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Determinants of high electrical energy demand in UK homes: Socio-economic and dwelling characteristics

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ABSTRACT

This paper provides an analysis of the socio-economic and dwelling factors contributing to high electrical energy demand in UK domestic buildings. The socio-economic, dwelling and electricity consumption data were collected during a large-scale, city-wide survey, carried out in Leicester, UK, in 2009–2010. Annual electrical energy demand was estimated for 315 dwellings and an odds ratio analysis used to identify the socio-economic and dwelling factors that led to high electricity consumption. The effects of a number of socio-economic and dwelling factors which have not previously been studied for the UK domestic sector are included. Thus, for the first time, presence of teenagers, having electric space heating as the primary form of heating, portable electric heating and electric water heating were identified as significant drivers of high electricity demand in UK homes. The employment status and education level of the Household Representative Person, the number of floors in a dwelling, presence of fixed electric heating, and the proportion of low-energy lighting were shown to have no effect on high electricity consumption in UK homes. Given the impetus to reduce electricity consumption and CO_2 emissions from the domestic sector, these observations can help shape energy saving campaigns and future energy policy.

1. Introduction

Electricity consumption from domestic buildings represented 35% of total UK electricity consumption in 2013, and since 1970, the UK domestic sector has experienced a general year-on-year rise in electricity use of around 1% [1]. The amount of electricity used in individual UK homes varies considerably. A large range, as well as highly skewed distribution exists and, whilst there is an absolute lower bound to electricity demand, there is no effective upper bound, with the upper quartile of electrical energy users consuming much more than the lower [2–4].

Previous UK energy research has identified that high electricity consuming households not only use more electricity, compared with others, but appear to be consuming even more electricity over time [5–7]. There is further evidence which shows that high consumers also have a greater potential to make energy savings than those who consume less [5,8,9].

Given the immediate need for reduction of electricity consumption and CO_2 emissions from the domestic sector, it has been suggested that future UK energy policy might focus on reducing the demand of high electricity consumers [5–10]. Therefore, understanding what drives high usage in domestic buildings is important to support decisions about how to reduce electricity use and CO_2 emissions.

This paper documents research undertaken to improve knowledge and understanding of the socio-economic and dwelling factors affecting high electrical energy consumption in UK domestic buildings. The socio-economic factors refer to the characteristics of the occupants residing in a home (e.g. number of occupants, presence of children, annual household income) and the dwelling factors describe the characteristics of the dwelling (e.g. building type, number of bedrooms, heating system type).

This analysis capitalises on primary data collected during a large-scale, city-wide survey, undertaken in Leicester, UK, during 2009–2010, as part of the 4M project [10]. To the authors' knowledge, it is the first city-scale energy survey carried out in the UK.

Many previous studies have been undertaken worldwide to investigate the impact of socio-economic and dwelling factors on the electricity consumption of domestic buildings [6,9,11–46]. However, for the UK, the few previous studies that have been undertaken [6,16,17,24,25] have examined a limited number of socio-economic factors (number of occupants, presence of children, age and economic status of the Household Representative Person

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(HRP), tenure, annual household income) and dwelling characteristics (dwelling type and age, number of rooms, number of bedrooms, total floor area). For some of these socio-economic factors and dwelling characteristics the impact on electricity demand has only been studied once before.

This paper adds to the current UK literature and, for the first time, investigates the effects of additional socio-economic factors (presence of teenagers, employment status of the HRP and education level of the HRP) and dwelling characteristics (number of floors, the presence of different types of electric space and hot water heating equipment and the proportion of low-energy lighting installed). The paper also specifically targets a better understanding of the drivers of high electricity consumption in UK homes.

2. Socio-economic and dwelling factors affecting domestic electricity consumption

Past literature has identified key socio-economic and dwelling factors that influence electricity consumption in domestic buildings [6,9,11–46]. Previous studies have been undertaken from either a top-down (e.g. [47]) or bottom-up approach (e.g. [9,14,24,29,46]) using data mining (e.g. [48–52]), regression (e.g. [11,19,24,30,37,46]) and econometric methods (e.g. [18,32,34,42,47]). A detailed international review and discussion of these factors and methods is provided by Jones et al. [53]. Thirty of the thirty-seven previous studies were from developed countries (20 from Europe, 9 from North America and 1 from Asia) and the remaining seven from developing countries (5 from Asia, 1 from Africa and 1 from Central America). The review investigated which factors had a significant (positive or negative) or non-significant effect on domestic electricity use and found that no less than 13 socio-economic factors and 12 dwelling factors potentially had an effect.

In relation to the socio-economic factors, the review identified that more occupants [11,13,14,18,19,22,23,25,27,29–31,33,36–38,41,43,44], the presence of teenagers [12,30,33,45], increased household income [6,14,17,18,22,26–28,30,31,33,37,38,41,42,44–46] and increased disposable income [3,19,23,25,36] lead to a significant increase (positive effect) in domestic electricity consumption. The number of studies that confirmed a positive effect was higher (at least three studies more) than the number indicating a significant negative or non-significant effect. The age of the Household Representative Person (HRP) also had a significant effect on residential electricity consumption [9,11,14,19,23,27,32,37], but a positive or negative correlation could not be established as the data was categorical.

The effects of the presence of children and elderly people (over 65 years old), tenure type, education level, employment status and socio-economic status of the HRP were all found as either inconclusive (i.e. a mix of effects identified) or had been studied infrequently (less than 3 previous studies), therefore no inferences of the actual effects could be drawn.

