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Factors Affecting Residential End-Use Energy: Multiple Regression Analysis Based on Buildings, Households, Lifestyles, and Equipment

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Abstract: Building characteristics, household compositions, lifestyles, and home equipment are recognized as the main factors influencing residential energy consumption, which has been a subject of extensive exploration for many years now. However, the quantitative correlation models between the above factors and residential end-use energy have not been fully studied. This paper aims to explore the determinants of residential end-use energy consumption by a comprehensive analysis based on the factors of building characteristics, household compositions, lifestyles, and home equipment. For this purpose, we investigated and collected the building information of 66 households and obtained the data through an installed measurement system of the annual residential end-use energy from July 2019 to June 2020. Subsequently, six multiple regression models were used to quantitatively analyze the valid determinants of each end-use energy. The main results were as follows: for cooling energy consumption, the greatest effective variable was FM_no (22–59, number of family members aged 22 to 59); the most influential variable was found to be FM_no (number of family members) for DHW and appliances energy consumption; for lighting and cooking energy consumption, the most effective variables were AREA (floor area) and Cooking (average daily cooking hours), respectively. Moreover, the order of influence of building characteristics, household compositions, lifestyles, and home equipment over each end-use energy consumption is as follows: households > equipment > lifestyles for cooling and DHW, households > buildings > equipment for lighting, equipment > lifestyles for appliances and cooking.

Keywords: residential energy; buildings; households; lifestyles; equipment; multiple regression analysis

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1. Introduction

The Paris Agreement aims to limit the rise in average global temperature to 1.5 °C or 2 °C above the preindustrial level, which requires all countries to do their utmost to rapidly reduce greenhouse gas emissions [1]. To meet this goal, China also promises to peak its energy-related carbon emissions by 2030 and achieve carbon neutrality by 2060 [2,3]. Building energy consumption is one of the largest energy consumption areas in the world, accounting for about 40% of global energy consumption and contributing more than 30% of carbon emissions [4]. Among all building consumption, the energy consumption of residential buildings is the biggest part, representing three-quarters of the energy consumption of the building sector [5,6]. Therefore, the energy-saving management measures of residential buildings need to be implemented to decrease greenhouse gas emissions. However, a better understanding of the determinants of residential energy consumption for improving energy conservation and emission reduction has not been elucidated. This is likely mainly attributable to too many factors affecting residential energy consumption, making it difficult to draw a comprehensive analytical conclusion.

Over the past couple of decades, numerous studies have been conducted to evaluate the effects of different factors on the energy consumption of residential buildings [7–11]. All factors related to residential energy consumption were classified into five main categories: climatic (location) factors, building characteristics, household compositions, lifestyles, and home equipment. For climatic (location) factors, variables such as HDD (heating degree day), CDD (cooling degree day), average temperature of the coldest month, average temperature of the hottest month, and annual average temperature were often used to distinguish climatic region, and previous studies had found that they always significantly related to residential energy consumption [12–15]. In the case of building characteristics, factors including floor area, construction year, residence type, living floor, and balcony extension status were found to be significant for residential energy consumption, and the floor area was the most commonly used variable in a large number of previous studies [16–19]. For household compositions, the number of family members was usually an effective variable. The age distribution of family members, family structure, family income, and the social class of the household were also shown to have an important impact on residential energy consumption [20–22]. In the case of lifestyles, variables including cooling method in summer, heating method in winter, air conditioning set temperature, use of energy-saving mode, and a habit of opening windows were presented to be the main effective determinants [23–25]. For home equipment, variables related to residential energy consumption, such as the number and type of cooling or heating equipment, average daily DHW usage hours, cooking-appliances source type, and the number and operating time of refrigerators, washing machines, air purifiers, and computers were also found to be valid [26–28].

Despite the large number of studies, a better understanding of the quantitative relationships existing between the characteristic variables and residential energy consumption has not been clarified. Most studies to date have been based on information on total energy consumption or energy type (e.g., electric energy, natural gas), rather than on the residential end-use energy consumption. For example, Debs et al. analyzed the impact of nine factors related to household demographics, building equipment, and building characteristics towards a home's total energy consumption while controlling for climate [29]. Jang et al. developed an apartment block energy consumption model considering occupant behavior to reflect variations in actual energy consumption in apartments [30]. However, in order to effectively encourage residents to save energy and reduce emissions, there is a need to conduct a quantitative analysis on residential energy consumption basing on end use categories (e.g., heating, cooling, and cooking), so that households can intuitively understand and distinguish the use of various types of energy consumption. Moreover, after broadening the understanding of residential end-use energy consumption, it will also help building officials to improve energy performance and encourage the establishment of specific policies. Therefore, it is necessary to carry out the study of energy consumption by end use and explore its significant determinants, to provide data support for evaluating residential energy consumption and to formulate measures to decrease consumption in the future.

Although the importance of a comprehensive understanding of the determinants of residential end-use energy consumption has been emphasized by a number of authors [31,32], technical methods to quantify residential end-use energy consumption are limited. The previous research methods mainly include simulations and surveys. For example, Grygierek et al. used Energy Plus 9.4 software to simulate the effects of climate change on heating and cooling energy demands in a single-family house in Poland [33]. Batih et al. conducted a survey on the characteristics of urban household electrical energy consumption in Indonesia and found that amps, television sets, refrigerators and air conditioning units are the appliances with the most potential to save energy consumption [34]. However, simulations are limited because it is difficult to fully reflect the actual residential energy consumption based on standard input values of simulation software. The surveys are also limited because most of the existing studies are based on a variable group (e.g., only climate factors or only household compositions). In contrast, based on a provincial research project, our study scientifically and comprehensively analyzes the impact of building characteristics, household compositions, lifestyles, and home equipment on residential end-use energy consumption through sample design, field survey and energy consumption measurements, and the determinants of residential end-use energy consumption: heating, cooling, DHW, lighting, ventilation, appliances, and cooking.

In conclusion, this paper aims to explore the determinants of residential end-use energy consumption, through a comprehensive analysis according to the factors of building characteristics, household compositions, lifestyles, and home equipment. We first collected the annual residential end-use energy data of 66 residential buildings units located in Guangzhou (China) from July 2019 to June 2020 using a field survey and an energy consumption measurement system. And then quantitatively analyze the valid determinants of each end-use energy consumption by six multiple regression [29] models (Model 1: analyze the greatest effect of a single variable; Model 2: consider only building characteristics; Model 3: consider only household compositions; Model 4: consider only lifestyles; Model 5: consider only home equipment; Model 6: consider all factors).

