

# Research on Energy-saving Regulation Mechanism of Residential Air-conditioning Loads Based on Multi-dimensional Information

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**Abstract.** With the increasing difference between peak and valley electricity loads in China, the proportion of air conditioning load during peak summer season has reached 40% -50%, becoming a key factor affecting the safe operation of the power grid. How to scientifically identify the factors affecting air conditioning energy consumption and evaluate their energy-saving and emission reduction potential is an important prerequisite for achieving flexible load regulation. This article proposes a research framework that integrates the Analytic Hierarchy Process (AHP) of Information Entropy with an explanatory structural model. By decoupling complex coupling factors, a system for identifying and analyzing the relationship between factors affecting air conditioning energy consumption is constructed. In response to the problem of traditional methods being difficult to quantify user needs, this article uses stratified sampling and principal component analysis to extract four core demand dimensions from 14 factors: thermal comfort, energy efficiency, ease of use and economic satisfaction; Further combining long short-term neural networks, a potential evaluation model that balances user satisfaction and energy-saving effects was established. The research results indicate that the analysis system constructed in this article can effectively identify 15 main factors and 6 root factors from 38 influencing factors; When the air conditioning temperature is set to 26°C, it can achieve 10% power savings while maintaining high user satisfaction. The research results provide scientific decision-making basis for intelligent air conditioning regulation in demand side management, and have important practical value for promoting energy conservation and emission reduction in the construction industry.

**Keywords:** Air Conditioning Load, Energy Conservation and Emission Reduction, Long Short-term memory Networks, Satisfaction with Energy Consumption.

## 1. Introduction

The process of China's economy and urbanization has promoted the popularization rate of household air conditioning, with the urban air conditioning popularization rate exceeding 80% and the rural area reaching 30% -50%. Air conditioning has become the main source of energy consumption in households, increasing household expenses and exacerbating climate change. The air conditioning load in the new power system has strong adjustability, multiple human factors for regulation, and high predictability of energy consumption. Intelligent prediction and management technology can assist in precise analysis and regulation, optimize usage habits, reduce energy consumption, improve energy efficiency, alleviate power conflicts, and have significant implications for energy transformation and the construction of new power systems.

The academic community has conducted extensive research on the factors affecting air conditioning load and energy conservation and emission reduction. Yan Yongcheng et al. mainly analyzed the energy consumption performance of air conditioning systems coupled with seasonal ice storage and evaporative cooling under different climatic conditions [1]. Guan Chunmin and others summarized the influencing factors of energy consumption in public buildings from the aspects of building itself, region, equipment, and behavior [2]. He Jun et al. proposed a three-layer control framework for variable frequency air conditioning loads and analyzed the energy response potential

of variable frequency air conditioning loads [3]. Li Jinbo et al. compared and analyzed the energy consumption performance of reverse turbocharging and forward turbocharging systems under different operating conditions [4]. In terms of assessing regulatory potential, Wu Tong et al. have shown that commercial building air conditioning systems can participate in grid regulation through demand response [5]. Jin Xu et al. used Hidden Markov Models to calculate the regulatory potential within different thermal comfort ranges [6]. Zeng Qingbin et al. proposed a monitoring system architecture based on software defined networks [7]. Gro et al. found that improving user behavior patterns can reduce energy consumption by up to 53.1% [8]. Ding Y. et al. evaluated the flexibility potential of building air conditioning systems under different demand response measures through quantitative analysis [9].

However, existing research mostly focuses on user behavior analysis in specific regions or from a single perspective, ignoring the multidimensional composite effects of multiple factors. At the same time, energy consumption models often rely on fixed patterns of simulation software, making it difficult to capture the complexity and user differences of actual use. In addition, research often considers the operation of the power grid, lacking sufficient consideration of environmental factors and user energy consumption. This article introduces 38 influencing factors and constructs a triple analysis framework using Analytic Hierarchy Process, Information Entropy Model, and Explanatory Structure Model to decouple the interaction relationships between factors. At the same time, actual energy consumption experience data was obtained through questionnaire surveys, and four typical energy demand dimensions were extracted using principal component analysis to construct an LSTM energy consumption prediction model. This model ensures accuracy while shortening calculation time, providing a more practical basis for demand side response.

