Climate Impact on Electrical Energy Consumption in Residential Building in Different Building Climate Zones of China

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Abstract

Residential building energy consumption is vulnerable to climate condition due to the cooling and heating energy demand and heat transfer between building wall and external environment. This study describes the research conducted in order to identify the climatic impact factors of residential building energy consumption, and to quantify how the relationship between them varies across the climate zones. Historical data of 405 residential buildings in three main climate zones in China are collected and 15 scenarios for simulation by EnergyPlus are created. The study finds that air temperature is the main influencing factor. The relationship between air temperature and Electricity Use Intensity (EUI_E) is not linear. Climate change shows little impact in Severe Cold Zone, but obvious influence in Cold Zone and Hot Summer and Cold Winter Zone. There exists large difference of the climate impact among climate zones but similar changing trend between sub climate zones in the same main climate zone. The effect changes from inhibition to promotion when the air temperature rises to 20℃ in Cold Zone and 15℃ in Hot Summer and Cold Winter Zone. The variation of impact also depends on building type. Multistory residential building (less than 7 storey) is the most sensitive type to climate change. The finding of variation represents a better understanding of climate impact on residential building energy performance and highlights the importance that energy policies to cope with climate change should be adapted to local conditions.

Introduction

Energy consumption in residential buildings accounted for 12.77% of Chinese total energy consumption from 2000 to 2016, of which 61.3% was used by household in cities and towns[1]. Electricity was the main source of building carbon emissions, accounting for 46%[1,2]. Electricity used in residential building, especially for cooling and heating, is mainly affected by climate condition[3-8]. In China, due to the large climate condition difference, the cooling and heating demand for resident varies a lot across different climate zones, as the mean temperature difference of the North and the South in January may reach 40℃.

The study on climatic impact on building energy consumption can be classified into three categories, historical data based regression analysis and prediction[9-11], modeling combined with field measurement to evaluate the impact under different scenarios[12,13], modeling for prediction of the future building energy performance under the effect of climate change[14-16]. The approach using historical data is usually self-calibrate because it takes the advantages of the relationship between climate and building energy consumption[9]. Since the uncertainty of future climate condition leading to no certain climate scenario[17,18], the discussion and evaluation of different scenarios are necessary[19]. For example, in Wang's work, over 1000 sets of climate coefficients were developed to separately adjust building heating, cooling, and fan energy use[20]. In Nik's work, 12 different scenarios have been created considering four uncertainty factors[19]. The prediction of future generally perform on temporal scale from the past to the future, using the historical data to calibrate the model [15,21,22] and on spatial scale refering to different climate zones in one or several countries[15,23].

The purpose of this study is to explore a more comprehensive treatment of the impact of climate on electrical energy consumption in residential building in different climate zones, and to highlight the importance that energy policies should be adapted to local climate conditions. We first use correlation analysis on monthly historical data to identify the main impact factors, then, quantitatively study the impact of climatic variables on electrical energy consumption. 15 scenarios are created, representing three residential building types in five sub climate zones of China.

The remaining of the article is organized as follows: a brief description of the Building Climate Demarcation of China along with the methodology used in this research; main climatic factor identification along with the evaluation of the impact strength; conclusions and limitations.

Methodology

Building Climate Demarcation of China

The Building Climate Demarcation of China includes 7 main climate zones and 20 sub climate zones (Fig. 1). It is carried out in the Code for Design of Civil Buildings (GB 50352-2005).

In this study, we choose the sample buildings in Severe Cold Zone ⅠC, Cold Zone ⅡA and ⅡB, and Hot Summer and Cold Winter Zone (HS&CW Zone) ⅢB and ⅢC (Table 1). Buildings in Severe Cold and Cold Zones must fully meet the requirements of cold prevention and heat preservation in winter. Heat prevention in summer may not be considered. Buildings in HS&CW Zone must meet the requirements of heat protection in summer.

