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Little detailed evidence has previously been available regarding the uptake rate or prevalence of energy efficiency interventions among specific household groups. This study uses the Home Energy Efficiency Database (HEED) to investigate both the combination of measures that have been installed, and in which dwellings, according to key neighbourhood socio-demographic variables, including income and tenure. Analysis of 2000–07 data indicates that approximately 40% (9.3 million) dwellings in England had approximately 23.7 million efficiency measures installed, with an average of 2.5 measures per dwelling. Building fabric-related measures were the most frequent (*e.g.* cavity wall insulation, loft insulation and glazing) with an average of 2.1 million installed each year. Dwellings with the highest number of fabric interventions (the top 20%) were more likely to be found in areas with low income, with more owner-occupied dwellings, experiencing lower winter temperatures, having a lower proportion of flats, and having a slightly higher proportion of older adults and children. Energy efficiency installations have tended to occur among specific types of households or parts of the building stock. These findings have implications for the design of future government programmes for targeting energy efficiency measures to specific household groups or dwelling types.

Keywords building stock, demographics, dwellings, energy efficiency, energy epidemiology, housing, policy impacts, retrofit, uptake

Introduction

Energy efficiency improvements in UK homes are a major part of the Government's decarbonization plans, which call for millions of retrofits to take place in the housing stock over the coming two decades under pathways set out by the UK Committee on Climate Change (UK CCC, 2010). These proposals broadly seek a 20% reduction in heating-related energy demand in the existing housing stock by 2030. As part of meeting these targets, the UK CCC mitigation pathways identify the need to insulate more than 7.5 million lofts, 4.6 million cavity walls and 3.3 million solid walls, and to complete 1.9 million double-glazing upgrades by 2030 (UK CCC, 2010).

Energy efficiency measures in the UK have historically been primarily delivered by government-backed schemes and supplier obligation programmes (which set targets for energy suppliers) (Mallaburn & Eyre, 2014; Rosenow, 2012). However, to deliver projected energy efficiency measures in the future, the UK government has proposed a combination of market-based and government-regulated interventions, under the 'Green Deal' and the 'Energy Company Obligation' (DECC, 2012). The market-based approach used by the Green Deal intends to grow the retrofit market by enabling private sector companies to offer energy efficiency measures to homeowners. The key enabling mechanism of the scheme is that the upfront cost of the measure is not borne by the homeowner but by the investment provider, who then subsequently recoups the investment through the electricity bill. In theory, the energy savings that occur following the refurbishment are used to pay back the measure, but that the added charge is not greater than the expected saving from the retrofit. This constraint on allowable investments is known under the programme as the 'Golden Rule'. The government acknowledges that there are dwellings and households where this market-based approach may not deliver the savings required, in particular those homes that require very expensive efficiency measures (*e.g.* solid-wall dwellings) that may not meet the ‘Golden Rule’, areas of low-income and rural areas, or households that currently struggle to heat their homes adequately, such as households on benefits. Instead, these groups will be targeted through the Energy Company Obligation (ECO), which requires energy companies to deliver energy efficiency measures (OFGEM, 2013).

The Green Deal represents a shift in emphasis towards delivering energy efficiency measures through private sources of funding (albeit through a government-backed scheme) for non-vulnerable or non-priority households. ECO is a more traditional approach, placing obligations on energy companies to target hard-to-treat homes and vulnerable customers.

The retrofit challenge is enormous in terms of the sheer number and range of interventions proposed. Meanwhile there is a pressing need to respond to other issues related to energy efficiency such as social welfare, health and well-being, and energy security. It is suggested that insight into the future of retrofit in the UK may be gained by examining historical rates of uptake.

Uptake of energy efficiency measures

A range of social, institutional, personal and physical factors influence the uptake or adoption of energy efficiency measures by households. Using interviews of approximately 200 persons, Pelenur & Cruickshank (2012) identified barriers related to uptake in dwellings that included beliefs and social norms, household practices and characteristics, upfront costs, perception of institutions (*e.g.* government or energy suppliers), the landlord–tenant split incentives, and the characteristics of the property itself. Other factors, such as past government policies and targets, hidden costs, market shape and broader fiscal issues such as economic performance and taxation have also been cited as drivers influencing the uptake of measures in housing (Mallaburn & Eyre, 2014; Mills & Schleich, 2012).

