et al. [25] proposed a phase change energy storage vapor compression cooling system for power peak-load shifting and concluded that when the volume of the PCM was increased from 38 L to 309 L, the peak load reduction could be increased from 12.7% to 18.7%. De et al. [26] proposed a PCM-based cold storage device connected to a chiller that could store 25 kWh of energy with a charge time of 2.5 h and a discharge time of 1.6 h. Hu et al. [27] investigated the temperature variation of three different sizes of PCM storage during charging and discharging, and found that the energy cost can be reduced by 7% compared with an HVAC system without PCM storage. Koželj et al. [28] compared the conventional sensible thermal energy storage tank with the mixed latent thermal energy storage tank. The experimental results showed that a 15% PCM in the water storage tank provided 70% more thermal storage than the conventional water storage tank with only water inside.

1.2. Peak-Shifting Strategy of Rural Home Hotels

Existing studies [29–32] verified the peak-load-shifting effect by using phase change energy storage in buildings, but most of them focused on single buildings and large-scale commercial buildings, such as office buildings and shopping malls. Rural home hotels are usually converted from rural residential buildings, and thus, they have some similar characteristics to residential buildings, such as being small-scale individual buildings and the large randomness of occupant activities. Therefore, the peak-load-shifting strategy for home hotels will differ significantly from that of large-scale commercial buildings. In particular, the load of a single rural home hotel is small, but the spatial distribution of multiple buildings is concentrated. The small-load users can jointly provide a larger regulation capacity [33]. However, the current peak shifting strategies on building clusters are mostly about incentive strategies for demand response [29,30], and the research objects are also mostly large buildings [31], independent hotel buildings [32] and industrial parks [34]; therefore, they cannot be directly applied to a home hotel cluster.

Unlike most buildings, rural home hotels are mostly located in remote areas, among mountains and forests, and in remote towns [35,36], with backward rural energy structures and high retrofitting potential. Wei et al. [37] pointed out that rural home hotels

could be retrofitted in many aspects, including floor plan design, energy-saving renovation of the envelope structure and the use of clean energy. They further concluded that retrofitted home hotels were significantly improved in terms of natural indoor lighting and thermal comfort, producing energy savings of more than 50%. Zhu et al. [38] modeled three types of rural tourism buildings, namely, two-in-one courtyard, triad courtyard and quadrangle courtyard, and optimized their pre-design to determine the design solution with the highest thermal comfort. Gutierrez Rodriguez et al. [39] studied the validation of three dynamic capabilities in nature tourism through the observation of dynamic capabilities absorption, adaptation and innovation in SMEs and tourism clusters composed of these companies. D'Agostino [40] applied the cost optimization method to a building in the Mediterranean region, evaluated and compared different energy measures, and found the cost-optimal solution for the existing structure. Rural tourism individuals are more suitable for management by combining them into clusters. The above studies about energy use in rural home hotels focused on the energy-saving renovations of existing buildings and the optimal design of new buildings. However, limited attention was paid to the difference between the electricity demand of home hotels and the grid supply.

1.3. Paper Contributions and Organization

The renovation period of a rural power grid is much longer than that of towns and cities, and the speed of rural power grid expansion is having trouble matching the rapid development of the rural home hotels industry. However, so far, relevant research mostly focused on the research of peak shifting strategy for a single building and the research on home hotels is still limited. The existing peak-load-shifting technologies are mismatched with the characteristics of home hotels.

Therefore, this study took a visitor home hotel village as the object, and the main contributions can be stated as follows:

- (1) Based on the data collection and field research, the electricity load characteristics of a home hotel village were comprehensively analyzed;
- (2) The adjacent rural home hotels were composed into a cluster to realize the electricity load regulation of the home hotel cluster through mutual energy storage;
- (3) A novel phase change energy storage load regulation system was proposed for a rural home hotel cluster by combining the advantages of phase change thermal storage technology and the load characteristics of rural home hotels.

Through a case study of a building cluster in this village, the peak-load-shifting effect of this system was obtained. The study results can be applied to rural home hotels to reduce the peak load and improve the grid stability of visitor villages.

The structure of this paper is as follows: the second part provides the characteristics of the energy consumption behavior of the home hotel village, which was obtained via on-site research. The third part gives the analysis results of the load characteristics of the home hotel buildings with the electricity consumption data of the home hotel village. The fourth part introduces the proposed cluster control strategy, including the phase change energy storage system and control logic. The last part describes the use of a home hotel cluster of the village as an example to simulate and analyze the peak-load-shifting effect of the cluster control strategy. The flow chart of the detailed methodology is shown in Figure 1.

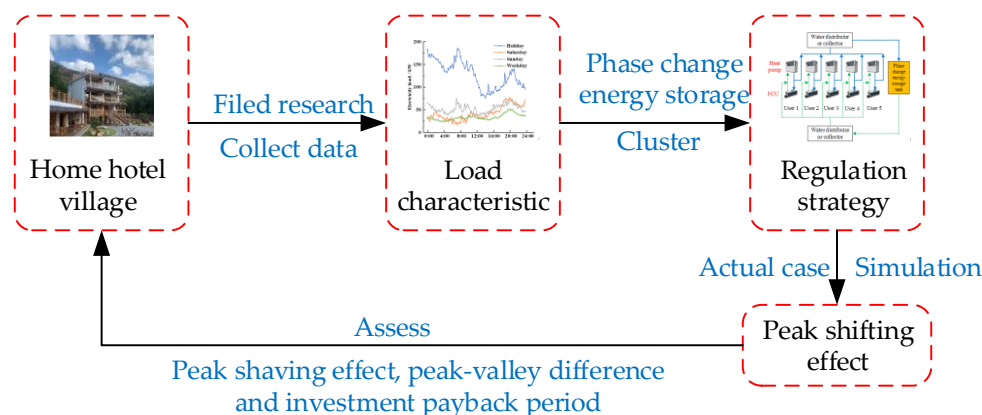


Figure 1. Flow chart of each research step.

2. Investigation of the Characteristics of Electricity Consumption Behavior of Rural Home Hotels

A home hotel village in Zhejiang Province was taken as the research object, which had a stable development, good development trend and a certain scale of home hotels; therefore, its electricity load characteristics were typical and representative. The energy consumption behavior and main energy-using equipment of the home hotel village were obtained via an on-site visit and questionnaire survey. The questionnaire regarding energy consumption behavior for home hotels and the main energy-using equipment is shown in Table 1.