2. Materials and Methods

2.1. Study Method Overview

Descriptive statistics and inferential statistics were used to evaluate how the main factors such as building characteristics, household compositions, lifestyles, and home equipment contribute to the end-use energy consumption in residential buildings. Figure 1 illustrates the conceptual framework of the study method. First, descriptive statistics are presented. Information on the main factors influencing residential building energy was collected through a field survey and in-depth interviews. This included physical characteristics of buildings (e.g., floor area, year built, and orientation), household compositions (e.g., number of members, and age distribution), lifestyles (e.g., cooling method, and cooling temperature setting), and home equipment (e.g., air conditioners operating hours, number of air conditioners, DHW usage hours, and number of refrigerators). The descriptive analysis results can provide an overview of the data for further inferential statistical analysis. Then, in term of inferential statistics, we performed an analysis of variance (ANOVA) to the valid determinants of heating, cooling, DHW, lighting, ventilation, appliances, and cooking energy consumption, through six multiple regression models. Model 1 was used to explore the maximum effect of a single variable by inputting information on all characteristics. Models 2–5 were used to explore the valid determinants of end-use energy consumption by inputting only building characteristics, household compositions, lifestyles, and home equipment, respectively. Model 6 was used to explore the valid determinants of the end-use energy consumption by inputting information on all characteristics. All models of the effects on end-use energy consumption were analyzed using the value of Adj-R^2, which represent the degree of correlation between independent and dependent variables.

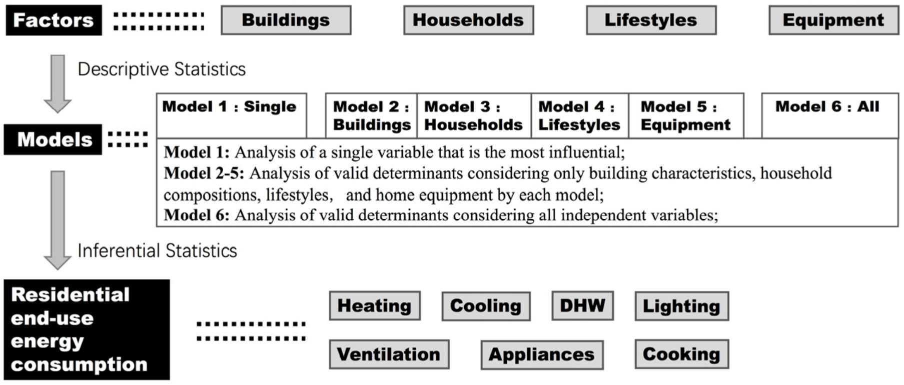


Figure 1. Study conceptual framework.

2.2. Overall Sample Design

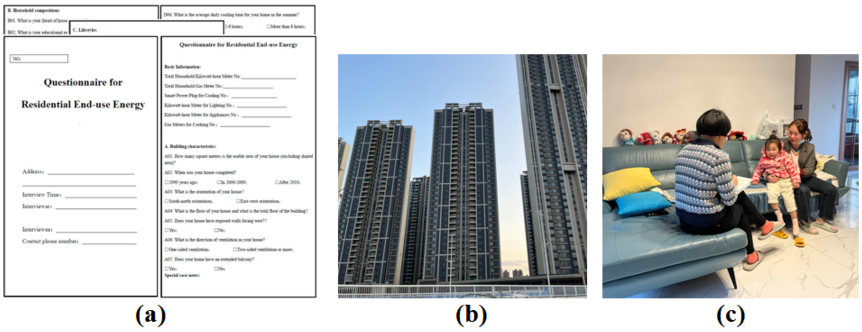
According to climate, China can be divided into severely cold areas, cold areas, warm areas, hot summer and cold winter areas, hot summer and warm winter areas. There is a large demand for energy in hot summer and warm winter areas due to the developed economy and dense populations. Furthermore, the residential buildings in these areas are very dense, and most of them are flats (an apartment type suitable for ordinary families in China). Therefore, the flats (range 5–33 floors and range 15–100 m height) located in Guangzhou, a representative city in the hot summer and warm winter areas, were selected as the specialized research target. Referring to the previous study [35], the overall sample design of residential buildings was conducted by using the Neyman allocation method (a common non proportional stratified sampling method), and the results are shown in Table 1. According to the periods of different insulation design standards, the construction years were classified into three categories: 1999 or earlier, 2009 or earlier, and 2010 or later. The classification levels of floor area were small (smaller than 60 m^2), middling (smaller than 110 m^2) and big (110 m^2 or larger) and were based on differences in the number of rooms and halls per residence. All classification variables and levels were within a 95% confidence level and 20% tolerance to ensure the rationality of sample design.

Table 1. Overall sample design of residential buildings.

Construction Year	Floor Area	Number of Sample Buildings
1999 or earlier	Smaller than 60 m^2	7
	Smaller than 110 m^2	8
	110 m^2 or larger	7
2009 or earlier	Smaller than 60 m^2	7
	Smaller than 110 m^2	8
	110 m^2 or larger	7
2010 or later	Smaller than 60 m^2	7
	Smaller than 110 m^2	8
	110 m^2 or larger	7
Sum	-	66

2.3. Field Survey Description

To collect statistical characteristics information on residential buildings, an in-depth field survey on the 66 households (12 residential districts, 5–6 households per district) in Guangzhou, China, and the interviews with inhabitants and community managers were conducted by specialized researchers, as shown in Figure 2. The data collected included four main factors influencing residential building energy: building characteristics, household compositions, lifestyles, and home equipment, and the details of independent variables are shown in Table 2.



B. Household composition:

C. Lifestyles

D06. What is the average daily cooling time for your home in the summer?

☐More than 8 hours.

NO.

Questionnaire for

Residential End-use Energy

Address: ____________________

____

Interview Time: ____________________

Interviewer: ____________________

Interviewee: ____________________

Contact phone number: ____________________

Questionnaire for Residential End-use Energy

Basic Information:

Total Household Kilowatt-hour Meter No.: ____________________

Total Household Gas Meter No.: ____________________

Smart Power Plug for Cooling No.: ____________________

Kilowatt-hour Meter for Lighting No.: ____________________

Kilowatt-hour Meter for Appliances No.: ____________________

Gas Meters for Cooking No.: ____________________

A. Building characteristics

A01. How many square meters is the usable area of your house (excluding shared area)?

A02. When was your house completed?

