INTERNATIONAL JOURNAL OF SUSTAINABLE CONSTRUCTION ENGINEERING AND TECHNOLOGY
VOL. 14 NO. 4 (2023) 354-367

IJSCET

http://publisher.uthm.edu.my/ojs/index.php/ijscet

ISSN : 2180-3242 e-ISSN : 2600-7959

International Journal of Sustainable Construction Engineering and Technology

Influence of Occupants' Space and Appliance Use Patterns and Behaviour during the Discomfort on Electricity Consumption in Mixed Mode Residences

Sivapriya Chelliah[1*], Subbaiyan G[1], Srinivas Tadepalli[1]

[1]National Institute of Technology, Tiruchirappalli – 620015, Tamil Nadu, INDIA

*Corresponding Author

DOI: https://doi.org/10.30880/ijscet.2023.14.04.026
Received 19 April 2023; Accepted 13 December 2023; Available online 28 December 2023

Abstract: Building characteristics, climate, socio-economic characteristics, and occupant behaviour influence the electricity consumption in buildings. In residential buildings, where people spend a lot of time and have high perceived control over their surroundings, electricity consumption for thermal comfort constitutes a higher proportion of overall energy consumption. Previous research studies mainly focused on the impact of building and household characteristics on electricity consumption in residences. In the Indian context, electricity usage in residential buildings may depend on lifestyle, family composition, daily routines and activity patterns, and consumption habits. In India, the space usage and sharing pattern of internal spaces depend on family composition and the number of rooms. In India, the usage of household appliances has been steadily increasing. During discomfort hours in humid conditions, people use fans with windows in the open position, switch on the air-conditioner or use the fan and air-conditioner together to attain thermal comfort. Therefore, the study aims to assess the impact of family composition, occupants' space and appliance use patterns and behaviour during the thermal discomfort on electricity consumption in Indian residential buildings. Information on the number of occupants, children, and elders; space usage at different hours of the day by the occupants; use of fans, air-conditioners, and other electrical appliances; and frequency and hours of opening of windows were collected through a questionnaire survey from 144 residences. Electricity consumption data for all 144 residences were collected from the utility bills. The variables influencing annual mean electricity consumption per unit area of residential buildings include the number of elders present, age of children, hours of air-conditioner use, space usage pattern, and occupants' behaviour during the discomfort.

Keywords: Electricity consumption, household characteristics, space usage pattern, use of appliances, mixed-mode residences

1. Introduction

India, the second largest populated country, is the third major economy considering the purchasing power of its people (Dalal, R., et.al., 2021). There is a steady increase in the demand and supply of various forms of energy due to the growth of industrial and other economic activities in India. India has high ambitions to reduce the emissions intensity in the near future. Energy efficiency practices must be followed in the building industry, which consumes more than 30% of India's total electricity production, to achieve the targeted emission reductions (Dalal, R., et.al., 2021). Residential buildings' gross electricity usage has steadily increased over a period. Significant factors influencing buildings' overall energy consumption are the place's climatic conditions, building characteristics, user characteristics and behaviour, building services systems and operation, and indoor environmental parameters (Wang, L. & Greenberg, S., 2015 and Yu, Z., et.al., 2015). Occupant behaviour significantly contributes to the total energy

*Corresponding author: contactjspriya@gmail.com

consumption in residential buildings (Sharma, A., & Sharma, V., 2022 and Delzendeh, E., et.al., 2022). The occupant behaviour includes space occupancy, appliance use pattern, and control of building systems (Fabi, V., et.al., 2011). Occupants depend on Heating, Ventilation, and Air-Conditioning (HVAC) systems to achieve thermal comfort (Balvedi, B.F., et.al., 2018, Gill, Z.M., et.al., 2010, and El-Zoklah, M.H., & Refaat, T., 2021). People use fans with the windows in the open position, air-conditioners independently, or air-conditioners and fan together during discomfort hours. The number and hours of usage of fans and air-conditioners might depend upon the space usage pattern of occupants, which is determined by the family composition. In addition to HVAC systems, occupants use other electrical devices daily. The number and pattern of usage of appliances contribute significantly to the overall energy consumption of buildings (Harish, V.S.K.V., & Kumar, A., 2016, Zuo, J., & Zhao, Z.Y., 2014, and McCoy, A.P., 2018). In Indian residential buildings, electricity is the primary energy source for lighting, HVAC, and various appliances and gadgets, whereas LPG (Liquefied petroleum gas) is used for cooking. Hence this study mainly investigates the influence of family composition and occupant behaviour, including space occupancy, appliance use pattern, and control of building systems variables on electricity consumption in residential buildings.

2. Literature Review

Identified drivers of residential energy consumption at the individual dwelling level are dwelling variables, household variables, appliance-related factors, and occupant behaviour. Identified dwelling factors include dwelling type, dwelling age, number of rooms, number of bedrooms, and floor area (Jones, R. V., et.al., 2015). Weismann (Wiesmann, D., et.al., 2011) found that floor area positively influenced residential energy consumption in Portuguese residences. Esmaeilimoakher (Esmaeilimoakher, P., et.al., 2016) found a negative correlation between electricity consumption per person per unit built-up area and dwelling size in Australia. The number of rooms and energy consumption are reported to have a positive relationship (Baker, K.J., & Rylatt, R.M., et.al., 2008 and Bedir, M., et.al, 2013). Leahy and Lyons (Leahy, E., Lyons Sean, S., et.at., 2010) 02102101noted that Irish residences with one or two rooms consume less energy than residences with five rooms. Each additional room in Indian residences accounted for 11% more electricity consumption (Tiwari, P., 2000), and in Irish residences, every additional bedroom is responsible for a 15.4% increase in energy consumption over six months (McLoughlin, F., et.al., 2015).

