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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 2 = 1940–1949 3 = 1950–1959 4 = 1960–1969	5 = 1970–1979 6 = 1980–1989 7 = 1990–1999 8 = 2000
	TYPEHOUSE	Type of Housing units	1 = Single-family detached 2 = Single-family attached	3 = Apartment in building with 2–4 units 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 2 = $5000–$9999 3 = $10,000–$14,999 4 = $15,000–$19,999 5 = $20,000–$29,999	6 = $30,000–$39,999 7 = $40,000–$49,999 8 = $50,000–$74,999 9 = $75,000–$99,999 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