☐1999 years ago. ☐In 2000-2009. ☐After 2010.

A03. What is the orientation of your house?

☐South-north orientation. ☐East-west orientation.

A04. What is the floor of your house and what is the total floor of the building?

A05. Does your house have exposed walls facing west??

☐Yes. ☐No.

A06. What is the direction of ventilation in your house?

☐One-sided ventilation. ☐Two-sided ventilation or more.

A07. Does your home have an extended balcony?

☐Yes. ☐No.

Special case notes:

Figure 2. Residential information collection through a field survey: (**a**) survey form, (**b**) outward appearance of a residential building, (**c**) interview with households.

Table 2. Details of independent variables.

Factors	Variable	Units	Scale	Description and Range
Building characteristics	AREA	m^2	Ratio	Floor area; 42–148
	YR *	-	Nominal	Residential completion year (Dummy variable, D1, D2); (0,0): 1999 or earlier (Base), (1,0): 2009 or earlier, (0,1): 2010 or later
	ORNT	-	Nominal	Residential unit orientation (Dummy variable, D1); 0: south or north (Base), 1: east or west
	FLR	EA	Nominal	Living floor (Dummy variable, D1); 0: bottom floor and middle floor (Base), 1: top floor
	EW_west	-	Nominal	Exposed wall on the west side (Dummy variable, D1); 0: have no (Base), 1: have
	VEN_dir	-	Nominal	Direction of ventilation (Dummy variable, D1); 0: single direction ventilation (Base), 1: two or more directions ventilation
	BAL-ext	-	Nominal	Balcony extension status (Dummy variable, D1); 0: not extended (Base), 1: extended
Household compositions	FM_no	Person	Ratio	Number of family members; 1–7
	HF_age	Year	Ratio	Head of family age; 21–85
	FM_no ($\geq$60)	Person	Ratio	Number of family members aged 60 or older; 0–4
	FM_no (22–59)	Person	Ratio	Number of family members aged 22 to 59; 0–3
	FM_no (8–21)	Person	Ratio	Number of family members aged 8 to 21; 0–3
	FM_no ($\leq$7)	Person	Ratio	Number of family members aged 7 or younger; 0–3
	FW_no	Person	Ratio	Number of family workers; 0–4
Lifestyles	COOL_sel	-	Nominal	Selection of cooling equipment (Dummy variable, D1); 0: fan (Base), 1: fan and air conditioner
	COOL_temp	°C	Ratio	Cooling set temperature; 16–29
	AIR_grade	-	Nominal	Air conditioner energy efficiency grade [1] (Dummy variable, D1, D2); (0,0): Level 1 (Base), (1,0): Level 2, (0,1): Level 3
	ESM_use	-	Nominal	Energy-saving mode use for electrical appliances (Dummy variable, D1); 0: not use (Base); 1: use
Home equipment	HEAT_type	-	Nominal	Heating-appliances source type (Dummy variable, D1); 0: air conditioner (Base); 1: electric heater
	HEAT_op	-	Nominal	Heating-appliances operating hour (based on average daily operating hours) (Dummy variable, D1, D2); (0,0): 2 h or less (Base), (1,0): 8 h or less, (0,1): more than 8 h
	AIR_no	EA	Ratio	Number of air conditioners mainly used; 0–4
	AIR_op	-	Nominal	Air conditioners operating hours (based on average daily operating hours) (Dummy variable, D1, D2); (0,0): 2 h or less (Base), (1,0): 8 h or less, (0,1): more than 8 h
	FAN_no	EA	Ratio	Number of air conditioners mainly used; 0–6
	FAN_op	-	Nominal	Fan operating hours (based on average daily operating hours) (Dummy variable, D1, D2); (0,0): 2 h or less (Base), (1,0): 8 h or less, (0,1): more than 8 h
	DHW_type	-	Nominal	DHW-appliances source type (Dummy variable, D1) 0: gas water heater (Base), 1: electric water heater
	DHW_h	Hour	Ratio	Average daily DHW usage hours; 0–4
	Lighting_h	Hour	Ratio	Average daily lighting hours; 0.5–12
	EF_no	EA	Ratio	Number of exhaust fans; 1–4
	AP_no	EA	Ratio	Number of air purifiers; 0–6
	Frige_no	EA	Ratio	Number of refrigerators; 0–2
	TV_no	EA	Ratio	Number of TVs (including video projectors); 0–4
	TV_hr	Hour	Ratio	Average daily TV usage hours; 0–14
	PC_no	EA	Ratio	Number of personal computers; 0–3
	PC_h	Hour	Ratio	Average daily PC usage hours; 0–16
	WF_no	EA	Ratio	Number of water fountains; 1–3
	WM_no	EA	Ratio	Number of washing machines; 0–3
	Cooking_type	-	Nominal	Cooking-appliances source type (Dummy variable, D1); 0: gas stove, 1: electric stove
	Cooking_h	Hour	Ratio	Average daily cooking hours; 0.5–4.5

Note: * The abbreviations of letters in the table can explained in the column of Description and range; [1] Air conditioner energy efficiency grade is the ratio of rated cooling capacity to rated power consumption, which is an important parameter to measure the performance of air conditioning.

In addition, we also collected the climate data from the National Meteorological Scientific Data Center, Beijing, China. The weather information including outdoor temperature and humidity was collected at hourly intervals. According to all collected weather data, the calculation results based on a 21.6 °C benchmark temperature showed that the Cooling Degree Days (CDD) and Heating Degree Days (HDD) from July 2019 to June 2020 were 1387 °C day and 804 °C day, respectively. Considering that all the sample households we investigated are in the same city (Guangzhou), we did not analyze the impact of climate information on residential energy consumption, and so the results of our study are only made available for similar climate areas of hot summers and warm winters.

2.4. Classification and Measurement

Numerous studies and standards have been conducted to classify and define the end-use energy consumption in residential buildings [27,36]. In general, according to the purpose of the end-use, residential end-use energy consumption is classified into heating, cooling, DHW, lighting, ventilation, appliances, and cooking, as shown in Table 3. In hot summer and warm winter areas, the energy sources provided for all seven end-use energy consumptions are electricity or gas. For heating, the energy consumption is mainly provided by air conditioning and electric heating equipment. For cooling, the energy consumption mainly comes from air conditioners and fans. For DHW, the energy consumption is mainly provided by hot water equipment, such as electric water heaters and gas water heaters. For lighting, the energy consumption mainly comes from whole indoor lighting devices providing by a separate lighting branch circuit. For ventilation, the energy consumption from exhaust fans for kitchens and air purifiers for bedrooms was mainly used. For appliances, the energy consumption of domestic appliances including washing machines, refrigerators, TVs, and computers, was mainly used. For cooking, the energy consumption mainly comes from electric cooking or gas cooking.