Table 1. Questionnaire on the energy consumption behavior of home hotels.

NO.	Question	Answer
1	Floor area	_m ²
2	Maximum accommodation number per day	_Person/day
3	Peak season	
4	Monthly electricity bill for the last year	_\$
5	Heating method	Central heating/air conditioning heating/gas heating/coal-fired heating
6	Cooling method	air conditioning cooling/other_____
7	Hot water method	Electricity hot water/gas hot water/other hot water_____
8	Distributed energy and quantity	1. Energy name: Quantity and power: 2. Energy name: Quantity and power: 3. Energy name: Quantity and power:
		Air source heat pump _kW Split Type Air Conditioner _kW TV _kW
9	Main equipment	Refrigerator _kW Washing machine _kW Hot water kettle _kW Water heater _kW Electric stove _kW
10	Other large appliances	Please specify _____ _kW

The survey showed that the village was a typical rural tourism resort, with more than 470 home hotels in the village. The peak number of visitors was more than 200,000 during the Spring Festival and National Day holidays. The village was located in an administrative county with eight power supply stations, of which the home hotel village accounted for one-third of the electricity consumption of the entire county. To meet the peak electricity demand of the home hotel village, the grid corporation adopted a capacity increase strategy. The home hotel village had 65 supply and distribution transformers and 6 grid lines. However, the power supply was still insufficient during the peak demand period.

The increase in capacity also brought a large surplus and uneconomic grid capacity during normal times. The home hotel village now focuses on safely keeping electricity and solving problems that may arise in the business of home hotels.

Combined with the questionnaire survey results, the characteristics of the energy consumption behavior of the home hotel villages were further analyzed.

(1) Basic information about the home hotel buildings

Basic information about the building determined the maximum reception level of the village and individual home hotels, which is one of the key parameters that affect the maximum electricity demand. According to the questionnaire result, most of the home hotels were converted from rural residential buildings. The building area (Figure 2) was mostly in the range of 300~600 m². The maximum number of receptions was in the range of 15~40. The per capita building area was 12~25 m².

(2) Configuration of energy-using equipment of the home hotels

The main energy-using equipment in the home hotels was similar to that in rural residential buildings, including air conditioning equipment, domestic hot water systems, TV, and hot water kettles. Among them, the air conditioning system was all cooling and heating dual-condition air conditioning. The system form was mostly an air source heat pump and fan coil system and a split-type air conditioner. Domestic hot water was heated using approximately 80% electric water heaters and the remaining 20% using air source heat pumps and solar water heaters (Figure 3).

(3) Occupancy rate characteristics

The occupancy rate of the home hotels in the village was mainly influenced by the day type. The holidays, especially Spring Festival and National Day, were the “big peak season”, with occupancy rates approaching 100%. Weekends, from Saturday to Sunday noon, were the “small peak season”, with occupancy rates around 60% and visitors always returned home on Sunday afternoon. Weekdays were the “slack season” with an average occupancy rate of approximately 10%.

In summary, a home hotel building is a hotel building converted from a common residential building. Therefore, it maintains the dual characteristics of residential and hotel buildings in terms of energy consumption. On the one hand, the fluctuation of air conditioning load due to seasonal changes can still be the main reason for the seasonal peak and valley load difference. On the other hand, since the number of visitors is much higher than the number of villagers, the daily load difference caused by the changes in visitor number and schedule will be more prominent. Therefore, the load characteristics of the home hotel village need to be quantitatively analyzed based on the electricity consumption data.

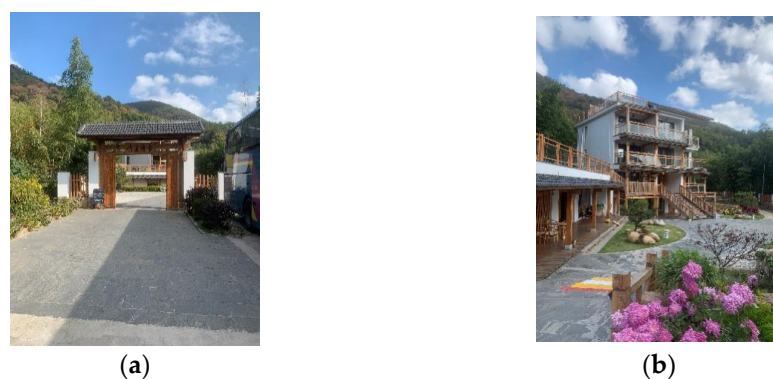


Figure 2. Photos of a site investigation of a typical home hotel: (a) exterior of the home hotel; (b) interior of the home hotel.

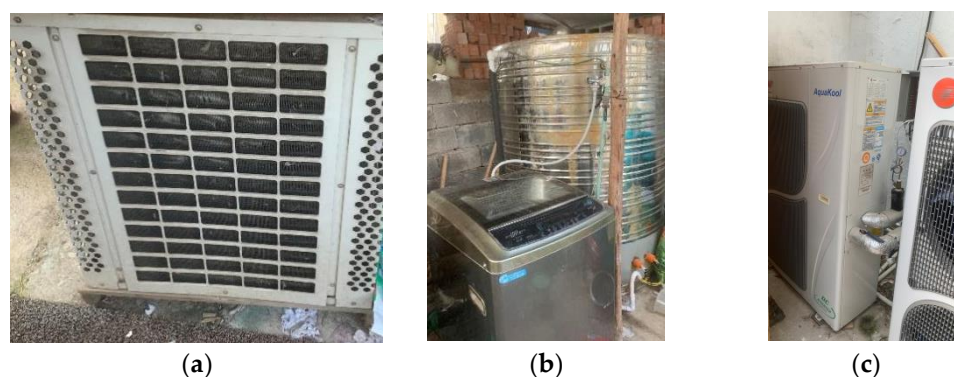


Figure 3. Photos of home hotel energy-using equipment: (a) air source heat pump as a water heater; (b) electric water heater; (c) air source heat pump for air conditioning.