Regarding the dwelling factors, dwelling age [12,17,19,22,23,31,35], number of rooms [14,23,24,37], number of bedrooms [9,16,20,24,27] and total floor area [6,11,12,17–19,22,24,27,29–33,35,36,40,43,44], all had significant positive effects on electricity use. The review also identified that dwellings with an electric space heating system [11–14,23,24,34,36], air-conditioning [13,18,29,41,43,46] or electric water heating system [9,11,13,23,29,34,43] had greater electricity demand. The dwelling type (level of detachment) was also seen to have an significant effect on the electricity consumption of domestic buildings

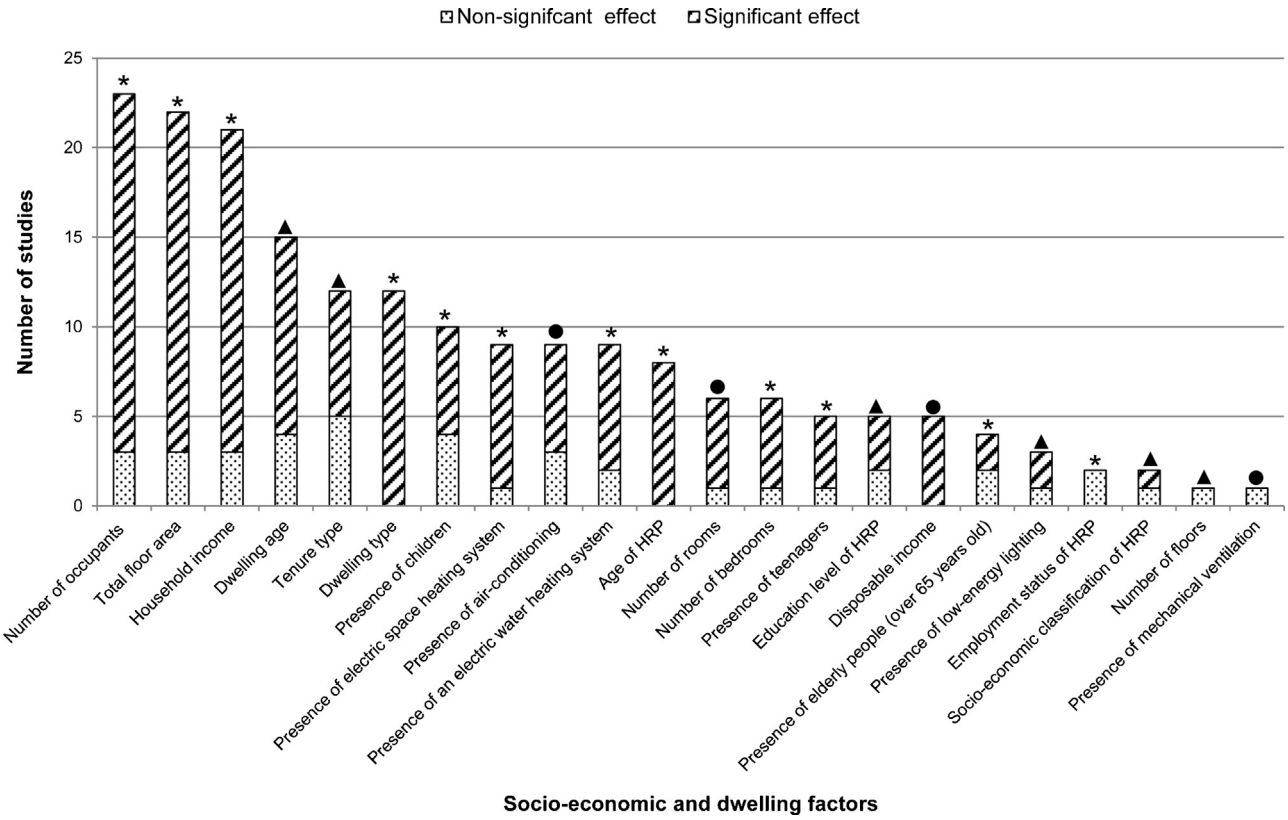

Fig. 1. Summary of the socio-economic and dwelling factors identified in the literature review, ranked by number of studies in which the factor has been identified as either significant or non-significant. *Factor identified as significant in the current study. ▲Factor identified as non-significant in the current study. ●Factor not investigated in the current study.

[9,11,14,16,17,19,22,23,27,30,33,37], but as the data was categorical this effect could not be classified as either positive or negative.

The effects of the number of floors, presence of mechanical ventilation and low-energy lighting were either mixed or the factors had been studied on only a few previous occasions and therefore too little evidence existed to draw conclusions.

Fig. 1 provides a summary of the significant and non-significant effects identified in the thirty-seven previous studies, ranked by the total number of studies that have identified each factor in the literature. It should be noted that the total number of studies may not indicate the factors with the most influence on domestic electricity use but rather the relative ease with which data about that factor can be obtained and any effects isolated.

3. Data and methods

3.1. Data collection: the 4M dataset

Initially, 1000 households living in the city of Leicester were approached to take part in the study. Of these, 575 households subsequently completed a face-to-face survey which was conducted on the behalf of the 4M team, between March and July 2009, by the National Centre for Social Research (NatCen). Households were selected randomly, after stratifying by percentage of detached homes and percentage of homes with no dependent children. The household survey provided the data about the socio-economic characteristics of the household and the characteristics of the dwelling.

To supplement the dwelling information, an estimate of the total floor area of the homes was obtained using a four step procedure[1] of geo-location; calculation of the building footprint area; conversion of footprint area to ground floor area; and conversion of ground floor area to total floor area.

During the initial household survey, participants were asked whether they would also like to take part in follow-up activities, one of which was regular electricity meter readings; 409 households agreed to provide meter readings. These were collected in three phases between March 2009 and July 2010. The first was taken during the NatCen house visit; the second was requested by letter; and the final reading was obtained by a further house visit followed by a letter request, for those houses that could not be accessed when visited.

As the meter readings for each household were taken on different dates, the electricity use was normalised to an annual consumption figure for 2009.[2] In total, normalised electricity consumptions were obtained for 256 households.

In addition to the meter readings, 241 households also signed a mandate which permitted access to their billed electricity use for 2009. Data was successfully obtained for 218 households. To verify that the current residents were responsible for the electricity consumption in 2009, a check against their year of first residence was completed using data from the initial household survey. The energy use data from the suppliers was treated with caution as some meter 'readings' were actually just estimates.

The data from both the meter readings and mandates were combined into a single dataset of 315 annual electricity consumptions. Where both meter reading and mandate data existed for a dwelling, the meter reading was used in preference.