## 2. Analysis of Satisfaction Index for Air Conditioning Energy Consumption

### 2.1. Sampling questionnaire survey

By extensively reading literature and relevant reports, combined with the ultimate goal of this survey, a preliminary questionnaire survey was designed. The questionnaire conducts a survey from three aspects: basic information, usage habits, and cognitive status. After completing the pre survey, a final questionnaire was formed under the guidance of Cronbach's coefficient test results, covering satisfaction issues in 14 aspects such as air conditioning energy saving, control flexibility, and user experience.

Furthermore, the correlation between variables was measured using the Kaiser Meyer Olkin test and Bartlett's ball test, and validated through factor analysis. The overall KMO value of the scale was 0.732, which passed the reliability and validity tests.

### 2.2. Principal Component Analysis of Satisfaction Indicators

Using principal component analysis method, multiple indicators can be transformed into several comprehensive indicators with minimal loss of information. To visually demonstrate the effectiveness of the extracted principal component factors, a table is used to display the variance explanations of the principal component analysis factors.

**Table 1.** Principal Component Analysis Explaining Total Variables.

Component	Factor extraction results		
	Eigenvalue	Variance contribution rate/%	Cumulative contribution rate/%
1	2.8912	28.912	28.912
2	2.5612	25.612	54.524
3	2.0932	20.932	75.456
4	1.7896	17.896	93.352

According to Table 1, the cumulative variance contribution rate of the first four principal component factors reaches 93.352%, indicating that the information contained in the four principal component factors exceeds 90% of the original variable information, and the selection of influencing factors is appropriate.

Therefore, based on the principal component load matrix table, 14 influencing factors were summarized and summarized. Table 2 shows the principal component load matrix table of the influencing factors.

**Table 2.** Principal Component Load Matrix of Influencing Factors.

Question number	influence factor	FactorZ <sub>1</sub>	FactorZ <sub>2</sub>	FactorZ <sub>3</sub>	FactorZ <sub>4</sub>
1	Indoor temperature comfort	0.794	0.624	0.479	0.336
2	Indoor temperature regulation effect	0.865	0.776	0.614	0.370
3	Air humidity control effect	0.743	0.538	0.348	0.163
4	Satisfaction with air conditioning energy consumption	0.584	0.705	0.443	0.359
5	Expected compliance of air conditioning energy consumption	0.513	0.837	0.411	0.208
6	Satisfaction with energy-saving of air conditioning system	0.426	0.815	0.332	-0.165
7	Convenience of operating the air conditioning control interface	0.548	0.471	0.819	0.217
8	Flexibility of air conditioning control function	0.414	0.295	0.803	-0.091
9	Satisfaction with automatic adjustment function of air conditioning	0.377	0.269	0.781	0.116
10	Satisfaction with the adjustment of air outlet speed and direction	-0.197	0.302	0.746	0.232
11	Satisfaction with the quality of air conditioning maintenance services	0.432	0.297	0.163	0.613
12	Response speed of air conditioning system maintenance	-0.278	0.315	0.284	0.748
13	Cost effectiveness of air conditioning system maintenance	0.209	0.232	0.216	0.689
14	Satisfaction with air conditioning failure rate	0.197	0.174	-0.277	0.625

According to Table 2, it can be seen that the 14 influencing factors are correlated under different factors. Under the four factor conditions, factors such as "indoor temperature regulation effect", "air conditioning system energy-saving satisfaction", "air conditioning automatic adjustment function satisfaction", and "air conditioning maintenance service quality satisfaction" have high loads. Therefore, factors Z1 to Z4 are named as "thermal comfort", "energy efficiency", "ease of use", and "economic satisfaction" influencing factors, respectively.