3. Electricity Load Characteristics Analysis of Rural Home Hotels

3.1. Monthly Load Characteristics

In order to correct for the deviation in the total monthly electricity consumption caused by the inconsistency in the number of days in each month, the average daily electricity consumption in each month was compared and analyzed (Figure 4)

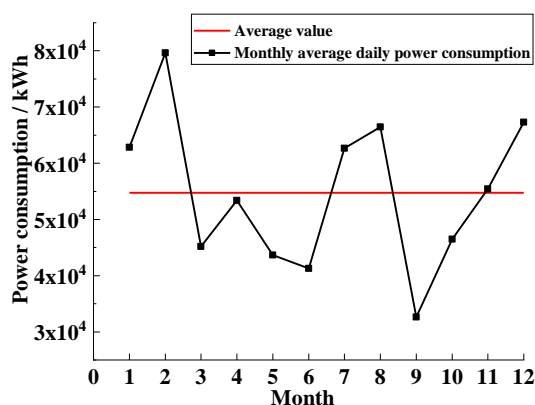


Figure 4. Monthly average daily power consumption of the home hotel village.

As can be seen from Figure 5, the electricity consumption of this rural home hotel village was obviously seasonal. This village was located in Zhejiang Province, without central heating facilities, and it needed air conditioning for heating, which led to the most prominent electricity consumption in winter. Therefore, the month type could be defined according to the average daily electricity consumption level of each month. The classification was as follows:

- (1) Heating months, which included the winter in this district and the low-temperature months of late autumn and early spring, and their average daily electricity consumption was 10% higher than the annual average daily electricity consumption.
- (2) Cooling months, which included the high-temperature months in summer of this district, and their daily average electricity consumption was 10% higher than the annual average daily electricity consumption.
- (3) Transition months, which included other months that were not defined as heating or cooling months.

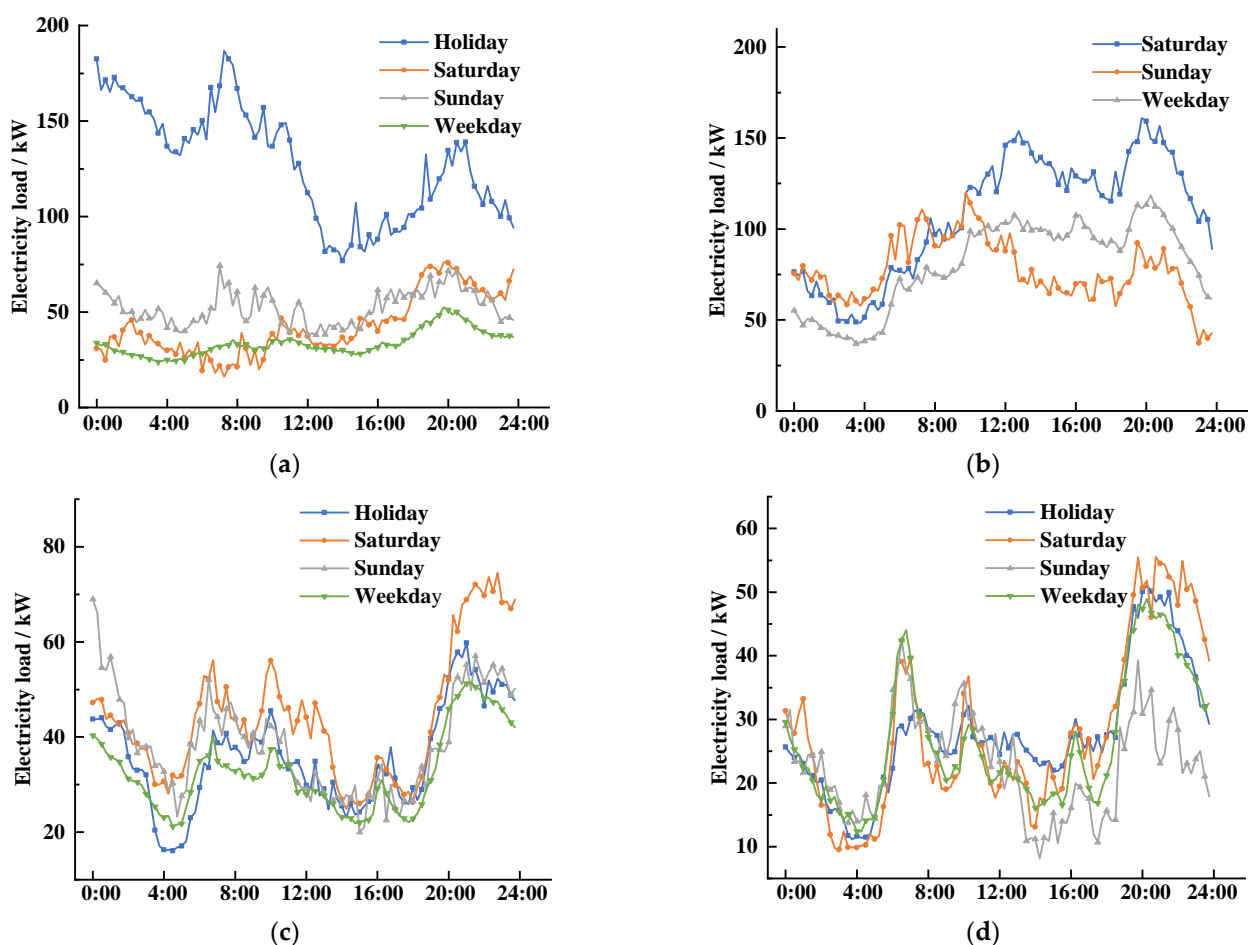


Figure 5. Typical electricity load curves of different day types: (a) heating month; (b) cooling month; (c) transition month (first half of the year); (d) transition month (second half of the year).

As shown in Table 2, based on the above division method, January, February and December were defined as heating months and July and August were defined as cooling months, which were when the average daily electricity consumption was around 60,000 kWh. Other months, namely, March, April, May, June, September, October and November, were transition months.

Table 2. Study time division of electricity load characteristics.

Month Type	Month	Day Type	Time Type
Heating month	January, February and December	Working day	Daybreak (0:00–8:00)
		Weekend (Saturday and Sunday)	Morning (8:00–12:00)
			Afternoon (12:00–18:00)
			Night (18:00–24:00)
Cooling month	July and August	Working day	Daybreak (0:00–8:00)
		Weekend (Saturday and Sunday)	Morning (8:00–12:00)
			Afternoon (12:00–18:00)
			Night (18:00–24:00)
Transition month	March, April, May, June, September, October and November	Working day	Daybreak (0:00–8:00)
		Weekend (Saturday and Sunday)	Morning (8:00–12:00)
			Afternoon (12:00–18:00)
			Night (18:00–24:00)

Then, according to the number of visitors, the day types were further divided into four types of each month type, i.e., weekday, holiday, Saturday and Sunday.