Overall, the final dataset used in this study consisted of: 575 records for household socio-economic and dwelling information; 575 estimates of total floor area; and 315 annual electricity consumptions (256 from meter readings and 59 from mandates). Owing to the patchy responses by households to all three components, the total sample size in different sections of this paper fluctuates depending on which data are being analysed. Only 183 households produced a complete dataset.

3.2. Stratification of households

For this study, the 315 homes for which annual electricity consumptions were available were stratified into three equally sized groups (thirds). The 105 lowest consuming households were classified as the 'low electrical demand group', the middle 105 as the 'medium electrical demand group', and the highest 105 as the 'high electrical demand group'. The low and medium consumption groups were also merged for the analysis because the purpose of the study was to understand the influence of socio-economic and dwelling factors on the probability of being a high electrical energy consumer.

This method of stratification was previously used by Firth et al. [5], Summerfield et al. [6,7], and Gram-Hanssen et al. [33], thus the current study maintains comparability with the existing body of literature. Table 1 provides a comparison between the measured electricity demands of the 4M sample and electricity demands of the high, medium and low consuming groups monitored by others. For the DECC study [3] the split into thirds to create the three consumption groups was done by the current authors, not those of the original study. Some variation existed between the ranges and means of the groups. It is assumed that these originate from the different sample sizes, the variations in the year of research and the specific contexts of low-energy and social housing in the studies of Firth et al. [5] and Summerfield et al. [6,7]. The cohort of households reported in Summerfield et al. [6] are a subset of those reported in [7]. The large national study reported by DECC [3], which includes the electricity consumptions of over 20 million homes in the UK, originates from their National Energy Efficiency Data-framework (NEED), which sources energy consumption data directly from the homes' energy providers. The means of all three 4M consumption

[1] (1) Geo-location: the address of each of the dwellings was matched against the OS MasterMap Address Layer 2 database, any that failed in automatic matching were looked up manually, this provided the *x*, *y* coordinates of each address. (2) Calculation of the building footprint area: the area of each polygon was measured in ESRI ArcInfo and assumed to be the building footprint area. (3) Conversion of footprint area to ground floor area: wall thickness was calculated from the reported wall type and building age using the RdSAP 2005 methodology (Appendix S: converting external measurements to internal measurements [60]), the footprint area was corrected to ground floor area using the wall thickness and reported building type as per the RdSAP 2005 methodology. For flats it was not possible to estimate the floor area as the number and layout of properties in each building was unknown, therefore a default value of 50 m^2 was assigned to all flats. (4) Conversion of ground floor area to total floor area: the ground floor was multiplied by the number of floors reported in the household survey questionnaire or from field observation during the meter readings or from Google street view images.

[2] Electricity was normalised to 365 days assuming no seasonal variation in use. Where meter readings existed between multiple dates, the 1st and 3rd meter readings were chosen in preference to the 2nd and 3rd, which were chosen in preference to the 1st and 2nd. This was because the duration between the 1st and 3rd meter readings was greater than the 2nd and 3rd, and both were greater than the 1st and 2nd. By inspection it was found that the normalisation from the 1st and 2nd meter readings was consistent with those calculated using the 2nd and 3rd or 1st and 3rd for the same dwelling. Where present, the normalisation result was checked for magnitude and consistency between multiple dates. Spurious results were inspected further and any errors corrected or the result removed from further analysis.

Table 1
Comparison of the 4M electrical demand groups, their mean annual electricity consumption and the minimum and maximum consumptions, with the corresponding data reported in previous UK studies.

Study UK location Description of dwellings Fuel used for space heating Measurement year(s)	*N*	Electrical energy demand group	Electricity consumption range (kWh pa)		Mean electricity consumption (kWh pa)
			Min	Max	
4M project **Leicester** **Representative sample of the city housing stock** **Dwellings with gas and electric heating (2009)**	315	Low Medium High	**259** **2554** **4048**	**2543** **4041** **25,587**	**1735** **3232** **6588**
Summerfield et al. [6] Milton Keynes "Low energy" owner occupied households Dwellings with gas heating only (1989/90 and 2005/06)	14	Low Medium High	– – –	– – –	2299 (1990) 2774 (2005) 4636 (1990) 4344 (2005) 5913 (1990) 10,330 (2005)
Firth et al. [5] Five different UK sites Four sites were social housing Dwellings with gas heating only (2002–2006)	72	Low Medium High	902 (yr 1) 920 (yr 2) 2174 (yr 1) 1195 (yr 2) 3273 (yr 1) 2994 (yr 2)	2160 (yr 1) 3447 (yr 2) 3247 (yr 1) 4600 (yr 2) 7743 (yr 1) 8775(yr 2)	1170 (yr 1) 1964 (yr 2) 2689 (yr 1) 2670 (yr 2) 4841 (yr 1) 5088 (yr 2)
Summerfield et al. [7] Milton Keynes "Low energy" owner occupied households Dwellings with gas heating only (1989/90 and 2005/06)	36	Low Medium High	– – –	– – –	2336 (1990) 3139 (2005) 4052 (1990) 3687 (2005) 5037 (1990) 8651(2005)
DECC [3] All over the UK Energy supplier meter data for UK homes Dwellings with gas and electric heating (2007)	20,851,507	Low Medium High	10 2481 4311	2480 4310 25,000	1568 3339 6850

groups lie within a couple of hundred kWh of the DECC [3] national values.

3.3. Odds ratio method

Odds ratio analyses were used to investigate the influence of the socio-economic and dwelling factors on the electrical energy demand of the 4M households. An odds ratio (OR) is a measure of the association between an exposure and an outcome. The OR represents the odds that an outcome will occur given a particular exposure, compared to the odds of the outcome occurring in the absence of that exposure [54]. Simply, ORs are used to compare the relative odds of the occurrence of the outcome of interest (a dwelling having high electricity consumption), given exposure to a factor of interest (e.g. number of occupants, presence of children, presence of electric space heating etc.). The OR can also be used to compare the change in likelihood of a household being a high electricity consumer based on a change in a socio-economic or dwelling factor, for example the change in the likelihood if the household size increases from three to four occupants.