The household variables that influence energy consumption include the number of occupants, family composition (presence of children, presence of teenagers, presence of adults, number of adults, and number of elderly people), age of occupants, employment status of occupants, education level, socio-economic classification, tenure type, household income, and disposal income(Lin, B., et.al, 2016 and Jones, R. v.,et.al., 2015). Tewathia (Tewathia, N., 2014) revealed that income, number of appliances, house size, household size, and educational level influence the monthly electricity consumption in Indian residences. Age of occupants, education level, gender, occupation, and occupancy density are significantly related to weekend heating patterns of residences in South-Eastern Europe (Ozarisoy, B., & Altan, H., 2022). The number and type of occupants greatly influence the energy consumption pattern in residential buildings (Estiri, H., 2014 and Ofetotse, E.L., et.al., 2021). Single-occupant Irish households consumed 19% less electricity per week than households with two or more occupants (Leahy, E., Lyons Sean, S., et.at., 2010), and households with four or more occupants consumed more electricity than other households (Yohanis, Y.G., et.al., 2008). Indian residences with five occupants consumed 23% more electricity than residences with two occupants (Tiwari, P., 2000). Previous studies reported an 8% increase in electricity consumption for every additional occupant in China (Zhou, S., & Teng, F., 2013) and a 21% increase for every additional occupant in Dutch households (Brounen, D., et.al., 2012). In contrast, Yohanis et al. (Yohanis, Y.G., et.al., 2008) reported a decrease in the electricity consumption per unit floor area per occupant with the increased number of occupants. Previous studies also revealed a lower per capita consumption in larger households in the USA and a negative correlation between electricity consumption per person per unit built-up area and the number of occupants in Australia (Esmaeilimoakher, P., et.al., 2016).

The occupants' age groups in the residential buildings significantly influenced electricity consumption (Belaïd, F.,2016). A positive relationship was observed between electricity consumption and the number of elders in US and Denmark residences (Wyatt, P., 2013). The employment status of the House Representative Person (HRP) was found to have no significant influence on electricity demand (Yohanis, Y.G., et.al., 2008 and Cramer, J.C., et.al., 1985). Irish residences where adults live with children consume more electricity than residences without children (McLoughlin, F., et.al., 2015 and Besagni, G., & Borgarello, M.,2010). Residences with children consumed 20% more electricity than residences without children in the Netherlands, and consumption increased with the age of children (Brounen, D., et.al., 2012). Bartiaux & Gram-Hanssen (Bartiaux, F., & Gram-hanssen, K., 2005) found an increase in the mean electricity consumption in Danish residences with children and a decrease in mean energy consumption in Belgian residences with children. Significant differences in energy consumption were not found between Belgian residences with and without teenagers (Gram-Hanssen, K., 2010).

Factors such as the number of appliances and hours of use of various appliances seem to influence the energy consumption pattern in residential buildings (Kim, M.J.,2018 and Wan Nur Hanani Wan Abdullah et.al, 2022). Sanquist (Sanquist, T.F.,et.al.,2012) found that air-conditioning, laundry usage, personal computers, the climatic zone of the study area, and TV use have a significant relationship with energy consumption in US residences. Previous studies established that annual energy consumption was influenced by the number of appliances (Zhou, S., & Teng, F., 2013) and reported that 37% of variations in energy consumption were explained by appliance use behaviour (Bedir, M., & Kara, E.C.,2017). Bedir et al. (Bedir, M., et.al, 2013) revealed a significant correlation between electricity consumption and the number of baths per week using electric water heaters in Dutch residences. The use of major cooking appliances such as electric ovens and induction stoves did not have a significant relationship (Filippini, M., & Pachauri, S.,2004), whereas laundry appliances significantly influence annual energy consumption (Bedir, M., & Kara, E.C.,2017). Garg et al. (Garg, A.,et.al.,2010) found that appliances such as air-conditioners, geysers and television influenced electricity consumption in higher-income Indian residences. Murthy (Murthy, K. V. N., et.al.,2010) found that appliances such as lamps, fans, mixers, television and iron account for higher energy consumption in urban residences than rural residences, in addition to location and socio-economic variables in India.

Occupants' comfort is achieved with control over building systems (Loengbudnark, W.,et.al., 2022). Hours of use of heating and cooling equipment, occupants' behaviour during discomfort hours, and occupants' preferences are found to have a significant relationship with energy consumption (Rinaldi, A.,et.al., 2018). Fabi et al. (2012) stated that occupant behaviour, such as window opening behaviour, use of air-conditioners, and set-point preferences, play an essential role in predicting energy consumption. People use fans with the windows in an open position, air-conditioners independently, or air-conditioners and fan together during discomfort hours in tropical conditions. Kubota et al. (Kubota, Tetsu;et.al,2011) revealed that 29% of the yearly household energy consumption was used for cooling in tropical conditions. Fans and air-conditioners consume about 10% and 17% of Malaysian residences' total annual electricity consumption (Kubota, Tetsu;et.al,2011). The usage pattern of appliances such as fans, air-conditioners and space heaters to achieve comfort in different climatic zones was found to influence the energy consumption in residential buildings in India significantly. Garg et al. (Garg, A.,et.al.,2010) found that 58%, 48% and 41% of electricity consumption accounted for space cooling in high, middle- and low–income Indian households. Rawal and Shukla (Shukla, Y.,et.al., 2011) found variations in electricity consumption due to differences in climatic zones in the study of eight hundred households in four cities covering four climatic zones of India.

3. The Need and Novelty of the Study

Previous studies established the influence of the number of occupants, age, sex, income, education level, number and age of children, presence of elders, number, ownership, and use of appliances on residential energy consumption. However, there is disagreement among the findings regarding the percentage increase in energy consumption for every additional occupant. Mixed results have been noticed regarding the influence of the presence of children on the mean energy consumption of residences. In India, the space usage and sharing pattern of internal spaces depend upon the number of people present in residence and their age group vis-à-vis the number of bedrooms or habitable rooms. In India, children up to 12 years share bedrooms with their parents. Children above 12 years of age use separate bedrooms or spaces, and the elders use bedrooms or living halls for sleeping. The space usage of patterns and its influence on energy consumption are not explored in detail in the previous studies. Air-conditioners are primarily installed in bedrooms in Indian residences. Bedrooms are also used for other activities, such as reading, etc., in Indian residential buildings, which may influence the duration of air-conditioner use.

Though previous studies focused on the end-use analysis based on appliance ownership and consumption data from Standards and Labelling, only a few studies concentrate on the actual usage pattern of appliances (Chunekar, A., & Sreenivas, A.,2018). In India, household usage of electric ovens and induction stoves has steadily increased. Hence the study of the influence of appliance usage patterns on energy consumption gains importance. Previous studies mainly dealt with the impact of discomfort behaviour, like turning on the heating system in cool climates (Rinaldi, A.,et.al., 2018). In warm and humid zones of India, people have the habit of either switching on the air-conditioner or using the fan and air-conditioner together. Debnath et al. (Debnath, K.B.,et.al., 2020) studied the behaviour of household occupants for achieving thermal comfort in a warm-humid climate zone of India by analysing the electricity demand profiles. Debnath et al. (Debnath, K.B.,et.al., 2020) noted that most households use fans, and some use the A/C to attain thermal comfort in the warm-humid zones of India. The A/C is not used continuously in the warm-humid zones. People use the A/C to cool the space, use fans to circulate the air, and again use A/C when the room is warm (Debnath, K.B.,et.al., 2020). The influence of the behavioural pattern of using fans and air-conditioners for thermal comfort on energy consumption in Indian households is seldom studied.

