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Energy efficiency uptake and energy savings in English houses: A cohort study

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ABSTRACT

The UK Government estimates that approximately 22 TWh of energy can be saved from English dwellings by 2020 from a range of fabric and heating energy efficiency retrofits. Yet the rate of retrofit uptake has been less than is needed to meet government targets and the retrofits impact on energy demand has been less than predicted. Two questions that must be addressed are: who have (and have not) taken up retrofits and what household factors affect this; and, what impact have these retrofits had on energy use and how does this differ among households. The purpose of this study is to provide a better understanding of the uptake of energy efficiency retrofits and the resulting change in energy demand. A cohort of 168,998 dwellings gas-heated English dwellings was used to examine retrofit uptake from 2002 to 2007 and the change in gas use from 2005 to 2007. The findings show that retrofits *do* have an attributable impact on reducing energy demand and that combining retrofits displays a dose–response like effect, after controlling for household and dwelling factors. Energy savings play a central role in meeting UK climate change mitigation targets and therefore understanding the take up of energy efficiency retrofits and their impact on energy demand and variations in these retrofits across the population is vital to understand their potential.

1. Introduction

As part of the UK's commitment to reduce greenhouse gas emissions, energy demand in the existing English housing stock needs to reduce through a comprehensive package of efficiency retrofits alongside decarbonising energy supply [1]. The government estimates that through increased efficiency an energy savings potential of 22 TWh is possible by 2020, a reduction of ~4.4% from 2012 demand levels of 500 TWh [2], delivered through a range of energy efficiency measures that focus on dwelling fabric and heating systems. These proposals include: insulating 7.3 million solid walled homes, 5.1 cavity walled homes, 7.4 million lofts, 19.2 million double glazing installations, 17.6 million boiler upgrades, along with millions of dwelling needing heating controls, draught-proofing, heating recovery systems, and smart meters [2]. Further, retrofits would help to mitigate household energy costs from price rises and protect against the effect of cold weather shocks on heating energy demand. Therefore, to address the priority of improving the energy performance of dwellings in the UK evidence is needed to advance understanding regarding the rate of uptake of energy efficiency retrofits across the residential sector and their resultant energy savings.

Approximately 12.2 million UK dwellings have received some form of energy efficiency retrofit since 2000 [3]. The majority of these retrofits were directed toward reducing space heating use through fabric insulation, ventilation control and more efficient heating systems, with many of the retrofits being installed in combination. Despite these installations, the rate of retrofit uptake across UK dwellings has been less than is required to meet UK targets [4]. Further, the impact that these retrofits have on energy demand has been less than predicted [5]. Together, the limited uptake and impact on energy demand pose a clear threat to meeting UK emission reduction targets.

A pressing question that emerges relates to who have (and have not) taken up retrofits and whether household factors affect this uptake over time? A second question is what impact have these measures had on demand and how does it differ among

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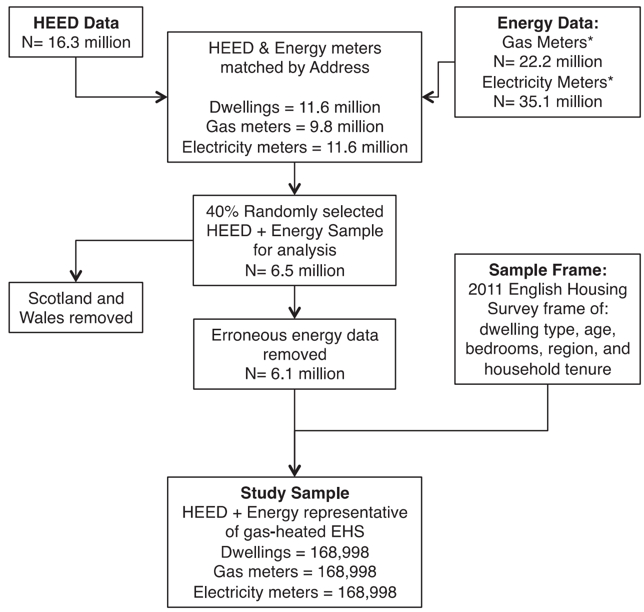

Fig. 1. Study sample selection process.

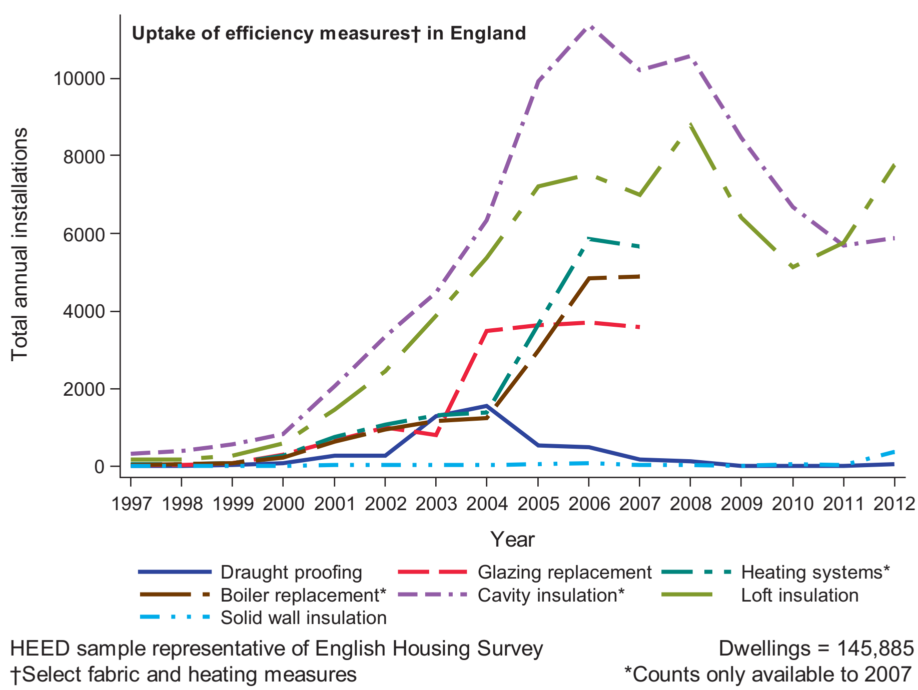

Fig. 2. Uptake of energy efficiency retrofits in England 1996–2012.

households? Several studies have shown that uptake has varied among English neighbourhoods by income groups, vulnerability, region and age of housing stock [3,6]. While several cross-sectional studies have shown how dwelling typologies influence retrofit take up, with older dwellings generally needing more insulation and others requiring specific types of retrofit (i.e. cavity filling insulation) and the influence of household characteristics on retrofit presence with lower income, privately renting households living in dwellings with the lowest levels of efficiency [7,8]. However, to date there has been little work to understand (a) how individual level household or dwelling characteristics modify uptake over time and the type and combination of retrofits, and (b) whether having a retrofit modifies the probability of installing subsequent measures. Further, while studies have attempted to quantify the impact that retrofits have had on energy demand in UK dwellings [9–11], there has been little work to understand (a) the extent to which dwelling and household characteristics modify changes in energy demand; and (b) whether cumulative retrofits result in more savings.

The purpose of this study is to provide a better understanding of the uptake of energy efficiency retrofits and the resulting change in energy demand that accounts for individual dwelling and household characteristics, adjusting for potentially confounding and interacting factors. The research questions asked were:

a) What is the rate of uptake of energy efficiency measures in the English housing stock, what dwelling, household and local area

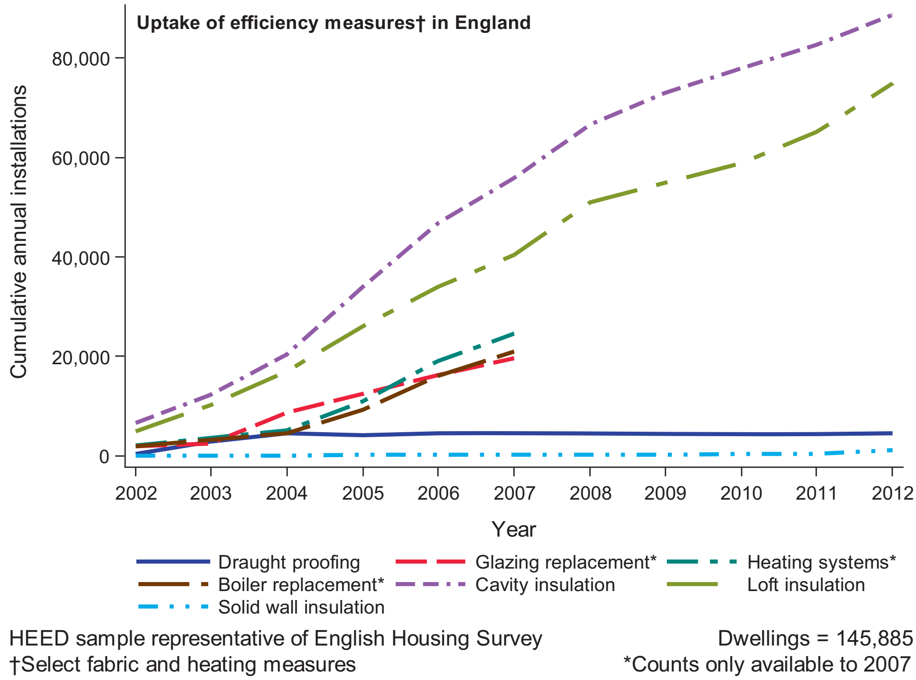

Fig. 3. Cumulative uptake of energy efficiency retrofits in England 2002–2012.