Earlier research on the uptake of energy efficiency in English dwellings identified that factors that affected adoption were related to households’ awareness and access to programmes, and their ability to invest, along with uncertainty about the energy or financial savings following a measure (Brechling & Smith, 1994). Using empirical data from the 1986 English House Condition Survey (EHCS) and focusing on loft and wall insulation and double-glazing installation, Brechling & Smith (1994) found that tenure played an important role in the uptake of measures (*i.e.* there were fewer efficiency features in privately rented than in owner-occupied dwellings), but that income level had only a small effect on adoption, which they proposed was related to previous government policies focusing on low-income households. This approach was extended in recent work by Tovar (2012) who made use of the 2003–07 EHCS (in 2007 the EHCS changed to the English Housing Survey – EHS) to assess the uptake energy efficiency measures, including cavity wall and loft insulation and boiler upgrades. Tovar also investigated the influence of characteristics of the dwelling (*e.g.* age and type), household (*e.g.* age, income, household formation) and occupancy (*e.g.* length of residence). Tovar found that these occupancy factors had an important impact on the investment in (or uptake of) efficiency measures.

Historically, the main mechanism through which energy efficiency measures have been delivered in English dwellings has been through government-backed programmes and supplier obligations (Dowson, Poole, Harrison, & Susman, 2012; Mallaburn & Eyre, 2014; Rosenow, 2012). In a recent review of the evolution of the UK’s supplier obligations since their inception in 1994, Rosenow (2012) sets out how the obligations were initially conceived to stimulate the efficient use of energy for reasons of economic productivity in the newly deregulated energy market, but how they evolved over time to be the main mechanism by which to tackle issues of climate change, energy costs and fuel poverty. Further, in an extensive review of UK energy efficiency policy from 1973 to 2013, Mallaburn & Eyre (2014) highlight the role that policy has had on uptake of interventions in the building stock. In their discussion they point out that the most effective policies (*i.e.* those that have been adopted and achieved a high rate of uptake) are a fine balance between market support and government intervention. Mallaburn and Eyre conclude that access to capital and the conditions under which it is made available are important, with loans being less expensive for government compared with grants, but requiring higher levels of occupant income to support their use. Obligations can also be effective at meeting uptake targets but give rise to issues in the distribution of subsidies.

It is well established that the drivers of energy efficiency in the UK encompass physical characteristics of the dwellings, household-level practices, institutional delivery mechanisms and policy priorities, along with the wider fiscal and environmental context. While the analysis reported in the literature makes use of temporal survey data to assess the relationship of these drivers with energy efficiency uptake in English dwellings, what is missing is any geographical investigation of these effects to show how local features may be associated with higher or lower levels of uptake. The research question asked in this study is therefore: what combinations of physical (dwelling), social (household), and environmental (geographical) characteristics and delivery mechanism are statistically associated with the uptake of energy efficiency measures under a range of programmes during the last decade?

This paper focuses on two related metrics of uptake of energy efficiency retrofits in the dwelling stock: incidence and prevalence. Incidence is the rate at which new reported installations of an efficiency measure occur in the housing stock during a specified time period (*e.g.* new cases reported annually). Prevalence is the proportion of the housing stock with a reported efficiency feature at a given point in time (*e.g.* in 2007). The metrics, often associated with health-related studies, offer an approach for examining associations between socio-demographic and physical characteristics seen in the population and changes in energy efficiency levels of the housing stock.

A longitudinal ecological study design was selected for this research, which is a means for investigating differences between populations, or for studying group-specific effects through the use of aggregated data. The analysis presented in this paper uses a national database of reported energy efficiency measures to describe the level of uptake of retrofit measures from 2000 to 2007, the period for which data were available for study, with a focus on England. The first part of the study provides background on historical energy efficiency programmes in England. The second part assesses the coverage of the energy efficiency database by comparing the reported uptake of measures with estimates of uptake using a series of national housing surveys over the same period. The third part investigates the relationship between the uptake rate of energy efficiency measures and a selection of household features at the neighbourhood level, which the literature suggests may be influential variables in this context. The aim of the work is: (1) to describe the uptake of energy efficiency in (and across) English dwellings from 2000 to 2007; and (2) to investigate the differences in uptake across England by programme type and measure, and their association with neighbourhood, dwelling and household characteristics.

