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Behavioural, physical and socio-economic factors in household cooling energy consumption

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ABSTRACT

As global warming continues, the current trend implies that the uptake of air conditioning in the residential sector will go up, thus potentially increasing domestic cooling energy consumption. In this context, this paper investigates the significance of behavioural, physical and socio-economic parameters on cooling energy in order to improve energy efficiency in residential buildings. It demonstrates that such factors exert a significant indirect as well as direct influence on energy use, showing that it is particularly important to understand indirect relationships. An initial study of direct factors affecting cooling energy reveals that occupant behaviour is the most significant issue (related to choices about how often and where air conditioning is used). This is broadly confirmed by path analysis, although climate is seen to be the single most significant parameter, followed by behavioural issues, key physical parameters (e.g. air conditioning type), and finally socio-economic aspects (e.g. household income).

1. Introduction

The United States is the biggest energy consumer in the world [1] and is highly dependent on fossil fuels [2]. Energy derived from fossil fuels accounted for over 90% of total US energy consumption in 2007, with current trends suggesting that fossil fuels would be still a major energy source through 2030 [3]. Thus, improving energy efficiency is an effective method to reduce anthropogenic carbon dioxide emission and is a useful strategy to mitigate global warming.

The residential sector is one of significant contributors to energy use in the US, which represented over 20% of the total US energy consumption in 2007 [3]. A large proportion of electricity is consumed for air conditioning in the US residential sector. The total electricity use for air conditioning in US residential buildings was larger than the electricity consumption for space heating [4], although the space heating in the residential sector relied greatly on other energy resources. Moreover, there was a tendency for an increasing uptake of air conditioning. The ownership of central air conditioning in the US has been raised from 23% in 1978 to 47% in 1997 and the frequency of air conditioning use has been also increased [4]. As warming trends of global temperature are already to a large extent unavoidable [5], the heavy reliance on the use of air conditioning in the residential sector is expected [6].

This paper addresses the question of what determines domestic cooling energy consumption. It does this by carrying out a detailed analysis of a large database of actual domestic energy use in the US. The underlying context for this work is that as global warming increases the demand for domestic cooling is likely to increase which may undermine energy efficiency strategies related to the improvement of building design and fabric, and environmental systems for lighting, heating and cooling. This work will determine the relative significance of behavioural, physical and socio-economic parameters on cooling energy in order to provide a better understanding of the interactions and to enable a more informed appraisal of interventions or incentives to improve energy efficiency.

2. Analysed data

2.1. The RECS 2001 data set

This study investigates household cooling energy consumption using existing extensive survey data, namely the Residential Energy Consumption Survey (RECS), conducted in 2001 by the US Department of Energy [7]. The data from the 2001 RECS was used because the latest survey data from the 2005 RECS were not fully available at the time of analysis. The use of an existing survey is beneficial to reduce the possible non-respondent and observation biases and to avoid the data collection effort [8]. The residential energy consumption data obtained from field surveys were also available for other countries such as Germany [8], China [9,10], UK [11,12], Hong Kong [13], and Japan [14].

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Table 1
Variables analysed for space cooling energy consumption.

Category	Variable	Description	Range	
Climate	CDD65	Cooling degree days to a base of 65 °F or 18.3 °C	*M* = 1469.79, SD = 926.36	
Building	TOTAREA	Total floor area (m^2)	*M* = 208.97, SD = 128.29	
	NUMWND	Number of windows	*M* = 3.78, SD = 0.97	
	AGEHOUSE	Year of construction	1 = Before 1940	5 = 1970–1979
			2 = 1940–1949	6 = 1980–1989
			3 = 1950–1959	7 = 1990–1999
			4 = 1960–1969	8 = 2000
	TYPEHOUSE	Type of Housing units	1 = Single-family detached	3 = Apartment in building with 2–4 units
			2 = Single-family attached	4 = Apartment in building with five or more units
Occupant	NHSLDMEM	Number of household members	*M* = 2.61, SD = 1.38	
	MONEYPY	Total annual income	1 = Less than $5000	6 = $30,000–$39,999
			2 = $5000–$9999	7 = $40,000–$49,999
			3 = $10,000–$14,999	8 = $50,000–$74,999
			4 = $15,000–$19,999	9 = $75,000–$99,999
			5 = $20,000–$29,999	10 = $100,000 or more
	HHAGE	Age of householder	*M* = 51.45, SD = 16.76	
Equipment	ACTYPE	Type of air conditioning equipment	1 = Individual units	
			2 = A central system	
			3 = Both central and individual units	
Behaviour	NUMACROOM	Number of cooled rooms	*M* = 4.91, SD = 2.36	
	USEAC	Frequency of air conditioning equipment use	0 = Not used at all	2 = Turned on quite a bit
			1 = Turned on only a few days or nights	3 = Turned on just about all summer
Energy	ENERGY	Total energy use for space cooling (kWh $year^{-1}$)	*M* = 2 136.04, SD = 2 103.65	

M = Mean, SD = standard deviation.

The 2001 RECS data set consists of information on actual energy consumption along with detailed energy-related characteristics of the housing units and occupants, collected from 4822 housing units from the 50 States and the District of Columbia in the US. The energy-related household characteristics were obtained from personal interviews with the main householder or the householder's partner, and information on the household energy consumption was collected from the energy suppliers. The cooling energy consumption in the RECS 2001 data was derived from the total energy consumption using non-linear regression technique [15,16]. The data set contains information on the characteristics of the households and occupant use of equipment, which enables socio-economic and occupant behavioural factors to be considered in the analysis of household energy consumption alongside physical parameters related to the climate, house and environmental system.

2.2. Filtering the data

A housing unit classification in the original 2001 RECS micro-data set contains mobile homes, but this type of housing was omitted from our study. The household data whose dwellings were used for business or where occupants had only moved in during 2001, was also excluded. Finally, this study excluded household data from dwellings whose air conditioning equipment was used to cool other households or buildings. In this paper data from households without air conditioning (AC) equipment are only used for the purpose of comparing households with and without AC equipment. As a result, the 2001 RECS data set used was reduced from 3 755 for households with and without AC equipment to 2718 for those with AC equipment only.

Table 1 summarises variables investigated in this study. Variables that have not been found to have consistently significant relationships with energy consumption are not included in this study. The factors which were not statistically significant included the type of neighbourhood (e.g. whether housing units are located in a city, a town, the suburbs, or in a rural area), the age of air conditioning equipment, the ownership of dwelling, and the status of householder's employment.