Hence this study attempts to study the impact of (i) family composition and space usage patterns at different hours of the day, (ii) activities in the bedroom other than sleeping, (iii) appliance use patterns, and (iv) behaviour during discomfort hours – windows opening/ closing behaviour and use of fans and air-conditioners independently and together on annual energy consumption per unit area of residences in warm-humid regions of India.

4. Materials and Methodology

This study was conducted in 144 mixed-mode residences (with air-conditioners) in Tiruchirappalli City, Tamil Nadu, India (Figure 1). The research focuses mainly on the influence of family composition, occupants' space, and appliance use patterns on electricity consumption, not on the impact of building envelopes on energy consumption. Hence residential blocks with similar building envelopes were selected. According to Koppen – Geiger climate classification, Tiruchirappalli is zoned under tropical dry and wet climates and located in a monsoon with dry season climatic region.

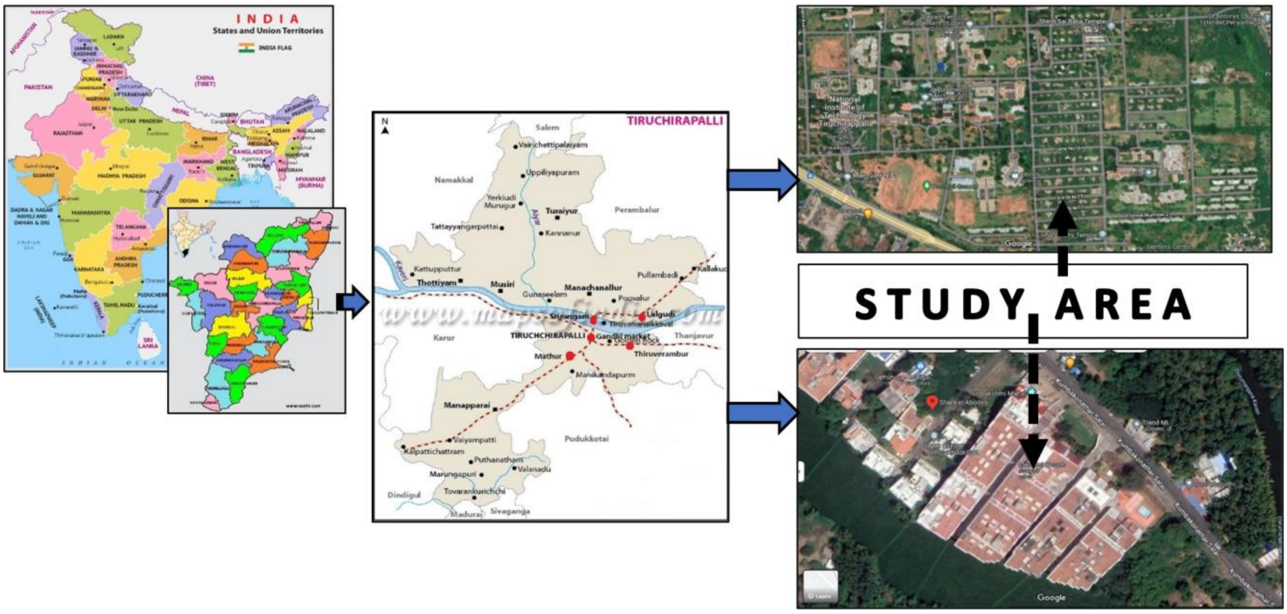

Fig. 1 - Map Illustrating the Location of Study Area

The residential buildings selected are three-story, classified (Type 1, 2 & 3) according to the number of bedrooms and plinth area. The plinth area of Type 1 with three bedrooms, Type 2 with two bedrooms, and Type 3 with one bedroom are 115m^2, 105m^2, and 44m^{2,} respectively. The study was carried out in 16 nos. Type 1, 106 nos. Type 2 and 22 nos. Type 3 residences (Table 1 & Figure 2). The annual electricity consumption data, obtained from the bi-monthly utility bills of the respective residences, varies from 836.00 kWh to 13230.00 kWh. As this study aims to analyse the impact of family composition and their space and appliance use pattern on electricity consumption, the electricity consumption data in annual electricity consumption per unit area of the residence (kWh/m^2.year) is considered.

Table1 1 - Building Characteristics of Three Types of Residences

S.NO	BUILDING ELEMENT	DESCRIPTION		
		Type 1	**Type 2**	**Type 3**
1.	Plinth Area	115 m^2	105 m^2	44 m^2
2.	Number of Bedrooms	3	2	1
3.	Walls	23 cm brick wall plastered on both sides with cement plaster		
4.	Roof	10 cm thick R.C.C Slab		
5.	Windows	Metal window with translucent glass shutter		

Fig. 2 - Building Layouts

A questionnaire-based survey was administered in all 144 residences to collect information on the number of occupants, elders, working adults, presence and the age of children; the number of air-conditioners and heaters; space occupancy patterns; hours of use of air-conditioners and heaters; family's weekend activities and occupants' behaviour during discomfort hours (keeping the windows open with fans switched on; the habit and frequency of using fans/ air-conditioners and fans and air-conditioners together). The details of family composition and the number and hours of use of appliances for the three types of residences are presented in Table 2.

