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Case Study on Effect of Climate Factors on HVAC Energy Consumption in Residential Buildings

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Abstract: The environmental climate factors have significant impact on building equipment energy consumption, especially in regions with hot summers and cold winters, where building energy consumption patterns are substantially influenced by seasonal climate variations. This research analyzed the actual energy consumption data of a residential building's HVAC system from July 2023 to February 2024. The Random Forest method was applied to analyze the influence of weather variables on HVAC system energy consumption. K-means clustering was used to categorize energy consumption patterns into high, medium and low and energy consumption characteristics in according to the weather variables in each pattern were analyzed. The results show that: (1) Temperature exerts the greatest influence on the energy consumption of building HVAC system, followed by solar radiation and humidity. (2) The distribution of three high-medium-low energy consumption modes shows significant seasonal characteristics, among which the moderate energy consumption mode is the main contributor to the total energy consumption of HVAC systems. (3) Building HVAC high energy consumption level is mainly driven by the weather conditions of high temperature and intense solar radiation in summer and low temperature with weak solar radiation in winter; Medium energy consumption is commonly seen during summer cooling and winter heating periods, when the HVAC system needs to be switched on but does not require high load operation; Low energy consumption normally corresponds to mild climatic conditions.

1. Introduction

According to the report by the United Nations Environment Program (UNEP), building energy consumption accounts for 32% of global energy use and 34% of global energy-related CO_2 emissions[1]. The climate change and extreme weather events has made the variation in building energy consumption more complex and difficult to predict[2]. In this context, building energy consumption is greatly influenced by climatic factors such as temperature, humidity, and solar radiation[3-4], especially in hot-summer-cold-winter regions where high temperature and humidity in summer, combined with a cold, damp winter, result in prolonged high-load operation of Heating, Ventilation, and Air Conditioning (HVAC) systems. Studying the driving factors of energy consumption in building HVAC systems in the hot summer and cold winner regions is crucial for energy optimization and energy-saving management.

Previous research has achieved substantial advances in exploring the influence of climatic variables on building energy use and related analytical approaches. Temperature plays a crucial role in determining the energy demand of HVAC systems, while variations in outdoor temperature predominantly determine buildings' heating and cooling requirements: low temperatures increase the HVAC's heat load energy, while high temperatures increase the cooling load[5]; Choi et al. (2025) states that extreme high temperatures can cause a non-linear increase in building cooling energy consumption[6]. Humidity indirectly affects energy consumption by affecting indoor thermal comfort. Under high humidity, air conditioning needs to synchronize cooling and dehumidification, which increases energy consumption[7-8]. Ma and Yu (2020) confirmed that for every 1% increase in relative humidity, HVAC system energy consumption changes by 2.3% and 1.1% respectively[9]. Solar radiation also has a significant influence on the energy consumption of buildings[10]. The increase in solar radiation transfers heat through external windows and walls, causing an increase in indoor temperature and an increase in the cooling burden of air conditioning[11]. In addition, factors such as wind speed and precipitation can also affect HVAC energy consumption, among which wind speed can lead to heat dissipation via air infiltration and leakage, affecting building energy efficiency[12].

Although existing research has confirmed the influence of weather factors on building energy consumption, further research is needed on the combination of meteorological conditions that trigger different HVAC operating modes.

In regard to analytical methods, data-driven methods have been applied in building energy consumption

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analysis due to their advantages in handling complex nonlinear relationships. Random Forest (RF) model can quantify the impact weights of various weather variables on energy consumption, providing a basis for key variable selection [13-14]. Zhu et al. (2025) confirms that Random Forest model can select the most strongly correlated influencing factors with heat load from multiple meteorological parameters[15]. At the same time, clustering algorithms represented by K-means have become important tools for identifying energy consumption patterns, capable of extracting patterns from large amounts of data [16]. For example, Guerrero Ramírez et al. (2025) proposed a combination method of "white box model calibration+K-means clustering" to distinguish between HVAC operating periods and free oscillation periods, and identified non periodic abnormal energy consumption patterns[17]. Nojedehi et al. (2025) identified 8 energy consumption patterns via clustering of a large volume of single-family residential building energy data, and explored their correlations with building thermophysical properties[18]. These studies have laid the methodological foundation for identifying key influencing factors of buildings and identifying consumption patterns in building energy data.