### 3. Progressive System of Influencing Factors on Air Conditioning Energy Consumption

#### 3.1. Model Construction Ideas

This chapter selects influencing factors of residential air conditioning load energy consumption from six dimensions: environmental factors, building structure and thermal insulation, air equipment performance, indoor-outdoor temperature and humidity differences, user behavior and habits, energy sources and policies through literature research and expert interviews. It includes 38 secondary factors. The index system is complex, and some are difficult to quantify. To determine the key influencing

factors, this chapter uses the Analytic Hierarchy Process (AHP) [10] to calculate and identify key factors.

To overcome the subjectivity of AHP and reduce the error of a single evaluation method, information entropy [12] is used as the criterion for feature selection to correct the weights of evaluation results. Meanwhile, the Interpretation Structural Model (ISM) is applied to decouple the progressive relationships among multi-dimensional complex influencing factors. Table 3 below shows the analysis system table of the influencing factors of air conditioning energy consumption.

**Table 3.** Analysis System of Influencing Factors on Air Conditioning Energy Consumption.

First-level Factors	Second-level Factors
Environmental Factors	Average Temperature
	Precipitation
	Average Relative Humidity
	Average Wind Speed
	Daily Maximum Temperature
	Daily Minimum Temperature
	House Area
	House Sealing Performance
	Window Area and Quantity
	Window Type
Building Structure and Thermal Insulation	Roof Material
	Wall Material
	Ground Material
	House Height
	House Orientation
	Energy Efficiency Ratio
	Service Life
	Maintenance Time
	Continuous Usage Duration
	Equipment Power Consumption
Air Equipment Performance	Refrigerant Capacity
	Smoke Exhaust Level
	Indoor-Outdoor Temperature Difference
	Indoor Humidity
	Indoor Ventilation Condition
	Air Conditioning Equipment Debugging Effect
	Frequency of Temperature and Humidity Changes
	Temperature Setting Value
	Indoor-Outdoor Temperature Difference Tolerance
	Air Conditioning Usage Frequency
Indoor and Outdoor Temperature Difference and Humidity	Energy-Saving Mode Usage Condition
	Indoor Ventilation and Air Exchange Condition
	Electricity Price
	Stability of Power Supply
	Air Conditioning Equipment Scrap Recycling Policy
	Life Cycle Cost of Air Conditioning Equipment
	Energy Efficiency Standard
	Air Conditioning Energy Consumption Supervision Mechanism

### 3.2. Identification and Analysis of Influencing Factors

#### 3.2.1. Weights of Key Influencing Factors Based on AHP

According to the AHP structural model, a questionnaire was generated, and nine experts in the field of energy economics from North China Electric Power University were invited to evaluate and fill it out. The judgment matrix was constructed based on the average evaluation, and the characteristic vector was calculated.

The importance of each factor under different criterion layers was quantitatively analyzed. By calculating the combined weights of each influencing factor, the importance of each factor in the scheme layer relative to the target layer was determined and ranked. The specific ranking results are shown in Table 4.

**Table 4.** Importance Ranking of Each Influencing Factor Based on AHP.

Factor Name	Weight	Factor Name	Weight
Average Temperature C1	0.1310	Frequency of Temperature and Humidity Changes C27	0.0139
Temperature Setting Value C28	0.0993	Energy Efficiency Standard C37	0.0139
Daily Maximum Temperature C5	0.0893	Air Conditioning Energy Consumption Supervision Mechanism C38	0.0139
Air Conditioning Usage Frequency C30	0.0687	Roof Material C11	0.0130
Precipitation C2	0.0535	Ground Material C13	0.0130
House Area C7	0.0446	Service Life C17	0.0113
House Height C14	0.0446	Indoor Humidity C24	0.0086
Indoor-Outdoor Temperature Difference Tolerance C29	0.0425	Window Area and Quantity C9	0.0085
Average Relative Humidity C3	0.0370	Electricity Price C33	0.0082
Energy Efficiency Ratio C16	0.0311	Continuous Usage Duration C19	0.0066
Equipment Power Consumption C20	0.0285	House Orientation C15	0.0058
House Sealing Performance C8	0.0277	Indoor Ventilation Condition C25	0.0052
Energy-Saving Mode Usage Condition C31	0.0276	Air Conditioning Equipment Scrap Recycling Policy C35	0.0048
Average Wind Speed C4	0.0260	Life Cycle Cost of Air Conditioning Equipment C36	0.0048
Smoke Exhaust Level C22	0.0231	Maintenance Time C18	0.0044
Indoor-Outdoor Temperature Difference C23	0.0221	Window Type C10	0.0042
Wall Material C12	0.0214	Air Conditioning Equipment Debugging Effect C26	0.0033
Indoor Ventilation and Air Exchange Condition C32	0.0172	Refrigerant Capacity C21	0.0032
Daily Minimum Temperature C6	0.0155	Stability of Power Supply C34	0.0029