The variables analysed in this study are broadly classified into climate, building, equipment, and occupant and behaviour categories. Cooling degree days (CDD65) were used as a weather indicator or climate factor in analysis of space cooling energy consumption. Cooling degree days in the RECS micro-data set were determined using temperature data obtained from the National Oceanic Atmospheric Administration (NOAA) weather station nearest to each household. A reference temperature of 18.3 °C (65 °F) was used to calculate CDD65. The average cooling energy consumption for households with air conditioning equipment was 2136 kWh $year^{-1}$ with a standard deviation (SD) of 2104.

The building category describes the physical characteristics of housing units, which includes the total floor area (TOTAREA), the number of windows (NUMWND), the year of construction (AGEHOUSE), and the housing type (TYPEHOUSE). Unheated garage spaces were not included in the total floor area of houses. The average total floor area was 209 m^2 (SD = 128 m^2). The number of each housing type is 1947 for single-family detached houses, 244 for single-family attached houses type, and 527 for apartment buildings. The types of space cooling equipment (ACTYPE) were classified according to whether it is a central system or individual units.

The occupant category represents social, economic, and demographic characteristics of the household. This includes the number of household members (NHSLDMEM), the total household annual income (MONEYPY), and the age of the head of a house or a householder (HHAGE). The average number of occupants who normally live in households (NHSLDMEM) was 2.61 (SD = 1.38).

The behaviour category specifies how occupants use their cooling equipment systems. This study, for example, analysed how often households used their AC equipment (i.e. the frequency of air conditioning use in summer, USEAC). Thirty-nine percent of households turned on air conditioning equipment only when really needed, 20% for households turned on the equipment quite a bit, and 38% for households turned on the equipment just about all summer. We also investigated how many rooms in a house were air conditioned (NUMACROOM) by occupants. Apart from behavioural aspects, the number of air conditioned rooms is likely influenced by the physical characteristics of housing units such as overall size and number of household members.

We examined whether all the variables analysed in this study had normal distributions because the General Linear Model and path analysis used in this study assume that the data follow a normal distribution [17–20]. Most variables followed normal distributions. However, total floor area (TOTAREA), cooling degree days (CDD65), and cooling energy consumption (ENERGY) are variables that did not meet the assumption of normality (e.g. skewness = 1.995, kurtosis = 5.669 for ENERGY). Therefore, we applied a square root transformation, thus improving the normality of the transformed variables (i.e., skewness <1 and kurtosis <1 for all the transformed variables). The transformed variables were named as SQTOTAREA, SQCDD, and SQENERGY.

3. Air conditioning systems in households

The ownership of air conditioning (AC) equipment (AIRCOND) in households was studied first as this is the most fundamental factor of household space cooling consumption. 72% of households analysed in this study had AC equipment in their housing units (i.e. 2718 out of 3755 households). Among those variables investigated, household income and weather condition were two most important factors in determining ownership of AC equipment.

Fig. 1 illustrates that the ownership of AC equipment was closely linked to weather conditions in that weather conditions for households with AC systems were warmer than those without AC systems. The average of square root of cooling degree days (SQCDD) was 36.83 for households with AC equipment and 26.37 for those without AC equipment (two-tailed t-statistic, t = 19.226, degree of freedom, df = 3753, p-value, P < 0.001). There was a positive relationship between cooling degree days (SQCDD) and the ownership of AC systems (AIRCOND) (Fig. 2). In order to calculate the likelihood of AC system ownership, the degree days were binned into ten categories with an equal number of cases in each bin. Fig. 2 indicates the likelihood of AC ownership related to climate conditions (F-statistic, F = 81.569, P < 0.001) and shows for example that AC ownership went up from 26% for the lowest bin of degree days to 51% for the second lowest bin, reaching 90% at the highest bin.

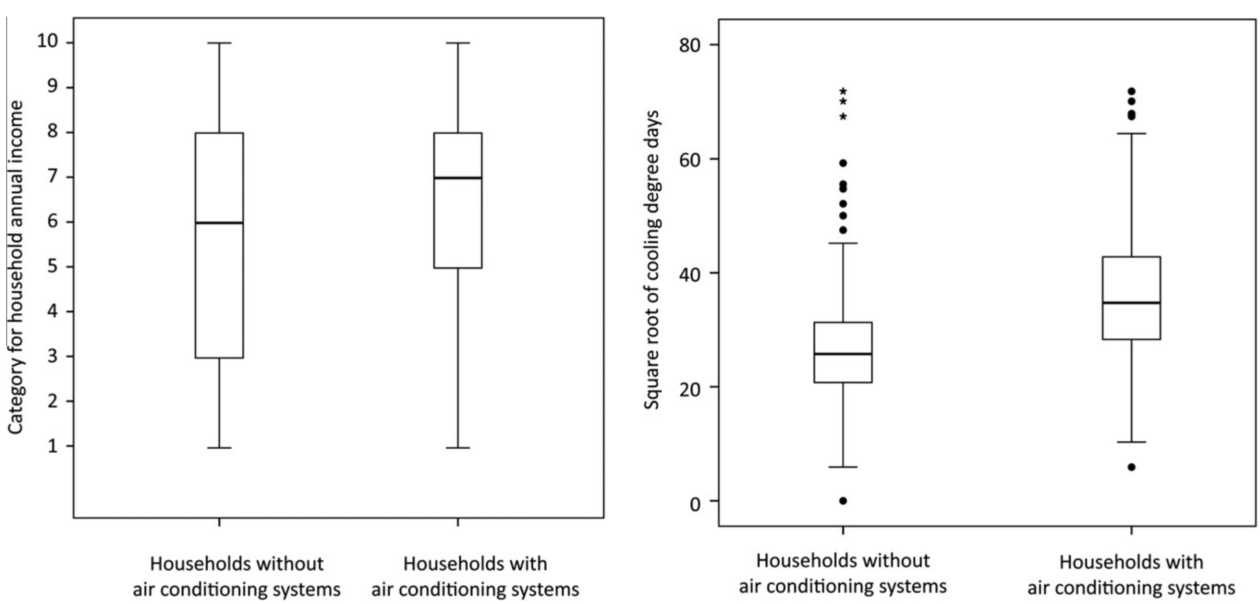
We also found that household income had a significant relationship with the patterns of AC systems ownership of households (Figs. 1 and 2). A median value of household income categories was 7 ($40,000–$49,999) for households with AC systems and was 6 ($30,000–$39,999) for those without AC systems (t = 8.02, df = 3753, P < 0.001). This difference was more obvious for lower income households. A 25 percentile for households with AC systems was 5 ($20,000–$29,999) for households with AC systems and 3 ($10,000–$14,999) for those without AC systems. The pattern of increasing ownership of AC systems with a rise in the household income was statistically significant (F = 154.409, df = 1, 8, P < 0.001).

