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Do homes that are more energy efficient consume less energy?: A structural equation model of the English residential sector

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ABSTRACT

Energy consumption from the residential sector is a complex socio-technical problem that can be explained using a combination of physical, demographic and behavioural characteristics of a dwelling and its occupants. A structural equation model (SEM) is introduced to calculate the magnitude and significance of explanatory variables on residential energy consumption. The benefit of this approach is that it explains the complex relationships that exist between manifest variables and their overall effect though direct, indirect and total effects. Using the English House Condition Survey (EHCS) consisting of 2531 unique cases, the main drivers behind residential energy consumption are found to be the number of household occupants, floor area, household income, dwelling efficiency (SAP), household heating patterns and living room temperature. In the multivariate case, SAP explains very little of the variance of residential energy consumption. However, this procedure fails to account for simultaneity bias between energy consumption and SAP. Using SEM its shown that dwelling energy efficiency (SAP), has reciprocal causality with dwelling energy consumption and the magnitude of these two effects are calculable. When non-recursivity between SAP and energy consumption is allowed for, SAP is shown to have a negative effect on energy consumption but conversely, homes with a propensity to consume more energy also have higher SAP rates.

1. Introduction

Buildings are a significant contributor to greenhouse gas emissions with space heating alone responsible for over half of all end use emissions from UK dwellings [1]. In 2007, the UK government put in place a National Energy Efficiency Action Plan (NEEAP) to reduce emissions from the UK housing stock by 31% on 1990 levels by 2020. More recently, the government's own Climate Change Act [2] sets a legally binding target to reduce greenhouse gas emissions by at least 80% on 1990 levels by 2050. It is recognised that meeting such a target will only be possible through radical reductions in energy consumption and necessary but strategic changes to energy supply and delivery. In addition, the residential sector has been repeatedly identified by government departments [1,3–6]; commercial organisations [7,8], non governmental organisations [1,9] and by academia [10–12] as having one of the lowest costs and largest impacts for reducing CO_2 emissions. Still, there remains significant debate about the best approach for reaching the CO_2 reductions imminently required. Moreover, there is insufficient empirical research quantifying the complex relationship between major driving forces purporting to explain residential energy consumption and in particular, the contribution that improved building efficiency can have on reducing final end use energy demand.

1.1. Contribution

This paper presents the first known application of structural equation modelling (SEM) for the explanation of residential energy consumption in England. This powerful statistical technique allows for the calculation of both direct and indirect effects that explain energy consumption in the residential sector. For example, household (HHLD) income is directly correlated with energy consumption but is also indirectly correlated and mediated by dwelling floor area. This is because homes having high annual incomes tend to also have larger floor areas and therefore require more heating. Using SEM it is possible to decompose the relative magnitude of these effects and therefore gain deeper understanding for what variables have the most impact when attempting to understand residential energy consumption. With this technique, it is possible to show the relative sensitivities of different explanatory variables on residential energy consumption. Sensitivity analysis is important for identifying where leverage points may be exploited within

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the system for maximum impact. In addition, this research presents new evidence to quantify the extent that SAP has on reducing residential energy consumption. More importantly, empirical proof is provided showing a reciprocal relationship between SAP and energy consumption, and that, ceteris paribus: dwellings with a propensity to consume more energy will, on average, have higher SAP ratings. However, the reverse is also true and dwellings with a high SAP value will, ceteris paribus, have reduced energy consumption owing to increased efficiency. Finally, these two effects are separately and empirically calculated.

1.2. Structure of paper

The first section of this paper presents important recent developments in the state-of-the-art in residential energy modelling. A thorough review of the literature has shown a serious lack in recent years in the development of bottom-up statistical models for explaining the driving forces behind residential energy consumption. In order to tackle this problem, a structural equation model is introduced with an emphasis on how this relatively modern statistical technique can be applied and used to provide deeper insight into understanding the cause and effect relationships behind residential energy consumption. What follows is a description of the dataset and preparation of the variables prior to analysis. The importance of SEM for conducting this type of analysis is highlighted by the results obtained from a typical multivariate regression model, a technique unable to directly measure non-recursivity or easily distinguish direct and indirect effects. Statistical results are then presented before leading into a discussion and the implication of this research for policy makers.