Finally, according to the behavior schedule of the occupants, the daily load could be divided into four periods: daybreak (0:00–8:00), morning (8:00–12:00), afternoon (12:00–18:00) and night (18:00–24:00).

3.2. Daily Load Characteristics

According to the analysis results in Section 3.1, there were obvious seasonal differences in the electricity load of the rural home hotel village. Furthermore, according to the survey results, the occupancy rate of this village was affected by the day type, holidays, weekends and weekdays. Since visitors mostly returned home on Sunday afternoon, the electricity load curves on Saturday and Sunday were obviously different.

3.2.1. Daily Load Characteristics in Heating Months

Among the heating months (Table 2), February had all four types of days, which facilitated the comparison of different day types. Therefore, taking February as the representative heating month, the daily electricity load curves of four types of days, namely, weekday, Saturday, Sunday and Spring Festival holiday, were analyzed (Figure 5a). The data of the week closest to the Spring Festival holiday was selected for analysis regarding the weekday, Saturday and Sunday day types. The workday data was the average of the workday load for that week.

Through the comparative analysis of different day types in Figure 5a, it was found that the peak load during the Spring Festival holiday was 4.5 times the load of other day types for the same time, indicating that the number of visitors had a great influence on the electricity load.

Therefore, holidays were the main object of peak-load shifting for the heating months. Further analysis of the daily load of the holidays showed that the load of the home hotel village started to increase at 4:00 a.m. At 7:15, the load reached the peak value of 186.74 kW and then began to decline, reaching the valley point of 76.68 kW at 14:00. A small peak of 138.89 kW occurred at 21:00.

3.2.2. Daily Load Characteristics in Cooling Months

The main cooling supply months of this home hotel village were July and August (Table 2), which do not include legal holidays, and the average daily electricity consumptions were similar. By taking August as an example of a cooling month, the daily load characteristics of the three non-holiday types of days, namely, weekday, Saturday and Sunday, were analyzed (Figure 5b). The data of the week in the middle of the cooling month was selected for the analysis of the weekday, Saturday and Sunday day types. The workday data was the average of the workday load for that week.

Through the comparative analysis of different day types in Figure 5b, an obvious positive correlation between the electricity load and the number of visitors was found. On Saturday afternoon, the electricity load reached a peak when the visitor number was the largest. On Sunday afternoon, when visitors gradually departed, the electricity load reached the minimum. The load was at the intermediate level on weekdays, when the visitor number was moderate.

Therefore, Saturday was the main object of peak-load shifting for the cooling months. Further analysis of the daily electricity load of Saturday showed that the load of the home hotel village started to increase at 4:00 in the morning and reached the peak value of 153.87 kW at 12:45. At 20:00, the load began to decline, and at 3:45 the next morning, the electricity load reached its valley point of 48.48 kW (Figure 5b).

3.2.3. Daily Load Characteristics in Transition Month

Regarding the transition months (Table 2), April and October were taken as representative transition months for the first and second half of the year, respectively. The daily electricity load curves of four types of days were analyzed (Figure 5c (April) and Figure 5d (October)). The data of the week closest to the holiday was selected for the analysis of weekday, Saturday and Sunday day types. The workday data was the average of the workday load for that week.

Although according to the survey results, the number of visitors on the holiday, weekend and weekday day types were significantly different, their electrical load did not show significant differences. As visitors went out during the day and returned to the hotel at night, a small peak electricity consumption occurred from 6:00 to 9:00 and from 20:00 to 23:00. Meanwhile, the peak load of the home hotel village was 74.52 kW in April and 55.54 kW in October, which were much smaller than the peak loads in the heating and cooling month. Therefore, the peak load caused by visitors was mainly the load of air conditioning. The daily-life load was relatively stable and low and did not change significantly due to the variation in the number of visitors. That is, the number of visitors in transition months had little impact on the electricity load.

Based on the analysis of the representative daily loads of each month type, the peak-to-valley difference in the transition months was much smaller than that of the heating months and cooling months. Therefore, the peak-load-shifting strategy should be focused on the heating and cooling months. In addition, both the highest daily load and the largest peak-to-valley difference occurred in the heating season. Therefore, taking the heating season as an example, this study further proposed the peak-load-shifting strategy on the demand side.

3.3. Load Characteristics Analysis for Air Conditioning

Through the analysis of the load characteristics of the home hotel village and the occupancy rate of home hotels, it was found that although there were obvious differences in the number of visitors on different day types in the transition seasons, the electricity load difference between different day types was not obvious due to the low utilization rate of air conditioning.

However, in the heating and cooling seasons, besides other electrical equipment, the visitors mostly used the air conditioning system to maintain thermal comfort. The loads of different day types were obviously different due to the different visitor numbers. Therefore, the peak power consumption of the home hotel village was mainly caused by the air conditioning system. The air conditioning power consumption can be transferred in the form of thermal storage, which is convenient for stabilizing the grid load. Through the following data analysis, the air conditioning electricity load was separated from the total power consumption data to further analyze the air conditioning electricity load.

3.3.1. Electricity Load of a “No Visitors Day”

The electricity load without an air conditioning load was defined as a “daily-life load” in this study. The daily-life load was mainly caused by the activities of dining, washing, leisure and entertainment, which were less affected by climatic conditions and depended on the number of people.

Therefore, the daily-life electricity load only caused by the villagers would be relatively stable throughout the whole year, which was less affected by climatic conditions, the number of visitors and other factors.

Furthermore, it can be considered that there were few visitors on the day with the lowest electricity load of each month, and the electricity consumption was mainly caused by the villagers, which was called “No Visitors Day”. Comparing the lowest daily loads of the heating and transition months, an interesting phenomenon was found. Both of the load curves remained at a low level, below 30 kW all day, and the general trends were

similar (Figure 6). Therefore, it can be inferred that the air conditioning electricity consumption caused by villagers was negligible. Thus, it can be considered that on “No Visitors Days” the load only included the daily-life load of villages.