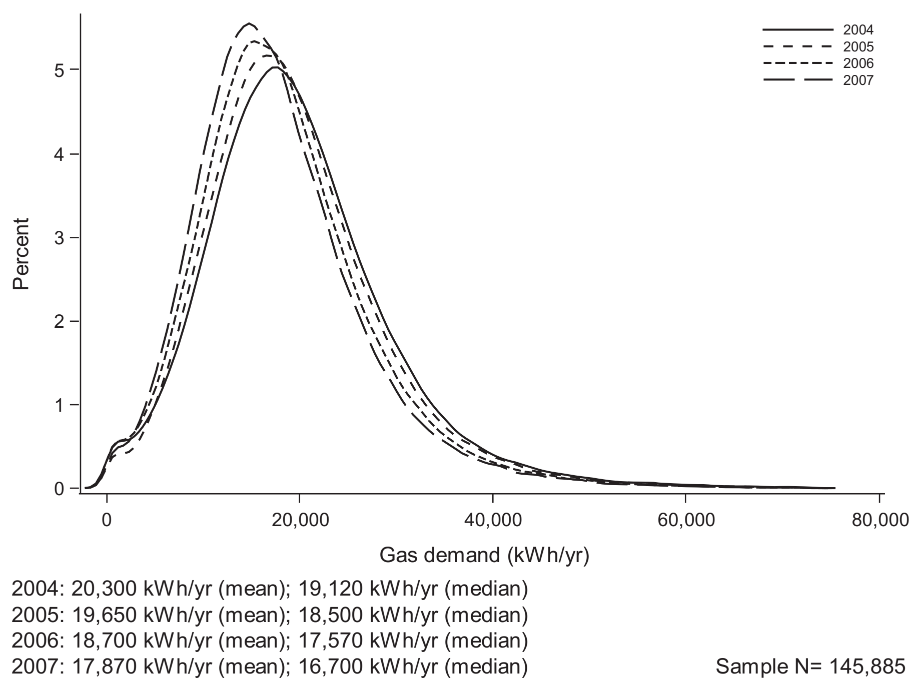

Fig. 4. Distribution of annual gas demand (kWh/year) per dwelling in study sample, 2004–2007.

features affect this rate, and what differences exist between those dwellings that installed/received efficiency measures?

b) What is the rate of change in energy demand in the English housing stock and what dwelling, household and local area features affect this rate? And,

c) What is the effect (individually and in combination) of heating system and fabric insulation energy efficiency measures on change in energy demand, and what factors affect these changes?

Factors that may be associated with energy efficiency uptake and the impact that retrofit measures have on energy savings include: household practices and their socio-economic characteristics, beliefs and social norms, upfront cost of measures, perception of risks and challenges, perception of institutions such as governments or energy suppliers, ownership, and dwelling characteristics [7,12]. Higher-income households may also be more able to reduce their energy demand than lower-income dwellings [13]. In this study, the following hypotheses are tested:

1. Households with lower incomes accept/receive more measures than higher income levels.
2. Households that own their homes accept/receive more measures than other tenures.
3. Older dwellings are more likely to take up energy efficiency measures.
4. Older dwellings are less likely to achieve energy savings compared to newer dwellings.
5. Lower-incomes households are less likely to realise energy savings compared to higher incomes.

A population-based cohort study of English dwellings was used to investigate the association between household and dwelling characteristics and the uptake of energy efficiency retrofits from 2002 to 2007 and also corresponding changes in energy use between 2004 and 2007. The study used a sample that was drawn to be representative of English dwellings with a gas connection (90% of all dwellings).

2. Background

Since 2000, English houses have received millions of energy efficiency interventions comprising fabric insulation, heating system replacements and ventilation control, which have largely been provided through a combination of energy supplier obligations, fuel poverty program and private installations of heating systems and glazing [3]. Despite these efforts, estimates suggest that the trajectory of uptake across all types of retrofit is falling short of the Government's medium ambition pathways [4]. Meeting GHG emissions reduction commitments requires a better understanding of where efficiency retrofits are being taken up (and where take up is lacking), and what impact retrofits have had on energy use in real terms [14]. A UK House of Commons report outlined the challenges being faced to meet these commitments including: a lack of incentives, cost of retrofits, cost of loans and interest rates for retrofit, complex policy mechanisms, technical installation challenges, inadequate installer capacity and training, minimal consumer interest, and unrealised energy savings [15].

Recent research for England has shown that the rate of uptake for all types of energy efficiency measures between 2000 and 2007 was lower in neighbourhoods with middle and high incomes and also in the rental market, and the highest rates were among neighbourhoods with lower incomes, more benefits and higher levels of owner-occupied dwellings [3]. Several studies for the UK suggest that the rate of uptake of efficiency measures is most influenced by decision-making autonomy (i.e. dwelling ownership), income levels, existing energy performance, and regulatory requirements [7,8,16], and the attitudes and barriers to adopting energy efficiency [12,17].

An obvious challenge to achieving a high rate of uptake of energy efficiency among UK homes is that there are real differences in terms of the dwellings' physical construction, design and size, energy performance, existing heating and ventilation systems and appliances, access to fuels and their location [18]. The effect is that seemingly similar houses can have very different levels of energy demand [19–21], reflecting real differences in the practices around energy demand.

The literature also shows that variation in the change in energy demand is dependant on the level of efficiency improvement sought (e.g. deep retrofits versus single component improvements) [11], the quality of the installation, and the response of household occupants (e.g. upfront cost and savings recuperation, comfort taking) [22]. Work by Wyatt showed that installing efficiency measures resulted in changes in gas demand (compared to dwellings with no efficiency measures), including reductions of: 10% for cavity wall insulation, 3% for loft insulation, 8% for condensing boiler installations, and 2% for double glazing installation [9].

Several of the above studies provide evidence of real changes in energy demand following the introduction of fabric and heating efficiency measures, but do not fully examine the potential variation in changes in energy demand due to dwelling or household features. Of interest in this study is what factors are associated with energy efficiency retrofits uptake, what the actual change in energy demand following the introduction of efficiency measures and whether this change can be attributed to the retrofit while accounting for those dwelling and household factors that affect savings.

3. Methods

A population-based cohort study was selected to examine the relationship between energy efficiency retrofit uptake and individual dwelling characteristics and the relationship between changes in energy use and installation of energy efficiency retrofits.

Cohort studies are observational studies of a selection of individuals over time and are well suited for studying incidence (i.e. detecting changes in outcome patterns) over time and to determine how outcomes might vary between those exposed to a factor or event and those who are not, with the aim of determining aetiological (causal) links. A cohort looks to follow a population over time to determine how outcomes (e.g. energy demand) change with exposure (e.g. retrofits), rather than being selected for already being exposed and compared (i.e. a case-control study). A cohort study offers the advantage of being able to study numerous factors and levels simultaneously.

3.1. Datasets

In this study, a cohort study sample of English dwellings was selected to be representative of the English housing stock using the Homes Energy Efficiency Database (HEED) connected to gas and electricity meters. The study focused on the uptake of energy efficiency retrofits dwellings with a gas connection, which comprises 90% of all primary heating systems in England [23]. Each dataset used in the analysis is described.

3.1.1. Homes energy efficiency database

HEED comprises information on the energy performance and installation of energy efficiency retrofits in England, covering a period from 1993 to 2013. The database is managed by the Energy Saving Trust as a repository of energy efficiency activities that have taken place in the UK and includes data from installers, industry accreditation bodies, energy suppliers, government-funded programs, local authorities and home surveys [24]. Information was collected at a dwelling level and includes a range of dwelling and energy efficiency details on over 16.4 million dwellings in the UK.

The database is broadly representative of the English stock in terms of size and dwelling type, except for flats which were under-represented, and is shown to provide a considerable breadth of geo-spatial coverage and is estimated to account for 90% of the energy efficiency interventions that took place between 2002 and 2007 [3].

3.1.2. Energy supplier meter point data

A database of annualised gas and electricity energy supplier meter point data for the years 2004–2007 was used to examine the impact of energy efficiency retrofits on energy demand. The energy data used in the study was the latest made available for

Table 1
Energy efficiency retrofit details collected in HEED.

Component	Energy efficiency interventions
Heating controls	Standby saver Central heating controls upgrade Delayed start thermostat Thermostatic radiator valves Load or weather compensation
Heating system	Community heating Ground source heat pump Replacement: biomass boiler, electric boiler, gas condensing boiler (standard and combi), gas boiler (standard and combi), oil condensing boiler (standard and combi), oil boiler (standard and combi) Room heater: electric, gas, solid fuel Solid fuel fire cassette Storage heaters Electric and gas warm air system
Cavity walls	Cavity wall insulation (pre and post-1976, and unknown property age)
Solid walls	External wall insulation to U-value of 0.37 W/m^{2}K, U-value of 0.45 W/m^{2}K Internal wall insulation to U-value of 0.37 W/m^{2}K Unknown solid wall insulation
Lofts	Loft insulation: 0–250 mm, 25–250 mm, 50–250 mm, 75–250 mm, 100–250 mm, 150–250 mm
Domestic hot water	Installed modern DHW cylinder
Ventilation	Draught proofing (general)
Glazing	Replacement double glazing
Smart systems	Real time displays Visual display unit

connection to the HEED.[1] The energy data was connected to HEED at the address level by DECC and provided for analysis in an anonymised form with only neighbourhood identifiers (i.e. lower layer census output area (LSOA)).

The annualised gas demand data is derived from two meter readings at least six months apart and corrected for seasonal normal demand (i.e. annual weather correction) and end-user climate sensitivity [25]. The annualising method provides a means of comparing total gas demand between years that removes the effect of cold or warm weather (described fully in Ref. [25]. The implication of the weather adjustment is that changes over several years are likely to be more appropriate for determining the impact of energy efficiency retrofits than year-to-year change [26]. The gas year is 1 October–30 September. The gas data does not contain an explicit flag for domestic meters, but is typically identified as being less that 73.2 MWh/year. It was assumed that the gas data connected to HEED are for domestic properties only.

The electricity demand data is also derived from meter readings and annualised using a process that allocates meters to domestic annual demand profiles.[2] Electricity data is not corrected for inter-annual weather. Domestic electricity meters are classed into unrestricted electricity or economy 7 meters. Economy 7 meters are on a time charge tariff that offers cheaper electricity during off-peak hours (DECC, 2009b), and are typically used for electric storage heating or hot water. Unrestricted meters are all other uses, which may also include heating and hot water. The annual period for electricity meters is from 30 January to 29 January.