Logistic analysis [17] of the 2001 RECS data also confirms that links between the ownership of AC systems (AIRCOND) and weather conditions (SQCDD) and between the ownership and household income (MONEYPY) were significant (Table 2). For example, the model to predict the ownership of AC systems as a function of weather conditions has a G-statistic of 623.251 and a Wald statistic of 429.488. This indicates both the overall model and independent variable in the model were significant at a level of at least 0.001. The analysis suggests that the association of air conditioning ownership and climate was stronger than its link with income. The coefficient of determination (R^2) for the model with climate (0.223) was much higher than the value for the model with income (0.024).

4. Physical, socio-economic and behavioural factors

4.1. General Linear Model analysis

Each variable was investigated with the General Linear Model (GLM) [18–20] to reveal direct relationships between the variable and cooling energy consumption. Total effects of variables on cool-



The box extends from 25th to 75th percentile and the line within in the box indicates the median.
Whiskers extend to largest and smallest values within 1.5 box lengths.

Fig. 1. Comparisons between households with and without air conditioning systems.

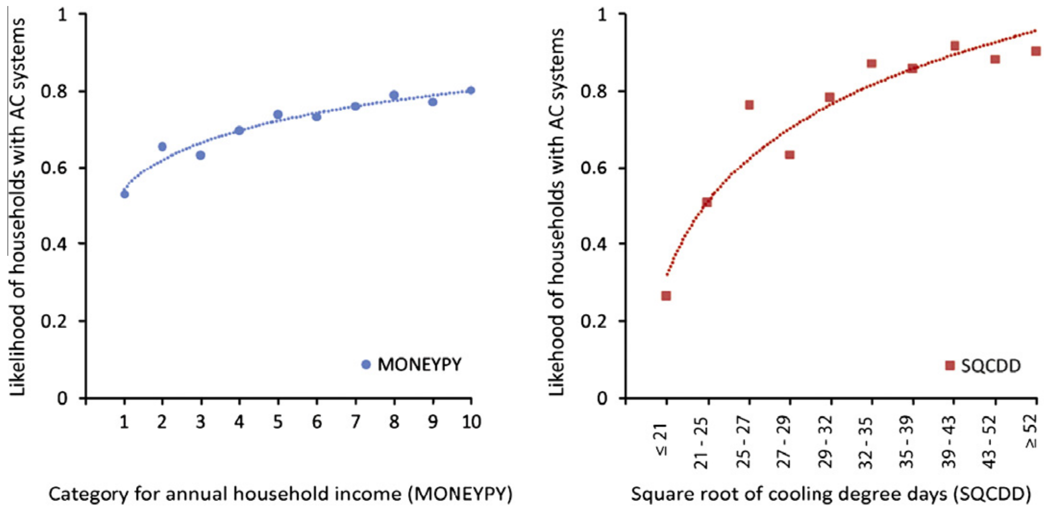


Fig. 2. Likelihood of the ownership of air conditioning systems as a function of cooling degree days and household annual income.

Table 2
Logistic regression results for links between the ownership of air-condition systems and climate conditions and between the ownership and the household annual income.

Model	Variable	R^2	Overall test		Independent variable test			
			G	p-value		SQCDD	MONEYPY	Coefficient
Model 1	SQCDD	0.223	623.251	<0.001	Coefficient (SE)	0.095 (0.005)		−1.942(0.140)
					Wald	429.488		192.445
					p-value	<0.001		<0.001
Model 2	MONEYPY	0.024	62.825	<0.001	Coefficient (SE)		0.120 (0.015)	0.300 (0.096)
					Wald		62.329	9.838
					p-value		<0.001	0.002

ing energy consumption including both direct and indirect effects will be investigated in Section 5. Table 3 summarises GLM results for space cooling energy consumption. All variables examined in this study had the statistically significant relationship with cooling energy consumption ($P < 0.001$, F-tests for all variables).

The GLM results suggest that behavioural patterns of air conditioning equipment use were the most influential element in household cooling energy consumption (Table 3 and Fig. 3). The frequency of AC use by occupants (USEAC) accounted for about 47% of a variation in cooling energy consumption ($F(3, 2714) = 789.516$, $P < 0.001$). The cooling energy consumption for households with air conditioning equipment, whose occupants reported no use of air-condition systems at all (household category 0), was zero (Fig. 3). The average of square root of cooling energy consumption was 27.02 (SD = 10.82) for household category 1 (turned AC on only a few days or nights) and was 56.30 (SD = 18.05) for household category 3 (Turned AC on just about all summer).

There was also a strong, positive relationship between the number of rooms cooled by occupants (NUMACROOM) and cooling energy consumption (SQENERGY) ($F(14, 2703) = 147.639$, $P < 0.001$, $R^2 = 0.433$). For example, households with five air conditioned

Table 3
General Linear Model (GLM) analysis for space cooling energy consumption, ranked by R^2.