The socio-economic characteristics that were investigated were: the number of occupants, presence of children and teenagers, age of the Household Representative Person[3] (HRP), employment status of the HRP, education level of the HRP, the National Statistics Socio-Economic Classification (NSSEC) of the HRP, tenure and annual household income.

The dwelling characteristics examined were: dwelling type, period during which the dwelling was built,[4] number of bedrooms and floors, total floor area, presence of electric space heating, presence of fixed electric heating, presence of portable electric heating and presence of electric water heating.

For each socio-economic and dwelling factor the OR was calculated, which reflects the likelihood that a household will be a high electrical energy user relative to a reference household in the same category. The reference for each characteristic was chosen for one of two reasons; either the household did not have the factor (e.g. no children, no electric space heating) or, the factor represented the majority of the sample.

For a given factor, the OR was the number of homes with high electricity demand (>4041 kWh pa) divided by the number with low or medium demand (<4042 kWh pa), divided by the same ratio for the reference group [55]. Eq. (1) shows an example of the odds ratio calculation for the presence of children.

Odds ratio calculation for the presence of children:

$$\mathrm{OR} = \frac{C_H/C_{LM}}{NC_H/NC_{LM}} = \frac{C_H \times NC_{LM}}{NC_H \times C_{LM}} = \frac{43 \times 161}{62 \times 49} = \frac{6923}{3038} = 2.28 \qquad (1)$$

where: OR = odds ratio; C_H = number of homes with children and high electric demand; C_{LM} = number of homes with children and low or medium electric demand; NC_H = number of homes with no

[3] The Household Representative Person (HRP) is the individual that is taken to represent that household. In this study it describes the highest income earner in the household.

[4] The period the dwelling was built refers to the year ranges: before 1900, 1900–1944, 1945–1990 and after 1990.

Table 2
Odds ratio results for the socio-economic and dwelling characteristics affecting high electricity consumption.

Characteristics and factors	Total homes	Number of homes		Odds ratio (95% CI)
		<4041 kWh pa (low-medium group)	>4041 kWh pa (high group)	
Socio-economic characteristics				
Number of occupants				
1	81	73	8	***0.30*** (0.13, 0.70)***
2	101	74	27	REFERENCE
3	48	22	26	**3.24** (1.58, 6.65)***
4	52	26	26	**2.74** (1.36, 5.52)***
5+	33	15	18	**3.29** (1.46, 7.43)***
Children (<16 years old)				
No children	223	161	62	REFERENCE
Children	92	49	43	**2.28** (1.38, 3.77)***
Teenagers				
None	259	187	72	REFERENCE
1	34	14	20	**3.71** (1.78, 7.74)***
2	22	9	13	**3.75** (1.54, 9.16)***
Age of HRP				
<35	67	44	23	0.66 (0.34, 1.25)
36–50	97	54	43	REFERENCE
51–65	76	50	26	0.65 (0.35, 1.21)
>65	75	62	13	***0.26*** (0.13, 0.54)***
Employment status of HRP				
Employed (full-time or part-time)	166	99	67	REFERENCE
Unemployed	60	40	20	0.74 (0.40, 1.37)
Retired	89	71	18	***0.37*** (0.21, 0.68)***
Education level of HRP				
Degree level or above	66	43	23	1.01 (0.54, 1.88)
Less than degree level	133	87	46	REFERENCE
NSSEC of HRP				
Managerial or professional occupation	77	48	29	1.42 (0.77, 2.60)
Lower supervisory or technical occupation	22	15	7	1.09 (0.41, 2.91)
Small employers or own account workers	29	19	10	1.23 (0.52, 2.92)
Intermediate occupation	32	20	12	1.41 (0.62, 3.18)
Semi-routine or routine occupation	117	82	35	REFERENCE
Tenure				
Own house outright	126	85	41	REFERENCE
Buying house with mortgage	94	56	38	1.41 (0.81, 2.45)
Rented or rent free	95	69	26	0.78 (0.44, 1.40)
Annual household income				
<£20,000	178	129	49	REFERENCE
£20,000 to £50,000	102	59	43	**1.92** (1.15, 3.20)**
>£50,000	13	4	9	**5.92** (1.74, 20.12)***
Dwelling characteristics				
Dwelling type				
Detached	36	19	17	1.31 (0.62, 2.79)
Semi-detached	116	69	47	REFERENCE
Mid-terrace	90	73	17	***0.34*** (0.18, 0.65)***
End-terrace	41	27	14	0.76 (0.36, 1.60)
Flat	32	22	10	0.67 (0.29, 1.54)
Period dwelling was built				
<1900	19	10	9	1.76 (0.67, 4.63)
1900–1944	139	92	47	REFERENCE
1945–1990	132	92	40	0.85 (0.51, 1.42)
>1900	25	16	9	1.10 (0.45, 2.68)
Number of bedrooms				
1	23	19	4	0.35 (0.11, 1.10)*
2	69	52	17	0.55 (0.29, 1.05)*
3	131	82	49	REFERENCE
>4	35	18	17	1.58 (0.75, 3.35)
Number of floors				
1 or 1.5	56	38	18	0.91 (0.49, 1.72)
2 or more	202	133	69	REFERENCE
Total floor area				
0–50 m^2	33	24	9	0.85 (0.37, 1.91)
50–100 m^2	228	158	70	REFERENCE
>100 m^2	54	28	26	**2.10** (1.15, 3.83)**
Electric space heating				
None	299	204	95	REFERENCE
Electric central heating and/or night storage heaters	16	6	10	**3.58** (1.26, 10.14)**
Fixed electric heating				
None	281	184	97	REFERENCE
Fixed electric heater	34	26	8	0.58 (0.25, 1.34)
Portable electric heating				
None	241	168	73	REFERENCE

Table 2 (*Continued*)