Table 3. Classification of end-use energy consumption in residential buildings.

Classification	Description	Energy Sources
Heating	Energy consumption of air conditioners and electric heaters	Electricity
Cooling	Energy consumption of air conditioners and fans	Electricity
DHW	Energy consumption for providing hot water equipment, such electric water heater, gas water heater	Electricity or gas
Lighting	Energy consumption of the whole indoor lighting devices	Electricity
Ventilation	Energy consumption from exhaust fans for kitchens and air purification devices for bedrooms	Electricity
Appliances	Energy consumption of appliances, such as refrigerators, washing machine, TV, computers, etc.	Electricity
Cooking	Energy consumption from electric cooking or gas cooking	Electricity or gas

In order to measure the data of residential end-use energy consumption in all sample buildings, we developed an energy consumption measurement system with reference to the previous study [35]. This measurement system includes kilowatt-hour meters, smart power plugs, and gas meters, as shown in Figure 3 and Table 4. The system can connect with a mobile phone through a WiFi network, and all measurement data can be viewed or exported by the mobile phone. Since 2018, each sample household had installed this energy consumption measurement system. According to the installed test system, we measured and collected the annual residential end-use energy consumption data of sample households from July 2019 to June 2020. Considering the convenience of comparison and analysis in the same unit, all the measured data of electric energy consumption and gas energy consumption was converted into kilowatt hours (kWh).


(a) (b) (c) (d) (e)

Figure 3. Installation of the energy measurement system: (**a**) kilowatt-hour meter for total household power, (**b**) smart power plug for cooling, (**c**) kilowatt-hour meter for lighting and appliances, (**d**) gas meters for cooking, (**e**) gas meters for domestic hot water (DHW).

Table 4. Details of the measurement instruments.

Instruments	Model Name	Specifications
(a)-Kilowatt-hour meter for total household power	RS485	Measurement voltage: 220 V ± 10% Measurement current: 60 A Error: ±0.6% Size: 217 × 145 × 53 mm
(b)-Smart power plug for cooling	CY711-16A	Measurement voltage: 220 V ± 10% Measurement current: 16 A Measurement power: 3500 W Error: ±0.5% Size: 86 × 86 × 36 mm
(c)-Kilowatt-hour meter for lighting and appliances	P06S-20	Measurement voltage: 110–250 V Measurement current: 20 A Measurement power: 4400 W Error: ±0.5% Size: 90 × 54.5 × 28 mm
(d)-Gas meters for cooking	LLQ-15	Maximum operating pressure: 10 kPa Maximum flowrate: 4.0 m^3/h Minimum flowrate: 0.016 m^3/h Error: ±1.5% Size: 125 × 100 × 60 mm
(e)-Gas meters for domestic hot water (DHW)	J4.0	Maximum operating pressure: 30 kPa Maximum flowrate: 6.0 m^3/h Minimum flowrate: 0.04 m^3/h Error: ±1.5% Size: 224 × 217 × 170 mm

Note: The measurement instruments a–e were corresponded to Figure 3.

2.5. Data Analysis

The data of Models 1–6 were subjected to statistical analysis by analysis of variance (ANOVA) using IBM-SPSS Statistics 22 software (IBM Corp., Armonk, NY, USA). The F-test was used for the overall test of the whole model, and when the value of F-Sig < 0.05, the Adj-R^2 (the correlation coefficient of the regression model, representing the degree of fit of the equation to the model) could be considered to be statistically significant. The F-test was used to test each independent variable one by one, and when the value of t-Sig < 0.05, the β (the standard regression coefficient, representing the change value of the dependent variable when the independent variable increased by 1 unit) was statistically significant.

3. Results

3.1. Basic Information

Table 5 shows the annual statistical data of residential end-use energy consumption based on the field measurement results. We conducted a preliminary and processing of the samples of all 66 households, and excluded measured values without complete annual data. In addition, too high and too low annual data (the top and bottom 10% trim) were also excluded to ensure the reliability of measured data. Finally, among the measured data of 66 households, heating data of 37 households, cooling data of 53 households, DHW data of 44 households, lighting data of 47 households, ventilation data of 39 households, appliances data of 45 households, and cooking data of 51 households were selected for multiple regression analysis of residential end-use energy consumption.

Table 5. Annual statistical data of residential end-use energy consumption (kWh/y).

Classification	Heating	Cooling	DHW	Lighting	Ventilation	Appliances	Cooking
Number of valid samples	37	53	44	47	39	45	51
Average	48	3384	904	368	40	1944	1312
Maximum	112	6899	2131	976	107	3412	1951
Minimum	0	673	217	149	0	1125	283
Standard deviation	41	1765	782	171	34	527	346
Average-based ratio	0.6%	42.3%	11.3%	4.6%	0.5%	24.3%	16.4%

In Table 5 and Figure 4, it can be that the average values of the annual end-use energy consumption were in the order of cooling > appliances > cooking > DHW > heating > ventilation. The annual average values of cooling, appliances, cooking and DHW were higher, 3384, 1944, 1312 and 904 kWh/y, respectively, while the values of heating and ventilation were lower, 48 and 40 kWh/y, respectively. The average annual energy consumption percentages were 42.3%, 24.3%, 16.4% and 11.3% for cooling, appliances, cooking and DHW, respectively. Therefore, when considering reducing the annual residential end-use energy consumption in Guangzhou (a representative city in the summer heat and warm winter area), cooling was the most important, followed by appliances, cooking and DHW. Besides, considering the average annual energy consumption, percentages of heating and ventilation were relatively low, at 0.6% and 0.5%, respectively, and so they were not applied in the regression analysis.

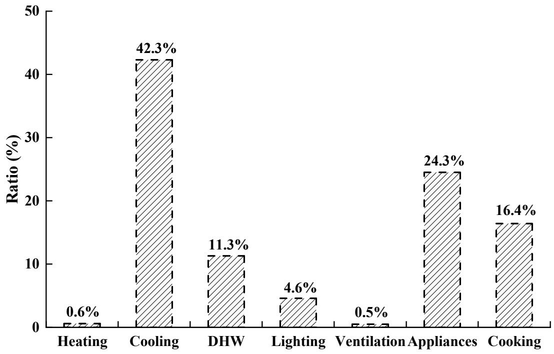


Figure 4. Ratio of different residential end-use energy consumption in a year.