Energy efficiency intervention programmes

During the period of interest, 2000–07, the UK government had a number of programmes aimed at providing energy efficiency retrofits to dwellings. In England, these were the Energy Efficiency Commitments 1 and 2 (EEC 1 & 2, 2002–08), Warm Front (launched in 2000 and ended in January 2013), and the Energy Efficiency Standards of Performance 3 (EESoP 3, 2000–02). The aim of Warm Front was to reduce the risk of ill-health for vulnerable households due to cold, damp homes, *i.e.* households with children, pregnant women, people with disabilities and long-term illness, and elderly households on certain types of benefits (EAGA, 2004). The EESoP 3 scheme also focused on disadvantaged customers (*i.e.* low income, elderly or in debt) with an expectation that two-thirds of the energy companies' expenditure on energy efficiency measures would be directed towards these households (Ofgem & Energy Saving Trust, 2003). EEC 1 & 2 required that delivery targets for 50% of the energy efficiency savings were focused on priority groups (*i.e.* those in receipt of particular benefits and tax credits). During this period, revisions to the Building Regulations of England & Wales (2002 and 2006) required refurbishments to comply with higher building fabric standards (walls, roofs, floors and windows) and meet higher ventilation and air-tightness standards (DTLR, 2002; ODPM (Later DCLG), 2006a, 2006b). New regulatory provisions also introduced certification of installed double-glazing (*i.e.* Fenestration Self-Assessment Scheme – FENSA[1]) as a means of ensuring quality standards around replacement, as well as guarantees for energy efficiency installations, including cavity wall insulation and loft insulation. Government-backed schemes, such as Warm Front, EESoP and EEC required the use of accredited installers and certified products when delivering efficiency measures (OFGEM, 2002). Certification bodies for windows and cavity wall insulation are intended to maintain standards of practice for registered installers. In principle, a wide range of retrofit measures is required by the 2006 and 2010 Building Regulations for England & Wales (ADL1b 2006 and 2010), but it is unclear how widely known or enforced these requirements are. Measures such as loft insulation and draught-proofing are not subject to specific regulatory accreditation, although they can be subject to building regulation, and can be undertaken by individual owners.

Through a number of organizations, the UK government has captured details of the uptake of energy efficiency measures for reporting purposes and programme evaluation. This information has been collected into the Homes Energy Efficiency Database (HEED) administered by the Department of Energy and Climate Change (DECC) and Energy Saving Trust (EST) (EST, 2009). HEED is the most comprehensive database of reported energy efficiency measures available in the UK since it draws together details from a range of data providers. In this study HEED is hypothesized to be a 'global' survey of the target population, *i.e.* a census of dwellings in England that have implemented energy efficiency measures.

Methods

This study comprised two main components. The first was a description of the historical incidence of energy efficiency installation in the housing stock, as reported in HEED, for a selection of retrofit measures during the period 2000–07, along with an examination of the prevalence of energy efficiency features in 2007. The study was restricted to England for the reason that a comparable dataset to test the census hypothesis was available for the study period (*i.e.* the EHS). The second component of the work was an analysis of the relationship between neighbourhood level[2] (*i.e.* lower super output area – LSOA) household details and the adoption of efficiency measures over the period of interest.

The representativeness of HEED for energy efficiency measures in England was determined by comparing successive EHSs over the study period. Information on dwellings and households at a neighbourhood level was drawn from the 2001 Census, Valuation Office Agency (VOA) dwelling attribute statistics, and inter-census administrative data from the Office of National Statistics (ONS). SAS 9.3 software was used in the data preparation and analysis (SAS Institute Inc., 2011).

Data sources

Compiled since 2001, HEED is a data framework maintained by EST and DECC. The database draws together information on installed energy efficiency measures across the UK from installers, industry accreditation bodies, energy suppliers, government-funded programmes, local authorities and home surveys (EST, 2011). HEED measures are reported at the dwelling level with address details, but no information on the dwellings' occupants. DECC and EST use address details to distinguish between individual dwellings and also to merge information coming from different reporting sources, therefore largely removing the risk of double-counting. HEED covers a period from 1993 to 2012 and currently contains information on over 13.8 million dwellings, or 47% of the UK's 27.3 million residential stock. Over the period of study (2000–07) in England, a count of dwellings in HEED determined that 9.3 million homes received efficiency retrofits, covering approximately 40% of England's 22.6 million dwelling stock. A recent comparison of reported physical dwelling characteristics in HEED against other British housing data sources showed that it contains more terraced dwellings and fewer flats and detached dwellings, had more social rental tenures and one-bedroom dwellings, and more dwellings from the north of England (Hamilton, Steadman, Bruhns, Summerfield, & Lowe, 2013). HEED was used to determine where and to whom energy efficiency measures were being delivered in England. HEED consists primarily of reported information on the energy efficiency characteristics of the dwelling along with some detail of physical dwelling features. However, because the database is collected from a variety of sources and its main focus is on reporting energy efficiency measures, the reporting of the physical dwelling details is imperfect (for more details see Appendix A). Neighbourhood-level details at the LSOA level were used in the analysis instead.