Both the gas and electricity data was provided in an annualised form for use in this analysis. The gas and electricity data was cleaned to remove potentially erroneous data points, including: missing, zero, negative, and very large values (i.e. above 73.2 MWh/year for gas and 50 MWh/year for electricity). A further cleaning was applied to inter-annual changes in demand: meters with missing readings or repeated values in any year (2004–2007) were removed; meters with large changes in demand were also removed, i.e. $>\pm 80\%$ of the preceding year. Further details on the meter data are available in Ref. [27].

3.1.3. *Neighbourhood level household characteristics*

To examine neighbourhood level effects, data at the LSOA level were used. Experian Mosaic Public Sector data on median income and household type (based on Mosaic classification) were used [28]. Data on age of population, number of benefit claims, and council tax bands were drawn from the Neighbourhood Statistics service [29]. The neighbourhood level data were not collected for every year in the study; therefore data from the nearest year to 2007 were used wherever available. The LSOA level data was connected subsequently using the LSOA codes provided in the anonymised HEED + Energy data. For further details on the LSOA level data, see Appendix A.

3.2. *Study population—English cohort*

To examine the uptake of energy efficiency measures in England's housing stock and its impact on gas demand, the combined HEED + Energy data, relating to approximately 11.6 million unique dwellings along with electricity and gas meters, was used as the basis for selecting the study sample (Fig. 1). Although HEED contained 16.3 million dwellings, the matched data made available from DECC used in this study comprised a match for 11.6 million dwellings. For computational and testing purposes, a 40% randomly selected HEED + Energy dataset was drawn from the full dataset for detailed analysis.

To draw a sample representative of English dwellings, a sample frame was constructed using the 2011 EHS, which is a

[1] N.B. the Dept. of Energy and Climate Change have released a more recent sample of energy data and retrofits, known as the National Energy Efficiency Data-framework (NEED), but was not used in this analysis due to limited information available on the households, the geographic covereage, and the sampling method being in appropriate for a cohort study design.

[2] Demand profiles for domestic meters are created using 30 min interval meter data for a statistically representative sample of domestic meters in a given network area for a year [43]. Profile coefficients, representing half-hourly fractions of demand are summed and applied to the meter reading advance (i.e. the difference).

cross-sectional survey that is representative of English dwellings and households [30]. The 2011 EHS comprises survey from 2010 to 2011 and was used because it was the latest data to align with HEED at the time of analysis. The sample frame was constructed to be representative of gas-heated English dwellings and comprised: dwelling age, dwelling type, number of bedrooms, government region, and household tenure. To align with HEED variables, EHS dwelling age, type and tenure were recorded to construct the sample frame (see Appendix B).

The sample was drawn using SAS 9.3 Proc Surveyselect [31]. A sample size of 200,000 dwellings was requested using a simple random sampling design, which is selection with equal probability and without replacement. The resulting study sample comprised 168,998 dwellings with gas electricity meters. A comparison of the original HEED + Energy dataset, the 2011 EHS and the study sample is provided in Appendix B.

3.3. Energy efficiency interventions

The data available for study spans 2002–2012, which includes a number of government programs (Warm front, 2000–2013), energy company obligations (Energy Efficiency Commitment (EEC) 1 & 2, 2002–2008; Community Energy Savings Program (CESP), 2008–2012; and Carbon Emission Savings Program, 2008–2012), retrofit building regulations assessment requirements for double glazing (Fenestration Self-Assessment Scheme (FENSA) from 2002), and gas system safety checks for private and social let properties Gas Safety Regulations, 1998 [3,32,33]. The retrofit installation process, including its management and financing, depended on the program or mechanism by which it was introduced to the dwelling. Most government and energy supplier programs included a third party installer to oversee the retrofit, while privately financed retrofits were most likely overseen by the resident or landlord.

Table 1 details the retrofit interventions available for analysis within HEED. A date (including month and year) of survey or retrofit installation was provided for each energy efficiency retrofit for every dwelling in HEED.

3.4. Outcome

For the analysis focused on the *uptake of energy efficiency retrofit interventions* the outcome of interest was the presence of an energy efficiency measure installed from 2002 to 2007. The analysis grouped all ‘major’ measures together, which included: cavity wall insulation, loft insulation to 250 mm, double glazing installation, heating system upgrades (including condensing boiler installation), and draught-proofing. Two further subgroups were derived that included ‘fabric’ measures (wall and loft insulation, glazing, and draught-proofing) and ‘heating’ measures (all heating system upgrades, including: heating controls, boiler upgrades). In addition to the presence of any intervention, the presence of additional interventions (i.e. any retrofit taking place following an initial retrofit) and the total number of retrofits (i.e. a package of fabric and heating retrofits) were examined. This was in order to determine whether, say, having a fabric intervention (e.g. cavity wall insulation) made a dwelling more or less likely to have subsequent retrofit (e.g. boiler replacement or loft insulation). Also, whether uptake over the period unfolded as packages of energy efficiency retrofits or single interventions. Three outcome measures were examined: (a) the presence of retrofit intervention(s) any time during the period 2002–2007; (b) the presence of subsequent intervention measures within the period; and, (c) the total number of any retrofits over the period.

For the analysis focused on the impact of *efficiency retrofit interventions on energy demand* the outcome of interest was the change in annualised gas demand between gas years. The available gas data covered only 2004–2007; therefore, the impact analysis only examines interventions within that period. The measures of change in annual gas consumption used for the analysis were the absolute change in demand (measured in kWh/year) and the proportion change in annual demand from one year to the next (measured as a proportional change in demand, unitless). For the purposes of analysis, all energy efficiency retrofit interventions were allocated to the gas year (i.e. 1 October–30 September). Further, there is a chance that households (in all tenures) may have moved during the study period. However, no data exists within the data to determine this and it is expected that these numbers are small[3] and randomly allocated within the sample.

3.5. Influencing and confounding factors

Influencing and potentially confounding factors were identified from the literature and accounted for in the analysis, where possible. These factors were classed into two types: physical dwelling characteristics and socio-cultural practices. Physical dwelling characteristics were related to those features of the dwelling that may have an effect on whether a dwelling was eligible for an efficiency retrofit. Dwelling age is likely an important influencing factor on the uptake of energy efficiency retrofits. The type of dwelling will also affect the retrofit take-up. Flats are unlikely to have lofts (unless in converted dwellings) and present more difficulties for wall insulation due to the impractical nature of insulating a single unit (if with external insulation) and more complex ownership structures. These physical factors were also considered to have an effect on changes in gas demand. Older dwellings have been shown to be colder dwellings [22], and may therefore have a higher potential for temperature take back. Dwelling type will also be a proxy for the number and area of detached walls available for heat loss, which could affect the savings from insulation.

Socio-cultural practices are related to the characteristics and preferences of the household occupying the dwellings that could affect energy efficiency uptake and changes in energy demand. Household income or benefit receipt have been shown to affect the ability to afford energy efficiency retrofits [7], but also eligibility for government assistance [32]. Household tenure may also affect efficiency uptake due to the decision-making autonomy of a household. Households living in social and private let dwellings are subject to the agreement of landlords to accept retrofits. These issues are also known to affect energy savings that might derive from installed energy efficiency retrofits. Low-income and households on benefits are known to have a higher exposure to poor-quality housing [22,34] and may have a higher temperature take back potential to achieve thermal comfort [35].

3.6. Statistical analysis

The analysis was carried out using SAS v9.3. Analysis of the uptake of efficiency interventions used logistic regression to examine the presence (0,1) of energy efficiency retrofits during the 2002–2007 period for all interventions, fabric and heating system. The probability of having had an energy efficiency retrofit was modelled for all dwellings, adjusted to control for influencing factors.

General linear models (GLMs) were used to analyse change in energy demand. All categorical variables were entered as classes and a reference class was used against which to determine parameter estimates. Estimates of change in gas demand were made for all dwellings and then adjusted to control for physical and

[3] The ONS estimates that during the study period there were approximately 1.5 million property transactions of the 23 million dwellings, or 6% [44].

socio-cultural factors. GLM was also selected because the change in energy demand had a Gaussian function distribution.

4. Results

As sample of 168,998 English dwellings were examined as part of the cohort study analysis. From 2002 to 2007, 39% received a major measure, 36% a fabric measure, and 9% a heating measure. The annual average change in energy demand across the stock was approximately −810 kWh/year (−740 kWh/year in 2004/05, −860 kWh/year in 2005/06, and −830 kWh/year in 2006/07). This amounted to an annual average proportion change of −3.6% for 2004/05, −4.4% for 2005/06, and −4.4% for 2006/07. The following sections concentrate on the uptake of energy efficiency measures within the cohort and then the impact of the energy efficiency retrofit interventions on changes in gas demand.

4.1. Uptake of energy efficiency retrofits among English dwellings

The uptake of fabric measures in the study sample over the period 2002–2007 was highest for cavity wall insulation and loft insulation, and heat systems (the majority of which were boiler installations)—see Fig. 2. In 2009, the annual uptake rates of reported cavity and loft insulation were around their peak of 50 per 1000 dwellings. Reported condensing boiler installations had a peak uptake rate of 21 per 1000 dwellings in 2007. Cavity and loft insulation and condensing boiler installations held a relatively constant uptake trajectory from 2002 to 2007 (see Fig. 3), though there was a change in the number of added installations in cavity and loft insulation in 2008, coinciding with the CERT program.

The incidence rate (i.e. dwellings with measures installed over all dwellings) of uptake over the study period differed considerably between dwelling characteristics. There was a higher uptake of fabric interventions compared with heating measures within the cohort (Table 2). By dwelling type, the incidence of all major measures was highest among detached dwellings (480 per 1000 dwellings) and lowest among flats (280 per 1000 dwellings). Older dwellings had lower rates of fabric measure uptake than newer dwellings. The majority of the fabric measures are cavity wall filling and therefore these dwellings are more likely to have brick or stone solid walls. The incidence of heating measures shows little difference by dwelling age bands. There is also a higher incidence of heating system installation by dwelling type, particularly detached dwellings and for privately let dwelling tenures.