Given the above discussion, this study focuses on the HVAC energy consumption of residential buildings in regions with hot summers and cold winters. The Random Forest model is used to determine the key weather variables affecting energy use. K-means clustering is then applied to recognize distinct modes of energy consumption. Finally, statistical analysis is employed to characterize the specific weather conditions associated with each identified pattern, providing a reference for a deeper understanding of the association between building energy consumption and meteorological conditions. The technical roadmap for this study is as follows (see Fig. 1).

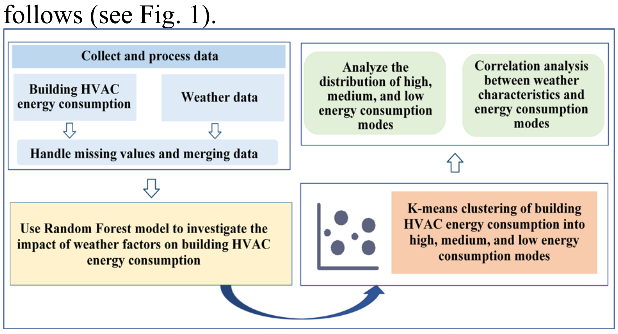

Fig. 1. Research design.

2. Data and Methods

2.1. Data Collection and Preprocessing

This study collected energy consumption data of HVAC systems in a residential building in Jiangxi Province China from July 2023 to February 2024, including minute level energy consumption records of outdoor units, indoor units, and fresh air systems (a part of the data is presented in Table 1). Meanwhile, daily averages for temperature (T), relative humidity (RH), solar radiation (SR), wind speed (WS), and precipitation (P) were acquired from Visual Crossing weather data website (a part of the weather data is presented in Table 2). To ensure data quality, The linear interpolation method used to handle missing values and ensuring the temporal continuity and integrity of the data series. Finally, merge the daily total energy consumption data with the corresponding weather data to provide complete data for subsequent analysis.

Table 1. Sample of Building HVAC Energy Consumption Data.

Date	Outdoor unit (kwh)	Indoor unit (kwh)	Ventilation (kwh)	Total (kwh)
2023/8/5 9:00	1.105	0.161	0.051	1.317
2023/8/5 10:00	1.235	0.16	0.05	1.445
2023/8/5 11:00	1.35	0.159	0.051	1.56
2023/8/5 12:00	1.967	0.16	0.05	2.177

Table 2. Sample of Weather Data.

Date	T(°C)	RH(%)	SR(W/m^2)	WS(m/s)	P(mm)
2023 8/5	31.3	75.5	275.4	4.2	0.2
2023 8/6	30.8	77.4	261.9	6.0	0.7
2023 8/7	29.2	82.6	247.8	6.9	0.1
2023 8/8	28.4	81.7	246	8.3	1.5

2.2. Data Analysis Methods

This study used statistical analysis, Random Forest, and K-means clustering methods to systematically analyze the factors affecting building energy consumption. The Random Forest can quantify the extent to which weather variables influence energy consumption through feature importance assessment[19]. By minimizing the distance between data points and their respective centroids, K-means clustering can identify patterns in energy consumption, ensuring intra class similarity and inter class difference. They have the advantages of high computational efficiency and easy implementation, and are suitable for large-scale data analysis[20]. This study also utilized the elbow method to ascertain the optimal number of clusters for K-means clustering[21]. Statistical analysis is used to calculate the characteristics of weather variables under different modes.

3. Results and Discussion

3.1. Impact of Climate Factors on Building HVAC Energy Consumption

As illustrated in Fig. 2, temperature (importance coefficient: 0.527) plays a central role in influencing building HVAC energy consumption, with an importance coefficient higher than the sum of all other weather factors. The change in temperature directly affects the thermal load of buildings. Solar radiation significantly outweighs humidity (importance coefficient: 0.204), especially in summer, where higher solar radiation intensity significantly elevates the demand for air conditioning, leading to a rise in energy consumption. Humidity also contributes to building energy consumption (importance coefficient: 0.152). At high temperatures, humidity increases the feeling of stuffiness, while at low temperatures, humidity intensifies the feeling of coldness. Relatively speaking, the impact of wind speed (importance coefficient: 0.046) and precipitation (importance coefficient, 0.070) on building HVAC energy consumption can be almost negligible.