This study focused on the uptake of reported energy efficiency retrofits, including: heating system replacement, glazing replacement, loft insulation and cavity wall insulation – other measures are also shown for interest. Heating system replacement includes the installation of storage heaters, heat pumps, warm air systems, and boilers. Replacement of gas boilers (condensing and non-condensing) accounts for 98% of all heating system replacements. Glazing replacement includes the installation of pre- and post-2002[3] double-glazing units and triple-glazing. Loft insulation includes both 'top-ups' (laying additional insulation over existing) and a smaller (and declining) number of 'virgin' installations; the data capture the level of insulation up to a maximum of 250 mm. Cavity wall insulation includes details of the filling of cavity walls built before and from 1976. This date marked the introduction of building regulations that required a nominal wall U-value of no more than 1.0 W/m^2 K. While this requirement could be met without filling wall cavities by using low-density expanded concrete blocks, some builders chose to fill or partially fill cavities in masonry walls with thermal insulation. The different energy efficiency measures reported under HEED were summed at the LSOA level for each year by data provider or programme source, without further quality assurance.

The database does not contain any information on the household (*i.e.* the occupants) other than tenure (not used in this study). However, the general location of the dwellings is known at the LSOA level. The location information was used to determine the number of installations on an area-by-area basis and was used to link the neighbourhood-level characteristics. The database contains a date stamp associated with the details describing the installation of the efficiency measure or collected data. The date information was used to determine the number of measures installed over the period.

The present study treated HEED as a 'census' of energy efficiency interventions in England over the study period. This decision was made on the basis that HEED contained information from the majority (if not all) of government-backed schemes and accreditation bodies and installers dealing with energy efficiency measures, along with extensive surveys of energy performance. The census hypothesis was tested through comparisons of selected reported efficiency measures at a national level against the EHSs.

In treating HEED as a census, this study acknowledges that there could be unreported or under-reported efficiency measures not included in the database, for reasons related to lost or missing information, or non-reporting. For measures such as loft insulations that are subject to 'do-it-yourself' (DIY) installations there may be an appreciable level of under-reporting. Also, as a further source of quantitative under-reporting, it should be noted that it was unclear whether HEED contains all installed measures from the EESoP 3 programme (2000–02) because there was no dataset that explicitly covered this programme. However, many of the interventions would have had to be undertaken by an accredited installer (*i.e.* boilers, cavity wall insulation and double-glazing) and therefore it was expected that the installer data would likely cover many of those EESoP 3 measures. In addition, energy suppliers were allowed to carry forward a proportion of earlier programmes (*i.e.* 10% of EESoP 3 measures could be installed under EEC 1). This carry forward may cover measures initiated prior to April 2002. Therefore, EESoP 3 was not explicitly shown in the analysis and was assumed to be included within the installer group and some within EEC. As a sensitivity test, the analysis was also prepared using 2002–07 data, the results of which are presented in Appendix D.

The EHS[4] was used as an independent source of comparison of energy efficiency measures over the period of interest at a national level. The EHS uses an unclustered stratified sample drawn randomly from a list of all addresses in England and has been updated and made available quinquennially since 1967 and yearly since 2008 (CLG, 2010a). Since 1996 approximately 17 500 households have been interviewed on the details of their home and household, and a further physical survey has been undertaken of approximately 8000 of the interviewed dwellings. Weighting factors are used for both dwellings and households in order to 'scale up' and represent the full stock; dwelling weighting factors were used for consistency, because HEED is reported by dwelling and not by household. The EHS contains details of selected efficiency features present in the dwelling (*i.e.* loft insulation thickness, the predominant type of window, type of wall and insulation, and boiler type). Loft insulation thickness distinguishes none, less than 100 mm, 100–150 mm and 150 mm or more. Windows are categorized as single- and double-glazed by casement material (*i.e.* UPVC, metal or wood). Wall insulation includes cavity with and without insulation and 'other' (*e.g.* solid wall, wood, pre-fabricated, etc). Boilers include standard (*i.e.* non-condensing), back boilers, combination boilers, condensing boilers and condensing-combination boilers. The EHS efficiency variables were not always directly comparable with HEED and therefore required careful grouping and selection for comparison; see Table 1 for details of the comparison.