Characteristics and factors	Total homes	Number of homes		Odds ratio (95% CI)
		<4041 kWh pa (low-medium group)	>4041 kWh pa (high group)	
Portable electric heater	74	42	32	**1.75** (1.03, 3.00)**
Electric water heating				
None	272	190	82	REFERENCE
Immersion heater and/or instant water heater	43	20	23	**2.66** (1.39, 5.12)***
Low-energy lighting				
None	36	24	12	REFERENCE
Up to half the lights	91	58	33	1.14 (0.50, 2.57)
More than half of the lights	90	54	36	1.33 (0.59, 3.00)
All lights	96	73	23	0.63 (0.27, 1.45)

Note: REFERENCE represents the reference category. Odds ratios in bold indicate that the factor increases the likelihood that a household will be a high electricity consumer (lower bound of CI greater than unity), whereas those in bold italics indicate that a household is less likely to be a high consumer (upper bound of CI less than unity).
HRP – Household Representative Person, which is the individual that is taken to represent the household. In this study it describes the highest income earner in the household.
NSSEC – the National Statistics Socio-Economic Classification.
* Significant at the 10% level.
** Significant at the 5% level.
*** Significant at the 1% level.

children and high electric demand; NC_{LM} = number of homes with no children and low or medium electric demand. The numerical values are in Table 2.

An OR value of 1 indicates that households with a given socio-economic or dwelling factor were just as likely to be high electrical energy consumers as the households in the reference group. An OR greater than 1 indicates a higher probability that a household would be high users compared to the reference group, whereas a ratio below 1 indicated that the probability is lower than for the reference group. In addition, the higher the value of the OR, the more likely it was that the households will be high consumers compared to the reference group.

The 95% confidence interval (CI) associated with each OR describes the uncertainty in the estimate [49]. Eq. (2) shows the formula for calculating the 95% CI for the presence of children. A narrow CI indicates that the effect was known precisely, whereas a wider interval indicated the uncertainty was greater, but there may still be enough precision to draw inferences about the effect. A CI spanning the value 1 (e.g. CI = 0.5, 1.5) indicates that the influence of the factor on high electricity consumption was unclear, however it would be incorrect to interpret a CI spanning the value 1 as indicating evidence for no association between the factor and high electricity consumption altogether, because the width of the CI is influenced by sample size and the variability in the data. Large sample sizes tend to give more precise OR estimates than smaller ones [55,56]. The CI was taken into consideration when interpreting the effects of households' socio-economic and dwelling characteristics.

95% CI for the presence of children:

$$\begin{aligned} CI_{+95\%} &= e^{\ln OR + 1.96\sqrt{\frac{1}{C_H}+\frac{1}{NC_H}+\frac{1}{C_{LM}}+\frac{1}{NC_{LM}}}} = e^{\ln 2.28 + 1.96\sqrt{\frac{1}{43}+\frac{1}{62}+\frac{1}{49}+\frac{1}{161}}} = 3.77 \\ CI_{-95\%} &= e^{\ln OR - 1.96\sqrt{\frac{1}{C_H}+\frac{1}{NC_H}+\frac{1}{C_{LM}}+\frac{1}{NC_{LM}}}} = e^{\ln 2.28 - 1.96\sqrt{\frac{1}{43}+\frac{1}{62}+\frac{1}{49}+\frac{1}{161}}} = 1.38 \end{aligned} \quad (2)$$

where: $CI_{\pm 95\%}$ = upper and lower 95% confidence interval; OR = odds ratio; C_H = number of homes with children and high electric demand; C_{LM} = number of homes with children and low or medium electric demand; NC_H = number of homes with no children and high electric demand; NC_{LM} = number of homes with no children and low or medium electric demand.

4. Results

The literature review undertaken to establish the factors previously identified as having an effect on electricity demand in domestic buildings (Fig. 1) was used to guide the choice of factors that should be investigated in the current study. The current study has also explored the effects of fixed and portable electric heating on domestic electricity use, which has not previously been studied in the literature. The impact of air-conditioning and mechanical ventilation on electricity consumption was not investigated as none of the dwellings in the study had these services installed. The number of rooms a dwelling has was also excluded from the analysis because it was considered as a proxy for total floor area, which was investigated in the study. The results of the odds ratio analysis are presented in Table 2.

4.1. Odds ratios for socio-economic characteristics

In general, the odds ratio (OR) analysis indicates that a greater number of occupants residing in a dwelling increases the probability of being a high electrical energy user (Table 2). Single occupant homes were significantly much less likely (OR = 0.30, $p < 0.01$) to be high electrical energy consumers than dwellings in the reference category with two occupants. Households with three or more occupants were all significantly more likely to be high consumers ($p < 0.01$) than those with two occupants. The data and the analysis did not, however, provide a clear indication of the extent to which increasing numbers of occupants affects the probability of being in the high use group.

Compared to homes without any children, the results show that those with at least one child were more than twice as likely to be in the high demand group (OR = 2.28, $p < 0.01$). As this was a binary factor (children/no children), the OR value does not specify for differences in the number or age of the children.

A factor associated with the total number of occupants and the number of children is the number of teenagers residing in the dwelling. The OR results indicated that households with teenagers living in them were significantly more likely to be high electrical energy consumers than those without any ($p < 0.01$). Dwellings with either one (OR = 3.71) or two teenagers (OR = 3.75) were found

to be more than three times more likely to be high consumers. Despite the fact that the maximum number of teenagers residing in any of the sample households was two, the similar OR values for both one and two teenagers may indicate that mere presence, rather than number of teenagers, is the more important factor.

The OR results for the age of the HRP indicated that dwellings with a HRP over 65 years old were significantly less likely (OR = 0.26, $p < 0.01$) to be high electricity consumers than those with a HRP between 36 and 50 years old. Households with a HRP aged less than 35 or from 51 to 65 years old were just as likely to be high electrical energy consumers as those in the reference category, demonstrated by the CI spanning the value 1.

The employment status of the HRP was only found to affect the likelihood of a dwelling being a high consumer if the HRP was retired. Homes with a retired HRP were significantly less likely (OR = 0.37, $p < 0.01$) to have high electrical energy demand than those with an employed HRP. Households with an unemployed HRP were equally likely to be high consumers compared to those with an employed HRP (CI values span 1).