Table 2 - Family Composition and Appliance Use Pattern of Three Types of Residences

Variables		**No. of Bedrooms (Type of Residences)**			**Total (144)**
		03 (Type 1)	**02 (Type 2)**	**01 (Type 3)**	
No. of Occupants	1	00	01	01	02 (01.39%)
	2	02	09	02	13 (09.03%)
	3	05	19	09	33 (22.92%)
	4	06	52	06	64 (44.44%)
	5	02	12	04	18 (12.50%)
	6	01	13	00	14 (09.72%)
Number of Elders	More than 2	13	40	06	59 (40.97%)
	Equal to or less than 2	03	66	16	85 (59.03%)
Number of Children	Absence of Children	06	12	03	21 (14.58%)
	Number of Children = 1	03	47	10	60 (41.67%)
	Number of children = 2	07	47	09	63 (43.75%)
Age of children	Less than or equal to 12 years	07	74	19	100 (69.44%)
	More than or equal to 12 years	03	20	00	23 (15.97%)
Number of Working Adults in the Family	Two working HRP	16	77	21	114 (79.17%)
	One working HRP	00	29	01	30 (20.83%)
No. of Air-conditioners	01	02	66	22	90 (62.50%)
	02	08	40	00	48 (33.33%)
	03	06	00	00	06 (04.17%)

Hours of use of air-conditioners	Below 1000 hours	07	72	22	101 (70.14%)
	Between 1000 – 1500 hours	09	18	00	27 (18.75%)
	Above 1500 hours	00	16	00	16 (11.11%)
Hours of use Heaters	Below 200 hours	02	23	22	47 (32.64%)
	Between 200 - 300 hours	12	52	00	64 (44.44%)
	Above 300 hours	02	31	00	33 (22.92)
Hours of use of fan	Below 15hours	02	07	00	09 (06.25%)
	Between 15 – 30 hours	00	11	4	15 (10.42%)
	Between 30 – 45 hours	13	81	18	112 (77.78%)
	Above 45 hours	01	07	00	08 (05.56%)

The window opening behaviour of occupants was recorded using the questionnaire survey and validated by monitoring using ARDUINO-based data loggers. The variation in the duration of windows in open position between the monitored and surveyed data is negligible.

The primary space occupancy patterns reported by the occupants reveal that

- Only one bedroom is used at night hours, and no spaces are used during daytime (9 am to 6 pm) in residences in which both HRPs are working, without any other elders and children;
- Two bedrooms are used at night hours, and the living/ dining/ kitchen/ bedroom is used during day time (9 am to 6 pm) in residences in which one HRP is working and with other elders and children;
- Bedroom and living space are used at night hours, and the living/ dining/ kitchen is used during daytime (9 am to 6 pm) in one-bedroom residences with more than two elders or children more than 12 years old; and
- Two bedrooms are used at night hours, and the living/ kitchen/ dining/ bedroom is used during daytime (9 am to 6 pm) in two and three bedroom residences with more than two elders or children more than 12 years old (Table 3).

Table 3 - Space Occupancy Pattern

No. of Elders	**Children above 12 + Age**	**working HRPs**	**Spaces Used**			
			6 am - 9 am	**9 am - 6 pm**	**6 pm – 9 pm**	**9 pm - 6 am**
2	Nil	1	L/ K/ D	L/ K / B	L/ K/ D/ B	B1
		2	L/ K/ D	No space	L/ K/ D/ B	B1
	1	1	L/ K/ D	L/ K/ B	L/ K/ D/ B	B1
		2	L/ K/ D	No space	L/ K/ D/ B	B1/ B2 or L
	2	2	L/ K/ D	No space	L/ K/ D/ B.	B1/ B2 or L
2+	Nil	1	L/ K/ D	L/ K/ D/ B	L/ K/ D/ B	B1/ B2 or L
		2	L/ K/ D	L/ K/ D/ B	L/ K/ D/ B	B1/ B2 or L
			L/ K/ D	L/ K/ D/ B	L/ K/ D/ B	B1/ B2 or L
	1	2	L/ K/ D	L/ K/ D/ B	L/ K/ D/ B	B1/ B2 or L
	2	1	L/ K/ D/ B1/ B2	L/ K/ B	L/ K/ B	B1/ B2 or L

2	L/ K/ D/ B1/ B2	L/ K/ B	L/ K/ B	B1/ B2 or L

L – Living; K – Kitchen; D – Dinning; B – Bedrooms

5. Results and Discussion

5.1 Building Typology and Annual Energy Consumption

ANOVA revealed a significant variation in the annual mean overall electricity consumption per residence [$F_{(2, 141)} = 21.897$, $p<.001$] and annual mean electricity consumption per unit area [$F_{(2, 141)} = 06.899$, $p=.001$] among the three types of residences. The post-hoc analysis revealed that the annual mean electricity consumption per residence and annual mean electricity consumption per unit area of two and three bedrooms residences are significantly higher than that of single-bedroom residences (Table 4). It is also observed that the annual mean electricity consumption per habitable space of a single bedroom is considerably lower than that of two- and three-bedroom residences. Though the number of habitable spaces and bedrooms is more in three bedroom residences, annual mean energy consumption per room is less than two bedroom residences. It is observed that the annual mean overall electricity consumption per residence and the habitable space is high in two bedroom residences mainly due to more usage of habitable and bedrooms by a high percentage of elders and children of more than 12 years.

Table 4 - Electricity Consumption of Three Types of Residences

Types of Residences (No. of habitable spaces/ No. of bedrooms)	**Annual Mean Overall Electricity Consumption Per Residence**	**Annual Mean Electricity Consumption per unit area**	**Annual Mean Electricity Consumption per room**
Type 1 (5/3)	4456.25^{a}	43.62^{a}	891.25
Type 2 (4/2)	4580.38^{a}	38.75^{a}	1145.10
Type 3 (3/1)	1100.00^{b}	25.00^{b}	366.67

Note: Means with different superscripts differ significantly from each other.

5.2 Annual Mean Electricity Consumption and Household Variables

The difference in the annual mean electricity consumption among the residences groups for each household variable is presented in Table 5. The difference in the annual mean electricity consumption per unit area among the six residential groups based on the number of occupants, i.e., single occupant, two, three, four, five, and six occupants, is insignificant [$F_{(5,138)} = 1.89$, $p=0.100$]. It is noticed that there is an increase in the annual mean electricity consumption per unit area of residences with the rise in the number of occupants confirming findings of certain previous studies (Leahy, E., Lyons Sean, S., et.at., 2010 and Yohanis, Y.G., et.al., 2008). However, it is found that the increase is not proportionate to the number of occupants, contrary to previous studies carried out in residences in India (Tiwari, P., 2000) and China (Zhou, S., & Teng, F., 2013).