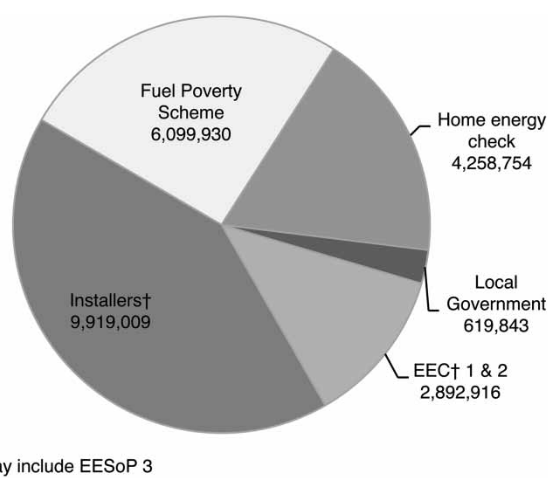

Figure 1 HEED data by programme or data supplier in 2007. Figures represent the sum of all recorded retrofit measures, 2000–07

Reported double-glazing was not compared between HEED and the EHS because of differences in the variables reported. HEED reports the occurrence of a double-glazing installation, which could be a single- or multi-window replacement, while the EHS reports the predominant type of window (*e.g.* < 80% or > 80% double-glazed). For the purposes of illustration, however, the two glazing variables are presented but not compared directly. A further issue that affected the comparison was the change in methodology between the 2001 and 2003 EHCSs relating to how loft insulation levels were collected, and in determining whether cavity walls were insulated (CLG, 2010b). For loft insulation, the survey forms were changed to increase the response categories for the level of insulation and the method for determining loft insulation in loft conversion, top-floor flats, flats with flat roofs and missing data. For cavities, the method to determine insulation eligibility was changed to account for constraints in wall construction and mixed wall types. These revisions were accounted for in the data compared but could have some unexpected consequences. These earlier years of the EHS should therefore be treated with caution.

Additional data at the LSOA level were used to describe a range of household features hypothesized as drivers of the uptake of energy efficiency measures. Data on median LSOA income and most common household type (following Mosaic classification) were drawn from Experian Mosaic Public Sector data (Experian, 2012). Data from the Office for National Statistics (ONS) were used for: age of population, level of central heating, number of benefit claims, and proportion of dwellings within council tax bands from the Neighbourhood Statistics service (ONS, 2012). Data on dwelling counts by age and type were drawn from the VOA property attribute datasets for 2010 (VOA, 2010). Also, data on the climate,

Table 1 Description of energy efficiency variables used for a comparison between the Home Energy Efficiency Database and the English Housing Survey (EHS)

Measure	HEED variables and 'class'	EHS variables and 'class'
Loft insulation	Loft insulation measure	Loft {loftins4]
	'Insulation to 250 mm' combined: '0–250 mm', '25–250 mm', '50–250 mm', '75–250 mm', '100–250 mm', '150–250 mm'	'150 mm or more'
Cavity wall insulation	Cavity wall measure	Wall insulation type {wallinsx]
	'Cavity wall insulation' combined: 'Cavity wall insulation (pre-1976)', 'Cavity wall insulation (post-1976)', 'Cavity wall insulation (unknown age)'	'Cavity with insulation'
Boiler replacement	Boilers	Type of boiler [boiler]
	'Condensing Boilers' combined: 'Condensing boiler', 'Condensing boiler and controls', 'Condensing–combination boiler', 'Condensing–combination boiler and control'	'Condensing boilers' combined: 'Condensing boiler', 'Condensing–combination boiler'
The following variables were not compared, but are presented for illustration		
Double-glazing installation	Glazing measure	
	'Double-glazing replacement' combined: 'Double pre-2002', 'Double post-2002'	
Double-glazing coverage		Predominant type of window [typewin]
		'double-glazed – wood', 'double-glazed – UPVC', 'double-glazed – metal'
		Extent of double-glazing [dblglaz2]
		'unknown', 'less than 80% double-glazed', '80% or more double-glazed'

measured in heating degree-hours in 2005, was drawn from the UK Meteorological Office (UK Met Office, 2012). Appendix B contains further details on these LSOA level variables.

Uptake of energy efficiency measures

HEED data were grouped into six categories according to the programme or data provider to analyse any change in uptake between government-sponsored programmes and those related to industry or household efforts. Figure 1 shows the breakdown of the total number of efficiency measures (not dwellings) by programme or provider for England in HEED in 2007.