Category	Variable	Statistic	P-value	R^2
Behaviour	USEAC	$F(3, 2714) = 789.516$	<0.001	0.466
Behaviour	NUMACROOM	$F(14, 2703) = 147.639$	<0.001	0.433
Climate	SQCDD	$F(1, 2716) = 1680.937$	<0.001	0.382
Equipment	ACTYPE	$F(2, 2715) = 411.246$	<0.001	0.233
Building	TYPEHOUSE	$F(3, 2714) = 82.970$	<0.001	0.084
Occupant	MONEYPY	$F(9, 2708) = 27.080$	<0.001	0.083
Building	SQTOTAREA	$F(1, 2716) = 234$	<0.001	0.079
Occupant	NHSLDMEM	$F(10, 2707) = 22.163$	<0.001	0.076
Building	AGEHOUSE	$F(7, 2709) = 30.779$	<0.001	0.074
Building	NUMWND	$F(6, 2711) = 25.921$	<0.001	0.054
Occupant	HHAGE	$F(1, 2659) = 66.586$	<0.001	0.024

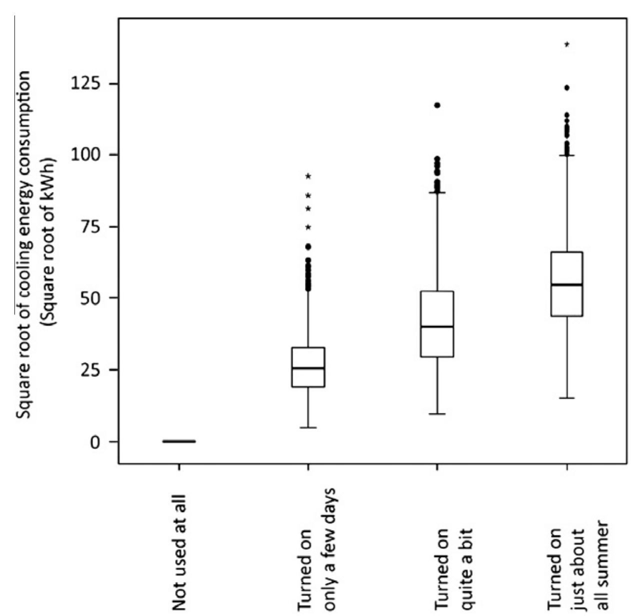


Fig. 3. Variation in cooling energy use as a function of the frequency of air conditioning equipment use.

rooms consumed twice as much cooling energy as those with two air conditioned rooms. As the number of air conditioned rooms was influenced by both occupants' AC use patterns and the number of rooms in housing units, we normalised this number (NUMACROOM) for each household by the total number of rooms in a house. Even after this normalisation there existed a clear influence of number of air conditioned rooms on cooling energy consumption ($F(1, 2716) = 1145.682$, $P < 0.001$, $R^2 = 0.297$).

Weather conditions (SQCDD) had a strong influence on cooling energy consumption (SQENERGY). As expected, cooling energy tended to go up with an increase in cooling degree days ($F(1, 2716) = 1680.937$, $P < 0.001$, $R^2 = 0.382$, Fig. 4). However, Fig. 4 shows that households never using AC systems were widely distributed and were even found in regions with risk of overheating (e.g. SQCDD of 40 and more).

The type of cooling equipment (ACTYPE, i.e. central or local systems) was also an influential determinant of cooling energy consumption ($F(2, 2715) = 411.246$, $P < 0.001$, $R^2 = 0.233$). For example, households with local air conditioning systems (individual units in windows or walls) consumed only 34% of the cooling energy for those with central systems.

Our analysis of relationships between physical characteristics of housing units and cooling energy consumption shows an interesting result. The physical characteristics of buildings appear to be marginal in terms of their effect on cooling energy consumption (Fig. 5). Although there were significant relationships between the type, size and age of housing units, and cooling energy consumption, low values of R^2 indicate that the direct relationships were less convincing. For example, the relationship between the size of dwellings (SQTOTAREA) and cooling energy consumption (SQENERGY) was less than evident ($F(1, 2715) = 234.13$, $P < 0.001$, $R^2 = 0.079$). The highest R^2 value for the relationship of cooling with the physical characteristics of housing units was 0.084.

The GLM analysis implies that direct influences of occupant economic and demographic factors on cooling energy use seemed rather limited. Although the relationships between individual economic and demographic factors (such as the number of household members, the household income and the age of householder) and energy use were statistically significant ($P < 0.001$ for all variables, F-tests), the relationships were weak ($R^2 < 0.10$ for all variables).

However, our preliminary analysis implies that the understanding of household energy consumption requires the consideration of not only direct but also indirect influences of variables on household energy consumption patterns. Although direct links between occupant socio-economic factors and household energy consumption were weak, key determinants of cooling energy consumption such as the type of AC systems (ACTYPE) and the number of air conditioned rooms (NUMACROOM) were closely related to both socio-economic factors and physical characteristics of housing units. For example, as a household's income went up, so did both the floor area of the dwelling ($F(9, 2708) = 94.053$, $P < 0.001$, $R^2 = 0.238$) and the numbers of rooms air conditioned (Fig. 6, $F(9, 2708) = 51.693$, $P < 0.001$, $R^2 = 0.147$). In addition, the floor area of housing units accounted for 19% of a variation for the number of air conditioned rooms ($F(1, 2716) = 624.518$, $P < 0.001$, $R^2 = 0.187$).

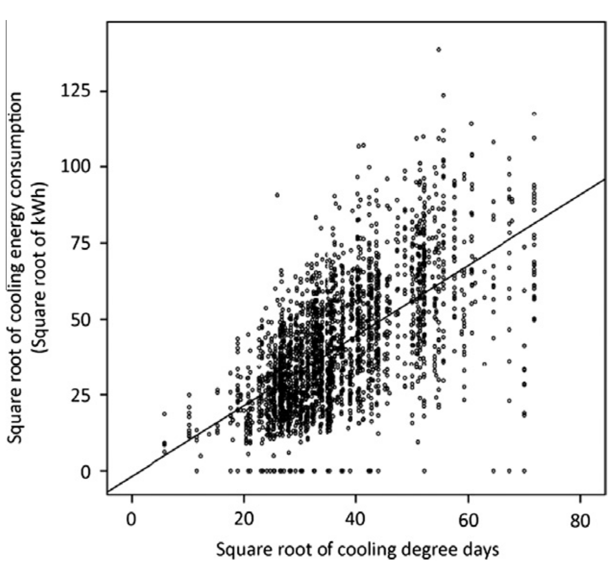


Fig. 4. Cooling energy consumption as a function of cooling degree days.