Table 5 - Annual Mean Electricity Consumption of Different Groups of Residences based on Household Variables and Space Usage Pattern

Variables	**Mean**	**T-test**		**One-way ANOVA**	
		T	**p-value**	**F**	**p-value**
Number of occupants					
1	19.00^{a}	-	-	1.89	0.10
2	39.92^{a}				
3	36.63^{a}				
4	39.09^{a}				
5	41.88^{a}				

6	55.14^{a}				
Number of Elders					
More than two elders	47.29^{a}	3.26	0.00	-	-
Equal to or less than two elders	35.34^{b}				
Number of Children					
Absence of Children	37.14^{a}	-	-	0.249	0.780
Number of Children = 1	40.40^{a}				
Number of children = 2	41.11^{a}				
Age of children					
Absence of children	37.14^{a}	-	-	10.16	0.00
Age of children ≤ 12 years	36.72^{a}				
Age of children > 12 years	58.35^{b}				
Number of Working Adults					
Family with two working HRP	33.44^{a}	8.81	0.00	-	-
Family with one working HRP	66.03^{b}				
Activities happening in the bedroom other than sleeping					
Sleeping	19.74^{a}				
Sleeping and others	46.81^{b}	-7.22	0.00	-	-
Weekend Activity					
Family spending weekend outside	24.50^{a}				
Family spending Sunday Alone outside	26.35^{b}				
Family spending weekend inside	52.84^{ab}	-	-	41.31	0.00

Note: Means with different superscripts differ significantly from each other.

The annual mean electricity consumption per unit area of residences with more than two elders is significantly higher than that of residences with two or fewer elders [$t_{(142)} = 3.26$, $p<0.001$]. This finding confirms the earlier results that a positive relationship exists between the number of elders and electricity consumption in US and Denmark residences (Wyatt, P., 2013). This difference may be attributed to additional space usage in all three types of residences with more than two elders compared to two or fewer elders.

The annual mean electricity consumption per unit area among the three groups of residences (residences without children, with one child and two children) is not significantly different [$F_{(2,141)}= 0.249$, $p=0.780$]. In contrast, the difference is significant between the three groups of residences classified based on the age of children [$F_{(2,141)} = 10.16$, $p<0.001$]. The annual mean electricity consumption per unit area of residences with children over 12 years was significantly higher than that of residences with children of age equal to or less than 12 years and residences without children. This finding confirms the previous findings that residences without children show less electricity consumption when compared to houses with older children (Jones, R. v.,et.al., 2015) , and electricity consumption increases with the increase in the age of children (Brounen, D., et.al., 2012). Children under 12 years mostly sleep with their parents. Children of more than 12 years using separate bedrooms in Indian families could be the reason for the increase in electricity consumption in residences with children older than 12.

The annual mean electricity consumption per unit area of the residences with two working adults is significantly less than that with single working adults [$t_{(142)} = 8.81$, $p<0.001$]. It confirms the results of the studies that residences with employed adults consume less electricity (Jones, R. v.,et.al., 2015) and residences with more adults who stay longer in the house consume more electricity (Zhou, S., & Teng, F., 2013). In this study, it is observed that the spaces are not used during the daytime (9 am to 6 pm) in residences where both HRPs work, without any other elders. The non-use or less use of spaces during the day could be the reason for less electricity consumption in residences with two working adults than in a single working adult.

The questionnaire survey revealed that occupants have the habit of using the bedroom for activities like relaxing, watching television, doing office work, etc., in 76% of the residences. The annual mean electricity consumption per unit area of residences in which the bedrooms are also used for sleeping and other activities is significantly higher than that in which the bedrooms are used for sleeping purposes only [$t(142) = -7.22$, $p < 0.001$]. As air-conditioners are mainly installed in bedrooms, the extended space usage of bedrooms might have resulted in a longer duration of use of air-conditioners and fans, leading to higher electricity consumption. The survey revealed that 15% of the families spend both days of the weekend, and 32% spend one day (Sunday) alone outside the house. At the same time, 53% spend both weekend days in the house. It is observed that the maximum annual mean electricity consumption per unit area of residences is in which occupants spend two days of the weekend in the house, followed by occupants spending one day and two days of the weekend outside the house. The difference in annual mean electricity consumption per unit area between the three groups of residences significantly varied [$F_{(3,140)} = 41.31$, $p<0.001$]. The increased hours of fans and air-conditioners due to the presence of people during weekends in residences where occupants spend two days of the weekend in the house might have resulted in higher energy consumption.

5.3 Annual Mean Electricity Consumption and Appliance Use

The t-tests and one-way ANOVA analyses to determine the difference in the annual mean electricity consumption per unit area among the residences groups for each appliance use variable are presented in Table 6. A significant difference in the annual mean electricity consumption per unit area was found among the groups of residences using the water heaters below 100, 100 to 200, 200 to 300 and above 300 hours [$F_{(3,140)} = 74.43$, $p<0.001$]. The electricity consumption per unit area of residences was proportionate with the hours of use of the water heaters, confirming the findings of earlier studies by Bedir et al. (Bedir, M., et.al, 2013) and Garg (Garg, A.,et.al.,2010). A significant difference in the annual mean electricity consumption per unit area was found among the groups of residences without an oven, using the oven below 100 hours, 100 to 200 hours, and above 200 hours [$F_{(3,140)} =30.681$, $p<0.001$].

Table 6 - Annual Mean Electricity Consumption of Different Groups of Residences based on appliance use Behavioral Variables

Variables	Mean	One way ANOVA		T-test	
		F	p-value	T	p-value
Hours of Use of Water Heaters (Annual)					
Below 100 hours	22.34 [a]				
Between 100 - 200 hours	28.50 [b]	74.43	0.00	-	-
Between 200 - 300 hours	37.67 [c]				
Above 300 hours	69.93 [d]				
Hours of Use of Oven (Annual)					
Nil/ Not present	38.01[a]				
Below 100 hours	28.79[a]	30.681	0.00	-	-
Between 100 - 200 hours	81.00[b]				
Above 200 hours	71.00[b]				
Hours of Use of Washing Machine (Annual)					
Below 300 hours	35.39[a]	-	-	-3.082	0.002
Above 300 hours	46.65[b]				
Hours of Use of Induction Stove (Annual)					
Below 100 hours	23.97[a]				
Between 100 - 200 hours	50.50[b]	73.808	0.000	-	-
Above 200 hours	62.14[c]				

Note: Means with different superscripts differ significantly from each other.

However, the electricity consumption per unit area of residences was not proportionate with the hours of use of the oven. These results confirm the findings of an earlier study that the use of electric ovens did not have a linear relationship with energy consumption (Grandjean, A.,et.al.,2018). The annual mean annual electricity consumption per unit area of the residences using washing machines below 300 hours is significantly less than that of the residences using washing machines above 300 hours [$t_{(142)} = 3.082$, $p<0.01$]. The analyses revealed a significant difference in the annual mean electricity consumption per unit area among the groups of residences using the induction stove below 100 hours, between 100 and 200 hours, and above 200 hours [$F_{(3,140)} =73.808$, $p<0.001$]. The annual mean electricity consumption per unit area of residences increases with the increase in the hours of induction stoves. These results contradict the findings of an earlier study that the use of induction stoves did not have a significant relationship with energy consumption (Grandjean, A.,et.al.,2018). This study found that the hours of use of water heaters, stoves and washing machines positively influenced the annual mean electricity consumption per unit area.