Table 1 Climate zones selected in this study

Zone Code	Zone Name	Main Climate Indicators	Case Study
Ⅰ	Severe Cold Zone	Mean TEMP in January < - 10 ℃ Mean TEMP in July ≤ 25 ℃	Harbin (ⅠC)
Ⅱ	Cold Zone	Mean TEMP in January : 10 ~ 0 ℃ Mean TEMP in July: 18 ~ 28 ℃	Wu'an (ⅡA), Qingcheng (ⅡB)
Ⅲ	Hot Summer and Cold Winter Zone	Mean TEMP in January: 0 ~ 10 ℃ Mean TEMP in July: 25 ~ 30 ℃	Changxing (ⅢB), Jintang (ⅢC)

Data Collection

The data base of this study is represented by 405 residential buildings of five cities and towns, which have been chosen in extensive field investigation in year 2018. 84 buildings are in the sub zone IIIB and IIIC in HS&CW Zone. 125 buildings are in the sub zone IIA and

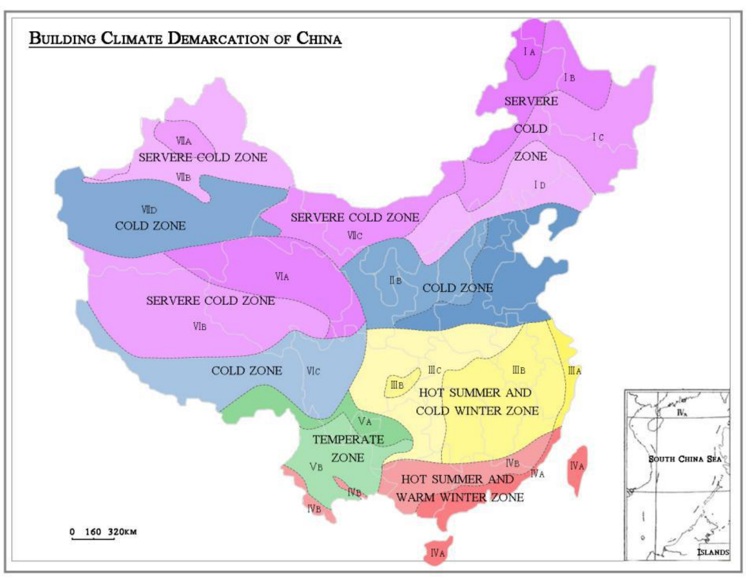

Figure 1. Building Climate Demarcation of China
Source. http://www.jianbiaoku.com/webarbs/book/27365/873596.shtml

IIB in Cold Zone. And 196 buildings are in the sub zone IC in Severe Cold Zone.

The climate data is collected from three ways, the local Meteorological Bureau, the National Meteorological Data Center, and field measurement. The historical building energy consumption data is mainly collected from the State Grid Corporation of China, and a little from other government sectors. Both climate data and building energy data are in months.

Building Energy Simulation Model

In the background of rapid urbanization in China, the form of residential buildings in each city tends to be the same. Therefore, in this study, three residential building prototypes are built according to the building storey, high-rise apartment with 31 storey, mid-rise with 9 storey and multistory with 6 storey. The simulation of the 15 scenarios is run by EnergyPlus, which is a widely used simulation engine in heating, cooling, lighting and other energy consumption analysis of buildings. The simulation parameter settings for the 15 scenarios are different, but the same with the survey buildings in each climate zone, including building material, building construction, general climate data, energy using schedule, HCAV system and so forth. Two kinds of cooling system (natural ventilation and fan, air-conditioning) and three kinds of heating system (air-conditioning, baseboard radiation, low temperature radiation) are built according to the climate zones.

In order to set the simulation environment closer to reality, this study uses the collected weather data of year 2018 which matches the actual energy consumption data, instead of the weather data package of EnergyPlus collected from the third Typical Meteorological Year (TMY3) collection [9].