Whilst the incidence rate provided a measure of the uptake, the likelihood (i.e. dwellings with measures installed over dwellings with no installation) provided a measure of the probability that a dwelling might have a measure installed, and accounts for the size of the population. Using the 'crude' probability (i.e. unadjusted for potentially influencing factors), Table 2 shows that the average dwelling had a 39% chance of having a major measure installed, a 36% chance of fabric measures and a 10% chance of a heating measure during the period. However, compared to the 'crude' stock average, dwellings were more likely to have had a major measure installed if they were: detached (22%), constructed between 1967–75 (40%), privately rented (12%), are with 3 bedrooms 6%), and located in the North East (32%), North West (15%) or the West Midlands (21%).

The impact of dwellings features on the probability of uptake among the study sample over the study period was examined using a logistic regression model. Table 3 shows regression coefficients for the association between dwelling features and the probability of having had a major measure, fabric measure or heating measure installed in the study sample from 2002 to 2007. Unlike Table 2, these results are modelled together. The results show that the probability of having a retrofit increases with detachedness, is increased in mid-century dwellings, is more likely as income increases or if living in the north and western regions of England.

4.2. Change in gas demand in English dwellings

The mean annual change in gas demand for the sample of English dwellings over the study period 2004–2007 was −810 kWh/year, or −4.2% per year. Fig. 4 shows the shift in the distribution in annual gas demand.

Using a GLM regression model, the presence of fabric or heating energy efficiency retrofit is shown to be significantly associated with a reduced demand for gas (see Table 4). Adjusting for dwelling type, age, tenure, size, region and median neighbourhood income, the presence of an installed fabric energy efficiency retrofit in English dwellings is on average −790 kWh/year, or a 3.9% reduction from the stock mean gas demand in 2006, and the presence of a heating energy efficiency retrofit is on average −1950 kWh/year, or a 10.4% reduction. In this model, the fabric and heating measures were not additive, and when installed in the same year represented an average reduction in demand of 2290 kWh/dwelling/year, or a 11.7% reduction. The presence of energy efficiency retrofits appears to have a significant impact on gas demand even after adjusting for differences in dwelling and household characteristics, such as number of exposed walls (i.e. dwelling type) and proxies of energy performance (i.e. dwelling age). These results suggest there is an impact on gas demand attributable to the retrofit alone.

The association of the change in energy demand from 2005 to 2007 and specific energy efficiency retrofits installed in 2006 are shown in Table 5, both unadjusted (model 1) and adjusted for dwelling type, age, tenure, size, region and neighbourhood income (model 2). In the following results, only the adjusted values are described, though there was little difference in the resulting values between the two models.

The mean change in gas demand associated with the installation of cavity wall insulation for dwellings was −1050 kWh/year, or 5.6% of the stock mean gas demand in 2006. For dwellings with loft insulation installed in 2006, this was associated with a 150 kWh/year increase (∼1% of mean 2006 demand), though this was not statistically significant at the 95% level. The installation of double-glazed windows was also not statistically significant and was associated with a mean change in demand of −12 kWh/year. Condensing boilers were associated with a mean change in demand of 1060 kWh/dwelling, or 5.7% of mean 2006 demand, significant at the 95% level.

The trends described above compare closely to the proportional change in gas demand from 2005 to 2007, shown in Table 6. The results, using a GLM model, are adjusted for dwelling type, age, tenure, size, region and neighbourhood income, and show that cavity wall insulation and condensing boiler installations had a −4.9% and −5.5% change in demand from 2005 to 2007, respectively. Note that loft insulation and double-glazing installation showed almost no associated change in demand. The combined effect of additional measures showed greater reductions in the change in demand, with combinations that included condensing boiler installations and cavity insulations being associated with the largest changes. The adjusted added effect of cavity wall and loft insulation and a condensing boiler was associated with an −11.2% change in demand. In this modelling, there is some evidence to suggest that the retrofits are additive, i.e. combined measures achieving the reductions for single measures added together. The Table also contains a sensitivity analysis that includes electricity in the dependant variable. Whilst the trend is the same, the magnitude of change is less when including electricity. Unrestricted electricity demand is approximately a one fifth the demand for gas, which means that it should

Table 2
Number (1000's) of major retrofits installed in a sample of English houses 2002–2007, derived from HEED.

Dwelling characteristic	Major measure (1000's) 2002–2007			Incidence rate[a]	Likelihood[b]	Odds[c]	Fabric measure 2002–2007		Incidence rate[a]	Likelihood[b]	Odds[c]	Heating measure 2002–2007		Incidence rate[a]	Likelihood[b]	Odds[c]
	Yes	No	All				Yes	No				Yes	No			
Dwelling type																
Flat, all	4.5	11.5	16.1	0.28	0.72	0.61	3.8	12.3	0.24	0.66	0.56	1.2	14.9	0.07	0.80	0.79
Terrace	17.4	33.8	51.3	0.34	0.87	0.81	16.0	35.3	0.31	0.88	0.82	2.7	48.5	0.05	0.59	0.57
Semi detached	21.0	32.5	53.6	0.39	1.01	1.01	19.9	33.7	0.37	1.04	1.07	2.5	51.0	0.05	0.52	0.50
Detached	23.0	25.1	48.1	0.48	1.22	1.43	20.5	27.6	0.43	1.20	1.34	8.8	39.3	0.18	2.03	2.26
Dwelling age																
1900-pre	2.3	9.0	11.2	0.20	0.51	0.39	1.6	9.7	0.14	0.39	0.29	0.9	10.3	0.08	0.91	0.90
1900–1949	17.2	32.3	49.5	0.35	0.89	0.83	15.3	34.2	0.31	0.87	0.81	4.2	45.3	0.09	0.94	0.94
1950–66	14.6	23.8	38.5	0.38	0.98	0.96	13.1	25.3	0.34	0.96	0.94	3.4	35.0	0.09	0.99	0.99
1967–75	14.3	12.1	26.4	0.54	1.39	1.84	13.7	12.6	0.52	1.47	1.97	2.4	23.9	0.09	1.02	1.03
1976–82	4.2	6.5	10.7	0.39	1.01	1.02	3.9	6.8	0.37	1.03	1.05	0.9	9.7	0.09	0.97	0.97
1983–90	4.8	8.7	13.5	0.36	0.92	0.87	4.4	9.1	0.32	0.91	0.87	1.2	12.3	0.09	0.99	0.99
1990-post	8.6	10.7	19.3	0.44	1.14	1.24	8.2	11.1	0.42	1.19	1.33	2.1	17.2	0.11	1.20	1.23
Tenure type																
Owner occupied	51.6	78.8	130.4	0.40	1.01	1.02	47.6	82.8	0.37	1.03	1.04	11.5	118.9	0.09	0.98	0.98
Private rented	4.4	5.7	10.1	0.44	1.12	1.22	4.0	6.1	0.40	1.12	1.21	1.2	8.9	0.12	1.36	1.42
Social rented	9.9	18.6	28.5	0.35	0.89	0.83	8.5	20.0	0.30	0.84	0.77	2.5	26.0	0.09	0.96	0.96
No. bedrooms																
1 Bedroom	2.6	8.0	10.6	0.25	0.63	0.51	2.0	8.6	0.19	0.52	0.41	0.9	9.7	0.08	0.91	0.91
2 Bedrooms	14.8	24.1	38.9	0.38	0.98	0.96	13.5	25.4	0.35	0.97	0.96	3.8	35.1	0.10	1.09	1.10
3 Bedrooms	34.7	49.5	84.2	0.41	1.06	1.10	32.7	51.6	0.39	1.09	1.15	6.6	77.7	0.08	0.87	0.85
4 Bedrooms	10.6	17.3	27.9	0.38	0.97	0.95	9.9	18.0	0.35	1.00	0.99	2.3	25.6	0.08	0.91	0.90
5+ Bedrooms	3.2	4.2	7.4	0.44	1.12	1.21	2.2	5.2	0.29	0.82	0.75	1.7	5.7	0.23	2.52	2.97
Region																
North East	5.0	4.7	9.7	0.52	1.32	1.66	4.7	5.0	0.48	1.36	1.70	0.9	8.8	0.10	1.07	1.08
North West	11.5	14.1	25.6	0.45	1.15	1.27	10.7	14.9	0.42	1.17	1.29	2.5	23.1	0.10	1.08	1.09
Yorkshire and the Humber	7.3	11.7	19.0	0.38	0.98	0.97	6.6	12.4	0.35	0.97	0.96	2.0	17.0	0.10	1.15	1.17
East Midlands	6.4	8.1	14.4	0.44	1.13	1.23	5.8	8.6	0.40	1.13	1.21	1.7	12.7	0.12	1.31	1.35
West Midlands	7.9	8.8	16.8	0.47	1.21	1.40	7.3	9.4	0.44	1.23	1.40	1.8	15.0	0.10	1.16	1.18
East England	7.0	10.3	17.3	0.40	1.03	1.05	6.3	11.0	0.37	1.03	1.04	1.7	15.6	0.10	1.09	1.10
London	5.2	17.1	22.4	0.23	0.60	0.48	4.4	18.0	0.20	0.55	0.44	1.3	21.1	0.06	0.64	0.62
South East	9.9	18.2	28.1	0.35	0.90	0.85	9.0	19.2	0.32	0.90	0.85	2.2	25.9	0.08	0.86	0.85
South West	5.8	9.9	15.8	0.37	0.95	0.92	5.4	10.4	0.34	0.96	0.95	1.2	14.6	0.08	0.84	0.83
All	66.0	103.0	169.0	0.39	1.00	1.00	60.1	108.9	0.36	1.00	1.00	15.3	153.7	0.09	1.00	1.00

[a] Incidence as a rate over study period.
[b] Likelihood compared to stock average ('All').
[c] Odds ratio of dwellings characteristic over stock average ('All').

Table 3
Logistic (probit) regression coefficients (as probabilities) representing the association between dwelling characteristics and installation of measures (major, fabric and heating) from 2002 to 2007.