Neither the education level of the HRP (degree or sub-degree level), the NSSEC of the HRP or the mode of tenure (owning, buying their home with a mortgage, or renting) appeared to have an effect on the probability of a household being a high electricity consumer (for all three characteristics the factors examined had an OR close to one and a CI that spanned unity).

Households with a higher income were identified as being significantly more likely to be high electrical energy users: income from £20,000 pa to £50,000 pa, $p < 0.05$; income greater than £50,000 pa, $p < 0.01$. The calculated OR for the highest earners was 5.92, easily the highest for any of the characteristics and factors examined (Table 2). Whilst, superficially, this indicates high earners are six times more likely to be high energy users than the reference group, the precision of the estimate was low (CI 1.74–20.12).

4.2. Odds ratios for dwelling characteristics

With the exception of floor area, the features of the dwelling itself, rather than the energy systems within it, generally had little impact on whether the household was likely to be a high consumer. Except for mid-terraced homes, all dwelling types were as likely to house people with high energy usage as the reference dwelling type (semi-detached house). Households in mid-terrace dwellings were identified as likely to use significantly less energy (OR = 0.34, $p < 0.01$) than those in semi-detached homes. The age of the dwelling, the number of bedrooms and the number of floors appeared to have no impact on the probability of the occupying household being a high consumer.

Concerning the size of homes, dwellings with a floor area greater than 100 m^2 were estimated to be twice as likely to be high electrical energy users (OR = 2.1, $p < 0.05$) than homes between 50 m^2 and 100 m^2.[5]

The mode of space and water heating tended, in general, to have an impact on the probability of being a high energy consumer. Dwellings in which electricity was the primary form of heating were significantly more likely (OR = 3.58, $p < 0.05$) to have high electricity use than dwellings heated using other fuel types; although the precision of the OR calculation is low due to the small sample. Regarding secondary electric heating, households with a fixed electric heater were just as likely to be either high or low consumers. However, those households owning at least one portable electric heater were significantly more likely (OR = 1.75, $p < 0.05$) to be high electrical energy users. Households in which water was heated using electricity were significantly more likely (OR = 2.66, $p < 0.01$) to be high consumers than those which heated water using another fuel, such as gas. It should be noted that some of the households that reported using an electric immersion heater or instant electric water heater, also stated they had a gas fuelled boiler. The portion of water heating undertaken by each method is not known.

The OR results indicate that it is not until all lights are fitted with low-energy lamps, that the probability of being in the high electrical demand group is reduced, but the effect is weak (the CI spans unity).

5. Discussion

The OR analyses found that households with more occupants, children and teenagers and higher annual household incomes were significantly more likely to be high electrical energy consumers. Families with an HRP over 65 years old or a retired HRP were significantly less likely to have high electrical energy demand.

Regarding the dwelling characteristics, homes with a larger floor area, electricity as the primary form of space heating, secondary portable electric heating, and electric water heating were also likely to be high electricity consumers. Mid-terrace dwellings were less likely to have high electricity use.

The other socio-economic and dwelling characteristics investigated had no effect on high electrical energy demand. It can be seen that these findings, all be they from a single city in the UK, are broadly consistent with the observations made by others (Fig. 1).

5.1. Socio-economic characteristics

The positive relationship observed between the number of occupants and domestic electricity consumption is consistent with a wide number of previous studies [6,11,13,18,19,23–25,27,29–31,33,35–37,39]. The result might arise because of an increased use of multiple appliances and lights at the same time. In addition, households with more members may have more appliances, including multiple ownership of some appliances such as TVs and computers, and they are also likely to have children and teenagers who tend to have more IT and entertainment appliances. Furthermore, households with more occupants will understandably generate more dirty laundry and dishes each week and require more showers and so use more electricity for washing machines, tumble dryers, dishwashers and electric showers.

The significantly increased electricity consumption in homes with children and teenagers consumption has also been observed in previous studies [9,19,22,40] and [12,30,33], respectively. Children and teenagers are perhaps less conscious of the electricity they use because they are disconnected from the financial implications of higher electrical energy demand.

The OR results indicated that dwellings with a HRP over 65 years old were significantly less likely to be high electricity consumers. This finding was supported by around half the previous studies [11,23,27]. A lower demand might be because such households have less disposable income than working families. Likewise it was also found that households with retired HRP's were significantly less likely to be high consumers than those with an employed HRP. In addition, households with a HRP over 65 probably have fewer occupants as their children have grown up and moved on and so may well own less electrical appliances, in particular those associated with a younger generation, such as video consoles and computers.

The education level of the HRP was found to have no effect on the probability of a household being a high electricity consumer. This finding is consistent with some previously published results [9,41], but the general impact of the HRP's education level is unclear, as

[5] The floor area of the average UK house is 92 m^2 [61].

an equal number of previous studies have identified a significant effect [18,23].

The NSSEC of the HRP had no clear influence on the likelihood of high domestic electricity demand. This outcome is consistent with the findings of Leahy and Lyons [23], but contrary to McLoughlin et al. [9] and Cramer et al. [41], who found that the HRP's socio-economic classification had a negative effect on total electricity consumption, with higher professionals consuming more electricity. This current finding is therefore perhaps unexpected, as the HRPs' socio-economic classification could be indicative of the annual household income, which was shown in this study to affect the likelihood of being a high electrical energy consumer. This relationship may not have emerged because households may have multiple incomes, such that two occupants working in routine occupations could earn as much as one occupant working in a managerial occupation.

Households had the same likelihood of being high consumers irrespective of mode of tenure. Other earlier studies have also concluded that tenure type has no significant effect on electricity use [11,14,23,29]. Some studies have however previously observed a significantly higher consumption in privately owned houses [16,17,22,27]. The latter study [27], credited the effect to the fact that in Northern Ireland the majority of rented accommodation is social housing, rented by lower income families. This explanation is less applicable to the current study as Leicester has a large stock of privately rented houses (22.7%) [57]. Unfortunately, the present study did not distinguish between social and privately rented homes and therefore no indication of whether any effect on the probability of high electricity consumption was established. Contrary to the other studies, Ndiaye and Gabriel [13] identified a higher electricity use in rented rather than owned houses. The authors attributed this to utility bills being included in the rent, so renters do not necessary pay the extra cost associated with excessive electricity consumption and have less incentive to save energy. Although, this may be the case in Canada, in the UK, with the exception of student rentals, the vast majority of occupants of both social and private rental properties are responsible for the payment of their energy bill.