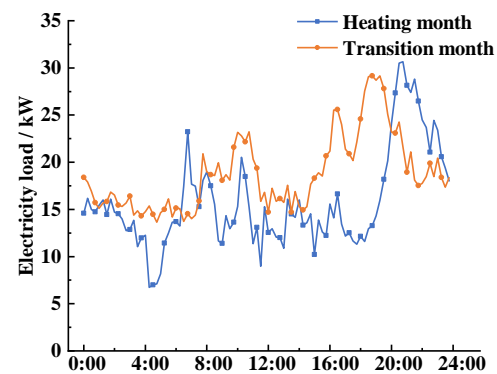


Figure 6. Minimum daily load curves in a heating month and a transition month.

3.3.2. Electricity Load of Air Conditioning

The electricity load of air conditioning can be obtained by removing the daily-life load from the total load. Based on the definition of a daily-life load, it can be simplified as a single-valued function of the number of people. Therefore, the total daily-life load caused by villagers and visitors can be represented by n times of the daily-life load only caused by villagers (the load of a no-visitor day), as represented in Equation (1). Based on the above logic, the air conditioning electricity load can be obtained by disaggregating the daily-life load from the total load (Equation (2)).

$$P_{SH} = n \cdot P_{SH-J}, \quad (1)$$

$$P_{AC} = P - P_{SH}, \quad (2)$$

where P_{SH} is the total daily-life load of visitors and residents, kW; n is the coefficient of the visitors; P_{SH-J} is the load of a no-visitor day, kW; P_{AC} is the electricity load of the air conditioning, kW; and P is the total electricity load, kW.

By combining the electricity load curves of the holiday with a no-visitor day, the load curve of the air conditioning in heating months can be obtained using Equations (1) and (2), as shown in Figure 7. The electricity load of the air conditioning was at a high level in most time periods, around 75 kW. The load level was lower only in short periods, such as 2:00 to 5:00, 8:00 to 10:00 and 18:00 to 20:00. Therefore, it was difficult to realize the energy storage and peak shifting within a day. Therefore, day-ahead energy storage and peak shifting should be adopted.

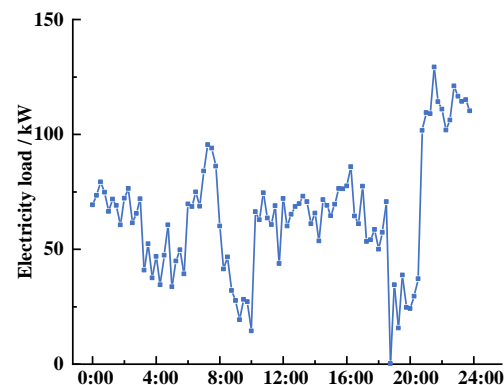


Figure 7. Load curve of the air conditioning in a heating month.

4. Peak-Load-Shifting Strategy

According to the above analysis, the number of visitors, i.e., the day type, was the key factor that affected the electricity load of the home hotel village. The scale of one home hotel was small, and thus, a cluster energy storage and peak-shifting strategy was proposed based on the load characteristics analysis. Several rural home hotels were combined into a cluster, and an energy storage tank was arranged in the cluster. Each user can absorb energy from and release energy into the energy storage tank. The control strategy was uniformly scheduled by the users' real-time electricity load.

A comparative analysis between monomer and cluster energy storage is shown in Table 3. It can be found that, for the home hotel village, the cluster energy storage for peak-load shifting is more compatible with the characteristics of a large change in the number of visitors and different peak hours of each home hotel.

Table 3. Comparison of energy storage peak-shifting strategies.

Day Type	Occupancy Rate Characteristics	Electrical Characteristics	Monomer Energy Storage	Cluster Energy Storage
Working day	The overall occupancy rate was low and the difference between each hotel was high	Peak time of electricity consumption was different	Energy storage and peak shifting did not match, the amount of equipment was large and the whole system was complex	Effective balance of energy storage and peak shifting in the cluster, and the amount of energy storage equipment was small
Weekend and holiday	The overall occupancy rate was high and similar among each hotel	Peak time of electricity consumption was similar	Individual load varied greatly and the peak-shifting system was complicated	Overall load variation was small and the flexibility was high

4.1. Cluster Division Principles

If the cluster control system is used for the energy storage and peak shifting of the cooling and heating loads, it is necessary to divide the home hotels first. Through comprehensive consideration of the system installation, control and peak-shifting effect, the principles of cluster division were put forward:

- (1) The distance between buildings in the same cluster should not be too large; otherwise, the system pipeline will be too long, which will increase the system operation and maintenance cost, and will also increase the thermal dissipation and decrease the system efficiency.
- (2) The buildings in the same cluster should not cross the main rural roads.
- (3) The number of buildings in the same cluster should not be too much. Too many buildings will lead to a large capacity of energy storage tanks, a large occupied area and high requirements for the site.

After the buildings were combined into clusters, the peak-load-shifting strategy of the cluster should follow the following main aspects:

- (1) Maximum peak shifting limit—the limit condition after peak shifting is that the peak value of the power consumption is equal to the valley.
- (2) Day-ahead peak shifting is the main method, supplemented by intra-day peak shifting. If there is a temporary peak electricity load of individual home hotels, the peak shaving can be completed by the surplus energy storage of other home hotels in the same cluster.
- (3) The energy storage should be carried out during the period of the valley electricity price, which was 22:00 to 8:00 of the next day in this home hotel village [41]. Villagers can get the benefits of the difference in peak and valley electricity prices.

- (4) The interval between the energy storage and release should not be too long and should not span weekends and holidays. Too long of an interval leads to an increase in thermal loss in the energy storage tank and a decrease in energy storage efficiency.

4.2. Cluster Control System Form

As shown in Figure 8, the control system structure was mainly divided into an energy-using end, energy storage and a pipeline. The energy-using end is the user end, which generates heat in the valley of electricity consumption and stores the extra thermal in the energy storage tank. In the peak period of electricity consumption, the thermal energy in the energy storage tank is extracted and supplied to the users. The PCMs in the energy storage tank are responsible for storing the heat generated by the users. The energy storage tank adopts a horizontal non-pressure shell tube type, which is convenient for switching PCMs in winter and summer. Thermal insulation materials are installed on the outer wall to reduce the thermal loss of the energy storage tank.

The pipeline connects the energy storage end and the energy-using end, including the electrical circuit, the water inlet circuit, the water outlet circuit and other pipeline accessories. The electric circuit can turn on the users' heat pump to store thermal energy in the energy storage tank during the valley electricity consumption period. In the peak period, the water pump is turned on and the thermal energy is extracted from the energy storage tank and sent to the end users. The water inlet and outlet circuit connect users with the phase change thermal storage tank to transfer the thermal energy.