Data on the number of installations (*i.e.* annual count) that occurred in HEED between 2000 and 2007 were used to examine both the rate of uptake of energy efficiency measures and the prevalence of measures in 2007. Prevalence in 2007 was recorded as the sum of incidence since 2000 – for some measures, this truncation will exclude a tail of installations that took place before 2000. The EHSs from 1996 to 2008 were used to describe the prevalence of the selected features in the English housing stock. No surveys were conducted from 1997 to 2000, and 2002, 2004 and 2006. An estimate of the prevalence was made for each year not covered through a linear interpolation between the known survey years. From these estimates the annual incidence for each of the selected measures was derived (*i.e.* $\text{Year}_{N+1} - \text{Year}_N$) for comparison with HEED. The interpolation should be interpreted with some caution, as they may not accurately reflect the prevalence of efficiency measures. Table C1 in Appendix C shows the results of the interpolation.

For further analysis at the neighbourhood level, the efficiency measures were grouped into three categories: all measures, heat-related measures (*i.e.* condensing and standard boiler replacement, hot water cylinder replacement, and solar hot water systems), and fabric-related measures (*i.e.* loft and cavity wall insulation, glazing replacement, and draughtproofing). The energy efficiency uptake rate at the neighbourhood level (*i.e.* LSOA) was determined using the incidence data as a proportion of the total number of dwellings within the neighbourhood as of 2005, determined using the Council Tax statistics[5] (CLG, 2005). 2005 was selected as a recent count of dwellings over the period covered. The rate of energy efficiency uptake was divided into quintiles for the analysis, with 5 being the highest rate of uptake.

Neighbourhood level data were used to examine relationships between household characteristics and the uptake of energy efficiency by programme. The SAS routine *Proc Logistic* was used to generate odds ratios (ORs) that describe the association of selected household variables and the highest uptake rate of energy efficiency compared with the lowest at the neighbourhood level. The OR represents the odds of an outcome (*e.g.* high uptake rate) in a group, given a particular feature (*e.g.* neighbourhood location) over the odds of not having an outcome (*e.g.* lowest uptake rate) given the same feature. If an outcome is associated with a feature the odds of exposure in the outcome group will be higher than the corresponding odds in the non-outcome group (*i.e.* OR > 1). If an outcome shows no association with a feature the odds will be the same in both groups (*i.e.* OR $= 1$). If an outcome is associated with a lack of a feature the odds of exposure in the outcome group will be lower than the corresponding odds in the non-outcome group (*i.e.* OR < 1). For continuous variables (*e.g.* proportion of dwelling tenure) a unit of change is specified (*e.g.* additional 10%) in order to estimate the corresponding OR for each unit of change. Where, as here, analysis is effectively performed on an entire population (*i.e.* treating HEED as equivalent to a census), confidence intervals (*i.e.* the quantification of uncertainty of the estimates from a sample population) are not provided. This is because a census represents the true population and therefore no (statistical) uncertainty is present.

Results

The annual uptake of reported energy efficiency measures in England, as determined using HEED, increased between 2000 and 2007 for all measures, with the exception of draughtproofing (Figure 2). On

