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Explaining domestic energy consumption – The comparative contribution of building factors, socio-demographics, behaviours and attitudes

Gesche M. Huebner [a,*], Ian Hamilton [a], Zaid Chalabi [b], David Shipworth [a], Tadj Oreszczyn [a]

[a] UCL Energy Institute, 14 Upper Woburn Place, London WC1H 0AE, England, United Kingdom
[b] London School of Hygiene and Tropical Medicine, Keppel Street, London WC1E 7HT, England, United Kingdom

HIGHLIGHTS

- Building characteristics explain most variability in domestic energy consumption.
- Controlling for building factors, socio-demographics add little explanatory power.
- Attitudinal variables contribute very little to explaining energy consumption.
- Length of heating season is a significant predictor, even after controlling for region.
- Multicollinearity is a crucial issue in analysis of energy consumption.

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ABSTRACT

This paper tests to what extent different types of variables (building factors, socio-demographics, attitudes and self-reported behaviours) explain annualized energy consumption in residential buildings, and goes on to show which individual variables have the highest explanatory power. In contrast to many other studies, the problem of multicollinearity between predictors is recognised, and addressed using Lasso regression to perform variable selection.

Using data from a sample of 924 English households collected in 2011/12, four individual regression models showed that building variables on their own explained about 39% of the variability in energy consumption, socio-demographic variables 24%, heating behaviour 14% and attitudes & other behaviours only 5%. However, a combined model encompassing all predictors explained only 44% of all variability, indicating a significant extent of multicollinearity between predictors. Once corrected for multicollinearity, building variables predominantly remained as significant predictors of energy consumption, in particular the dwelling's size and type. Of the sociodemographic predictors, only the household size remained significant, and of the heating behaviours only the length of heating season was significant. Reported beliefs about climate change were also a significant predictor.

The findings indicate that whilst people use energy, it is physical building characteristics that largely determine how much is used. This finding, together with the relatively greater time-invariant nature of building characteristics underlines their importance when focusing on seeking to understand residential energy consumption at a stock level. Retrofitting and behaviour change initiatives remain important avenues to reduce consumption, as suggested through the lower energy consumption associated with full double-glazing and shorter heating season. However, the dominance of building size also indicates that living in appropriately sized buildings is of great importance for energy consumption. The results also indicate that more than half of the variability in energy consumption cannot be explained, even when using a wide range of predictors. The paper also discusses the need to collect better occupant-related variables to give a correct representation of the impact of behaviour, such as heating demand temperatures. Furthermore, choices about dwelling characteristics could also be seen as a type of behaviour, even though it cannot be modelled in a cross-sectional analysis as used in this study.

* Corresponding author.
E-mail addresses: g.huebner@ucl.ac.uk (G.M. Huebner), i.hamilton@ucl.ac.uk (I. Hamilton), Zaid.Chalabi@lshtm.ac.uk (Z. Chalabi), d.shipworth@ucl.ac.uk (D. Shipworth), t.oreszczyn@ucl.ac.uk (T. Oreszczyn).

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1. Introduction

Energy use in buildings is one of the largest contributors to energy consumption both locally and globally. In the UK, residential buildings are responsible for about a quarter of total carbon emissions [1]. The 2008 Climate Change Act requires a 34% reduction in 1990 greenhouse gas emissions by 2020, and an 80% reduction by 2050. Dwellings are an important target area for emission reduction: The UK Government established the goal of reducing emissions from homes by 29% by 2020 [2]. Energy efficiency improvements in UK homes form a central part of the decarbonisation plans, with millions of retrofits of domestic homes planned over the next decades [3]. Achieving this improvement in energy efficiency requires having a better understanding of those drivers that have the greatest impact on energy demand.

Previous research has shown that building factors alone explain at least 40% of the variability in energy use, as summarised below. However, not all of the building predictors commonly examined can be impacted on through energy efficiency retrofits. Other factors, such as behaviours, are also widely considered to have a large impact on energy consumption and are likewise the subject of interventions such as feedback and use of social norms.

The aim of this paper is to show in a representative sample of the English housing stock (1) how much of the variability of residential energy consumption can be explained by different categories of predictors, contrasting the explanatory power of building variables, socio-demographics, self-reported heating behaviour, and attitudes towards energy, and (2) which individual predictors have the greatest impact on energy consumption. The findings are important to (1) understand which variables need to be measured to understand energy consumption, and (2) to shape interventions with the greatest potential impact.