Factors	Retrofits installed 2002–2007		
	Major retrofit $N = 168{,}988$	Fabric[a] retrofit $N = 168{,}988$	Heating retrofit[b] $N = 168{,}988$
	Coefficient estimate[*] (confidence limits at 95%)		
Intercept	−1.14 (−1.2, −1.07)	−1.49 (−1.56, −1.43)	−1.4 (−1.49, −1.31)
Dwelling type			
Terrace			
Semi detached	0.1[*] (0.08, 0.11)	0.28 (0.26, 0.3)	0.96 (0.93, 0.99)
Detached	0.38[*] (0.36, 0.4)	−0.06 (−0.09, −0.03)	0.14 (0.09, 0.18)
Flat, all	−0.05 (−0.08, −0.02)	0.1 (0.08, 0.12)	0 (−0.02, 0.03)
Dwelling age			
Pre-1900			
1900–49	0.4[*] (0.37, 0.43)	0.53 (0.5, 0.56)	−0.02 (−0.06, 0.02)
1950–66	0.43[*] (0.4, 0.46)	0.57 (0.54, 0.6)	−0.09 (−0.14, −0.05)
1967–75	0.87[*] (0.84, 0.9)	1.07 (1.04, 1.11)	−0.15 (−0.2, −0.11)
1976–82	0.5[*] (0.47, 0.54)	0.69 (0.65, 0.73)	−0.19 (−0.25, −0.14)
1983–90	0.36[*] (0.33, 0.4)	0.54 (0.5, 0.58)	−0.29 (−0.34, −0.24)
1990-post	0.57[*] (0.54, 0.6)	0.8 (0.76, 0.83)	−0.19 (−0.23, −0.14)
Household tenure			
Private rented			
Owner occupied	−0.13[*] (−0.15, −0.1)	−0.09 (−0.11, −0.06)	−0.31 (−0.35, −0.28)
Social rented	−0.19[*] (−0.22, −0.15)	−0.22 (−0.25, −0.19)	−0.12 (−0.16, −0.08)
Number of bedrooms			
1 Bedroom			
2 Bedrooms	0.31[*] (0.28, 0.34)	0.42 (0.39, 0.45)	0.04 (0, 0.08)
3 Bedrooms	0.37[*] (0.33, 0.4)	0.49 (0.45, 0.52)	0.03 (−0.01, 0.07)
4 Bedrooms	0.22[*] (0.19, 0.26)	0.35 (0.31, 0.39)	−0.15 (−0.2, −0.1)
5+ Bedrooms	0.44[*] (0.4, 0.49)	0.26 (0.21, 0.31)	0.43 (0.37, 0.48)
Government region			
South East			
East England	0.1[*] (0.08, 0.12)	0.09 (0.06, 0.11)	0.11 (0.08, 0.15)
East Midlands	0.13[*] (0.11, 0.16)	0.12 (0.1, 0.15)	0.15 (0.12, 0.19)
London	−0.13[*] (−0.16, −0.11)	−0.17 (−0.2, −0.14)	0.09 (0.05, 0.13)
North East	0.38[*] (0.35, 0.41)	0.39 (0.36, 0.42)	0.14 (0.1, 0.19)
North West	0.23[*] (0.21, 0.26)	0.25 (0.23, 0.27)	0.14 (0.1, 0.17)
South West	0(-0.03, 0.03)	0.02 (-0.01, 0.04)	−0.06 (−0.1, −0.02)
West Midlands	0.24[*] (0.22, 0.27)	0.24 (0.21, 0.26)	0.15 (0.11, 0.18)
Yorkshire and the Humber	0.05 (0.02, 0.07)	0.04 (0.01, 0.06)	0.16 (0.12, 0.19)
Median neighbourhood income quintile			
Quintile 1			
Quintile 2	−0.03 (−0.05, 0)	−0.01 (−0.04, 0.01)	−0.07 (−0.1, −0.03)
Quintile 3	−0.1[*] (−0.12, −0.07)	−0.06 (−0.09, −0.04)	−0.18 (−0.22, −0.14)
Quintile 4	−0.15[*] (−0.18, −0.13)	−0.11 (−0.14, −0.08)	−0.27 (−0.31, −0.23)
Quintile 5	−0.24[*] (−0.27, −0.21)	−0.18 (−0.22, −0.15)	−0.37 (−0.41, −0.32)
Neighbourhood rurality			
Rural or village hamlet			
Town and fringe	0.04 (0.01, 0.08)	0.03 (−0.01, 0.07)	0.05 (0, 0.1)
Urban > 10 K	0.05 (0.01, 0.08)	0.03 (−0.01, 0.06)	0.09 (0.05, 0.14)
Proportion of neighbourhood in receipt of benefit			
<33%			
33–66%	0.02 (0, 0.04)	0.02 (0, 0.04)	0.02 (−0.01, 0.06)
>66%	0.04 (−0.01, 0.08)	0.04 (−0.01, 0.08)	0.08 (0.02, 0.14)
Proportion of neighbourhood in receipt of pension			
≤10%			
>10%	0.03 (0.02, 0.05)	0.05 (0.03, 0.07)	−0.02 (−0.05, 0.01)

[a] Fabric retrofits include: cavity wall insulation, loft insulation, or double glazing installation.
[b] Heating retrofits include: boiler replacement, heating controls.
[*] Significant at the 95% confidence level.

have little overall effect. However, due to its low annual rate of change (i.e. ∼1%) it slightly reduces the magnitude.

When stratified by household tenure, the presence of an energy efficiency retrofit is significantly associated with changes in gas demand for owner-occupiers (Table 7). An analysis of variance using least squared means (due to the unbalanced nature of the design, i.e. uneven group sizes) showed no significant difference in the change in gas demand between tenure types (test not shown). However, the associated change in demand for owner-occupiers was higher than the stock averages shown in Table 6. Focusing on cavity wall insulation, socially rented dwellings show the lowest change in demand (∼−3%), while privately rented dwellings

Table 4
Regression coefficients (standard deviation) of gas demand per dwelling adjusting for selected dwelling, household and neighbourhood characteristics with and without fabric and heating retrofits.

Factors	Gas demand in 2006			
	Energy demand N = 168,988	Fabric[a] retrofit N = 168,988	Heating retrofit[b] N = 168,988	Heating and fabric retrofit[b] N = 168,988
	Coefficient estimate* (standard error)			
Sample mean	18400	18400	18400	18400
Intercept	22030* (216)	21800* (149)	21820* (149)	21850* (149)
Energy efficiency retrofit in 2005				
Fabric retrofit		−800* (60)		−460* (63)
No fabric retrofit		0		0
Heating retrofit			−1990* (96)	−1760* (101)
No heating retrofit			0	0
Dwelling type				
Detached	3950* (59)	4000* (59)	4120* (59)	4130* (59)
Semi-detached	1440* (51)	1450* (51)	1440* (51)	1450* (51)
Flat, all	−1990* (88)	−1990* (88)	−1960* (88)	−1970* (88)
Terrace	0	0	0	0
Dwelling age				
Pre-1900	3930* (95)	3900* (95)	3980* (95)	3950* (95)
1900–49	2630* (69)	2630* (69)	2680* (69)	2660* (69)
1950–66	1410* (71)	1410* (71)	1450* (71)	1440* (71)
1967–75	1100* (75)	1170* (75)	1120* (75)	1160* (75)
1976–82	−210 (94)	−200 (94)	−200 (94)	−190 (94)
1983–90	−1160* (88)	−1190* (88)	−1180* (87)	−1200* (87)
Post-1990	0	0	0	0
Dwelling tenure				
Owner occupied	1290* (62)	1270* (62)	1240* (62)	1240* (62)
Private rented	500* (96)	460* (96)	500* (96)	480* (96)
Social rented	0	0	0	0
Number of bedrooms				
1 Bedroom	−7320* (129)	−7360* (129)	−7400* (129)	−7420* (129)
2 Bedrooms	−6610* (102)	−6620* (102)	−6700* (102)	−6700* (102)
3 Bedrooms	−3960* (98)	−3960* (98)	−4050* (98)	−4040* (98)
4 Bedrooms	260 (102)	240 (102)	120 (103)	130 (103)
5+ Bedrooms	0	0	0	0
Government region				
East England	−2080* (83)	−2050* (83)	−2060* (83)	−2050* (83)
East Midlands	−1560* (86)	−1540* (86)	−1560* (86)	−1540* (86)
London	−1060* (89)	−1000* (86)	−980* (86)	−990* (86)
North East	800* (98)	840* (97)	800* (97)	820* (97)
North West	−440* (75)	−400* (75)	−420* (74)	−410* (74)
South East	−2170* (76)	−2160* (76)	−2170* (76)	−2170* (76)
South West	−3340* (84)	−3350* (84)	−3370* (84)	−3370* (84)
West Midlands	−1100* (83)	−1030* (83)	−1050* (83)	−1030* (83)
Yorkshire	0	0	0	0
Median neighbourhood income				
Quintile 1	−3210* (96)	−3010* (73)	−2970* (73)	−2960* (73)
Quintile 2	−2830* (74)	−2710* (67)	−2680* (67)	−2670* (67)
Quintile 3	−2390* (65)	−2350* (64)	−2330* (64)	−2330* (64)
Quintile 4	−1750* (62)	−1740* (61)	−1730* (61)	−1730* (61)
Quintile 5	0	0	0	0
Model R-square	0.242	0.242	0.243	0.243

[a] Fabric retrofits include: cavity wall insulation, loft insulation, or double glazing installation.
[b] Heating retrofits include: boiler replacement, heating controls.
* Significant at the 95% confidence level.

change the most (∼−8%). Changes in energy demand associated with condensing boiler installations are greatest for owner occupiers (∼−6%), while socially and privately rented dwellings show changes around −4%. The stratified change in gas demand associated with retrofits by dwelling age shows larger changes in gas demand for the 1967–75 group (see Table 8). Stratifying by neighbourhood income shows a more consistent trend with neighbourhoods in the lower-income quintile associated with on average lower changes in gas demand and higher incomes having greater changes (see Table 9).