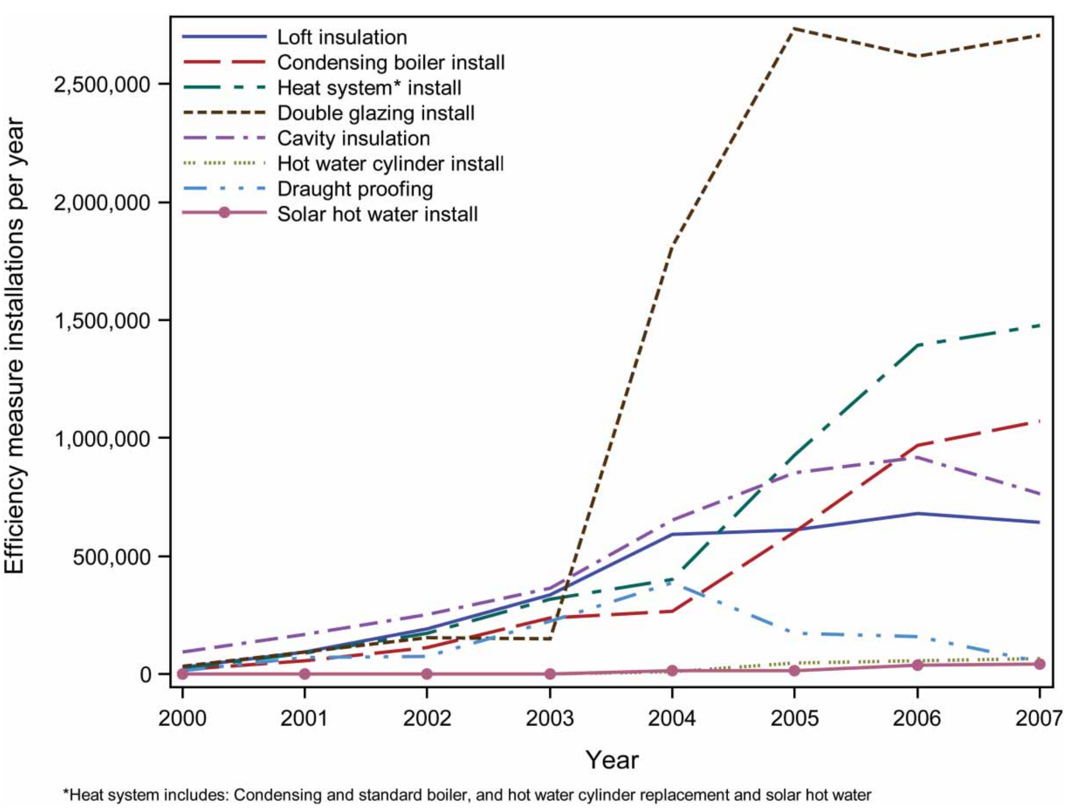

Figure 2 Number of energy efficiency measure installations per year in England between 2000 and 2007 drawn from HEED. $N =$ 9.3 million dwellings

Table 2 Energy efficiency installation uptake (count per year) in England between 2000 and 2007 by data provider or programme, drawn from HEED ($N = 9.3$ million dwellings)

Efficiency installations in England (thousands)	Year								Period total	Percentage of total
Measure/source	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**		
Heat[a]										
Local Government	0.5	0.5	0.8	1.0	0.2	7	70	12	92	0.4
EEC 1 & 2	0.4	0.1	24	73	41	161	99	116	515	2.2
Installers	4	6	15	19	105	447	744	1044	2385	10.0
Fuel Poverty Scheme	8	48	81	211	194	280	280	–	1102	4.6
Home energy check	12	35	56	16	86	92	296	409	1002	4.2
Fabric[b]										
Local Government	6	5	8	8	1.5	35	369	94	527	2.2
EEC 1 & 2	3	0.6	80	207	334	936	417	401	2378	10.0
Installers	54	44	60	36	985	1781	1969	2604	7534	31.7
Fuel Poverty Scheme	46	229	338	768	1642	1206	769	0	4998	21.0
Home energy check	57	150	188	49	478	415	850	1069	3257	13.7

Notes: [a]Heat includes: condensing and standard boiler, and hot water cylinder replacement and solar hot water.
[b]Fabric includes: loft, cavity wall insulation, draughtproofing and double-glazing.

average, the uptake for fabric measures over the eight-year period was 0.87 per dwelling, and for heating system measures was 0.24 per dwelling for all dwellings in England. Loft insulation increased from approximately 29 000 installations per year to 700 000 installations per year by 2007, a 22-fold increase. Double-glazing installations increased from 34 000 installations per year in 2000, to 2.8 million installations per year by 2007, an 81-fold increase. Cavity wall insulations increased from 99 270 installations in 2000 to 822 000 installations by 2007, a six-fold increase. Condensing boiler replacement increased from 18 500 installations in 2000 to 1.1 million installations by 2007, a 59-fold increase. This increase almost certainly follows the mandating of increased efficiency of boilers under the 2005 revision to the Building Regulations (OPDM, 2005). Most measures follow a relatively stable incidence trajectory, with the exception of double-glazing installations, which increased dramatically between 2003 and 2005. This is most likely a result of the Building Regulations requirements and introduction of FENSA. Building fabric measures have seen the largest number of installations since 2000, approximately 18 million in total. The largest numbers of fabric installations by measures were glazing (55% of the final total), cavity wall insulation (22%), loft insulation (17%) and draughtproofing (6%). There were approximately 5 million heating measures installed over the period, condensing boilers making up 65% of the final total.

Table 2 provides a count of the total annual number of installations for England for the period 2000–07. Uptake was highest in the installers group at 42%; gas boiler and window installers provided the bulk of the installers' data. Installations for government-related schemes (*i.e.* energy supplier obligations and fuel poverty) comprised 41% of total installations from 2000 to 2007. Homeowner surveys provided 18% of the data on installations and local government the remaining 2% for the period. These figures provide the means to determine whether there are differences in uptake levels associated with programme types.

Across England, fabric and heat efficiency interventions were shown to be highest in the North East and North West regions and lowest across London and much of the southern region (Figure 3). The uptake incidence rate (*i.e.* total number of installations for the period 2000–07 over the total number of dwellings in 2005) for the fabric measures is highest around midland and northern cities such as Leicester, Birmingham, Liverpool, Manchester, Leeds and Hull. Heating system installations are also found in the large urban areas in the north and also in smaller cities in the south (*e.g.* Milton Keynes, Oxford, Southampton and Portsmouth).