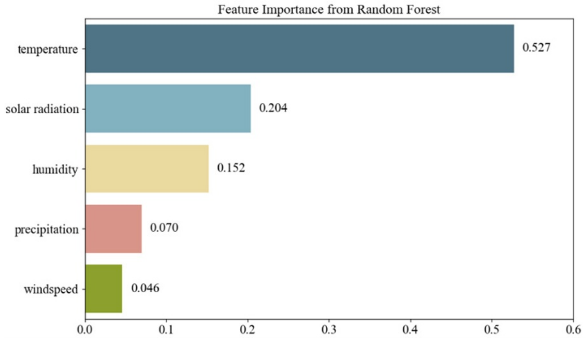

Fig. 2. Importance ranking of weather factors.

3.2. Energy Consumption Pattern Recognition and Distribution Characteristics

To identify the typical operating states of building HVAC systems, this study used K-means clustering to cluster daily energy consumption data. Using the elbow method, three clusters were identified as the optimal number, and their distribution is visualized using a box plot (Fig. 3).

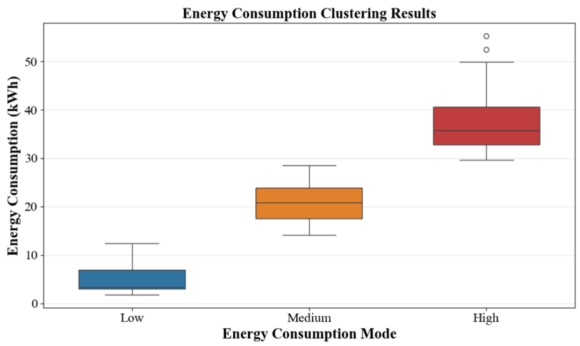

Fig. 3. Energy consumption clustering boxplot.

The findings reveal that the main distribution intervals for the three energy consumption modes are as follows: low energy consumption mode is 2.98–6.88 kWh, medium energy consumption mode is 17.61–23.91 kWh, and high energy consumption mode is 32.87–40.61 kWh. At the same time, the distribution of energy consumption patterns shows obvious seasonal characteristics (Fig. 4): low-energy consumption patterns mainly occur in the transitional season of autumn; Medium energy consumption mode occurs primarily in summer and winter; The high energy consumption mode occurs exclusively during summer and winter. Further analysis of energy consumption distribution (Fig. 4) reveals that during 16.8% of the time, high energy consumption mode accounted for 37.5% of total HVAC energy consumption. Medium energy consumption mode represented 49.5% of total HVAC energy consumption, occurring on 39.8% of days, constituting the primary component of HVAC system energy consumption.

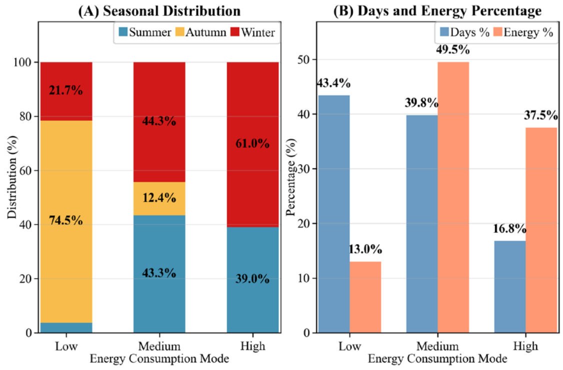

Fig. 4. Distribution of Energy Consumption Clusters.

3.3. Analysis of the Relationships between Weather Characteristics and Different Energy Consumption Modes

3.3.1 Relationship between temperature and energy consumption mode

The Random Forest model identifies temperature as the most critical factor affecting residential building HVAC energy consumption. To visually illustrate this dominant influence, Fig. 5 presents the time-series correspondence between temperature and energy consumption modes. The analysis shows that the HVAC system tends to operate in high energy consumption mode when the temperature exceeds 28 °C or falls below 3 °C. The medium energy consumption mode is mainly distributed in summer at 25-28 °C and in winter at 3-10 °C, whereas the low-energy mode primarily occurs across the 10-25 °C comfortable temperature range. The distribution of the three modes along the temperature axis clearly reflects the significant impact of temperature on the operating status of the HVAC system.