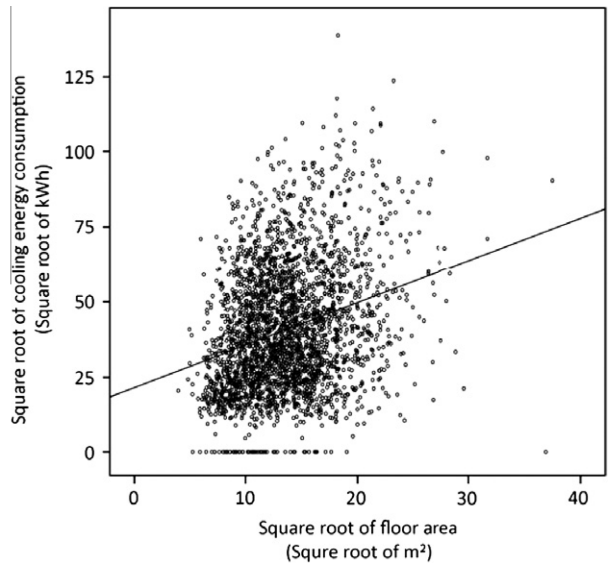


Fig. 5. Cooling energy consumption as a function of the floor area of housing units.

The next section provides in-depth analysis of household cooling energy consumption by revealing the complex inter-relations between climate, building and equipment characteristics, occupant factors (e.g. demographic and economic factors), and occupant behaviour of cooling equipment use.

4.2. Path analysis

Path analysis identifies causal relations between variables by analysing the relative strengths of the direct and indirect links between variables [18,20]. In order to evaluate the scope of direct, indirect and total effects of the investigated variables on cooling energy consumption of households, we applied path analysis and the results are presented here.

Fig. 7 illustrates path diagrams for space cooling energy consumption where the thickness of each path line approximates the strength of direct relationship between connecting variables. Table 4 summarises path coefficients (i.e. values for the path lines) that describe the strength of direct relationships between connecting variables. A minus value of the path coefficient indicates a negative relationship between the variables. The path coefficients are standardised values measured on the same scale, with a mean of 0 and a standard deviation of 1. Thus, they are directly comparable to one another. For example, a path coefficient between the number of air conditioned room (NUMACROOM) and the number of household members (NHSLDMEM) was 0.117 and NUMACROOM and air conditioning type (ACTYPE) was 0.46. This indicates that the direct influence of ACTYPE on NUMACROOM was almost four times greater than that of NHSLDMEM.

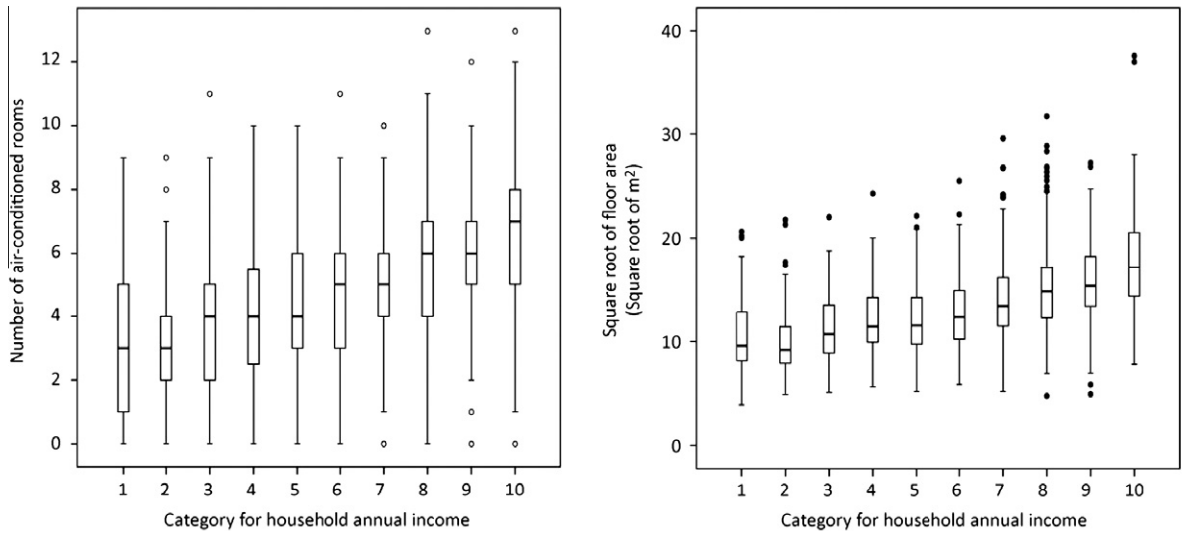


Fig. 6. Relationships between household annual income and the physical characteristics of housing units.

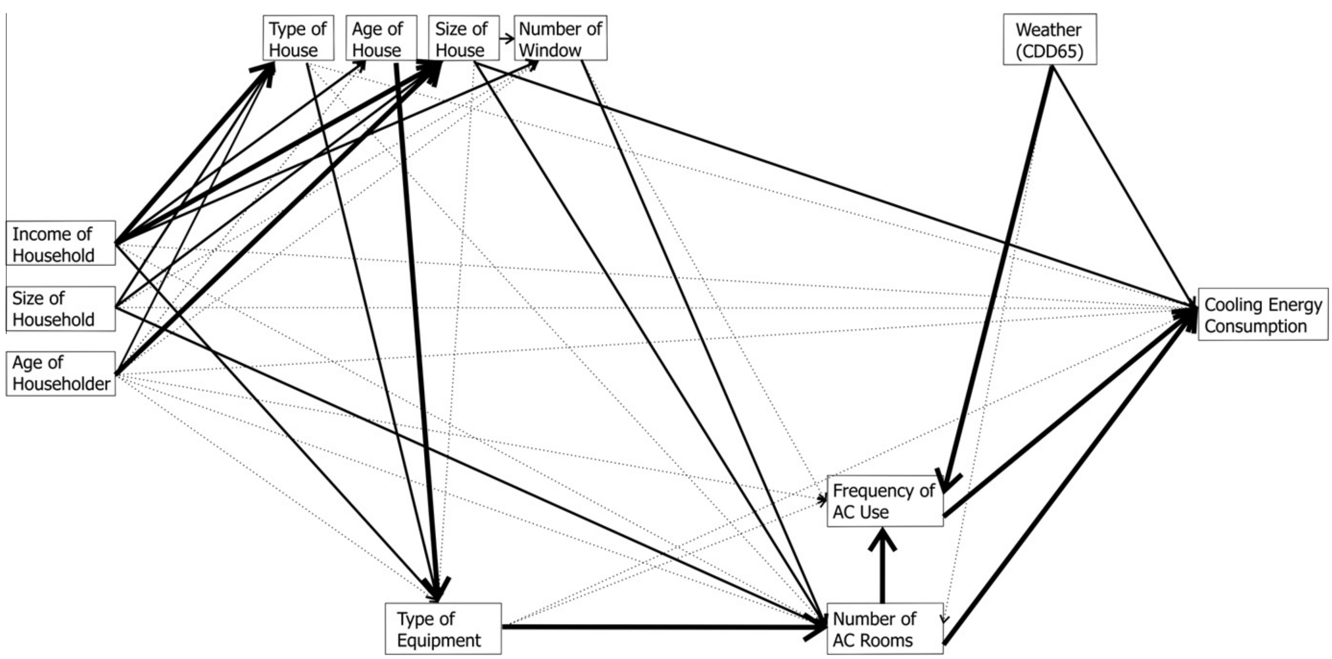


Fig. 7. Path diagram for space cooling energy consumption.