2. The epistemology of residential sector energy modelling

2.1. Energy demand modelling in the residential sector

Over the last two decades, there has been a plethora of national level domestic energy models that vary in data requirement, disaggregation level, socio-technical assumptions and the type of scenarios or predictions that can be modelled [13]. This brief literature review is intended to provide an overview of the major epistemic approaches that have previously been used for modelling residential energy consumption and emissions in the UK. Due to the fact that several relatively recent publications provide excellent reviews on different residential sector modelling techniques, this section has purposefully been kept brief [13–21].

Since the advent of computers many national level models have been developed to assist in the prediction and analysis of domestic energy consumption. Most authors agree that the majority of models generally take two broad epistemic approaches described as being either top-down or bottom-up. Top-down methods use econometrics and multiple linear regression methods for the explanation of variance between dependent and independent covariates. Such models lack the resolution required to calculate the potential of different technologies or policy options available for estimating energy demand. Several models have been developed in the UK using these methods [22–24].

Advances in recent years have seen the development of sophisticated hybrid models that integrate both of these approaches into a single model. In parallel with these integrated techniques, a number of advances have been made in machine learning, new statistical approaches and GIS methods [25] capable of modelling the interaction between energy, economy, environmental systems and technology in the built environment. For example, a neural-network based national energy consumption model has been developed for the Canadian residential sector [26] and other innovative statistical techniques such as decision tree analyses are being used to model residential energy consumption at the national level in Hong Kong [14]. However, Hitchcock [27] argues that energy consumption patterns are a complex technical and social phenomenon and in order to be understood appropriately must be tackled from both engineering and social science perspectives concurrently.

Although aggregate regression methods help to show trends in total dwelling stock energy consumption patterns, they cannot explain the various components that contribute to energy consumption at the household level. For this type of analysis it is necessary to conduct investigations at the micro-level. Bottom-up methods take a disaggregated approach and estimate energy demand and emissions using high resolution data using a combination of physical, social, behavioural and demographic properties for a household [28–30]. The empirical data requirement for bottom-up models is significantly more demanding requiring large, high resolution datasets that contain specific characteristics for each dwelling that include physically measured variables, demographic information and details about energy consuming behaviour [31]. With bottom-up methods, it is also possible to combine, or aggregate micro-level data in order to generate new variables that provide information about the total dwelling stock. There are two types of bottom-up methods that are contingent on the data and structure of the analysis required. These are the engineering method and the statistical method. The engineering method uses a sample of houses and technologies to represent the national housing stock and apply heat balance equations to estimate energy demand. In the UK several engineering models exist for the UK residential sector [10,32–34].

More in line with the research presented in this paper are bottom-up econometric methods. Such models are largely neglected in reviews on residential energy modelling and almost entirely neglected for estimating energy consumption in the UK. While one or two models were developed in the 80’s and early 90’s using large statistically powerful datasets [35] the full potential of these models has never been realised. More recent models rely on data obtained from very small-localised datasets representing just a small subset of the population with, perhaps, a few hundred representative cases [36]. The main reason for this significant gap in the literature can be explained by a serious lack of statistically significant, high quality, high resolution data combining household level energy consumption data along with the physical characteristics of the dwelling and user behaviour. Indeed, there are many benefits of Multiple Linear Regression (MLR) techniques over other methods including their simplicity and adaptability to almost any problem. A downside of this approach is the assumption that a single dependent variable is a linear function of multiple independent variables. It is also difficult to ascertain the underlying causal mechanism behind the model as standard multiple regression techniques only provide evidence of correlation and therefore can sometimes suffer from multicollinearity and misinterpretation. As shown in this paper, structural equation modelling is a robust, well known statistical method and when applied to the residential sector is able to provide new insight and overcome many of the weaknesses and pitfalls of many other methods.

3. Methodology

3.1. The dataset

The model is based solely on publicly available data and comprises information available from two principle datasets: The 1996 English House Condition Survey (EHCS) and the 1996 Fuel and Energy Survey (FES). The EHCS is conducted every five years and is the only survey to provide thorough data on the condition of the national housing stock [37]. The 1996 EHCS consists of 12,131 real