Statistical Analysis

Energy simulation is based on the ideal individual condition without the impact of local surroundings. Therefore, we consider the difference between measured data and simulation result is caused by the local external climate condition. Electricity use intensity difference (EUI_{Ed}) is used to quantify the impact, defined as the energy consumption difference between the measured value and simulation result (Eq. 1):

$$EUI_{Ed} = EUI_{Ea} - EUI_{Es} \quad (1)$$

where EUI_{Ea} is the measured building electricity use intensity, EUI_{Es} is the simulation result.

The EUI_E values across twelve months for the whole year of 2018 combined with the weather data are aggregated to observe the fluctuation of energy consumption difference along with climate change on temporal dimension. Spearman correlation analysis is used to identify the influencing factors with significant impact first. Then, a multiple regression model is built to quantitatively study the sensitivity of climate impact to building energy consumption (Eq. 2).

$$f(x) = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \varepsilon \quad (2)$$

where f(x) is the dependent variable (EUI_{Ed}), β_0 is the intercept, x_i is the impact factor i, β_i is the regression coefficient of influencing factor i, n is the number of factors, and ε is the error term.

Result and Discussion

Identification of Climate Impact Factor

The monthly EUIEa value of residential buildings in each climate zones shows a moderate correlation with air temperature, and does not represent a obvious relationship with wind speed and humidity (Table 2).

Table 2 Correlation coefficient between EUI_{Ea} and climate factors

		Monthly air temperature(℃)	Monthly wind speed (m/s)	Monthly humidity(%)
EUI_{Ea}	Correlation Coefficient	.423**	-.161	.075
(kwh/m²)	Sig. (2-tailed)	.042	.265	.543
	N	405	405	405

**. Correlation is significant at the 0.01 level (2-tailed).
。 Correlation is significant at the 0.05 level (2-tailed).

Although varying by the climate conditions, building types, and months, the values still show a similar trend with air temperature changes (Fig. 2). The peak value appears at the months of high (August and September) and low temperature (January and March) of the year. The change of EUI_{Ea} value in the other months is relatively stable. The regression analysis result indicates that the climatic impact on electrical energy consumption is not a simple linear relationship, but a cubic curve (Fig. 3). This explains why the interaction

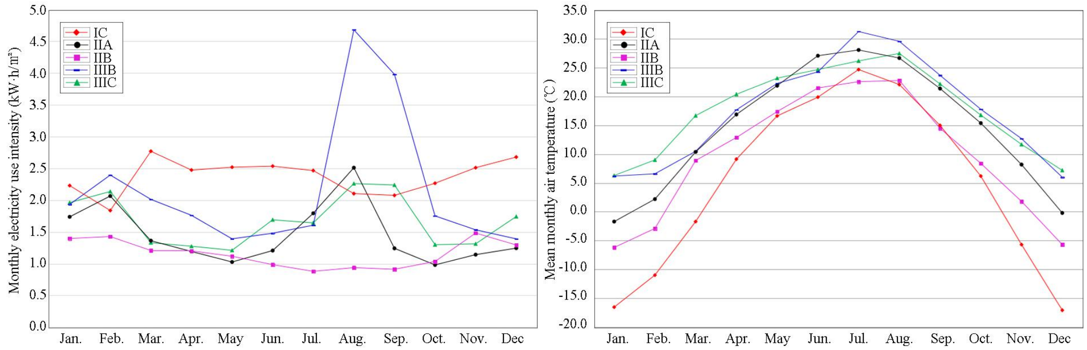

Figure 2. Monthly EUI_{Ea} of residential buildings and mean air temperature in five sub climate zone
Source. Self-drawn by the authors