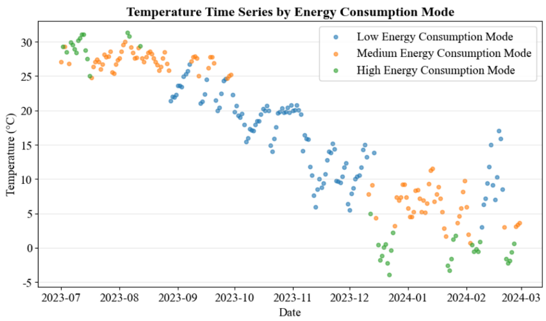

Fig. 5. Distribution of Energy Consumption Clusters by Temperature.

3.3.2 Characteristic analysis of weather variables

Beyond univariate temperature analysis, this study further investigates the combined effects of the other key weather factors (humidity and solar radiation) to comprehensively profile the meteorological conditions of each mode. Statistical analysis was employed to quantify the distribution of all three weather variables, with the results visualized in Fig. 6 , where line segments show ranges and markers indicate mean values.

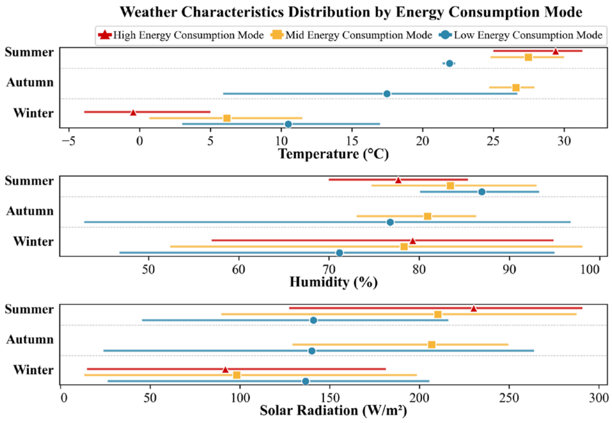

Fig. 6. Statistical Distribution of Weather Variables in Different Energy Consumption Modes.

The high energy consumption mode is closely related with specific meteorological combinations that induce high-load system operation. During summer, this mode features high temperature (average 29.39 °C) combined with intense solar radiation (average 230.24 W/m²); In winter, it corresponds to the combined effects of low temperature (average -0.46 °C), high humidity (average about 80%), and weak solar radiation (average 91.76 W/m²). The interplay of these meteorological variables primarily drives the system in high-load operation.

For the medium energy consumption mode, summer conditions present temperatures (average 27.47 °C) above the comfort range yet below high-load thresholds. In addition, the average solar radiation intensity (210.29 W/m²) is lower than that in the high energy consumption mode, allowing the refrigeration system to operate under normal load conditions. Winter conditions show comparable humidity (78.31%) and solar radiation (98.1 W/m²) to high-consumption mode, but its average temperature (6.17 ℃) is significantly higher than that of the high-energy consumption winter (-0.46 ℃). The temperature difference reduces heating demand, eliminating the need for high load operation of the heating system, and maintaining the overall energy consumption of HVAC at a moderate level.

In contrast, the low energy consumption mode occurs under mild climatic conditions, leading to minimal HVAC system operation, and the HVAC system has the lowest operating energy consumption.

4. Conclusion

Utilizing operational data from residential buildings HVAC systems in a hot-summer and cold-winter climate, this study reveals the inherent correlation between meteorological factors and building HVAC energy consumption patterns through Random Forest, K-means clustering, and statistical analysis methods. The main findings are as follows:

(1) Temperature is the most critical meteorological factor affecting residential building HVAC energy consumption, and its changes are significantly correlated with energy consumption mode transitions. The Random Forest model result shows that the importance coefficient of temperature (0.527) is significantly higher than other meteorological parameters.

(2) The building HVAC system presents three typical energy consumption patterns with significant seasonal characteristics. The medium energy consumption mode is the main contributor to the total energy consumption of HVAC systems, accounting for up to 49.5%; The high energy consumption mode is concentrated in the hot summer and cold winter months, and although the proportion of days is relatively low, it contributes significantly to the total energy consumption of building HVAC.

(3) Different energy consumption modes are driven by specific meteorological conditions: high energy consumption modes correspond to high temperatures and strong solar radiation in summer or low temperatures and high humidity in winter; The medium energy consumption mode mainly occurs under typical weather conditions that require cooling or heating.

This study has identified the effects of key weather variables such as temperature, relative humidity, and solar radiation, on building HVAC energy consumption, and has revealed the weather characteristics associated with different energy consumption patterns. Future research can focus on this direction by constructing quantitative models to quantify the combined impact and underlying patterns of multi-variable combinations on building HVAC energy consumption.

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