3.2. Cooling

The valid determinants analyses of six multiple regression models for cooling energy consumption were carried out, and the results are found in Table 6 and Figure 5. In model 1, the most influential variable on cooling energy consumption was FM_no (22–59, number of family members aged 22 to 59) with an Adj-R^2 (the correlation coefficient of regression model, representing the degree of fit of the equation to the model) of 0.219. This suggests that the single variable of FM_no (22–59, number of family members aged 22 to 59) can explain about 22% of cooling energy consumption. Moreover, according to the β value (the standard regression coefficient, and when the independent variable increased by 1 unit, the change value of the dependent variable), it can be found that when the number of family members aged 22 to 59 increases by one person, the energy consumption for cooling increases by 715 kWh/y.

Table 6. Analysis results of valid determinants for cooling.

Cooling		**Buildings**		**Households**		**Lifestyles**		**Equipment**			**Adj-R^2/ F-Sig.**
		FLR (D1)	**EW_ west (D1)**	**FM_no (22–59)**	**FM_no**	**COOL_ sel (D1)**	**COOL_ temp**	**AIR_ no**	**AIR_op (D1)**	**AIR_op (D2)**	
Model 1 (Single)	β			715							0.219/0.003
	Std. error			118							
	t-Sig.			0.003							
Model 2 (Buildings)	β	457	582								0.374/0.001
	Std. error	71	92								
	t-Sig.	0.006	0.014								
Model 3 (House-holds)	β			549	233						0.485/0.000
	Std. error			67	48						
	t-Sig.			0.004	0.002						
Model 4 (Lifestyles)	β					1071	356				0.361/0.006
	Std. error					185	41				
	t-Sig.					0.007	0.013				
Model 5 (Equipment)	β							337	584	1155	0.407/0.002
	Std. error							52	95	176	
	t-Sig.							0.011	0.024	0.015	
Model 6 (All)	β		217	353		772			384	562	0.673/0.000
	Std. error		46	51		134			55	77	
	t-Sig.		0.009	0.003		0.005			0.012	0.008	

Note: Adj-R^2, the correlation coefficient of the regression model, representing the degree of fit of the equation to the model; F-Sig, Significance value of overall test of the whole model; When the value of F-Sig < 0.05, the Adj-R^2 was statistically significant; β, the standard regression coefficient, representing the change value of the dependent variable when the independent variable increased by 1 unit, Std. error, Standard Error of regression model; t-Sig, Significance value of regression analysis of each independent variable test one by one. When the value of t-Sig < 0.05, the β was statistically significant.

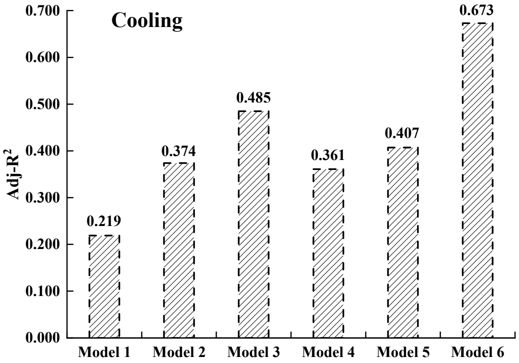


Figure 5. The Adj-R^2 of six cooling energy consumption models.

In model 2, when only buildings factors were considered, the valid variables were FLR (living floor) and EW_west (exposed wall on the west side) and the Adj-R^2 was 0.374. The results showed that these two variables can reflect about 37% of cooling energy consumption. As described in Table 2, when there are dummy variables, the β value represents the change value of dependent variable relative to the base state value. The FLR (living floor) indicated, in terms of cooling energy consumption, the top floor households consumed 457 kWh/y more than the bottom and middle households, and the EW_west (exposed wall on the west side) implied that the cooling energy consumption of households with an exposed wall on the west side was 582 kWh/y more than that of households without a westerly exposed wall.

In model 3, when only household factors were considered, the valid variables were FM_no (22–59, number of family members aged 22 to 59) and FM_no (number of family members), with an Adj-R^2 of 0.485. In model 4, if only lifestyles factors were considered, COOL_sel (selection of cooling equipment) and COOL_temp (cooling set temperature) became valid variables with an Adj-R^2 of 0.361. In term of model 5, considering only the equipment, the valid variables were AIR_no (number of air conditioners) and AIR_op (air conditioners operating hours) with an Adj-R^2 of 0.407. As for model 6, when all variables were taken into account, the valid variables became EW_west (exposed wall on the west side), FM_no (22–59, number of family members aged 22 to 59), COOL_sel (selection of cooling equipment) and AIR_op (air conditioners operating hours), and the Adj-R^2 also changed to 0.673.

As can be seen from Figure 5, among models 2–5, the Adj-R^2 value calculated by Model 3 was maximum, which is only a little different to that calculated by Model 6. The above results indicated that cooling energy consumption is more influenced by household factors than equipment, buildings and lifestyles. This agrees with the observation made by Lee [27], who found that the age distribution of family members had a significant relationship with cooling energy consumption in Korean apartment units and the correlation coefficient was higher than 0.3. In addition, as shown in Figure 4, the average annual energy consumption proportion of cooling was 42.3%, which was the largest part of residential energy consumption. Therefore, the household composition was the most important factor, which should be considered to establish measures for reducing energy consumption in the summer heat and warm winter areas.

3.3. DHW

The valid determinants analyses of six multiple regression models for DHW energy consumption were conducted, and the results are shown in Table 7 and Figure 6. In model 1, the most influential variable on DHW energy consumption was FM_no (number of family members) with an Adj-R^2 of 0.386, which showed that the single variable of FM_no (number of family members), can explain about 39% of DHW energy consumption. In addition, according to the β value, the energy consumption of DHW increases 211 kWh/y for each increase in family members.

In model 2, when only buildings factors were considered, there was no valid variable in relation to the DHW energy consumption. Model 3 only considers household factors, and FM_no (number of family members), FM_no ($\geq$60, number of family members aged 60 or older) and FM_no ($\leq$7, number of family members aged 7 or younger) as valid variables were found, and the Adj-R^2 was 0.437. In model 4, if only lifestyles factors were considered, the valid variables were ESM_use (Energy-saving mode use for electrical appliances), and its Adj-R^2 was 0.225. In term of model 5, only considering the equipment factors, DHW_h (average daily DHW usage hours) became the valid variable with an Adj-R^2 of 0.341. In model 6, the valid variables were FM_no (number of family members), and DHW_h (average daily DHW usage hours) with an Adj-R^2 of 0.441, when considering all variables.