Through AHP, the weights of each influencing factor evaluation index were compared, and the fifteen key factors influencing air conditioning load energy consumption were preliminarily identified as: Average Temperature C1, Temperature Setting Value C28, etc.

**3.2.2. Weights of Key Influencing Factors Corrected Based on Information Entropy**

To overcome the subjectivity defect in the AHP evaluation process, information entropy was further used to correct the weights of each influencing factor evaluation index. The corrected weights and ranking results are shown in Table 5:

**Table 5.** Ranking of Influencing Factors Corrected Based on Information Entropy.

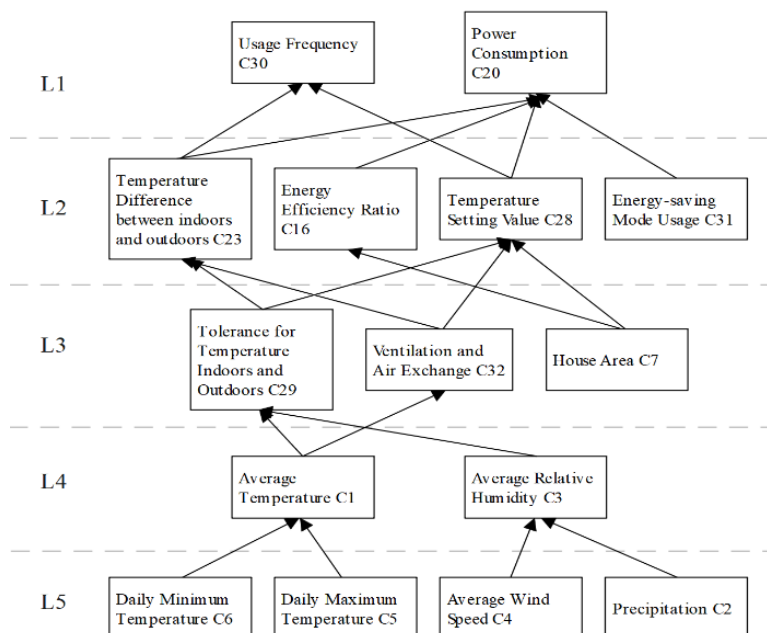
Factor Name	Weight	Factor Name	Weight
Average Temperature C1	0.1457	House Sealing Performance C8	0.0154
Temperature Setting Value C28	0.1048	Energy Efficiency Standard C37	0.0123
Daily Maximum Temperature C5	0.0955	Conditioning Energy Consumption Supervision Mechanism C38	0.0121
Air Conditioning Usage Frequency C30	0.0659	Service Life C17	0.0116
Precipitation C2	0.0615	Ground Material C13	0.0114
Indoor-Outdoor Temperature Difference Tolerance C29	0.0404	Roof Material C11	0.0111
House Area C7	0.0393	Indoor Humidity C24	0.0099
Daily Minimum Temperature C6	0.0389	Continuous Usage Duration C19	0.0074
Average Relative Humidity C3	0.0387	Window Area and Quantity C9	0.0069