5.4 Annual Mean Electricity Consumption and Occupant Behavioral Variables during the Thermal Discomfort

Discomfort hours in the study area are evaluated using HUMIDEX. They are rated using 5- point scale as Extreme Severe Discomfort, Severe Discomfort, High Discomfort, Moderate Discomfort, and Comfortable. Analysis of discomfort hours shows high discomfort hours from March to September (Figure 3). People use the fan and keep windows open, use only air-conditioners, or use fans and air-conditioners together to achieve thermal comfort. The usage of fans and air-conditioners is high from April to July due to discomfort. It is observed that the fans are used longer than air-conditioners, as found in the study at Auroville, India (Debnath, K.B.,et.al., 2020).

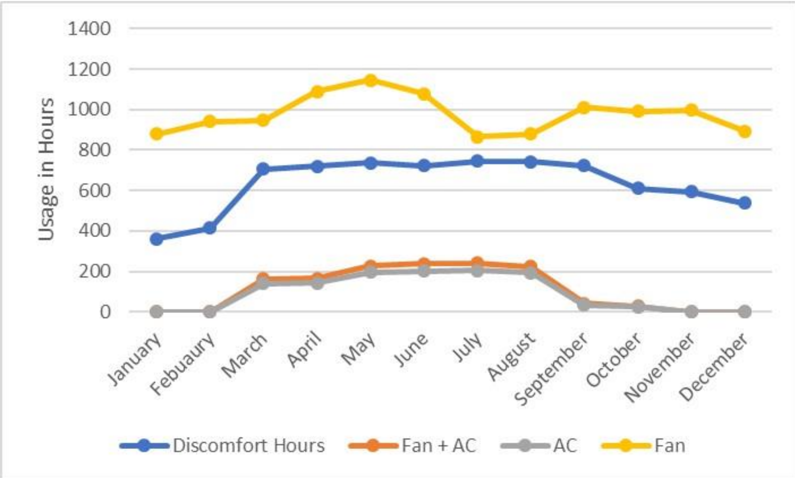

Fig. 3 - Relationship between usage of Fan, AC and Discomfort hours

The annual mean electricity consumption per unit area significantly varied between the four groups of residences categorized based on the occupants' behaviour during discomfort hours [$F_{(3,140)} = 73.26$, $p<0.001$]. The annual mean electricity consumption per unit area of residences where the occupants use an air-conditioner alone and use fans and air-conditioners together is significantly higher than in residences where the occupants use the fan, and use the fan and keep the windows open during discomfort hours (Table 7).

There is a significant difference in annual mean electricity consumption per unit area [$F_{(5,138)} = 15.60$, $p<0.01$] among the five categories of residences grouped according to the frequency of using fans and air-conditioners together. The annual mean electricity consumption per unit area is highest in residences where the occupants never use the fans and air-conditioners together and lowest in residences where the occupants use the fans and air-conditioners together at all times. The air-conditioners are used for fewer hours when used with a fan than alone. The average hours of air-conditioner use by the occupants with and without the habit of using both fan and air-conditioner together are 856 hours/year and 1301 hours/year, respectively (Fig. 3). Using fans and air-conditioners together reduces the room temperature quickly, allowing the occupants to set a higher set-point temperature in the air-conditioners (Wang, L., & Greenberg, S.,2015). After achieving a comfortable temperature, occupants might switch off the air-conditioner and use the fan for air circulation (Debnath, K.B.,et.al., 2020). The reduced hours of use of air-conditioners while using air-conditioners and fans together reduce the energy consumption of residences.

The annual mean electricity consumption per unit area is significantly different between the residences groups based on air-conditioner use hours [$F_{(2,141)} = 182.53$, $p<0.001$]. The average hours of use of air-conditioners are maximum in two-bedroom residences (996.63 hours/ year), followed by three-bedroom (984.11 hours/ year) and single-bedroom (661.54 hours/ year) residences. It is also found that strong correlation between the number of working adults and hours of use of air-conditioners (-0.599, $p<0.001$) and a moderate correlation between hours of use of air-conditioners and the number of elders (0.338, $p<0.001$) and age of the children (0.247, $p<0.001$). The space occupancy pattern also revealed the usage of an additional bedroom or living room during night hours and occupancy of more spaces during daytime in houses with more than two elders, children of more than 12 years old, and one HRP working. The higher space occupancy pattern led to more hours of air-conditioners for thermal comfort.

Table 7 - Annual Mean Electricity Consumption of Different Groups of Residences based on Occupant behaviour variables related to thermal discomfort

Occupant Behavior	Mean	One way ANOVA	
		F	p-value
Occupant behaviour during the discomfort			
Switching on Fan	25.82[a]		
Switching on the fan and windows open	25.75[a]		
Switching on air-conditioner	56.71[b]		
Switching on both the fan and air-conditioner	62.37[b]	73.26	0.00
Frequency of using both fan and air-conditioner together			
Always	24.66[a]		
Very often	29.14[a]		
Sometimes	40.25[ab]		
Rarely	45.53[ab]		
Never	51.80[b]	15.60	0.000
Hours of use of air-conditioners (Annual)			
Below 1000 hours	29.57 [a]		
Between 1000 – 1500 hours	51.88 [b]	182.53	0.000
Above 1500 hours	87.87 [c]		
Hours of use of Fans (Annual)			
Below 5000 hours	29.86[ab]	4.369	0.01

Note: Means with different superscripts differ significantly from each other.

The presence of two or more air-conditioners in two- and three-bedroom residences, compared to one in single-bedroom residences, could be the reason for the higher hours of air-conditioner use in two- and three-bedroom residences. A significant difference in the annual electricity consumption per unit area [$F_{(3,140)} = 4.369$, $p<0.01$] among the residences using fans below 15 hours/day, 15 - 30 hours/day, 30 – 45 hours/day, and above 45 hours was noticed. The additional occupied spaces due to the presence of children over 12 years and elders and the elders' preference for fans might have led to increased hours of fans in residences with higher occupants.