Table 4
Values between connecting variables in path analysis for cooling energy consumption.

	SQCDD	NUMACROOM	USEAC	SQTOTAREA	HHAGE	NHSLDMEM	ACTYPE	MONEYPY	TYPEHOUSE	WINDOWS	AGEHOUSE
TYPEHOUSE					−0.268	−0.168		−0.304			
AGEHOUSE					−0.06			0.181			
SQTOTAREA					0.214	0.151		0.473			
NUMWND				0.479	0.081	0.08		0.113			
ACTYPE				0.041	0.065			0.114	−0.138		0.395
NUMACROOM	0.071			0.181	0.035	0.117	0.46	0.095	−0.089	0.127	
USEAC	0.352	0.326			−0.084		0.044			−0.036	
SQENERGY	0.455	0.341	0.334	0.137	−0.086	0.064	0.061	0.025	−0.023		

The path diagram (Fig. 7) suggests that there were significant indirect as well as direct links between investigated variables and household cooling energy consumption, and that the identification of these links is essential to understanding the patterns of household cooling energy consumption. For example, direct effects of the age of houses (AGEHOUSE) on household cooling energy consumption (SQENERGY) were insignificant. However, there was a clear influence of house age on air conditioning type (ACTYPE), which had a positive, direct relationship with energy use. The air conditioning type also indirectly affected energy use through intervening factors (e.g. number of air conditioned rooms had a direct link with energy use).

The path analysis shows that socio-economic factors of households performed a vital role in determining space cooling energy consumption. The age of householders (HHAGE), for example, had significant, direct relationships with all variables including space cooling energy consumption. Path coefficients (i.e. values of path lines) for householder age ranged from −0.06 for house age (AGEHOUSE) to −0.268 for house type (TYPEHOUSE). Household annual income (MONEYPY), in particular, had dominant influences on critical determinants of space cooling energy consumption such as house floor area (SQTOTAREA), type of air conditioning (ACTYPE), and number of air conditioned rooms (NUMACROOM). The value for a direct link between income (MONEYPY) and floor area (SQTOTAREA) was 0.473. This means that an increase of one standard deviation in income would result in a standardised household's floor area increasing by a factor of 0.473.

Behavioural patterns of air conditioning use (USEAC and NUMACROOM) were the most influential factors in space cooling energy consumption (SQENERGY), apart from climate conditions (SQCDD). The following analysis investigates factors affecting occupant use of air conditioning.

Climatic, physical and socio-economic factors were analysed to have statistically significant relationships with the number of air conditioned rooms (NUMACROOM) and they in total accounted for 48% of variation in the number of air conditioned rooms (Table 4). The most influential factor affecting NUMACROOM was the type of air conditioning system (ACTYPE), followed by the floor area of housing units (i.e. the direct effect is 0.46 for ACTYPE and 0.181 for SQTOTAREA). On the other hand, climate conditions was analysed to have a weak link with the number of air conditioned rooms (i.e. the direct effect is 0.071).

The frequency of air conditioning use was not statistically related with the household income (Table 4). The two most influential factors affecting the occupant use of AC equipment were climatic conditions (SQCDD) and how many rooms were air conditioned (NUMACROOM). As cooling degree days and number of air conditioned rooms went up, occupants tended to more frequently use air conditioning equipment. Despite the above insights, factors affecting occupant behaviour of cooling equipment were still unclear. The path analysis explained only 26% of variation in the frequency of AC system use.

Table 5 summarises the direct, indirect, and total effects of each variables on household cooling energy consumption. The climate (SQCDD) was the most dominant and influential factor in cooling energy consumption (SQENERGY), followed by the number of AC rooms (NUMACROOM) and the reported frequency of AC use (USEAC). The standardised effect of climate (SQCDD) increased from a direct effect of 0.455 to the total effect of 0.605. An increase of 0.109 was observed in the number of AC rooms (NUMACROOM). The standardised effect of climate (SQCDD) increased from a direct effect of 0.455 to the total effect of 0.605. An increase of 0.109 was observed in the number of AC rooms. The increase in the size of the effects arises as some of the effects of climate (SQCDD) and AC room number (NUMACROOM) on energy (SQENERGY) were transmitted through the frequency of use of air conditioning (USEAC) (Table 4).

The indirect, rather than the direct effects of socio-economic factors were important. For example, there was a weak and almost negligible relationship between the household annual income (MONEYPY) and energy use (SQENERGY) when considering only the direct link between the two factors (i.e. standardised direct effect = 0.025). However, when the indirect effects were taken into account, income had a strong, positive relationship with energy consumption (standardised total effect = 0.251). The indirect effect of the type of AC systems (ACTYPE) was also much higher (0.222) than its direct effect (0.061).

5. Predictive regression model

In this section we present a predictive regression model for cooling energy consumption. As explained in Section 2, square root transformations were applied to non-normally distributed variables such as the floor area of houses (TOTAREA), cooling degree days (CDD65), and cooling energy consumption (ENERGY), in order to meet the assumption of normal distributions.

The model enables us to predict household annual cooling energy consumption (SQENERGY) and to assess the relative effects of variables on the household cooling energy consumption. The predictive model from multiple regression analysis is statistically and substantively significant ($F(9, 2651) = 1310.775$, $P < 0.001$, $R^2 = 0.817$, Table 6). However, not all variables investigated have significant relationships with cooling energy (SQENERGY) in the multiple regression model. The number of windows (NUMWND) and the age of houses (AGEHOUSE) are not significant for cooling energy consumption (i.e. the direct effects of NUMWND and AGEHOUSE on SQENERGY were not significant). Thus, these non-significant variables were excluded from the predictive model. *T*-tests indicate that the individual variables in Table 6 are statistically meaningful at least at the significance level of $P < 0.05$.