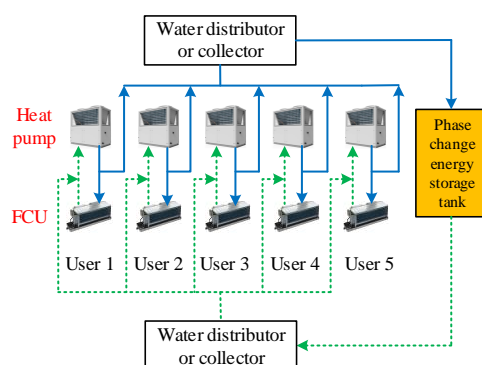


Figure 8. Theoretical framework of the control system.

4.3. Cluster Control Logic

The whole control logic was divided into two processes, namely, thermal storage and thermal release, which constituted a cycle period. The flow chart is shown in Figure 9.

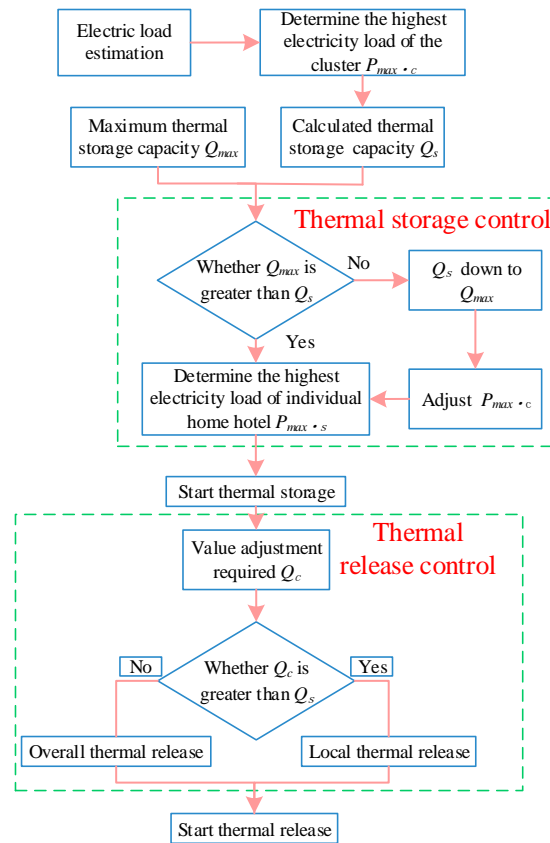


Figure 9. Control logic of the cluster control system.

4.3.1. Thermal Storage Process

- (1) The maximum load after cluster peak shifting P_{max-c} is determined. When the electricity load after peak shifting in the valley is equal to the electricity load in the peak, the electricity load is P_{max-c} , as shown in Equation (3).

$$\sum (P_{max-c} - p_{i-s}) \times \alpha = \sum (p_{i-r} - P_{max-c}), \quad (3)$$

where P_{max-c} is the highest electricity load after peak shifting under ideal conditions, kW; p_{i-s} is the load below the load of an individual home hotel during the predefined thermal storage period, kW; p_{i-r} is the load above the highest load of an individual home hotel during the predefined thermal release period, kW; and α is the thermal dissipation coefficient during thermal storage.

- (2) The highest load of an individual home hotel P_{max-s} is determined. The highest load in the cluster is divided by the number of home hotels to obtain the highest load for an individual home hotel, as shown in Equation (4).

$$P_{max-s} = P_{max-c} / m, \quad (4)$$

where P_{max-s} is the highest electricity load of an individual home hotel, which is the electricity load achieved by each home hotel in the cluster after peak shifting under ideal conditions, kW; m is the number of home hotels in the cluster.

- (3) Thermal storage calibrations. The theoretically calculated thermal storage capacity (i.e., calculated thermal storage capacity Q_s , Equation (5)) is calibrated against the thermal storage capacity that can be produced by the maximum working intensity of the thermal storage tank (i.e., maximum thermal storage capacity Q_{max} , Equation (6)), and it is ensured that Q_s does not exceed Q_{max} . If Q_s does exceed Q_{max} , Q_s is reduced to Q_{max} .

$$Q_s = \sum (P_{max-s} - p_v) t, \quad (5)$$

where Q_s is the calculated thermal storage capacity, kJ; p_v is the valley electricity load of an individual home hotel in the cluster, kW; and t is the thermal storage time, s.

$$Q_{max} = \rho V \cdot (r + C_p \Delta T) \cdot \eta, \quad (6)$$

where Q_{max} is the maximum thermal storage capacity, kJ; ρ is the density of the PCM, kg/m³; V is the limited capacity of the thermal storage, m³; r is the phase change latent thermal energy of the PCM, kJ/kg; C_p is the specific thermal capacity at a constant pressure of the PCM, kJ/(kg·K); ΔT is the sensible temperature rise value of the PCM during the thermal storage, K; and η is the thermal storage coefficient, which represents the thermal storage capacity of the PCM under the actual working conditions (generally, it is 60–80%).

- (4) Start thermal storage. Increase the valley electricity load of an individual home hotel to the peak electricity load for thermal storage.

4.3.2. Thermal Release Process

- (1) Thermal release control. The measured electricity load of an individual home hotel is compared with the P_{max-s} , and the total peak load shifting value is compared with the total thermal storage (Equation (7)). If the total load shifting value does not exceed the total thermal storage, the overall thermal release will be carried out so that the electricity load of an individual home hotel in the cluster at each moment is controlled below the P_{max-s} . If the total load-shifting value exceeds the total thermal storage, the local thermal release will be carried out. First, the highest electricity load users will be satisfied, and at the same time, the thermal release system structure will be relatively simple.

$$Q_c = \sum (p_p - P_{max-s}) t, \quad (7)$$

where Q_c is the total peak-load-shifting value in the cluster based on the measured electricity load of an individual home hotel, kJ; p_p is the peak load of an individual home hotel in the cluster, kW.

- (2) Start the thermal release. The thermal release starts when the electricity load of an individual home hotel exceeds p_p .