5. Discussion

Using a cohort of gas-connected English dwellings, the study examined the associations between the uptake of energy efficiency retrofits (insulation, heating and draught proofing) over the period 2002–2007 and a number of dwelling features (type, age, size, region) and household characteristics (tenure, median neighbourhood income). The study tested: whether older dwellings, owner-occupied dwellings and low income dwellings were more likely to the have higher rates of energy efficiency retrofit uptake; and whether older dwellings and households living in lower income

Table 5
Regression coefficients (standard error) of change in gas demand (2005–2007) per dwelling adjusting for selected dwelling, household and neighbourhood characteristics with and without fabric and heating retrofits.

Factors	Change in gas demand from 2005 to 2007			
	Cavity insulation	Loft insulation	Double glazing installation	Condensing boiler replacement
	Coefficient estimate* (standard error)			
Model 1—unadjusted				
Intercept	−1456* (15)	−1456* (15)	−1456* (15)	−1456* (15)
Measure in 2006	−1107* (76)	99 (88)	40 (184)	−1055* (137)
No measure 2005–2007				
Model 2—fully adjusted[a]				
Intercept	−1497* (126)	−1525* (127)	−1524* (128)	−1496* (128)
Measure in 2006	−1047* (77)	153 (88)	−12 (183)	−1059* (138)
No measure 2005–2007				

[a] Adjusted for dwelling type, age, tenure, number of bedrooms, region and neighbourhood income quintile.
* Significant at the 95% confidence level.

Table 6
Regression coefficients (standard error) of proportional change in gas demand (2005–2007) per dwelling adjusting for selected dwelling, household and neighbourhood characteristics with and without fabric and heating retrofits.

Interventions[a]	*N*	Proportional change[c] in demand from 2005 to 2007 with measure in 2006	
		Gas	Gas + electricity
		Adjusted[b]	
		Coefficient estimate* (standard error)	
Cavity insulation	104,623	−0.049* (0.003)	−0.042* (0.003)
Loft insulation	103,615	0.009 (0.004)	0.008 (0.004)
Double glazing installation	101,391	0 (0.008)	0.003 (0.008)
Boiler installation	101,897	−0.055* (0.006)	−0.045* (0.006)
Cavity and loft insulation	102,661	−0.057* (0.005)	−0.052* (0.005)
Boiler, cavity and loft insulation	101,061	−0.112* (0.012)	−0.1* (0.011)
Glazing, boiler, cavity and loft insulation	100,771	−0.1 (0.033)	−0.131 (0.004)
Glazing, cavity and loft insulation	101,160	−0.034 (0.01)	−0.034 (0.01)
Glazing, boiler and loft insulation	100,778	−0.099 (0.014)	−0.104 (0.007)
Glazing and cavity wall insulation	101,474	−0.031[a] (0.008)	−0.019 (0.007)

[a] Adjusted for dwelling type, age, tenure, number of bedrooms, region and neighbourhood income decile.
[b] Intercept not shown.
[c] Divide by 100 for %.
* Significant at the 95% confidence level.

Table 7
Regression coefficients (standard error) of proportional change in gas demand (2005–2007) per dwelling by household tenure, adjusting for selected dwelling, household and neighbourhood characteristics with and without fabric and heating retrofits.

Interventions[b] in 2006	Proportional change[c] in gas demand from 2005 to 2007		
	Household tenure		
	Owner occupied	Private rented	Social rented
	Coefficient[a] estimate* (standard error)		
Cavity insulation	−0.053* (0.004)	−0.076 (0.026)	−0.03 (0.009)
Sample size *n*=	83,122	6280	15,221
Loft insulation	0.003 (0.004)	0.008 (0.023)	0.034 (0.011)
Sample size *n*=	82,271	6302	15,042
Double glazing installation	0.008 (0.009)	−0.048 (0.047)	−0.016 (0.02)
Sample size *n*=	80,547	6216	14,628
Boiler installation	−0.063* (0.008)	−0.043 (0.028)	−0.041 (0.013)
Sample size *n*=	80,759	6271	14,867

[a] Adjusted for dwelling type, age, number of bedrooms, region and neighbourhood income quintile.
[b] Intercept not shown.
[c] Divide by 100 for %.
* Significant at the 95% confidence level.

neighbourhoods had lower than average energy savings. In the following, the dwelling and household determinants of energy efficiency retrofits and of energy savings are discussed along with the implication the findings have on providing packages of energy efficiency retrofits and in shaping energy policy.

5.1. Determinants of energy efficiency retrofits uptake

Owner-occupied, 3 bedroom detached dwellings built in the mid-20th century in areas of lower neighbourhood income in the northern English regions were associated with a higher probability

Table 8
Regression coefficients (standard error) of proportional change in gas demand (2005–2007) per dwelling by dwelling age, adjusting for selected dwelling, household and neighbourhood characteristics with and without fabric and heating retrofits.

Interventions[b] in 2006	Proportional change[c] in gas demand from 2005 to 2007						
	Dwelling age						
	Pre-1900	1900–1949	1950–1966	1967–1975	1976–1982	1983–1990	Post-1990
	Coefficient[a] estimate[*] (standard error)						
Cavity insulation	−0.06 (0.053)	−0.035[*] (0.008)	−0.029[*] (0.007)	−0.072[*] (0.006)	−0.04 (0.011)	−0.015 (0.013)	−0.054[*] (0.011)
Sample size *n*=	7258	31,762	23,857	15,056	6800	8563	11,327
Loft insulation	−0.012 (0.019)	0.015 (0.008)	0.013 (0.009)	0.007 (0.007)	0.019 (0.017)	0.004 (0.016)	−0.002 (0.012)
Sample size *n*=	7374	31,907	23,527	14,446	6580	8491	11,290
Double glazing installation	−0.018 (0.035)	0.018 (0.014)	−0.013 (0.016)	−0.05 (0.029)	0.002 (0.033)	0.025 (0.025)	−0.008 (0.025)
Sample size *n*=	7281	31,341	23,213	13,602	6476	8404	11,074
Boiler installation	−0.058 (0.022)	−0.037 (0.011)	−0.055[*] (0.011)	−0.092[*] (0.019)	−0.112[*] (0.025)	−0.054 (0.022)	−0.035 (0.025)
Sample size *n*=	7349	31,491	23,390	13,668	6502	8423	11,074

[a] Adjusted for dwelling type, tenure, number of bedrooms, region and neighbourhood income quintile.
[b] Intercept not shown.
[c] Divide by 100 for %.
[*] Significant at the 95% confidence level.

Table 9
Regression coefficients (standard error) of proportional change in gas demand (2005–2007) per dwelling by neighbourhood income quintile, adjusting for selected dwelling, household and neighbourhood characteristics with and without fabric and heating retrofits.

Interventions[b] in 2006	Proportional change[c] in gas demand from 2005 to 2007				
	Quintile ranking of neighbourhood income				
	Rank 0	Rank 1	Rank 2	Rank 3	Rank 4
	Coefficient[a] estimate[*] (standard error)				
Cavity insulation	−0.039[*] (0.008)	−0.051[*] (0.008)	−0.049[*] (0.007)	−0.055[*] (0.008)	−0.056[*] (0.008)
Sample size *n*=	19,708	20,586	21,105	21,373	21,851
Loft insulation	0.018 (0.009)	0.001 (0.009)	0.008 (0.009)	0.012 (0.009)	0.001 (0.009)
Sample size *n*=	19,541	20,412	20,792	21,135	21,735
Double glazing installation	0.011 (0.021)	0.024 (0.018)	−0.039 (0.018)	−0.013 (0.019)	0.013 (0.015)
Sample size *n*=	18892	19,930	20,383	20,757	21,429
Boiler installation	−0.01 (0.013)	−0.053[*] (0.013)	−0.057 (0.016)	−0.081[*] (0.015)	−0.105[*] (0.013)
Sample size *n*=	19,087	20,075	20,429	20,822	21,484

[a] Adjusted for dwelling type, tenure, number of bedrooms, and region.
[b] Intercept not shown.
[c] Divide by 100 for %.
[*] Significant at the 95% confidence level.

of having measures. This reflects both the nature of the measures (i.e. older more inefficient homes), the ability to accept or undertake measures, and being the target of government programs.

The uptake model found that as neighbourhood incomes increased, the probability of having a major measure installed over the study period decreased, offering further support that households living in areas marked by higher incomes are not investing in their property compared to low-income areas that are the focus of government policy, therefore supporting the hypothesis (H1) that low-income households are more likely to receive and accept energy efficiency retrofits. Broadly speaking, ownership and income remain important determinants of having energy efficiency retrofits.

The findings supports the notion that there is a lack of investment by owner occupiers but ultimately rejects the hypothesis that people who own their home receive and accept more measures than other tenure types (H2). However, the finding is not necessarily suggesting that this household type is a driver of uptake, but rather reflects the investment in energy efficiency for vulnerable customers through supplier obligation (which comprise the bulk of the interventions in England) and government schemes over the study period [32], and interest [17].

Older dwellings were less likely than the stock average to have reported retrofits during the study period. The model showed an inverted 'U-shape' curve for the uptake of fabric retrofits, with both older (and in theory less efficient) and newer dwellings not having insulation installed, and with dwellings built in the 1967–75 and 1976–82 age bands having the highest probability of retrofits over the period. This was particularly the case for fabric measures and the high uptake rates of cavity wall insulation. This finding rejects the notion that older dwellings are more likely to have energy efficiency measures (H3). While older dwellings may be relatively more inefficient and are therefore in greater 'need' of retrofits that improve the fabric, the finding points to the nature of the insulation needed. Older English dwellings are more likely to be constructed of solid brick or stone and that means 'cheap' insulation techniques such as blown insulation in cavity walls is not a viable option. Both the supplier and government programs excluded insulation for solid-walled dwellings.