As for Figure 6, household compositions were found to be the most influential factors according to the maximum Adj-R^2 value among Models 2–5. Besides, in Model 3, the β value was 221 for FM_no ($\geq$60, number of family members aged 60 or older) and 257 for FM_no ($\leq$7, number of family members aged 7 or younger), and both were larger than the β value (177) of FM_no (number of family members). The results showed that the DHW energy consumption for each person of elderly people and children was higher than for young adults. This was in line with previous findings [8,16], and analysis pointed out that the composition of family members was related to the DHW energy consumption. The main reason may be that elderly people and children are more sensitive to temperature changes, and spend more days bathing with hot water than adults in the summer heat and warm winter areas.

Table 7. Analysis results of valid determinants for DHW.

DHW		Households			Lifestyles	Equipment	Adj-R^2/ F-Sig.
		FM_no	FM_no (≥60)	FM_no (≤7)	ESM_use (D1)	DHW_h	
Model 1 (Single)	β	211					0.386/0.000
	Std. error	43					
	t-Sig.	0.000					
Model 2 (Buildings)	β						-
	Std. error						
	t-Sig.						
Model 3 (Households)	β	177	221	257			0.437/0.000
	Std. error	54	72	85			
	t-Sig.	0.003	0.005	0.008			
Model 4 (Lifestyles)	β				−282		0.225/0.000
	Std. error				93		
	t-Sig.				0.011		
Model 5 (Equipment)	β					269	0.341/0.000
	Std. error					85	
	t-Sig.					0.003	
Model 6 (All)	β	164				203	0.441/0.000
	Std. error	83				64	
	t-Sig.	0.002				0.001	

Note: Adj-R^2, the correlation coefficient of regression model, representing the degree of fit of the equation to the model; F-Sig, Significance value of overall test of the whole model; When the value of F-Sig < 0.05, the Adj-R^2 was statistically significant; β, the standard regression coefficient, representing the change value of the dependent variable when the independent variable increased by 1 unit, Std. error, Standard Error of regression model; t-Sig, Significance value of regression analysis of each independent variable test one by one. When the value of t-Sig < 0.05, the β was statistically significant.

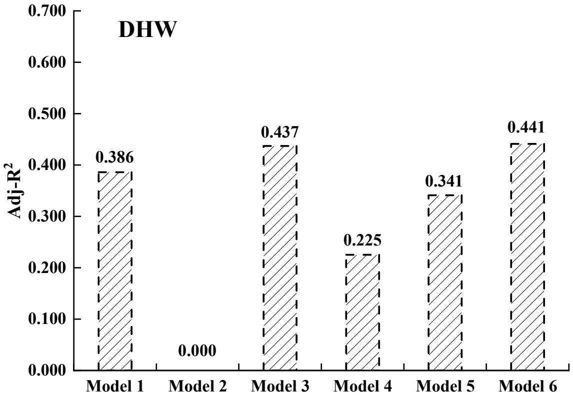


Figure 6. The Adj-R^2 of six DHW energy consumption models.

3.4. Lighting

In Table 8 and Figure 7, the analysis results regarding valid determinants of six multiple regression models for lighting energy consumption are presented. In models 1 and 2, when analyzing the maximum impact of a single variable and considering only buildings factors, the most influential variable on lighting energy consumption was AREA (floor area), with an Adj-R^2 of 0.291. This result shows that the single variable of AREA (floor area) can explain about 29% of lighting energy consumption. Moreover, as shown by the β value, there is a 5 kWh/y increases in lighting energy consumption for every square meter increase in floor area.

Table 8. Analysis results of valid determinants for lighting.

Lighting		Buildings	Households		Lifestyles	Equipment	Adj-R^2/ F-Sig.
		AREA	FM_no	FM_no (8–21)	ESM_use (D1)	Lighting_h	
Model 1 (Single)	β	5					0.291/0.001
	Std. error	1					
	t-Sig.	0.001					
Model 2 (Buildings)	β	5					0.291/0.001
	Std. error	1					
	t-Sig.	0.001					
Model 3 (Households)	β		63	71			0.342/0.000
	Std. error		23	19			
	t-Sig.		0.000	0.023			
Model 4 (Lifestyles)	β				−137		0.183/0.008
	Std. error				42		
	t-Sig.				0.008		
Model 5 (Equipment)	β					65	0.279/0.002
	Std. error					21	
	t-Sig.					0.002	
Model 6 (All)	β	4		63		42	0.516/0.000
	Std. error	1		15		19	
	t-Sig.	0.003		0.001		0.004	

Note: Adj-R^2, the correlation coefficient of regression model, representing the degree of fit of the equation to the model; F-Sig, Significance value of overall test of the whole model; When the value of F-Sig < 0.05, the Adj-R^2 was statistically significant; β, the standard regression coefficient, representing the change value of the dependent variable when the independent variable increased by 1 unit, Std. error, Standard Error of regression model; t-Sig, Significance value of regression analysis of each independent variable test one by one. When the value of t-Sig < 0.05, the β was statistically significant.

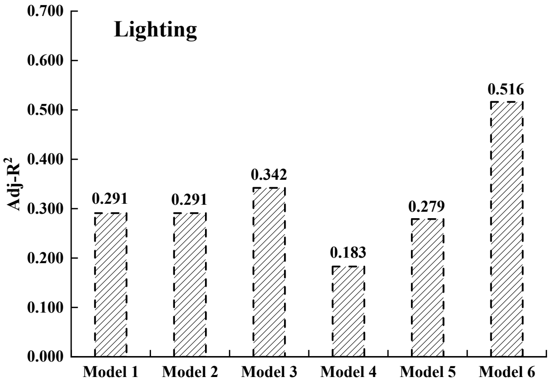


Figure 7. The Adj-R^2 of six lighting energy consumption models.

Model 3 only considered household factors, FM_no (number of family members), FM_no (8–21, number of family members aged 8 to 21) were proposed as valid variables, and their Adj-R^2 was 0.342. In model 4, if considering lifestyle factors only, the valid variable was ESM_use (Energy-saving mode use for electrical appliances) with an Adj-R^2 of 0.183. In term of model 5, only equipment factors were taken into account, the valid variables (AIR_no (number of air conditioners) and Lighting_h (average daily lighting hours)) were found, with an Adj-R^2 of 0.279. As for model 6, if total variables were taken into account, the valid variables became AREA (floor area), FM_no (8–21, number of family members aged 8 to 21), and Lighting_h (average daily lighting hours), and then, the Adj-R^2 also changed to 0.516.