5. Operation Simulation and Analysis of Cluster Control Strategy

5.1. Analysis of the Actual Electricity Load in a Case Study

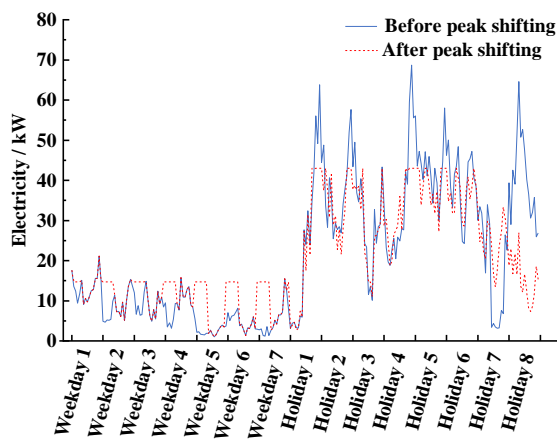
In the village, the home hotels showed a characteristic of extending to both sides with the road as the center, as shown in Figure 10. Due to the natural landforms between the mountains, the buildings were naturally divided into blocks. Five home hotels on one side of the road were selected as the study object, with the distances between every two buildings not exceeding 10 m and not crossing the main roads in the village. These five home hotels were integrated into a cluster control system.

The Spring Festival holiday and the working day one week before the holiday were selected as the research period. During the Spring Festival, the home hotel village had the highest electricity load and its peak shifting was the most difficult, and thus it was more representative.

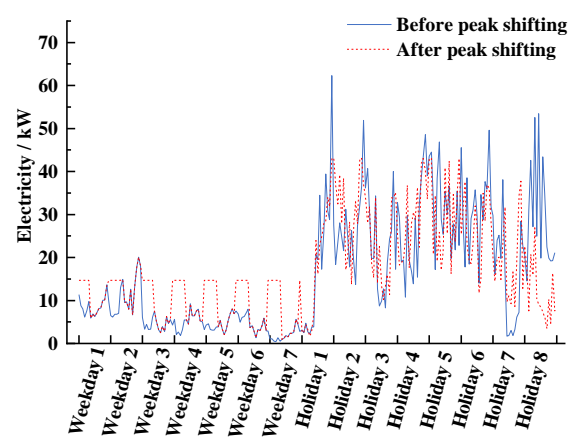


Figure 10. Topographic map of the home hotel village: (a) overall topographic map of the home hotel village; (b) local topographic map of the home hotel village.

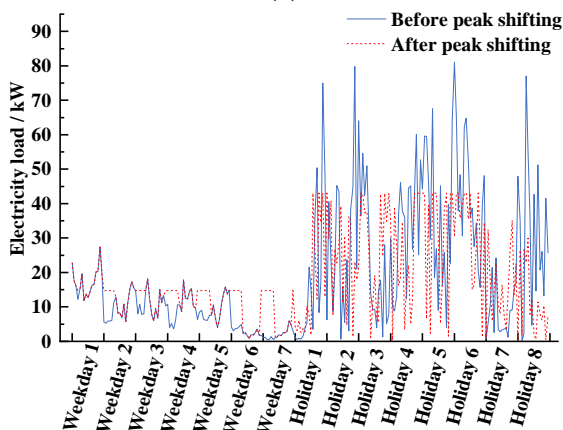
The overall electricity load curve of each home hotel is shown in Figure 11. The daily electricity load on working days was much lower than that on the holidays. The daily electricity load on working days was about 30 kW, but the average electricity load on holidays was about 80 kW, up to 120 kW. During the holidays, the electricity load fluctuated greatly, with the lowest value of 25 kW and the highest value of 120 kW, and the peak-valley difference phenomenon was serious. Furthermore, the electricity load curves of users were relatively consistent, which showed that the peak periods of electricity consumption were similar. This will easily lead to a sharp rise in the electricity load of the same station area within a certain period, forming a peak load at the station level.



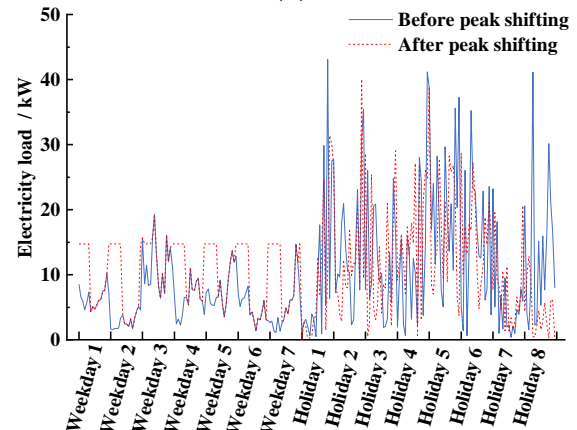
(a)



(b)



(c)



(d)

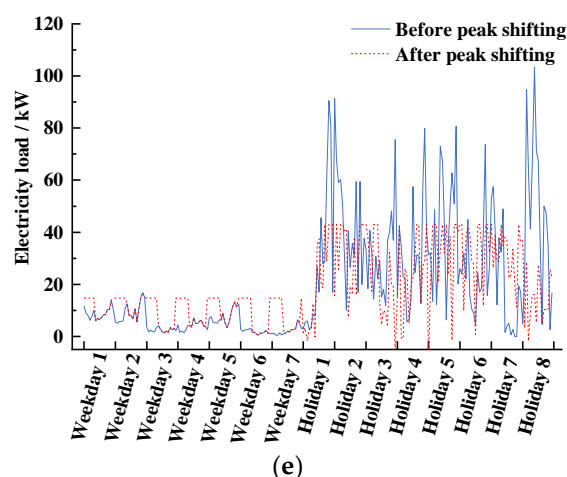


Figure 11. Peak-load changes of the home hotel cluster during the Spring Festival holidays and seven days before the holiday before and after peak shifting: (a) user 1; (b) user 2; (c) user 3; (d) user 4; (e) user 5.

The single-user electricity load characteristics matched the overall characteristics of the heating season holidays. Therefore, the regional cluster regulation with thermal storage and peak shifting as the technical core was also applicable to this case. Since air conditioning was the main cause of the load peak, when the phase change energy storage tank was used to transfer the air conditioning load, the total load of the cluster also changed obviously.