5.2. Determinants of energy savings

Introducing energy efficiency retrofits resulted in attributable energy savings, after controlling for the effects of dwelling type, size, age, tenure, region and neighbourhood income. The retrofit associated with the largest change in (adjusted) energy demand over the three-year period was the installation of a condensing gas boiler, −5.2%, with the second largest being cavity wall insulation at around −3.8%. The effect of the combined installation of a condensing boiler, and cavity and loft insulation was around −11%. These findings are very similar in scale to results from a previous study of British houses under the Warm Front scheme, which found that loft and full cavity wall insulation reduced demand within a one-year period by 10–17% [36]. While the change in energy demand associated with the retrofit are lower compared to notional 'savings' or the Hong et al. study, it is important to bear in mind that these changes control for physical, household and area-based factors. The effect of controlling for physical factors on energy 'savings' means that the effect of number and area of exposed walls is removed as is any effect related to the age of the dwelling, while household effects could reflect ability to afford larger areas to heat and greater comfort conditions. By controlling for these factors, the effect of the retrofit can be isolated, which is important for determining a 'baseline' of expected change in demand on which future estimates could rely.

After adjustment, neither loft insulation or double glazing were associated with significant energy savings over the three-year period. In these cases, it may be that the effect is on average fairly small and/or cannot easily be detected using annualised energy data. Although glazing is one of the thermally weakest elements of the building fabric, the area of double glazing replaced will have an effect on the potential energy savings. However, because of the way the data was reported, it was not possible to account for glazing area replaced. The majority of loft insulations were top-ups of around 5–75 mm and therefore the change in gas demand would be minimal.

There are differences in the savings associated with certain household/dwelling groups. Dwelling age appears to have an inconsistent effect on changes in gas demand, with the 1967–75 group having much greater reduction in demand for all single retrofit measures compared to other age bands. It is not necessarily the case, therefore, that older dwellings are less likely to have greater energy savings than newer dwellings (H4). The variation may in part be explained by the eligibility and type of retrofits installed. Cavity wall filling is most applicable to mid-century and onward dwelling age bands, with few being applicable to pre-1950 or post-1990 dwellings. The impact of boilers among this mid-century group was also greater (after controlling for size), which could reflect a number of building design features, such as the nature of the installed heating systems which according to the 2011 EHS have a higher prevalence of gas central heating [37].

Changes in energy demand were lower among households with low socio-economic levels, such as renting or living in areas of lower income, therefore supporting the hypothesis that lower incomes are less likely to realise energy savings compared to higher-income households (H5). This trend may be attributed to these households have higher levels of energy utility (i.e. greater need for the amount used) [16]. Both social renting and living in lower income neighbourhoods is associated with reduced energy demand, even after controlling for type and age of dwelling (Table 4), which may also suggest that these households have a greater potential for increasing demand that energy efficiency retrofits enable. The differences could also be construed as 'comfort taking', whereby these households in areas of lower income reduce the potential 'energy savings' by taking the savings in the form of temperature increases, an effect that has been shown in a study of vulnerable households in England [35].

5.3. Whole-house retrofit packages

The impact of energy efficiency retrofits, after adjustment for physical and household factors, demonstrated a dose–response effect whereby combined packages of retrofits was associated with increasing changes in energy demand. Larger increases in reductions in gas demand were associated with boilers and cavity wall insulation, with only minor additional effects from lofts and glazing. The largest change in gas demand was associated with the combined installation of a condensing boiler, and cavity and loft insulation at −10.8%. Although not always statistically significant, when combined the changes in energy demand were generally greater than additive, e.g. the individual change attributable to cavity insulation (−3.8%) and condensing boiler installation (−5.2%) and loft insulation (1.2%) ought to result in a change of −7.8%, but was instead greater (though in some other combinations less). The findings point to the potential impact that undertaking deep retrofits could have on energy demand. Combining retrofits into single package may have benefits in achieving energy demand reduction and potential cost-savings of installation (e.g. wall scaffolding is only set up once). It may also be that there is a 'take-back' threshold after which rebound related to thermal comfort is lessened (i.e. the potential rebound has been met).

A 'whole-house' retrofit package delivered to all homes in England is needed in order realise the potential energy savings set out in the DECC energy efficiency strategy. If an average energy savings of 10% (e.g. ∼2300 kWh reduction) were achieved from the average UK dwelling, it would take approximately 9,565,000 'whole-house' retrofits to achieve the estimated 22 TWh of energy savings by 2020, which is equivalent to retrofitting 40% of UK dwellings. To achieve a 10% reduction in 2006 levels by 2020 (i.e. 54 TWh) through energy efficiency alone would take the equivalent of every home in the UK being refurbished (i.e. 23,500,000). Although further efficiencies may be gained from water heating and appliances, space-heating related energy comprises the bulk of residential demand and therefore should remain a high priority under government policy. Achieving these savings is an enormous task that will require a significant increase in historical rate of retrofit uptake. However, this research shows that these savings are achievable using widely available technologies and insulating techniques that rely on an existing deployment system and skill base.

5.4. Implications for energy efficiency policy

There is a strong historic track record in the UK of policy helping to improve the energy efficiency of dwellings occupied by vulnerable and low-income households. However, future policies will need to address the gap in the uptake of retrofits among older, owner occupied dwellings in areas of higher incomes. This middle-income household group also use more energy on average, after controlling for home size, age and type, and thus the potential impact on absolute energy savings is greater. However, the shift in government policy toward encouraging middle-income households to self-invest in their dwelling's energy efficiency has faced an uphill struggle. For example, the UK Government's Green Deal prioritised self-investment by providing access to upfront capital and a payback process that assured the cost of the retrofit would be equal to the notional savings, known as the 'golden rule' [38]. The policy, however, failed to reach anywhere near its target and was closed in mid-2015. While this research suggests that the Green Deal was broadly targeting the right household groups and dwelling types (i.e. those with historically lower uptake rates), the low retrofit take up suggests that the Green Deal was not addressing actual barriers to uptake or exploiting the motivations of the targeted household groups. A recent survey found that most households considering energy efficient retrofits were doing so for reasons that related to amenity renovations and not for energy savings alone; that energy efficiency retrofitters were a select group more likely to be older, owner-occupier homes with few dependants; and that emergency repairs was a strong trigger for retrofitting existing systems [39]. Given the size and potential of this group, barriers around the cost of financing and trigger points could be addressed to potentially improve uptake.

There is good evidence to show that notional energy savings are rarely achieved in reality. As such, government policymakers tend to take an approach of 'factoring' estimated savings in order to reflect this shortfall. However, this introduces a number of complications: first, using modelled estimates of energy demand will inevitably fail to be representative of actual demand and therefore savings [5]; second, the using factors should not penalize potential savers or undermine the potential payback of the retrofit. Instead, it would be preferable to directly use empirical data to estimate energy savings that reflects a number of socio-technical factors, such as those in this study. In doing so, it would be possible to provide more accurate estimates of energy savings for individual households (with appropriate uncertainty bands) and more widely for the housing stock.

5.5. Strengths and weaknesses

The study relies on reported retrofits drawn from a number of programs over the study period collected by the Energy Saving Trust into the Home Energy Efficiency Database. Whilst EST undertook precautions to check data for erroneous entries and applied 'trust' flags to data from different suppliers (i.e. accredited installers and surveyors were more trusted than web-based surveys), using this data means that it is not possible to verify the accuracy of the reported data. This could mean that some homes may have reported some retrofits when none were installed (or vice versa). However, it was assumed in this study that such events would likely occur randomly (i.e. without systematic bias) because of the number of data providers and the low theoretical probability of installers, assessors and homeowners consistently mis-reporting the same class of retrofit. Also, many retrofits require specialist installers (cavity wall insulation and double glazing installation) and are regulated (i.e. condensing boiler and double glazing installation).

Another potential weakness are changes in energy performance standards related to the installed retrofits. However, the findings from this research are still broadly applicable to present day interventions being installed. In the UK the regulations governing retrofits ('Part L1 B—Conservation of fuel and power in existing buildings') were updated in 2006 (from 2003), 2010 and 2013. The analysis on the impact of the retrofits in 2006 would be subject to the 2006 regulations and while the changes in the 2010 regulations did seek to build on the 'minimum standards' of energy performance (as set out for new buildings), they maintained considerable flexibility.

In terms of the representativeness, the study sample was drawn to be representative of six key English dwelling and household variables, including: dwelling age, type, number of bedrooms, and age, the region and household tenure, it means that sample cannot necessarily represent other non-sampled variables, particularly as they related to the household (e.g. occupants or income levels). The study should only be used for the purposes of describing the housing stock and not the households therein. Finally, within the English dwelling stock, households will move, split, grow and cease. Such changes could have an impact on these results but are assumed to occur randomly and are expected to be small. The cohort design of the study allows for these effects within English dwellings because of the representative sampling strategy and through the size of the sample.

6. Conclusions

This study has shown that it is possible to construct a robust cohort sample from pre-existing datasets that is broadly representative of the English housing stock and to use population level analysis techniques to assess the take up of energy efficiency retrofits and the impact of these interventions on energy demand over a defined study period. This study provides a step toward a more robust empirically-based population-level approach to studying energy demand that accounts for variation among different dwelling and household groups. The method emphasises associations, rather than causation, as a means for generating hypotheses that can be further explored in more detailed studies.

Energy efficiency retrofits do have an attributable impact on reducing space-heating related energy demand and that combining retrofits displays a dose–response like effect on energy demand, after controlling for household and dwelling factors. In order to meet the intended energy efficiency targets, the retrofit take up rate will need to significantly increase. Meeting these uptake and energy savings targets can be broadly achieved using existing technologies and deployment process.

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Appendix A. : LSOA level variables

See Table A1.

Table A1
List of datasets and variables (with geographic levels) used in the energy efficiency uptake analysis in England for the period 2000–2007.