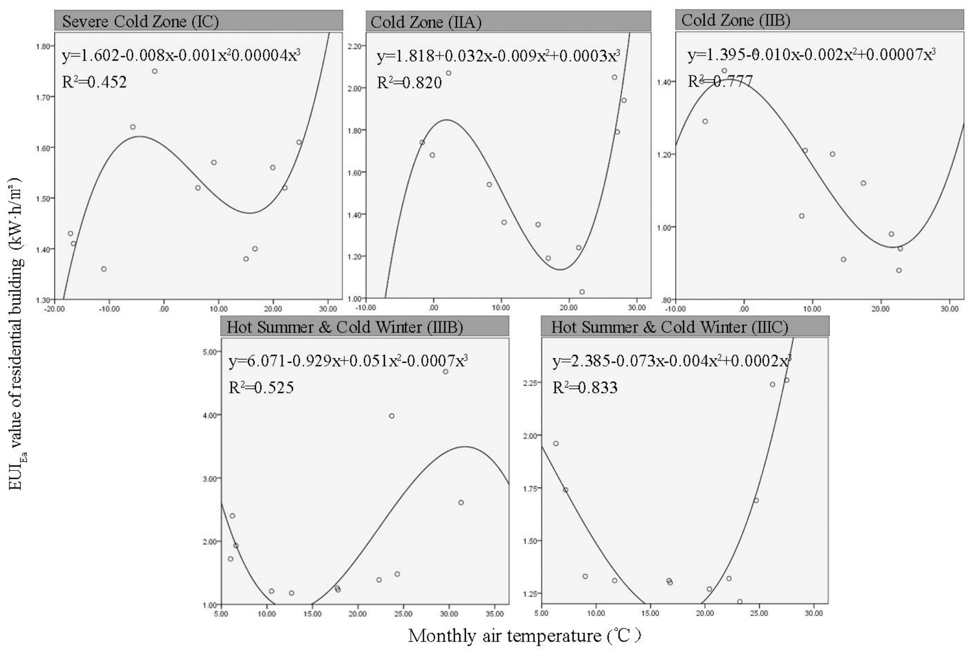

Figure 3. Regression analysis of the climate impact on EUI_{Ea} of residential building
Source. Self-drawn by the authors

between them analyzed by Spearman correlation is not strong.

Climate Change Impact across Building Climate Zones

The littlest EUI_{Ed} for the whole year appears in Severe Cold Zone IC, especially for multistory residential building where the monthly mean difference is close to zero (0.17 kW·h/㎡) (Table 3). By contrast, the EUI_E of multistory residential buildings in IIIB, the EUI_E of mid-rise in IIC and the EUI_E of the high-rise in IIA are more sensitive than others to climate change (Fig. 4). The positive and negative of the difference indicates whether the influence of external climate environment on energy consumption is promoted or inhibited.

Table 3 The monthly EUI_{Ed} of three types of residential buildings in five sub climate zones (kW·h/㎡)

	Multistory					Mid-rise					High-rise				
	I C	II A	II B	IIIB	IIIC	I C	II A	II B	IIIB	IIIC	I C	II A	II B	III B	IIIC
Jan.	-.10	-.43	-.09	-.99	.13	.17	-.06	.31	-.15	-.05	-.54	-.83	-.49	-.08	-.53
Feb.	-.19	.24	.27	-.89	.02	-.68	-.12	-.15	.03	-.89	-1.09	-.63	-.63	.37	-.23
Mar.	.55	-.75	-.30	-1.46	-.98	-.28	-1.43	-1.06	-.90	-1.76	-.38	-1.59	-1.18	-.35	-1.52