Equipment Power Consumption C20	0.0283	Electricity Price C33	0.0066
Energy Efficiency Ratio C16	0.0278	Indoor Ventilation Condition C25	0.0062
Indoor-Outdoor Temperature Difference C23	0.0274	Maintenance Time C18	0.0049
Indoor Ventilation and Air Exchange Condition C32	0.0258	House Orientation C15	0.0049
Average Wind Speed C4	0.0247	Life Cycle Cost of Air Conditioning Equipment C36	0.0042
Energy-Saving Mode Usage Condition C31	0.0243	Air Conditioning Equipment Scrap Recycling Policy C35	0.0041
Smoke Exhaust Level C22	0.0178	Air Conditioning Equipment Debugging Effect C26	0.0040
Wall Material C12	0.0172	Window Type C10	0.0036
Frequency of Temperature and Humidity Changes C27	0.0172	Refrigerant Capacity C21	0.0034
House Height C14	0.0164	Stability of Power Supply C34	0.0025

The fifteen key factors influencing air conditioning energy consumption after correction are: Average Temperature C1, Temperature Setting Value C28, Daily Maximum Temperature C5, Air Conditioning Usage Frequency C30, Precipitation C2, Indoor-Outdoor Temperature Difference Tolerance C29, House Area C7, Daily Minimum Temperature C6, Average Relative Humidity C3, Equipment Power Consumption C20, Energy Efficiency Ratio C16, Indoor-Outdoor Temperature Difference C23, Indoor Ventilation and Air Exchange Condition C32, Average Wind Speed C4, and Energy-Saving Mode Usage Condition C31. The results consider the impact of indoor-outdoor temperature and humidity on residential air conditioning load and adjust the influencing factors of other dimensions internally.

### 3.2.3. Progressive Relationships of Influencing Factors on Residential Air Conditioning Energy Consumption

Based on AHP and information entropy, the 15 key influencing factors on air conditioning energy consumption were determined. These key factors were re-coded, and suggestions from experts in the field of air conditioning energy consumption research were consulted to determine the influence relationships between the above factors, and a multilevel hierarchical structure diagram of influencing factors on air conditioning energy consumption was drawn, as shown in Figure 1.



**Figure 1.** Multilevel Hierarchical Structure Diagram of Air Conditioning Energy Consumption Influencing Factors.

The 15 key factors are divided into 5 levels. The influencing factors at the bottom and sub-bottom levels all come from B1 environmental factors, indicating that natural factors such as temperature, humidity, and wind speed have a root effect on air conditioning energy consumption. Meanwhile, the linking and transmitting role of bottom-level factors on upper-level factors makes them have a certain impact on other factors, finally affecting the size of air conditioning energy consumption.

### 3.2.4. Corresponding Relationships between Residential Air Conditioning Energy Consumption and Key Influencing Factors

From the classification of first-level influencing factors, the 15 key influencing factors finally screened by the collaboration of AHP and ISM show obvious hierarchical characteristics (Table 6). Among them, the six elements included in environmental factors B1 account for 40% in quantity, confirming the core position of meteorological parameters of the natural environment as the basic driving force of air conditioning load. Factors of user behavior and habits B5 rank second, accounting for 26.7%. Factors of building structure and thermal insulation B2, air conditioning equipment performance B3, and indoor-outdoor temperature and humidity difference B4 together account for only 33.3%, but the ISM model shows that elements such as energy efficiency ratio C16 and house area C7 are in the key hub position of the system, which can produce a lever effect by affecting equipment operation efficiency or spatial thermal load distribution.

**Table 6.** Categories of Key Influencing Factors.

First-level Factors	Second-level Factors
B1	Average Temperature C1
B5	Temperature Setting Value C28
B1	Daily Maximum Temperature C5
B5	Air Conditioning Usage Frequency C30
B1	Precipitation C2
B5	Indoor-Outdoor Temperature Difference Tolerance C29
B2	House Area C7
B1	Daily Minimum Temperature C6
B1	Average Relative Humidity C3
B3	Equipment Power Consumption C20
B3	Energy Efficiency Ratio C16
B4	Indoor-Outdoor Temperature Difference C23
B2	Indoor Ventilation and Air Exchange Condition C32
B1	Average Wind Speed C4
B5	Energy-Saving Mode Usage Condition C31

## 4. Research on Energy-Saving and Emission-Reduction Pathways for Residential Air Conditioning

To explore energy-saving and emission-reduction pathways for residential air conditioning loads, this chapter selects six key variables from the B1 environmental factors (which have the highest weight, are located at the bottom of the system, and are highly monitorable) and employs the Long Short-Term Memory (LSTM) algorithm to predict the energy consumption simulation data of household air conditioners in Beijing's a residential area, ensuring a balance between user satisfaction and energy-saving effects.