Households with higher annual incomes were more likely to be high electrical energy users. This finding is consistent with a large number of previous studies [6,14,15,17,18,22,26–28,30–33,36–39,41,42] and may be due to an increased ownership and use of electrical appliances and an ability to easily pay electricity bills. Households with a higher income may also purchase new and high end appliances. Whilst the energy efficiency of appliances has increased in recent years, suggesting that occupants with newer appliances might enjoy lower energy bills, this potential saving has been widely offset by an increase in the size of appliances, for example LCD TVs and American style fridge-freezers. These larger 'power hungry' appliances also tend to be higher end devices with higher price tags, which are consequently more likely to be purchased by households with a high income.

5.2. Dwelling characteristics

With the exception of mid-terrace dwellings, which were significantly less likely to have a high electricity use than semi-detached properties, all other dwelling types were equally likely to have a high electrical energy demand. Kavousian et al. [11] and Baker and Rylatt [24] also found no significant correlation between electricity consumption and dwelling type. The finding that mid-terrace dwellings had a lower probability of high consumption may relate to them having smaller floor areas than other dwelling types, particularly semi-detached and detached homes. A smaller floor area will reduce space heating requirements, but is only relevant in this case if the dwelling is electrically heated. The floor area of mid-terrace homes is also commonly smaller than end-terrace dwellings, which have a greater potential for extensions to the floor area. Whilst flats are often regarded as having small floor areas, the growth of modern apartment buildings in the UK, associated with the regeneration of cities has led to larger more desirable flats, which offer comparable floor areas to terrace properties. Furthermore, flats frequently have electric rather than gas fuelled heating, increasing the dwelling type's potential for high consumption. A smaller floor area will also restrict the number and size of domestic appliances owned. Additionally, mid-terrace properties have less exposed walls than other dwelling types, which should reduce electric heating demand.

The period in which a dwelling was built had no significant influence on the likelihood of being a high electricity consumer. This finding is consistent with a number of previous studies [11,16,29]. Earlier studies [19,23,35] which have identified an effect, attribute higher electricity use in older homes to increased heat loss associated with less insulation and less efficient appliances. Other studies [21,36] that found modern homes to have a higher electrical energy demand suggest that increased presence of air conditioning, a higher wiring capacity in newly built houses and a greater use of appliances are responsible factors. In the current study, greater heat loss associated with less insulation was mitigated as the number of electrically heated homes in the study sample was low. Moreover, none of the homes in the study used air conditioning reflecting the overall situation in the UK building stock. For these two primary reasons, the effect of building age on the likelihood of high electricity consumption may not have emerged in the current research.

The number of bedrooms a dwelling possesses was found to have no significant effect on high electrical energy consumption. This finding is contrary to the results of previous studies [9,14,16,20,24,27]. This variation may relate to the lack of electrically heated homes in the current sample. Houses with more bedrooms probably have a greater total floor area and require more heating; however this will only affect the probability of high consumption for homes with electric space heating. In addition, compared to other rooms in a home, bedrooms in general have fewer electrical appliances and are occupied for a shorter duration reducing any effect of additional bedroom lights.

The number of floors was also found to not increase the probability of a household being a high electricity consumer. This is in line with the result of Bartusch et al. [12]. This finding could reflect that floor area varies little between homes with one and two or more floors and instead multi-storey homes simply have a reduced footprint area. Moreover, in UK homes, floors above the ground floor are traditionally bedrooms, which were previously shown to have no effect on the probability of high consumption.

Homes with a floor area greater than 100 m^2 were significantly more likely to be high electricity consumers than those with a floor area between 50 and 100 m^2. Previous research also found that dwellings with a larger floor area have higher electricity consumption [6,11,15–18,22,24,27,30,32,33,36,40]. In general, earlier research attributed the influence of floor area on electricity consumption to a greater demand for space heating and cooling, because larger houses require more electric heating in the winter and cooling in the summer. In this instance, this explanation is insufficient due to both the low penetration of electrically heated and non-existent air conditioned homes in the study cohort. Therefore, the increased probability of high consumption may relate to the fact that larger homes have more space for additional electrical appliances and more lights. Another possible reason could be that larger homes probably have a greater number of occupants and have a higher wealth, both of which have been shown in this study to affect high electrical energy demand.

Dwellings for which electric space heating was the primary form of heating were significantly more likely to be high electricity

consumers than those households using other fuel types. Previous studies [11–14,23,24,34,36] consistently agree that there is a significant and positive effect of the use of an electric space heating system on electricity use. This result is unsurprising and easy to understand. As space heating accounts for about 60% of the total energy use in a domestic property [1], if this service is provided by electricity, rather than say gas, the likelihood of being a high electricity consumer should clearly be greatly increased.

Two forms of secondary electric space heating were also investigated. Households with a fixed electric heater were just as likely to be high electrical energy consumers as those homes without. However, dwellings owning a portable electric heater were significantly more likely to be high electrical energy users. Larsen and Nesbakken [34] previously found that households owning portable electric heaters had significantly higher electricity use. The variation in impact of fixed and portable electric heaters on high consumption may highlight differences in their use by building occupants and occupants' preferred system for providing supplementary heating. Fixed electric heaters are most commonly found in a dwelling's living or family space, which is an area almost certainly heated by the primary heating system, thereby reducing the system's utility. By comparison, portable electric heaters offer freedom to heat areas of the home that are not covered by the primary heating system, such as conservatories, and the option to heat individual rooms or spaces of the home, as opposed to using the main central heating. In addition, fixed electric heating might have been installed in the dwelling prior to the current occupants residing there, whereas, portable heating is likely to have been introduced by the occupants themselves, presumably, to improve their thermal comfort. So fixed electric heaters may never be used but portable heaters are more likely to be used.