Apr.	.35	-.83	-.20	-1.31	-.84	.15	-1.02	-.33	-.52	-1.27	-.41	-1.55	-.92	-.55	-1.37
May	.19	-1.22	-.55	-1.39	-.62	-.45	-1.85	-1.11	-.65	-1.77	-.61	-1.98	-.50	-.50	-1.72
Jun.	.41	-.82	-.56	-.48	-.43	.22	-1.00	-.67	-.82	-.92	-.34	-1.53	-.55	-.22	-.70
Jul.	.24	-.27	-.83	-1.43	-.66	-.19	-.69	-1.17	-.30	-1.09	-.54	-1.03	.20	-.47	-.98
Aug.	-.23	.43	-.84	1.09	.21	-.87	-.22	-1.40	.92	-.77	-1.02	-.38	-1.58	.60	-.68
Sep.	.05	-.67	-.57	.89	.32	.08	-.64	-.47	.87	-.80	-.67	-1.37	-1.25	.61	-.22
Oct.	-.06	-1.27	-.68	-1.56	-1.27	-1.14	-2.14	-1.51	-1.29	-2.21	-1.01	-2.11	-1.53	-.83	-1.59
Nov.	.29	-.99	.15	-1.84	-1.21	-.93	-1.83	-.70	-1.67	-1.96	-.78	-1.88	-.78	-.83	-1.60
Dec.	.56	-.77	-.05	-1.15	-.73	-.49	-1.45	-.73	-1.27	-1.05	-.51	-1.67	-.97	-.53	-1.01
mean	.17	-.61	-.35	-.88	-.51	-.37	-1.04	-.75	-.48	-1.21	-.66	-1.38	-.85	-.23	-1.01

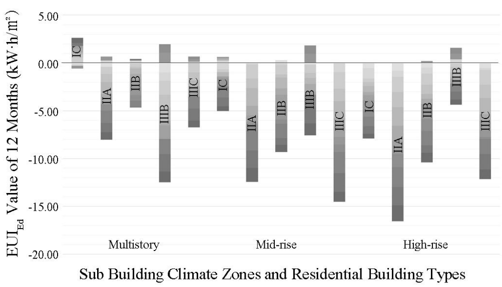

Figure 4. Stacking value of EUI_{Ed} of three residential building types in five sub climate zones
Source. Self-drawn by the authors

Regression analysis of EUI_{Ed} and climate change are made for the 15 scenarios. Despite the impact of climate change on EUI_{Ed} value varies across each sub climate zone, the trends are similar in each main climate zone. Fig. 5 presents the interaction between the air temperature and monthly mean EUI_{Ed} value.

The weakest relationships are found in Severe Cold Zone. Due to the climate condition of cool summer and cold winter, there is little cooling demand in summer and the central heating system declines the electrical heating demand. Therefore, electricity used for residential building in Severe Cold Zone mainly depends on daily indoor activities which are less affected by external climate condition.

By contrast, within each sub climate zone, there exists a obvious pattern of climatic impact on EUI_{Ed} of residential building in Cold Zone. The turning points of each sub zone mainly appear between 15℃ and 20℃ in all six scenarios where the strength of climate impact in the two sub climate zone starts to go different ways. In other words, when the