According to Models 2–5, it can be found that the building characteristics and household compositions had a greater impact on lighting energy consumption than lifestyles and home equipment, and the AREA (floor area) and FM_no (number of family members) were the main valid variables. However, the related coefficients between all factor groups and lighting energy consumption are relatively small, all below 0.35. Therefore, when combining the information of building characteristics, household compositions and home equipment, it will give a better explanation of the lighting energy consumption, and the results are shown in Model 6.

3.5. Appliances

In Table 9 and Figure 8, the analysis results regarding valid determinants of six multiple regression models for appliances energy consumption are presented. In models 1 and 3, when analyzing the maximum impact of a single variable and considering only household factors, the most influential variable on appliances energy consumption was FM_no (number of family members), with an Adj-R^2 of 0.163. Model 2 only considered building factors, AREA (floor area) was proposed as a valid variable with an Adj-R^2 of 0.141. Model 4 considers household factors only, and ESM_use (Energy-saving mode use for electrical appliances) as valid variables was found with an Adj-R^2 of 0.182. In model 5, if considering equipment only, the valid variables were AIR_op (air conditioners operating hours), DHW_h (average daily DHW usage hours), PC_h (average daily PC usage hours), and Cooking_h (average daily cooking hours) with an Adj-R^2 of 0.391. As for model 6, when all variables were taken into account, the valid variables became FM_no (number of family members), IR_op (air conditioners operating hours), DHW_h (average daily D, HW usage hours), PC_h (average daily PC usage hours), and Cooking_h (average daily cooking hours), and then, the Adj-R^2 also changed to 0.537.

Table 9. Analysis results of valid determinants for domestic appliances.

Appliances		**Buildings**	**Households**	**Lifestyles**	**Equipment**					**Adj-R^2/ F-Sig.**
		AREA	**FM_no**	**ESM_use (D1)**	**AIR_ op(D1)**	**AIR_ op(D2)**	**DHW_h**	**PC_h**	**Cooking_h**	
Model 1 (Single)	β		321							0.163/0.008
	Std. error		94							
	t-Sig.		0.008							
Model 2 (Buildings)	β	18								0.141/0.007
	Std. error	3								
	t-Sig.	0.007								
Model 3 (Households)	β		321							0.163/0.008
	Std. error		94							
	t-Sig.		0.008							
Model 4 (Lifestyles)	β			−652						0.182/0.006
	Std. error			101						
	t-Sig.			0.005						
Model 5 (Equipment)	β				317	243	189	67	135	0.391/0.002
	Std. error				127	95	88	21	56	
	t-Sig.				0.005	0.003	0.014	0.012	0.009	
Model 6 (All)	β		19		296	217	141	75	118	0.537/0.000
	Std. error		3		105	91	75	23	42	
	t-Sig.		0.006		0.002	0.005	0.011	0.008	0.006	

Note: Adj-R^2, the correlation coefficient of regression model, representing the degree of fit of the equation to the model; F-Sig, Significance value of overall test of the whole model; When the value of F-Sig < 0.05, the Adj-R^2 was statistically significant; β, the standard regression coefficient, representing the change value of the dependent variable when the independent variable increased by 1 unit, Std. error, Standard Error of regression model; t-Sig, Significance value of regression analysis of each independent variable test one by one. When the value of t-Sig < 0.05, the β was statistically significant.

According to Models 2–5, it can be inferred that although AREA (floor area), FM_no (number of family members) and ESM_use (Energy-saving mode use for electrical appliances) are the valid variables related to appliances energy consumption, the highest correlation coefficient is only 0.182. The results show that the three factor groups of building characteristics, household compositions and lifestyles have relatively little impact on appliances energy consumption. In contrast, the information of home equipment has a better explanation for appliances energy consumption, and the Adj-R^2 is 0.391. Therefore, the equipment is the main factor group for formulating measures to reduce the appliances energy consumption in the future.

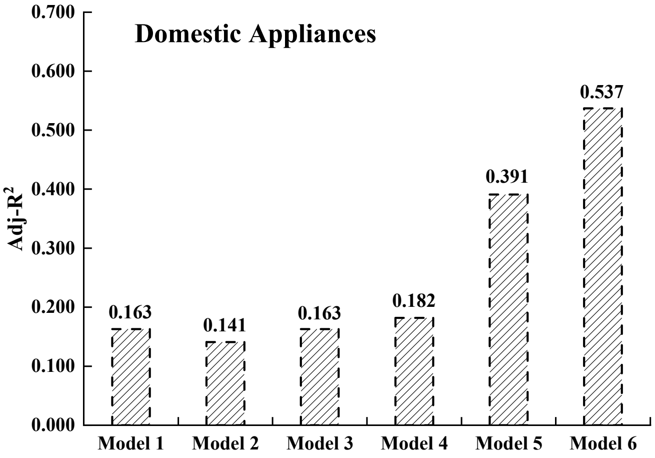


Figure 8. The Adj-R^2 of six domestic appliances energy consumption models.

3.6. Cooking

Table 10 and Figure 9 show the analysis results regarding valid determinants of six multiple regression models for cooking energy consumption. In models 1 and 5, when analyzing the maximum impact of a single variable and considering only equipment factors, the most influential variable on cooking energy consumption was Cooking_h (average daily cooking hours) with an Adj-R^2 of 0.215. In models 2 and 4, when only buildings factors or lifestyles were considered, there was no valid variable in relation to cooking energy consumption. In terms of model 3, only considering the household factors, AIR_no (number of air conditioners) FM_no (number of family members), FW_no (number of family workers), FM_no ($\leq$7, number of family members aged 7 or younger), and FM_no ($\geq$60, number of family members aged 60 or older) became valid variables with an Adj-R^2 of 0.384. Model 6 considers all variables, and FM_no (number of family members), FM_no ($\geq$60, number of household members aged 60 or older), and Cooking_h (average daily cooking hours) as valid variables were found with an Adj-R^2 of 0.415.