### 4.1. Data Analysis

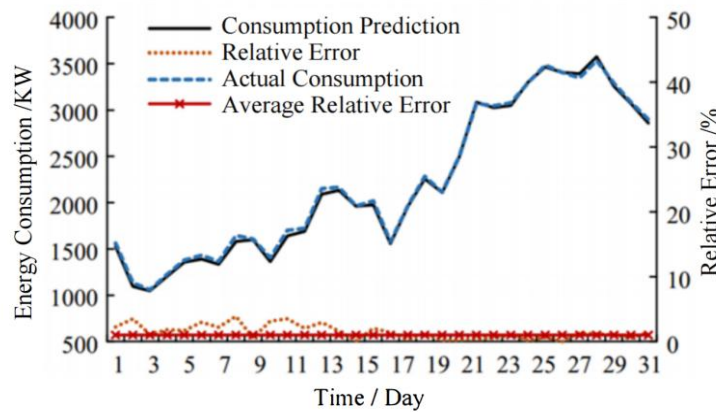
Based on literature reviews and preliminary research, this study compiles and selects the correlation coefficients between key influencing factors and household air conditioning energy consumption, as shown in Table 7 below.

**Table 7.** Correlation Coefficients Between Key Influencing Factors and Air Conditioning Energy Consumption.

Season	Average Temperature	Daily Maximum Temperature	Daily Minimum Temperature	Precipitation	Average Wind Velocity	Average Relative Humidity
Summer	0.92	0.88	0.90	-0.62	-0.15	-0.53
Winter	-0.85	-0.84	-0.72	-0.13	0.43	-0.12

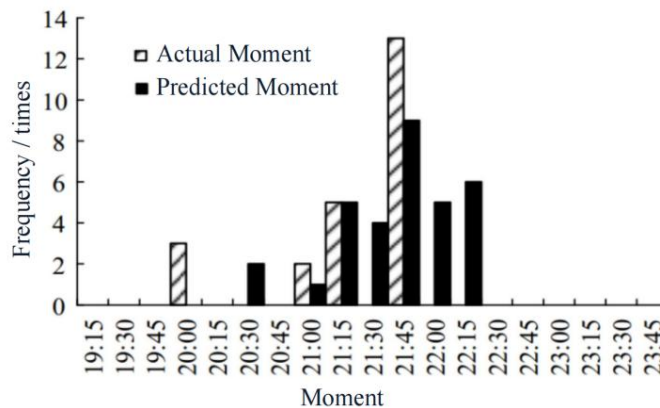
This study uses the above six key factors influencing residential air conditioning energy consumption as independent variables for the subsequent energy consumption prediction model. The training dataset consists of daily maximum air conditioning energy consumption simulation data and the six key influencing factors collected from some buildings in a residential area from January 2022 to June 2023. The prediction dataset comprises the daily peak energy consumption of residential areas in July 2023.

Since the accuracy of monthly predictions was unsatisfactory, the daily maximum energy consumption was analyzed to refine the prediction results. After reducing data granularity, the prediction results are shown in Figure 2. The highest relative error occurred on the 6th day, approximately 4%, while the average relative error was only 1%, indicating a significant improvement in prediction accuracy. Compared to other models, the LSTM model meets the precision requirements for potential analysis while requiring shorter computation times, making it suitable for practical applications.