Homes heating water using electricity were also significantly more likely to be high consumers. Several other studies have also observed a significant influence of the use of electric hot water heating systems [9,11,13,23,24,29,34]. The result obtained reflects the fact that water heating represents on average 6% of electricity use in UK dwellings [1], and therefore dwellings with electric water heating have an elevated potential for electricity consumption. It should be noted that some of the households that reported using an electric immersion heater or instant electric water heater, also stated they had a gas fuelled boiler. The portion of water heating undertaken by each method is not known. Furthermore, whilst the rate of water use in a home will dictate the total electricity required to maintain a sufficient hot water supply, households with an electric immersion heater will periodically consume electricity irrespective of hot water use, as a result of the water stored in the immersion tank cooling down and requiring reheating, thereby increasing the probability of high consumption.

A significant energy-efficiency strategy imposed under the European Union's 2005 Eco-Design Directive [59] is the phasing out of inefficient incandescent and halogen lighting between 2009 and 2012; thereby 'encouraging' households to use low-energy lamps instead. However, it would appear that regardless of the portion of low-energy lamps installed, no clear reduction in the probability of high consumption is achieved. Bartiaux and Gram-Hanssen [30] likewise determined that there is no significant correlation between having low-energy lights and electricity consumption. As lighting accounts for less than a fifth of total electricity use in an average UK household [58], it is not perhaps unreasonable to expect a weak impact of low-energy lighting on electricity demand.

5.3. Applications for the research

The research reported in this paper capitalises on primary data collected during a large-scale, city-wide survey, undertaken in Leicester, UK, during 2009–2010, as part of the 4M project [10]. To the authors' knowledge, it is the first city-scale energy survey carried out in the UK. The immediate beneficiary of the research is principle project partner Leicester City Council. The research can enable the city council, as well as other commercial organisations to target both technical measures (refurbishment and energy efficient products) and social interventions (behaviour change) at the high electricity consuming households in the city. The city council can also use the results to better target specific energy policies and energy reduction campaigns at those households where electricity consumption might be greater.

Furthermore, as previous UK energy research has identified that the high electricity consuming households not only use more electricity, compared with others, but also appear to be consuming even more electricity over time [5–7], the results of this study should be of key importance to central government policy makers, as well as energy supply companies who are interested in the future planning of the UK energy supply network. The results provided by this paper identify the key socio-economic characteristics of the building occupants, as well as the characteristics of the dwellings which are more likely to have high electricity consumption and thus could be used to inform how electricity demand in the UK domestic sector might change as the housing stock and socio-economic profile of the nation evolves in future. These key socio-economic and dwelling characteristics could also be mapped on to other UK national datasets to identify where hot-spots of high demand households may exist and where the supply network may require more capacity in future.

From a research perspective, the current study also provides a method to pre-screen households for future studies focusing on high electricity consumption based on the households' socio-demographic and dwelling characteristics, when actual electricity consumption data is not available. This could make household recruitment for projects more efficient.

5.4. Limitations and future research

This study has contributed to an improved understanding of the socio-economic and dwelling factors driving high electrical energy consumption in UK homes. The results obtained are however limited by the relatively small sample size (315 dwellings), which was collected in a single UK city. The results may not therefore be representative of the wider population of UK homes, reducing the ability to generalise the research findings. A much larger future study would be beneficial to improve the representativeness of the results and to validate the findings of the existing study.

Furthermore, the current study relied on manual meter readings to obtain the annual electricity consumptions of the dwellings; future studies would be able to take advantage of the high resolution (30 min) electricity consumption data that will become available due to the smart meter rollout in UK homes between now and 2020. This will permit analysis of the temporal nature of high electricity demand, for example, time of day, seasonal and year-on-year changes in demand. Looking further into the future, as smart and connected homes become more prevalent, an aspect of the so-called, Internet of things, masses of data will enable statistical analyses of the impact of appliance and energy system usage on electricity consumption.

The socio-economic and dwelling factors that tend to coincide with high electrical energy consumption, as identified in this paper, are also likely to influence the ownership (presence and number), power demand and use of appliances in the home, as well as the operation of space and hot water heating equipment. Before actual measured data on appliance and heating system variables becomes available from smart homes, research could investigate the impact

of these variables on high electricity consumption in UK homes using self-reported data from household surveys.

6. Conclusions

This paper provides an analysis of the socio-economic and dwelling factors contributing to high electrical energy demand in UK domestic buildings. The socio-economic, dwelling and electricity consumption data were collected during a large-scale, city-wide, survey carried out in Leicester, UK, during 2009–2010, as part of the 4M project. To the authors' knowledge, it is the first city-scale energy survey carried out in the UK. An odds ratio (OR) analysis was used to investigate the effects of the socio-economic and dwelling factors on the electrical energy demand of the 315 UK households.

The results of the study suggest that high electricity consumption in UK domestic buildings is related to a combination of the socio-economic characteristics of the building occupants and the characteristics of the dwelling in which they live. This study identified for the first time that the presence of teenagers, having electric space heating as the primary form of heating, portable electric heating and electric water heating are key drivers of high electricity demand in UK homes. In addition, the employment status and education level of the Household Representative Person, the number of floors a dwelling possesses, the presence of fixed electric heating, and the proportion of low-energy lighting were shown to have no effect on high electricity consumption in UK homes.

Overall, for the socio-economic characteristics, the OR analysis found that households with more occupants, children and teenagers, and higher annual household incomes, are more likely to be high electrical energy consumers. Families with a Household Representative Person that is retired or over 65 years old are however less likely to have high electrical energy demand.

In relation to the dwelling characteristics, the OR results indicate that domestic buildings with: a floor area greater than 100 m^2, electric space heating as the primary form of heating, secondary portable electric heating, and electric water heating have a greater likelihood to house high electricity consumers. Mid-terrace dwellings were less likely to have high electrical energy users.

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