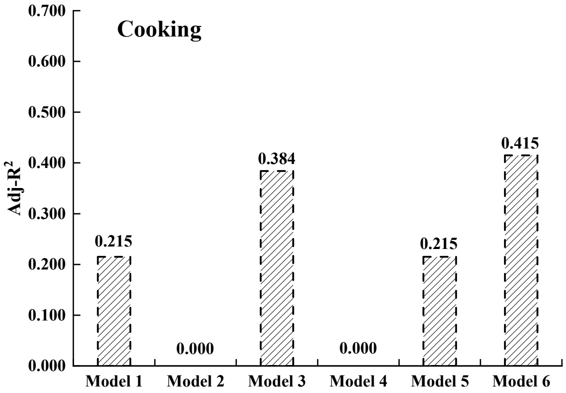


Figure 9. The Adj-R^2 of six cooking energy consumption models.

As for Models 2–5, it can be inferred that only households and equipment affects the cooking energy consumption, and their Adj-R^2 values are lower ($\leq$0.384). Although all factors are considered in Model 6, the correlation coefficient is only 0.415, which means that cooking energy consumption needed more samples over a longer period to increase the explanatory power, or the use of other statistical methods.

Table 10. Analysis results of valid determinants for cooking.

Cooking		Households				Equipment	Adj-R^2/ F-Sig.
		FM_no	FW_no	FM_no ($\leq$7)	FM_no ($\geq$60)	Cooking_h	
Model 1 (Single)	β					437	0.215/0.002
	Std. error					162	
	t-Sig.					0.002	
Model 2 (Buildings)	β						-
	Std. error						
	t-Sig.						
Model 3 (Households)	β	213	−13	78	63		0.384/0.000
	Std. error	41	5	36	23		
	t-Sig.	0.000	0.007	0.005	0.010		
Model 4 (Lifestyles)	β						-
	Std. error						
	t-Sig.						
Model 5 (Equipment)	β					437	0.215/0.002
	Std. error					162	
	t-Sig.					0.002	
Model 6 (All)	β	176			37	379	0.415/0.000
	Std. error	38			9	146	
	t-Sig.	0.001			0.005	0.003	

Note: Adj-R^2, the correlation coefficient of regression model, representing the degree of fit of the equation to the model; F-Sig, Significance value of overall test of the whole model; When the value of F-Sig < 0.05, the Adj-R^2 was statistically significant; β, the standard regression coefficient, representing the change value of the dependent variable when the independent variable increased by 1 unit, Std. error, Standard Error of regression model; t-Sig, Significance value of regression analysis of each independent variable test one by one. When the value of t-Sig < 0.05, the β was statistically significant.

4. Conclusions

In order to explore the determinants of residential end-use energy consumption, this study conducted a comprehensive analysis according to the factors of building characteristics, household compositions, lifestyles, and home equipment. An in-depth field survey was conducted to collect statistical characteristics information on the 66 residential building units located in Guangzhou, China, and an energy consumption measurement system was installed in each household to measure the energy consumption data of each end-use from July 2019 to June 2020. According to the obtained data, the valid determinants of each end-use energy consumption were quantitatively analyzed by six multiple regression models (Model 1: analyzed the greatest effect of a single variable; Model 2: only building characteristics were considered; Model 3: only household compositions were considered; Model 4: only lifestyles were considered; Model 5: only home equipment was considered; Model 6: all factors were considered). The main results include:

(i) In terms of cooling energy consumption, the most influential variable was FM_no (22–59, number of family members aged 22 to 59). Figure 10 shows Adj-R^2 of buildings, households, lifestyles, equipment factor groups with cooling energy consumption, and its influence order is as follows: households > equipment > buildings > lifestyles. The results indicate that the greatest effect for cooling energy consumption is households.

(ii) In DHW energy consumption, the FM_no (number of family members) was found to be the most influential variable. Figure 10 shows Adj-R^2 of buildings, households, lifestyles, equipment factor groups with DHW energy consumption, and its influence order is as follows: households > equipment > lifestyles. The results show that households have the greatest impact on DHW energy consumption.

(iii) For lighting energy consumption, AREA (floor area) became the most influential variable. Figure 10 shows Adj-R^2 of buildings, households, lifestyles, equipment factor groups with lighting energy consumption, and its influence order is as follows:

households > buildings > equipment > lifestyles. The results show that it is also households that have the greatest impact on lighting energy consumption.

(iv) In term of appliances energy consumption, FM_no (number of family members) was seen as the most influential variable. Figure 10 shows Adj-R^2 of buildings, households, lifestyles, equipment factor groups with appliances energy consumption, and its influence order is as follows: equipment > lifestyles > households > buildings. As the results show, the equipment has the greatest impact on the energy consumption of appliances.

(v) As for energy consumption of cooking, the most influential variable was Cooking_h (average daily cooking hours). Figure 10 shows Adj-R^2 of buildings, households, lifestyles, equipment factor groups with cooking energy consumption, and its influence order is as follows: equipment > lifestyles. It was found that equipment had the greatest impact on cooling energy consumption compared to other factors.

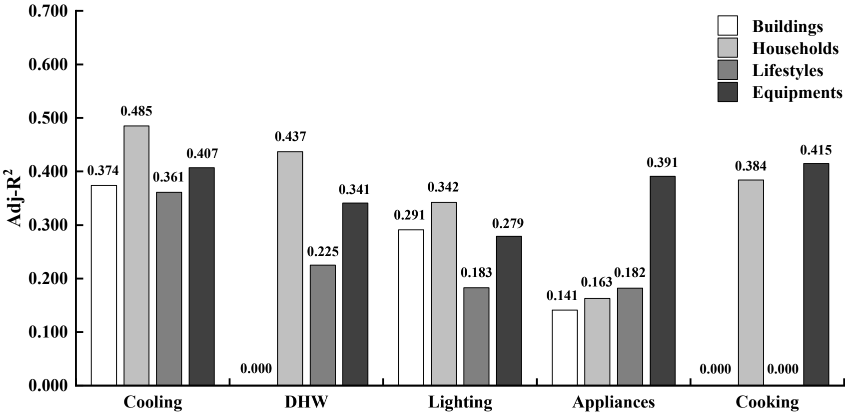


Figure 10. The Adj-R^2 of models 2–5 for five end-use energy consumption.

This study does not analyze the impact of different climate zones on the energy consumption for each end use, which means that the results are only applicable to similar climate areas of Guangzhou, China (the hot summer and warm winter areas, CDD 1387 °C day and HDD 804 °C day). Therefore, it is necessary to measure and analyze the data of residential end-use energy consumption from regions of different climate in the future. In addition, for the factors with a larger error, more samples and related studies are needed to improve the estimation models. Our research plans to perform more field surveys and data measurements to explore the determinants of residential end-use energy consumption.

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