Results from the path analysis in Section 4 indicate that building, occupant, equipment, and behaviour factors in this study were inter-correlated. Thus, we investigate the potential effects of correlated variables on the robustness of the predictive model.

First, we checked the results of *t*-tests and whether there were collinearity problems. Collinearity happens when there are highly correlated variables in multiple regression models. This is known to result in the loss of accuracy in prediction results of regression models because the standard errors of individual coefficients for collinear variables are increased [20]. *T*-tests for collinear variables tend to be non-significant because *t*-test is defined as the ratio of the standard error of a variable to the value of a variable. Results from *t*-tests for the regression models in this study (shown in Table 6) are all statistically significant and this implies that the estimation of results from the predictive model is reliable and robust.

High tolerance values for independent variables for the regression models also support that the predictive regression models are free from collinearity problems. Tolerance values for independent variables in the regression models are much higher than 0.2, with a minimum tolerance value of 0.489 for the number of cooled rooms variable (Table 6). Tolerance measures a degree of the independence of a variable from the other variables and a value of

Table 5
Standardised direct, indirect, and total effects in path analysis for cooling energy consumption, ranked by total effects on cooling energy.

Effect	SQCDD	NUMACROOM	USEAC	ACTYPE	MONEYPY	SQTOTAREA	NHSLDMEM	AGEHOUSE	TYPEHOUSE	NUMWND	HHAGE
Direct	0.455	0.341	0.334	0.061	0.025	0.137	0.064	0	−0.023	0	−0.086
Indirect	0.15	0.109	0	0.222	0.251	0.115	0.112	0.112	−0.079	0.045	0.085
Total	0.605	0.45	0.334	0.283	0.276	0.252	0.175	0.112	−0.102	0.045	−0.001

Table 6
Multiple regression results for household cooling energy consumption.

Linear regression model
Square root of cooling energy consumption (Square root of kWh) = $\sum(b_i x_i + b_o)$
Overall model test
$F(9, 2651) = 1310.775$, $P < 0.001$, $R^2 = 0.817$
Regression results and individual coefficient tests

i	b_i	Std. error	t-Statistic	P-value	Tolerance	Partial correlation
SQCDD65	0.835	0.017	47.901	0.000	0.792	0.681
MONEYPY	0.214	0.092	2.336	0.020	0.647	0.045
HHAGE	−0.104	0.012	−8.673	0.000	0.729	−0.166
NHSLDMEM	0.948	0.143	6.627	0.000	0.739	0.128
TYPEHOUSE	−0.427	0.197	−2.168	0.030	0.718	−0.042
SQTOTAREA	0.654	0.054	12.123	0.000	0.595	0.229
ACTYPE	2.464	0.438	5.630	0.000	0.652	0.109
NUMACROOM	2.949	0.105	27.992	0.000	0.489	0.478
USEAC	7.459	0.221	33.714	0.000	0.718	0.548
Constant (b_o)	−29.502	1.521	−19.391	0.000		

tolerance ranges from 0 to 1 [20]. Although there is no clear criterion of tolerance values for the existence of collinearity, Pean and Barton [21] suggest tolerance values less than 0.2 indicate collinearity.

The above analysis confirms the robustness and statistical significance of the predictive model. This model predicts annual cooling energy consumption of a household as a function of climatic, physical, economic, and behavioural factors. One example of the application of the model is to evaluate energy implications of global warming (i.e. increasing cooling degree days). According to the US Department of Energy, the number of cooling degree days in 2010 is expected to be 10% greater than the past 30 year average [22]. The model estimates that this results in an increase of 7.4% in the cooling energy consumption of a household.

6. Discussion

This paper illustrates close links between occupant, building, equipment, and behaviour factors and household cooling energy consumption from path analysis on the 2001 RECS micro-data set. We demonstrate the importance of taking into account both direct and indirect links between the factors for a better understanding of cooling energy use patterns of households.

Fig. 8 conceptualises household cooling energy consumption models in the context of direct and indirect links between energy-related factors and energy consumption patterns. The energy consumption patterns are directly influenced by various energy-related factors such as climate, physical characteristics of buildings and environmental control systems, and user control behaviour of the systems, and they are closely inter-connected.

For example, the socio-economic characteristics of households were important, intrinsic factors in household cooling energy consumption. Although direct links between socio-economic factors and cooling energy consumption were weak, they were influential determinants of the physical characteristics of housing units and AC equipment, which in turn influenced user control behaviour and thus cooling energy consumption patterns. Therefore, taking into account both direct and indirect links affecting household cooling energy consumption is essential.

Previous studies also confirmed relationships between demographic and economic factors and household energy consumption. In particular, links between household income and energy consumption were found in numerous studies [23–29]. Santamouris et al. [25] found that household income was an important determinant of the size, age, type, envelope quality of dwelling and type of equipment. Schuler et al. [8] found that socio-economic characteristics of households were significant factors but, their effects were

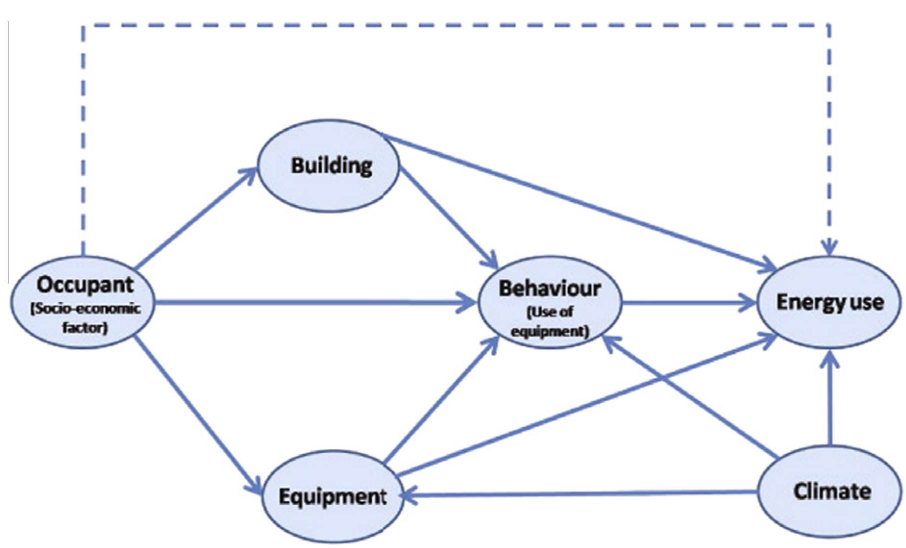


Fig. 8. Empirical model for household energy consumption.

less influential than physical characteristics of houses in space heating energy consumption. A study by Druckman and Jackson [29] found that there was a positive correlation between disposable income and both energy consumption and associated carbon emissions. They also observed that the amount of household energy consumption by the poorest 10% of households was only 43% of the energy consumed by the richest 10% of households in the UK.