5.2. Case Parameter Selection and Result Analysis

- (1) Treatment of the electricity load. First, the electricity load of each user in the cluster during one peak-shifting period of energy storage was obtained. The highest electricity load of the cluster was calculated to be 120.71 kW by putting the electricity load of each user together.
- (2) Determination of calculated thermal storage capacity. According to Equation (6), the calculated thermal storage capacity was 4507.5 kWh.
- (3) Determination of the maximum thermal storage capacity of a thermal storage tank. In this case, paraffin was selected as the energy storage material, which had the characteristics of large latent thermal phase change and good heat stability. The selected paraffin has 23 carbon atoms, and its phase change temperature is 47.5 °C, density is 900 kg/m³, latent heat of phase change is 234 kJ/kg and specific heat capacity at constant pressure is 2.64 kJ/(kg·K). According to the cluster electricity load estimation, the effective thermal storage capacity of the thermal storage tank was 50 m³, and the sensible temperature rise value of the PCM designed for thermal storage was 6 K. The heat storage coefficient was 70%. According to Equation (5), the maximum thermal storage capacity was 7,869,960 kJ = 2186 kWh.
- (4) The calculated thermal storage capacity was 4507.5 kWh, which was greater than the maximum thermal storage capacity of 2186 kWh. It is necessary to reduce the calculated thermal storage capacity to the maximum thermal storage capacity. The maximum thermal storage load value was 74.47 kW and the minimum thermal release load value was 148 kW.
- (5) The maximum thermal storage load of a single user was calculated to be 14.72 kW, and the minimum thermal release load of a single user was 46.17 kW.
- (6) The results of the calculated thermal storage and thermal demand of every household are shown in Table 4.

Table 4. Thermal storage and thermal demand of the home hotels cluster.

	User 1	User 2	User 3	User 4	User 5
Thermal storage	1603.04	1906.58	1400.22	1751.69	2074.75
Thermal demand	1299.71	76.23	2096.42	16.28	5248.82

Unit: kW.

The results of the overall electricity load change after the peak shifting of the home hotels cluster are shown in Figure 11. Compared with that before the peak shifting, the peak load during holidays was significantly reduced. The highest value of the electricity load dropped from 120 kW to 46.72 kW, with a decrease of about 61.1%. The electricity load was transferred to the valley period of the working days before the holiday when the electricity load was low, and the difference in electricity load during the day was largely alleviated.

6. Discussion

According to the above analysis, the PCM energy storage tank required for the load peak regulation was about 50 m³ for a cluster of five users. The reconstruction cost of the 50 m³ energy storage tank system was about USD 100,000, and the PCM cost was about USD 200,000. After the completion of the transformation, the operation cost can be reduced by USD 18,000 per year, and a government subsidy of USD 11,000 per year could be obtained. The investment return period was 10.3 years, which is acceptable. Furthermore, the period can be further shortened after quantity production, which has great investment potential.

According to the field survey results, the village had a total of 470 home hotels. The home hotels were transformed from ordinary rural houses, and thus, they had the characteristics of similar scale (between 300–600 m²), the same equipment type (the main electrical equipment is air conditioning) and similar occupancy rates (affected by holidays and weekends). Therefore, the proposed peak-shifting system is theoretically applicable to all home hotels in the village. If the system was used for peak load regulation for all the home hotels, according to the case analysis results, the maximum load was reduced from the original 186.74 kW to 72.64 kW, and the peaking shifting effect was very significant. This strategy could also effectively absorb renewable energy and avoid the waste of resources caused by expanding the power grid.

The proposed strategy is only applicable to districts with significant air conditioning loads. Furthermore, the concentrated rural home hotels are more applicable. For districts with short heating and cooling periods, its effect and economy will be reduced. The strategy is not applicable to small or scattered rural home hotel buildings because they cannot be divided into a cluster well, which is not conducive to mutual energy storage.

7. Conclusions

The prominent contribution of this study was the proposal of a novel peak-shaving strategy for rural home hotels cluster, which can relieve the difference between the rapid developments of rural tourism and the difficulty of power grid upgrading for a rural area. The conclusions were as follows:

- (1) The electricity loads of the home hotel village were greatly affected by the number of visitors, especially on weekends and holidays in the heating and cooling months. The electricity loads in the transition months were less affected by the number of visitors, and the differences in electricity loads on working days, weekends and holidays were small. The main peak electricity loads of the village were generated by the heating and cooling air conditioning equipment of visitors.
- (2) The cluster regulation peak-load-shifting system is applicable to the building clusters with similar load characteristics, which are difficult to regulate for single buildings. The building clusters in rural areas show obvious aggregation phenomena according

to the natural geographical conditions. This system will reduce the peak electricity load of the cluster and achieve the purpose of peak load shifting on the demand side of the rural home hotel industry.

- (3) The simulation operation of the cluster peak-load-shifting system was carried out through an actual case study. After peak load shifting, the highest peak electricity load was reduced from 120 kW to 46.72 kW, and the reduction rate was 61.1%. The valley and peak values of the electricity load were 14.72 kW and 46.17 kW, respectively, and its peak-to-valley difference was 31.45 kW, which was only 28.6% of that before peak shifting.

The proposed peak-load-shifting system and energy storage can effectively reduce the difference between peak and valley electricity loads and provide technical support for a rural home hotel electricity peak-shifting system.

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Abbreviations

Nomenclature

C_p	Specific thermal capacity at constant pressure	kJ/(kg·K)
m	Number of home hotels in the cluster	
n	Number coefficient of visitors	
P	Total electricity load	kW
P_{AC}	Electricity load of the air conditioning	kW
p^{ir}	Load above the highest load of individual home hotel during the predefined thermal release	kW
p^{is}	Load below the highest load of an individual home hotel during the predefined thermal storage	kW
P_{max-c}	Highest electricity load of the cluster	kW
P_{max-s}	Highest electricity load of individual home hotel	kW
p_p	Peak load of an individual home hotel in the cluster	kW
P_{SH}	Total daily-life load of visitors and residents	kW
P_{SH-j}	Load of a no-visitor day	kW
p_v	Valley electricity load of an individual home hotel in the cluster	kW
Q_c	Total peak-load-shifting value in the cluster based on the measured electricity load of individual home hotel	kJ
Q_{max}	Maximum thermal storage capacity	kJ
Q_s	Calculated thermal storage capacity	kJ
r	Phase change latent heat	kJ/kg
t	Thermal storage time	s
V	Limited capacity of thermal storage	m ³
ΔT	Sensible temperature rise value of PCM during thermal storage	K
α	Thermal dissipation coefficient during thermal storage	
η	Thermal storage coefficient	
ρ	Density	kg/m ³
PCM	Phase change material	

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