**Figure 2.** Daily Maximum Energy Consumption Prediction Results After Reducing Data Granularity.

As shown in Figure 3, the daily peak energy consumption in residential areas occurs in the evening, concentrated between 21:00 and 22:30. Both predicted and actual values peak at 21:45, with prediction errors within 0.5 hours, demonstrating the validity and practicality of the predictions.



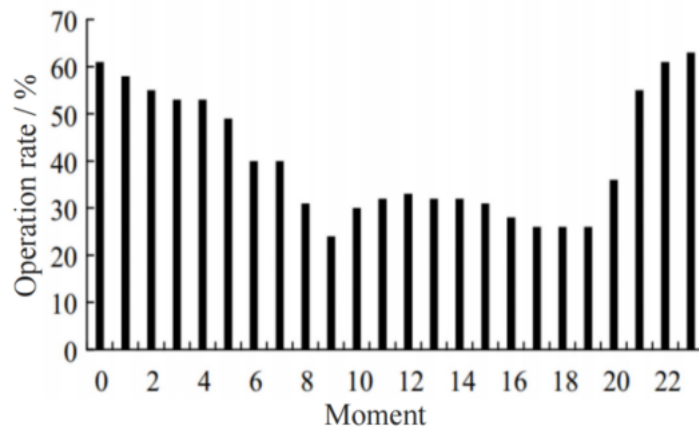
**Figure 3.** Timing of Daily Peak Energy Consumption.

**4.2. Results Analysis**

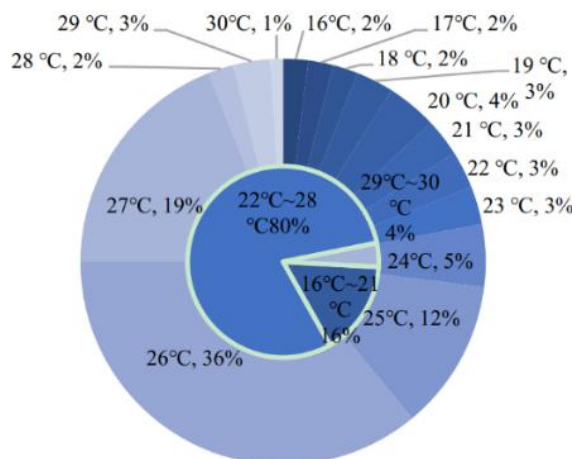
During summer heatwaves, grid peak loads occur between 11:00 and 23:00, with residential energy-saving and emission-reduction potential primarily stemming from air conditioning energy consumption. The energy-saving potential of residential air conditioners during this period was analyzed. Based on the LSTM-based energy consumption prediction model, the highest energy consumption in July occurred on the 29th, which was selected as the study day. On that day, the average temperature was 34.2°C, the maximum temperature was 36.7°C, and the minimum temperature was 32.6°C, indicating that cooling air conditioners were operating at full capacity.

Considering residents' comfort requirements, when air conditioners participate in demand response, their power output is reduced. The residential area comprises approximately 1,960 households, with an urban air conditioner ownership rate of 148.3 per 100 households. Historical statistics on air conditioner usage rates and temperature settings at different times are shown in Figure 4 and Figure 5. Air conditioner usage is highest at night and gradually decreases after midnight. The most common temperature setting is 26°C, followed by 27°C and 25°C, with 80% of users preferring settings between 22°C and 28°C.

Based on the energy consumption prediction results for July 29th and the above parameters, the dynamic energy-saving and emission-reduction potential was calculated.