5.5 Overall Predictors of Energy Consumption

Multiple regression analysis was used to determine the best linear combination of the independent variables - all household variables, the appliance uses behavior and occupants' behavioral variables during discomfort hours on the dependent variable annual electricity consumption per unit area of individual residences. The results indicate that 07 variables explained 88.9% of the variance (adjusted $R^2=0.889$; $F_{(5,138)}= 230.888$, $p<0.001$) in annual electricity consumption per unit area of individual residences. It was found that the variables, i.e., hours of use of air-conditioners ($\beta=0.594$, $p<0.01$), Hours of use of fan and windows in the open position ($\beta= - 0.445$, $p<0.001$), frequency of using air-conditioner and fan together ($\beta=0.074$, $p<0.01$), number of elders ($\beta=0.081$, $p<0.01$), and age of children ($\beta=0.065$, $p<0.05$) significantly predicted annual electricity consumption per unit area of individual residences. The results reveal that the pattern and hours of use of air-conditioners and fans are the main predictors, followed by the number of elders and the age of children. The number of elders and the age of children determines the space occupancy pattern in the residential building. Thus the study establishes that the space occupancy pattern and behaviour of occupants during discomfort hours have a major impact on the energy consumption in residential buildings located in warm-humid climatic zones.

6. Conclusion

This study established that occupants of the residence and their space and appliance use pattern influence the annual electricity consumption per unit area of residences. The factors significantly influencing the annual electricity consumption include the number of elders, age of children, number of working adults, hours of use of heaters (to heat water for bathing), occupant activities during the weekend, and behaviour during discomfort hours. This study identified revealed that people use fans for a longer time compared to air-conditioners and in most residences, people use fans and air-conditioners together in warm-humid climatic ones. The use of fans and air-conditioners together led to a reduction in the overall hours of use of air-conditioners and thereby a reduction in energy consumption. From the study, it is understood that occupants prefer to run the residences in mixed-mode operation by using the air-conditioner only when it is required. This indicates that an energy-efficient building envelope can achieve a reduction in uncomfortable hours. This study established that family composition influences the space usage and appliance use pattern and, in turn, the energy consumption of residential buildings. This paper contributes to a better understanding the factors influencing electricity consumption in residential buildings, especially the occupants' space usage, habits and behaviour. Understanding these effects through the current study's findings can support predicting and planning the future electricity consumption of the residential sector. This study may be extended to other geographical regions, climatic zones and building typologies. Further detailed studies may be carried out by monitoring energy consumption at the individual appliance level and occupants' energy-related behaviours.

Acknowledgement

This work was supported in part by the Department of Science and Technology, Ministry of Science and Technology, Government of India through the project–CEDRI under Grant DST/TMD/UK-BEE/2017/20}

References

Baker, K.J., Rylatt, R.M., (2008), *Improving the prediction of UK domestic energy-demand using annual consumption-data.* Appl Energy 85, pp.475–482.

Balvedi, B.F., Ghisi, E., Lamberts, R., (2018), *A review of occupant behaviour in residential buildings*, Energy Build 174, pp. 495–505.

Bartiaux, F., Gram-hanssen, K., (2005), *Socio-political factors influencing household electricity consumption: A comparison between Denmark and Belgium.* ECEEE Summer Study, pp.1313–1325.

Bedir, M., Hasselaar, E., Itard, L., (2013), *Determinants of electricity consumption in Dutch dwellings*. Energy Build 58, pp. 194–207.

Bedir, M., Kara, E.C., (2017), *Behavioral patterns and profiles of electricity consumption in Dutch dwellings.* Energy Build 150, pp.339–352.

Belaïd, F., (2016), *Understanding the spectrum of domestic energy consumption: Empirical evidence from France.* Energy Policy 92, pp.220–233.

Besagni, G., Borgarello, M., (2020), *What are the odds? On the determinants of high residential energy expenditure.* Energy and Built Environment 1, pp.288–295.

Brounen, D., Kok, N., (2012), Quigley, J.M., *Residential energy use and conservation: Economics and demographics.* Eur Econ Rev 56, pp.931–945.

Chunekar, A., Sreenivas, A., (2018), *Towards an understanding residential electricity consumption in India*. Building Research and Information 0, pp.1–16.

Cramer, J.C., Miller, N., Craig, P., Hackett, B.M., Dietz, T.M., Vine, E.L., Levine, M.D., Kowalczyk, D.J., (1985), *Social and engineering determinants and their equity implications in residential electricity use.* Energy 10, pp.1283–1291.

Dalal, R., Bansal, K., Thapar, S., (2021), *Bridging the energy gap of India's residential buildings by using rooftop solar PV systems for higher energy stars*, Clean Energy 5, pp. 423–432.

Debnath, K.B., Jenkins, D.P., Patidar, S., Peacock, A.D., (2020), *Understanding residential occupant cooling behaviour through electricity consumption in warm-humid climate*. Buildings 10.

Delzendeh, E., Wu, S., Lee, A., & Zhou, Y., (2022), *The Impact of Occupants' Behaviours on Building Energy Analysis: A Research Review*, Renewable and Sustainable Energy Reviews 80, pp.1061–1071.

El-Zoklah, M.H., Refaat, T., (2021), *How to measure the green façades environmental effectiveness? A proposal to green façade systems technical guide*, International Journal of Sustainable Building Technology and Urban Development 12, pp.154–169.

Esmaeilimoakher, P., Urmee, T., Pryor, T., Baverstock, G., (2016), *Identifying the determinants of residential electricity consumption for social housing in Perth, Western Australia*. Energy Build 133, pp. 403–413.

Estiri, H., (2014), *Building and household X-factors and energy consumption at the residential sector. A structural equation analysis of the effects of household and building characteristics on the annual energy consumption of US residential buildings*. Energy Econ 43, pp.178–184.

Fabi, V., Andersen, R., Corgnati, S., (2011), *Description of occupant behaviour in building energy simulation: state-of-art and concepts for improvements,* Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November, pp. 2882–2889.

Filippini, M., Pachauri, S., (2004), *Elasticities of electricity demand in urban Indian households*. Energy Policy 32, pp.429–436.

Garg, A., Maheshwari, J., and Upadhyay, J. (2010), *Load Research for Residential and Commercial Establishments in Gujarat*. https://www.beeindia.gov.in/sites/default/files/ctools/Load Research Report for Gujarat-1024.pdf,.

Gill, Z.M., Tierney, M.J., Pegg, I.M., Allan, N., (2010), *Low-energy dwellings: The contribution of behaviours to actual performance*, Building Research and Information 38, pp.491–508.