The research presented carefully addresses the problem of multicollinearity, which occurs when two or more predictor variables in a multiple regression model are highly correlated. The presence of multicollinearity means that regression coefficients cannot be reliably interpreted. For each regression analysis, variance inflation factors are inspected to see if multicollinearity exists, and if it does, Lasso regression is carried out which sets redundant predictors to zero [4], therefore performing variable selection and removing multicollinearity.

The following review of existing research is almost entirely based on empirical estimates as opposed to modelled data. This is because research has repeatedly shown a gap between modelled and actual energy consumption of dwellings (e.g. [5–7]), and the aim of this paper is to identify factors determining *measured* energy consumption. For research on determinants of modelled and simulated energy consumption, see e.g. Aydinalp et al. [8], Kialashaki and Reisel [9], Koo et al. [10], or Martinaitis et al. [11]. In addition, this review does not include studies looking just at energy consumption excluding space heating (e.g. [12]), given the aim of understanding total energy consumption better which, at least in the UK, is largely driven by space heating.

1.1. Impact of building characteristics on energy use

Several studies have looked at the impact of building variables on energy use (for an excellent summary and overview, see [13]). Building factors were found to explain about 42% [13] and 54% [14] of the variability in energy consumption. Without providing a combined score for the total predictive power of building factors, Steemers and Young Yun [15] found that building factors were more important than occupant characteristics in explaining space heating demand. Generally, predictors that could not be easily changed through energy-efficiency interventions, such as floor area (e.g. [16–19,13]), dwelling type [13,19], climate [20,15] and weather [21] were most important in predicting energy demand. The role of dwelling age, has been shown to have a negative linear relationship with energy consumption in some studies (e.g. [13]) but not in others (e.g. [18]) which might reflect that building technologies or retrofitting programs occurred at different times in different countries. Presence of basement, shed, and garage were all associated with greater energy use [13].

Of those variables that could be targeted by energy-efficiency interventions insulation levels of walls, floors, and windows are associated with energy consumption [16,13,18,15]. Whilst these studies do not cite the joint amount of variability explained by the above-mentioned factors, their respective impact weight (i.e. beta coefficient in regression analysis) is generally lower than those of the more fixed factors of dwelling type and size [13].

1.2. Impact of occupants on energy use

When reviewing studies on the impact of any occupant characteristics, the composition of the study sample needs to be considered. If occupants live in very similar building types in the same location, i.e. there is hardly any variation in building factors, one would expect that the remaining variability is mainly due to non-building factors, e.g. occupant characteristics. Indeed, a number of studies have shown that in similar buildings, energy consumption can vary greatly due to occupant characteristics (e.g. [22,23]). However, in these studies building factors are already accounted for indirectly by the choice of very similar buildings; hence, the remaining variability is more likely to be due to non-building factors. Therefore, studies are reviewed below only if they have *not* restricted the sample to very similar buildings.

Guerra Santin et al. [13] found that when controlling for building characteristics, occupant characteristics explained an additional 4.2% of the variability in domestic energy consumption. For space heating, occupant characteristics account for 20% of the variability in energy use [15], a much higher value, but the authors do not address or discuss the issue of multicollinearity of predictors. Sonderegger [14] concluded that 18% of the variability in gas consumption was due to occupant behaviour; however, this was estimated from changes observed when houses changed occupants which could have also brought other significant changes.

1.2.1. Household characteristics

Two of the most well-documented household characteristics with known impacts on energy use are income and household size. Generally speaking energy consumption increases with higher income (e.g. [24–26]). Household size has been shown to be positively correlated with total energy usage (e.g. [25,26]). The role of householder age is less clear, with some studies finding a negative relationship between age and energy consumption (e.g. [27]), some found no significant relationship [24], while others found a positive relationship between age and energy consumption (e.g. [28,13]); these differing findings might be due to the fact that studies were not consistent in whose age they measured, e.g. any respondent, household reference person, or eldest occupant. Tenure is related to energy consumption. However, it is also likely to be confounded with building characteristics, e.g. socially rented dwellings tend to be better insulated and privately rented dwelling fare the worst [1]. Working from home has been shown to be significantly associated with gas and electricity usage [16].

1.2.2. Occupant heating behaviour

In the models of domestic energy consumption that are most commonly used in the UK (BREDEM models, for an overview see Kavgic et al. [29]), occupant influence can be modelled using the