The two most significant factors associated with the ownership of AC systems (AIRCOND) were climate (SQCDD) and household annual income (MONEYPY). The trend in AC ownership was closely related to climate in particular ($G = 623.251$, $P < 0.001$, Wald = 429.488, $P < 0.001$, $R^2 = 0.223$). The climate was also the most dominant factor in household space cooling energy consumption in the path analysis. As cooling degree days increase, there was a tendency towards more uptake and frequent use of AC systems, which were in turn also closely associated with higher cooling energy consumption.

The close relationship between AC ownership (AIRCOND) and climate (SQCDD) identified in this study has significant energy implications, particularly in the light of global warming. The heavy reliance on air conditioning typically increases energy use, thus adding to negative impacts of global warming [30]. One solution is to apply passive design solutions that utilise natural energy to reduce fossil fuel use in buildings without sacrificing comfort requirements. For example, the combined effects of exposed thermal mass and user-friendly windows which allow secure night-time natural ventilation can reduce summertime room temperatures by up to 4 °C, compared to thermal conditions in rooms without night-time ventilation [31].

Occupant behaviour related to equipment control was the second most dominant factor in determining household cooling energy consumption in our path analysis. The total effects of the frequency of air conditioning use and of the number of rooms air conditioned had path strengths of 0.334 and 0.450, respectively. The effect of occupant control behaviour on cooling energy consumption would be more substantial if other behavioural patterns not included in the 2001 RECS data set were considered. They include, for example, the choice of indoor temperatures, its relationship with outdoor temperature, the duration of air conditioning systems use, the use of windows and shading devices, occupancy patterns in the hottest hours, etc.

Such behavioural factors can account for a large variation in the energy consumption of households of similar type and size. The importance of user behaviour in cooling energy consumption is supported by a previous study [32] which through field monitoring revealed that cooling energy consumption across physically similar apartments changed by two orders of magnitude mainly due to differences in user control behaviour of air conditioning.

Further understanding of occupant behaviour in buildings can potentially improve the robustness and accuracy of technical simulation results. There are frequently large discrepancies between simulated and actual building energy consumption [33,34] and the main reason for inaccurate simulation results are the different occupancy and internal heat gains patterns and user control behaviour of equipment (e.g. operation schedule and thermostatic setting) departing from simulation assumptions. Further studies, and in particular field experiments, are needed in order to extend our understanding of occupant behaviour in buildings in order to anticipate realistic performance of buildings and implications of climate change on energy use.

It should be mentioned that the findings of this study are based on a limited data set. Particularly, only one survey question result was used to describe occupants' use of air-condition analysed in this paper. Further field studies to monitor directly when and how occupants use air-condition at home are crucial to confirm the findings of this study. For example, direct investigations of occupant behavioural patterns have been widely used in studies of natural ventilation [31,35,36] and thermal comfort [37–39]. Only 2001 RECS micro-data set which includes the survey results of 2718 households was analysed in this study. The use of the limited data set might be potential reasons for wide variations in air-conditioning energy use for a given climate and floor area shown in Figs. 4 and 5. Further investigations with up-to-date and extensive data such as a series of RECS micro-data sets are requried to validate the findings of this study.

7. Conclusions

This paper has quantified the significance of socio-economic, behavioural and physical factors for domestic cooling energy demand. It has also demonstrated that such parameters exert a significant indirect as well as direct influence on energy use, showing that it is particularly important to understand indirect relationships through path analysis.

An initial study of direct factors affecting cooling energy reveals that occupant behaviour is the most significant issue (related to choices about how often and where air conditioning is used). This is followed by key physical parameters (notably climate, air conditioning type and house type), and finally socio-economic aspects (income, household size, age of householder). This is broadly confirmed by the path analysis, although climate is seen to be the single most significant parameter, followed by behavioural issues.

What is perhaps most surprising from the path analysis is that key building design parameters rank low in terms of influence on cooling energy. These parameters are related to windows, house type, age and, by implication, construction standards regarding insulation and air tightness. This finding suggests that occupants use air conditioning as a function of exterior conditions (as opposed to interior).

As global warming continues and cooling degree days increase, the current trends shown in this work imply that energy demand per household will also increase. However, if housing design and refurbishment interventions adopt strategies to reduce overheating risks, then this increase can be counteracted.

Behaviour is shown to be an important aspect of energy use and thus as living standards continue to increase there is a risk that centralised air conditioning systems will become the norm in new dwellings. In this paper we have shown that this leads to a tripling of the energy use compared to a decentralised air conditioning system. Thus the responsiveness and controllability of AC units are features that are likely to limit energy consumption and encourage more efficient use.

To mitigate and adapt to global warming, and limit the demand for cooling energy, household occupants must be able and encouraged to behave appropriately. This requires systems and building design to be energy efficient and responsive to individual choices.

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Glossary

RECS: Residential Energy Consumption Survey
CDD65: Cooling degree days to a reference temperature of 18.3 °C (65 °F)
SQCDD: Square root of cooling degree days
AC: Air conditioning
AIRCOND: Ownership of air conditioning equipment
SD: Standard deviation
TOTAREA: Total floor area
SQTOTAREA: Square root of the total floor area
NUMWND: Number of windows
AGEHOUSE: Year of construction
TYPEHOUSE: Housing type (detached, attached or apartment)
ACTYPE: Type of space cooling equipment (central system or individual units)
NHSLDMEM: Number of household members
MONEYPY: Total household annual income
HHAGE: Age of the head of a household
USEAC: Frequency of air conditioning use in summer
NUMACROOM: Number of rooms in a house were air conditioned
GLM: General Linear Model analysis
ENERGY: Cooling energy consumption
SQENERGY: Square root of cooling energy consumption