Gram-Hanssen, K., (2010), *Residential heat comfort practices: Understanding users. Building Research and Information 38*, pp.175–186.

Grandjean, A., Adnot, J., & Binet, G. (2012), *A review and an analysis of the residential electric load curve models. Renewable and Sustainable Energy Reviews*, *16*(9), pp.6539–6565. https://doi.org/10.1016/j.rser.2012.08.013

Harish, V.S.K.V., Kumar, A., (2016), *A review on modeling and simulation of building energy systems*. Renewable and Sustainable Energy Reviews 56, pp.1272–1292.

Jones, R. V., Fuertes, A., Lomas, K.J., (2015), *The socio-economic, dwelling and appliance related factors affecting electricity consumption in domestic buildings*. Renewable and Sustainable Energy Reviews 43, pp. 901–917.

Jones, R. v., Fuertes, A., Lomas, K.J., (2015), *The socio-economic, dwelling and appliance related factors affecting electricity consumption in domestic buildings*. Renewable and Sustainable Energy Reviews 43, pp.901–917.

Kim, M.J., (2018), *Characteristics and determinants by electricity consumption level of households in Korea.* Energy Reports 4, pp.70–76.

Kubota, Tetsu; Jeong, Sangwoo; Toe, Doris Hooi Chyee; Ossen, D. R., (2011), *Energy Consumption and Air-Conditioning Usage in Residential Buildings of Malaysia. Journal of International Development and Cooperation*, *17*(3), pp.61–69. https://doi.org/10.15027/32444

Leahy, E., Lyons Sean, S., (2010), *Energy use and appliance ownership in Ireland*. Energy Policy 38, pp. 4265–4279.

Lin, B., Wang, Z., Liu, Y., Zhu, Y., Ouyang, Q., (2016), *Investigation of winter indoor thermal environment and heating demand of urban residential buildings in China's hot summer - Cold winter climate region*. Build Environ 101, pp.9–18.

Loengbudnark, W., Khalilpour, K., Bharathy, G., Voinov, A., Thomas, L., (2022), *Impact of occupant autonomy on satisfaction and building energy efficiency*. Energy and Built Environment,

McCoy, A.P., Zhao, D., Ladipo, T., Agee, P., Mo, Y., (2018), *Comparison of green home energy performance between simulation and observation: A case of Virginia, United States*. Journal of Green Building 13, pp. 70–88.

McLoughlin, F., Duffy, A., Conlon, M., (2015), *A clustering approach to domestic electricity load profile characterisation using smart metering data*. Appl Energy 141, pp.190–199.

Murthy, K. V. N., Sumithra, G. D., & Reddy, A. K. N. (2001), *End-uses of electricity in households of Karnataka state, India. Energy for Sustainable Development*, *5*(3), pp.81–94. https://doi.org/10.1016/S0973-0826(08)60278-1

Ofetotse, E.L., Essah, E.A., Yao, R., (2021), *Evaluating the determinants of household electricity consumption using cluster analysis.* Journal of Building Engineering 43, pp.102487.

Ozarisoy, B., Altan, H., (2022). Significance of occupancy patterns and habitual household adaptive behaviour on home-energy performance of post-war social-housing estate in the South-eastern Mediterranean climate: Energy policy design. Energy 244,

Rinaldi, A., Schweiker, M., Iannone, F., (2018), *On uses of energy in buildings: Extracting influencing factors of occupant behaviour by means of a questionnaire survey*. Energy Build 168, pp.298–308.

Sanquist, T.F., Orr, H., Shui, B., Bittner, A.C., (2012), *Lifestyle factors in U.S. residential electricity consumption.* Energy Policy 42, pp.354–364.

Santin, O.G., 2010, *Actual energy consumption in dwellings. The effect of energy performance regulations and occupant behaviour*.

Sharma, A., Sharma, V., (2022), *Impact of change in the design of naturally ventilated mass housing on life cycle energy and life cycle cost, International Journal of sustainable building technology and urban development*, pp.96–108.

Shukla, Y., Campus, K. L., Rawal, R., Shnapp, S., Buildings, G., & Network, P. (2011), *Residential Buildings in India : Energy Use Projections and Savings Potentials*. *2030*, pp.1193–1206.

Tewathia, N., (2014), *Determinants of the household electricity consumption: A case study of Delhi.* International Journal of Energy Economics and Policy 4, pp.337–348.

Tiwari, P., (2000), *Architectural, Demographic, and Economic Causes of Electricity Consumption in Bombay*. J Policy Model 22, pp. 81–98.

Wan Nur Hanani Wan Abdullah, Asniza Hamimi Abdul Tharim, Asmat Ismail, Asmalia Che Ahmad., (2022), *Determination of Design Solutions to Overcome the Daylighting Design Failure Observed in Existing Educational Building*, International Journal of Sustainable Constrution Engineering and Technology, VOL. 13 NO. 2 (2022) 153-167.

Wang, L., Greenberg, S., (2015), *Window operation and impacts on building energy consumption*, Energy Build 92, pp.313–321.

Wang, L., Greenberg, S., (2015), *Window operation and impacts on building energy consumption*. Energy Build 92, pp.313–321.

Wiesmann, D., Lima Azevedo, I., Ferrão, P., Fernández, J.E., (2011), *Residential electricity consumption in Portugal: Findings from top-down and bottom-up models*. Energy Policy 39, pp. 2772–2779.

Wyatt, P., (2013), *A dwelling-level investigation into the physical and socio-economic drivers of domestic energy consumption in England*. Energy Policy 60, pp.540–549.

Yohanis, Y.G., Mondol, J.D., Wright, A., (2008), *Norton, B., Real-life energy use in the UK: How occupancy and dwelling characteristics affect domestic electricity use*. Energy Build 40, pp. 1053–1059.

Yohanis, Y.G., Mondol, J.D., Wright, A., Norton, B., (2008), *Real-life energy use in the UK: How occupancy and dwelling characteristics affect domestic electricity use*. Energy Build 40, pp.1053–1059.

Yu, Z., Fung, B.C.M., Haghighat, F., Yoshino, H., Morofsky, E., (2011), *A systematic procedure to study the influence of occupant behaviour on building energy consumption*, Energy Build 43, pp. 1409–1417.

Zhou, S., Teng, F., (2013), *Estimation of urban residential electricity demand in China using household survey data.* Energy Policy 61, pp.394–402.

Zuo, J., Zhao, Z.Y., (2014), *Green building research-current status and future agenda: A review*. Renewable and Sustainable Energy Reviews 30, pp.271–281.