Dataset	Source	Level	Year	Variables used	Measurement	Description	Reference
Mid-2005 population estimates, all persons	Office for National Statistics	LSOA	2005	'0–15', '16–29', '30–44', '45–64 Males & 45–59 Females', '65+ Males & 60+ Females'	Estimate of number of persons	Dataset of the number of persons by age bands and sex for England. The estimates are made using the Kannisto–Thatcher method, based on modified survival ratios for the population	[40]
Benefits data: summary statistics	Office for National Statistics	LSOA	2005	'Disability Living Allowance', 'Incapacity Benefit/Severe Disablement Allowance', 'Income Support', 'Jobseekers Allowance', 'Pension Credit'	Count of claimants (persons)	Dataset of summary statistics from Department of Work and Pensions covering benefit claims during the period of August 2005	[29]
Median household income	Experian	LSOA	2004	'Median income'	Estimate of median LSOA level income	Dataset of median income levels of households in an LSOA estimated by Experian using a multi-stage modelling approach	[41]
Heating degree days	Met office	LSOA	2005	'Heat degrees'	Estimate of the annual average degrees below 15.5 in °C.	Dataset of annual sum of heating degrees below 15.5 °C over a $5 \times 5\,km^2$ grid of England. Data are converted to LSOA by an overlay and averaging of the grid points	[42]
Dwelling stock by council tax band	Office for National Statistics	LSOA	2005	'Band A' to 'Band H' for England	Count of domestic properties	Dataset of the number of domestic properties in council tax bands provided by the Valuation Office Agency, covering 23,101,020 dwellings in England	[29]

Appendix B. : EHS sampling frame

See Tables B1 and B2.

Table B1
EHS sample frame variables recoding for HEED selection.

EHS variable	EHS categories	HEED category
Dwelling type (dwtypenx)	End terrace, mid terrace	Terrace (end and mid)
	Semi-detached	Semi-detached
	Detached, bungalow	Detached (inc. bungalows)
	Converted flat, purpose built flat (low and high rise)	Flats (all types)
Dwelling age (dwage9x)	Pre-1850, 1850–1899	Pre-1900
	1900–1918, 1919–1944	1900–1944
	1945–1964	1950–1966
	1965–1974	1967–1975
	1975–1980	1976–1982
	1981–1990	1983–1990
	Post-1990	Post-1990
Number of bedrooms (nbedsx)	1 Bedroom	1 Bedroom
	2 Bedroom	2 Bedroom
	3 Bedroom	3 Bedroom
	4 Bedroom	4 Bedroom
	≥5 Bedroom	5+ Bedroom
Government office regions (gorehs)	North East	North East
	North West	North West
	Yorkshire and the Humber	Yorkshire and the Humber
	East Midlands	East Midlands
	West Midlands	West Midlands
	East	East
	London	London
	South East	South East
	South West	South West
Household tenure (tenure4x)	Owner occupied	Owner occupied
	Private rented	Private rented
	Local authority, registered social landlord	Social or local authority rented

Table B2
Comparison between source data (HEED + Energy), EHS data and HEED study sample.

	HEED + Energy		2011 EHS (full weighted dataset)		HEED study sample	
	Frequency	Percent	Frequency	Percent	Frequency	Percent
Dwelling type						
Terrace	424,079	21.47	5,872,437	31.32	51,264	30.33
Semi detached	660,698	33.46	5,194,761	27.71	53,565	31.70
Detached	757,739	38.37	4,907,771	26.18	48,107	28.47
Flat, all	132,284	6.70	2,771,945	14.79	16,062	9.50
Frequency missing = 1,243,037						
Dwelling age						
Pre-1900	65,358	4.30	2,088,451	11.14	11,237	6.65
1900–49	401,360	26.41	5,137,574	27.40	49,489	29.28
1950–66	267,347	17.59	4,002,610	21.35	38,450	22.75
1967–75	346,591	22.81	2,647,092	14.12	26,355	15.59
1976–82	103,696	6.82	1,171,748	6.25	10,671	6.31
1983–90	77,799	5.12	1,507,953	8.04	13,497	7.99
Post-1990	257,528	16.95	2,191,486	11.69	19,299	11.42
Frequency missing = 1,698,158						
Household tenure						
Owner occupied	1,370,498	78.01	12,983,750	69.26	130,403	77.16
Private rented	128,607	7.32	2,717,408	14.50	10,096	5.97
Social rented	257,717	14.67	3,045,756	16.25	28,499	16.86
Frequency missing = 1,461,015						
Number of bedrooms						
1 Bedroom	116,051	6.95	1,947,798	10.39	10,586	6.26
2 Bedrooms	359,325	21.52	4,757,929	25.38	38,886	23.01
3 Bedrooms	840,557	50.33	8,372,237	44.66	84,243	49.85
4 Bedrooms	194,227	11.63	2,911,931	15.53	27,886	16.5
5+ Bedrooms	159,884	9.57	757,019	4.04	7397	4.38
Frequency missing = 1,547,793						

Table B2 (*Continued*)

	HEED + Energy		2011 EHS (full weighted dataset)		HEED study sample	
	Frequency	Percent	Frequency	Percent	Frequency	Percent
Government office region						
North East	278,986	8.67	1,045,135	5.57	9710	5.75
North West	422,740	13.14	2,724,241	14.53	25,633	15.17
Yorkshire and the Humber	441,648	13.72	2,032,134	10.84	18,962	11.22
East Midlands	310,359	9.64	1,644,482	8.77	14,424	8.54
West Midlands	288,355	8.96	1,976,435	10.54	16,757	9.92
East England	352,260	10.95	1,894,819	10.11	17,257	10.21
London	325,643	10.12	2,711,469	14.46	22,352	13.23
South East	509,342	15.83	2,998,696	16.00	28,139	16.65
South West	288,504	8.97	1,719,503	9.17	15,764	9.33

Appendix C. : Detailed proportional change models

See Table C1.

Table C1
Proportional change in gas demand from 2005 to 2007.

Factors	Cavity insulation N = 106,753	Loft insulation N = 105,759	Double glazing installation N = 103,478	Condensing boiler replacement N = 104,014
	Coefficient estimate[a] (standard error)			
Model 1—unadjusted				
Intercept	−0.074[a] (0.001)	−0.074[a] (0.001)	−0.074[a] (0.001)	−0.074[a] (0.001)
Measure in 2006	−0.052[a] (0.003)	0.006 (0.004)	0.001 (0.008)	−0.056[a] (0.006)
No measure 2005–2007				
Model 2—fully adjusted[b]				
Intercept	−0.063[a] (0.005)	−0.064[a] (0.005)	−0.064[a] (0.005)	−0.063[a] (0.005)
Measure in 2006	−0.049[a] (0.003)	0.009 (0.004)	0 (0.008)	−0.055[a] (0.006)
No measure 2005–2007				
Dwelling type				
Detached	−0.002 (0.002)	−0.002 (0.002)	−0.001 (0.002)	−0.002 (0.002)
Semi detached	0.003 (0.003)	0.004 (0.003)	0.004 (0.003)	0.003 (0.003)
Flat, all	−0.001 (0.002)	−0.001 (0.002)	0 (0.002)	0 (0.002)
Terrace				
Dwelling age				
1900-pre	−0.003 (0.002)	−0.002 (0.002)	−0.003 (0.002)	−0.003 (0.002)
1900–49	0.003 (0.003)	0.003 (0.003)	0.003 (0.003)	0.003 (0.003)
1950–66	−0.001 (0.002)	−0.001 (0.002)	−0.002 (0.002)	−0.002 (0.002)
1967–75	−0.009 (0.003)	−0.007 (0.003)	−0.007 (0.003)	−0.007 (0.003)
1976–82	−0.008 (0.003)	−0.008 (0.003)	−0.009 (0.003)	−0.009 (0.003)
1983–90	0.004 (0.003)	0.003 (0.003)	0.003 (0.003)	0.003 (0.003)
Dwelling tenure				
1990-post				
Owner occupied	0 (0.002)	0 (0.002)	0.001 (0.002)	0 (0.002)
Private rented	−0.004 (0.003)	−0.004 (0.003)	−0.003 (0.003)	−0.004 (0.003)
Social rented				
No. bedrooms				
1 Bedroom	−0.002 (0.005)	0 (0.005)	0 (0.005)	−0.002 (0.005)
2 Bedrooms	−0.002 (0.004)	0 (0.004)	−0.001 (0.004)	−0.002 (0.004)
3 Bedrooms	−0.003 (0.004)	−0.002 (0.004)	−0.003 (0.004)	−0.004 (0.004)
4 Bedrooms	−0.003 (0.004)	−0.001 (0.004)	−0.002 (0.004)	−0.002 (0.004)
5+ Bedrooms				
Region				
East England	0 (0.003)	0 (0.003)	−0.001 (0.003)	−0.001 (0.003)
East Midlands	−0.005 (0.003)	−0.005 (0.003)	−0.005 (0.003)	−0.005 (0.003)
London	0.002 (0.003)	0 (0.003)	0.001 (0.003)	0 (0.003)
North East	0.002 (0.003)	0.002 (0.003)	0.003 (0.004)	0.002 (0.004)
North West	0.001 (0.003)	−0.001 (0.003)	0 (0.003)	−0.001 (0.003)
South East	0.011[a] (0.003)	0.01[a] (0.003)	0.01 (0.003)	0.01 (0.003)
South West	−0.011[a] (0.003)	−0.011[a] (0.003)	−0.012[a] (0.003)	−0.012[a] (0.003)
West Midlands	0.002 (0.003)	0.001 (0.003)	0.001 (0.003)	0.001 (0.003)
Yorkshire				
Income quintiles				
Quintile 1	−0.013[a] (0.002)	−0.013[a] (0.002)	−0.013[a] (0.003)	−0.012[a] (0.003)
Quintile 2	−0.01[a] (0.002)	−0.011[a] (0.002)	−0.01[a] (0.002)	−0.01[a] (0.002)

Table C1 (*Continued*)

Factors	Cavity insulation N = 106,753	Loft insulation N = 105,759	Double glazing installation N = 103,478	Condensing boiler replacement N = 104,014
	Coefficient estimate[a] (standard error)			
Quintile 3	−0.007 (0.002)	−0.008 (0.002)	−0.008 (0.002)	−0.007 (0.002)
Quintile 4	−0.003 (0.002)	−0.003 (0.002)	−0.003 (0.002)	−0.003 (0.002)
Quintile 5				

[b]Adjusted for dwelling type, age, tenure, number of bedrooms, region and neighbourhood income decile.

[a] Significant at the 95% confidence level.

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