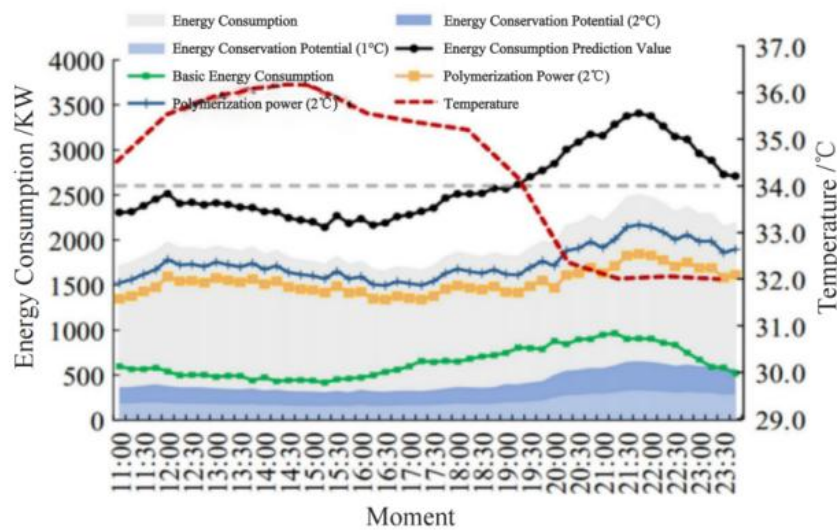
**Figure 4.** Air Conditioner Usage Rates at Different Times.



**Figure 5.** Preferences for Air Conditioner Temperature Settings.

In Figure 6, the gray area represents the aggregated power of air conditioners not participating in demand-side energy-saving measures. The blue and orange curves represent the aggregated power of residential air conditioners under normal conditions and after raising the temperature setting by 1°C and 2°C, respectively. The difference between them reflects the energy-saving potential. The light blue and dark blue areas represent the energy-saving potential achieved by raising the temperature setting by 1°C and 2°C, respectively. In this case study, when the outdoor temperature ranges from

32°C to 36°C, raising the air conditioner temperature setting by 1°C and 2°C can increase energy-saving potential by 10% and 21%, respectively.



**Figure 6.** Dynamic Energy-Saving and Emission-Reduction Potential of Residential Air Conditioners.

From the daily energy-saving potential results, it is evident that the potential is positively correlated with air conditioning energy consumption but not strongly linked to temperature. Between 11:00 and 23:30, as temperatures drop in the evening, energy-saving potential increases for two reasons: Lower ambient temperatures make residents more willing to raise their air conditioner temperature settings. Residents' daily routines lead to increased energy consumption in the evening, expanding the energy-saving potential.

To ensure that adjusting temperature settings maintains a certain level of user satisfaction, this study established the relationship between energy-saving potential and temperature adjustments. Using the average preferred temperature of 25°C (with a satisfaction score of 1), and based on the comprehensive energy consumption satisfaction model, calculate the satisfaction at other temperatures, the relationship between temperature adjustments and energy-saving potential is shown in Table 8:

**Table 8.** Relationship Between Temperature Adjustments and Energy-Saving Potential.

	Increase by 3°C	Increase by 2°C	Increase by 1°C	Reduce by 1°C	Reduce by 2°C	Reduce by 3°C
Potential	28%	21%	10%	7%	13%	18%
satisfaction	0.423	0.688	0.935	0.836	0.647	0.215

As the temperature adjustment increases, user satisfaction decreases. When the temperature is raised by 1°C (to 26°C), satisfaction decreases by 6.5%, but residents barely perceive the change, while achieving a 10% energy-saving potential. Therefore, setting the air conditioner temperature to 26°C can meet user comfort needs while significantly reducing energy consumption.

## 5. Main Conclusions

(1) The proposed framework for identifying influencing factors and analyzing hierarchical relationships for residential air conditioning energy consumption extracts six key factors from 38 candidates and constructs a dual-layer system. This system reveals the hierarchical relationships and interactions among these factors, demonstrating that environmental and climatic conditions are the root causes of air conditioning energy consumption.

(2) Through surveys and analysis, this study finds that residential air conditioning energy demand is primarily driven by four dimensions: thermal comfort, energy efficiency, ease of use and economic cost, accounting for 93.352% of the factors. These demand characteristics are crucial for formulating energy-saving and emission-reduction policies.

(3) Based on LSTM model predictions, this study proposes that adjusting air conditioner temperature settings can reduce energy consumption without compromising user comfort. The results demonstrate that setting the temperature to 26°C minimizes user perception of changes while achieving a 10% reduction in electricity consumption, balancing high user satisfaction with energy-saving goals.

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