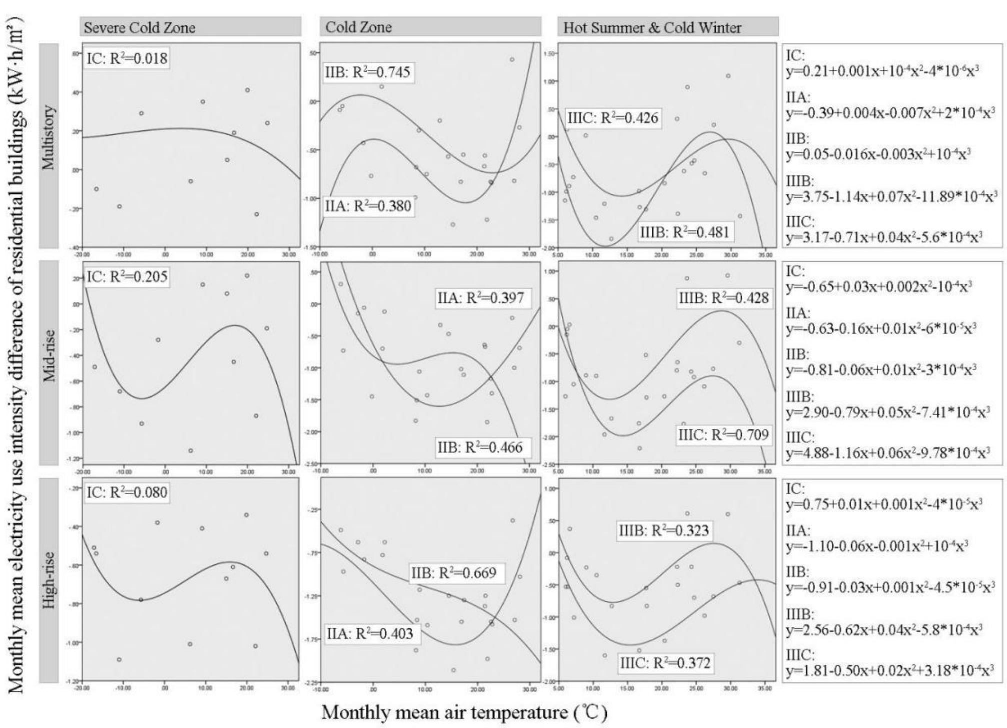

Figure 5. Regression analysis of the impact of climate change on EUI_{Ed} of residential building across climate zones and building types
Source. Self-drawn by the authors

temperature is below 15℃, the increase of air temperature has a similar inhibitory effect on electrical energy consumption of residential buildings (similar inclination of the curve). When the temperature is higher than 20℃, the inhibitory effect continues in the mid-rise and high-rise in IIB, despite a little increasing of mid-rise type. The impact of climate change of the mid-rise and high-rise in IIB approximate to a linear function. However, in IIA, the effect turns to be a dramatic promotion. It should be noted that the the EUI_{Ed} of multistory building in Cold Zone is also promoted by temperature rise below 0℃.

In HS&CW Zone, the climatic impacts of the two sub climate zones IIIB and IIIC represent similar changing trend. When the temperature is lower than 12 ℃, the inhibitory effect of the temperature rise on the EUI_E of residential buildings is stronger than its promoting effect when higher than 15 ℃. The impact shows an opposite trend when the temperature is higher than 30℃.

The strength of such variation also depends on building type. For instance, in HS&CW Zone, the temperature change from 20℃ to 21℃will result in 0.227 kW·h/㎡ EUI_{Ed} difference in multistory residential building, 0.196 kW·h/㎡ difference in the mid-rise and 0.104 kW·h/㎡ difference in the high-rise. The situation is similar in Cold Zone. Multistory residential building is the most sensitive one to climate change among all the three types.

Conclusion

This study identifies the main climatic factor and evaluates the climate impact on electricity use intensity of residential building across three main climate zones.

We find that air temperature is the main climatic impact factor of electrical energy consumption of residential building in all three main climate zones. The electricity use intensity varies along with air temperature changes as a cubic curve. Large variation of the impact is found across three main climate zones. The weakest influence is found in Severe Cold Zone due to the less demand for cooling and little electrical heating necessity. The lowest monthly mean difference is 0.17 kW·h/㎡ of the multistory, nearly 1/7 of the highest appearing at the high-rise in IIA. By contrast, residential building in the other two climate zones are more sensitive to climate change. Although varying among three main climate zones, the impacts in sub climate zones of the same main zone still represent similar changing trends. The turning point of Cold Zone is between 15℃ to 20℃ where the impact of climate change on electrical energy consumption turns to be promotion from inhibition. The point in HS&CW Zone is between 12℃ to 15℃. It is worthwhile to note that the variation of impact also depends on building type. Multistory residential building is the most sensitive type to climate change, following by mid-rise and high-rise.

In this study, due to the limitation of field investigation, we can only obtain energy consumption data and climate data of three main climate zones for this moment. In the future study, we are going to collect and simulate the data of the other four climate zones to better understand the variation of the impact in different climate zones.

Acknowledgement

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Endnotes

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