Comparison of uptake in England

Comparisons between HEED and the EHS show that boiler and loft measures track each other closely

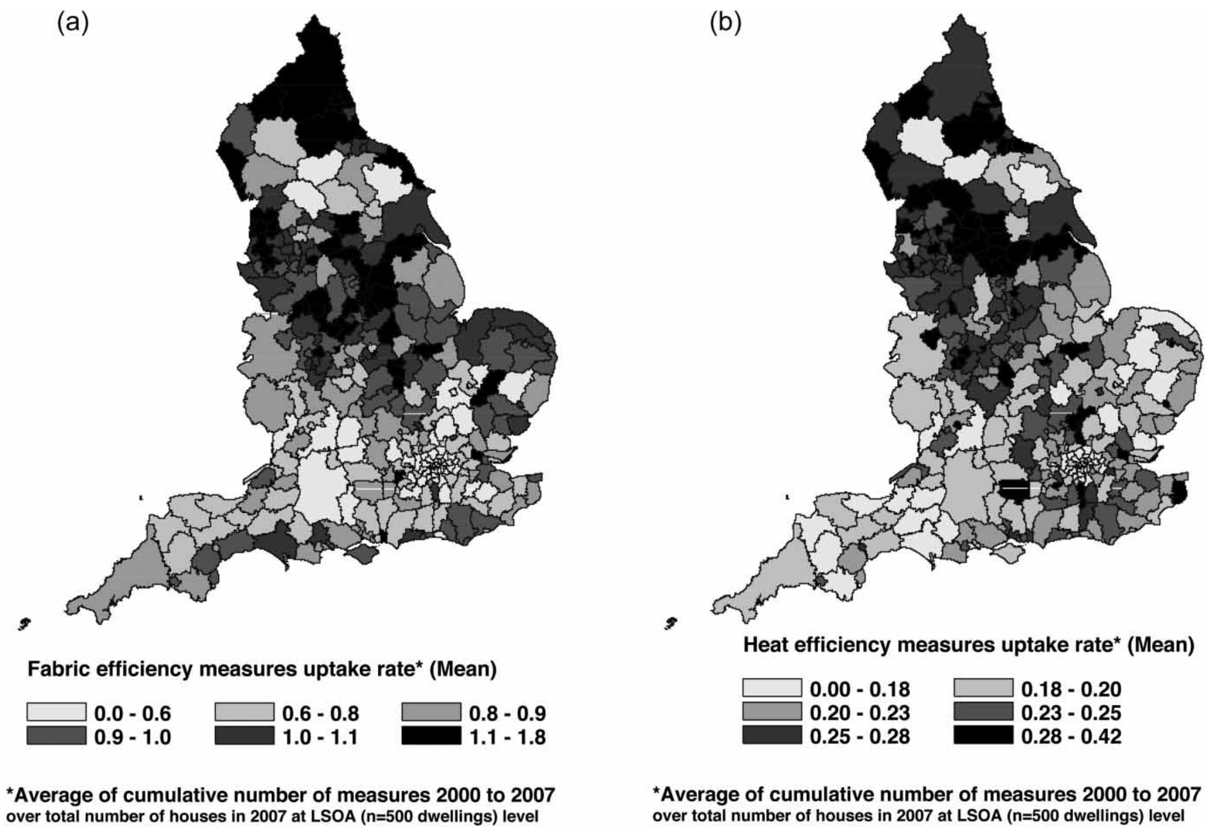

Figure 3 Total energy efficiency measure installations for (a) fabric measures and (b) heating system measures from 2000 to 2007 as a ratio of the number of dwellings in 2005, drawn from HEED. $N = 9.3$ million
Figure created by the authors.
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(lofts more so in later years), but that cavity wall insulations diverge over the period of interest (Figure 4). It is not clear from the data why this might be the case. One possibility is that the process for reporting cavity walls in the EHS has an unexpected effect on the estimates. Figure 5 shows the installation of double-glazing as reported in HEED and the coverage of double-glazing estimated in the EHS. The double-glazing installations profile in HEED shows a dramatic increase following 2002. The EHS shows that the incidence of dwellings (*i.e.* new installations) where the predominant window type was double-glazing fell during the period, which reflects a reduced number of dwellings achieving > 80% coverage in double-glazing. The estimate of the total proportion of dwellings with > 80% double-glazing coverage during the period increased from 55% to 80%. The prevalence of measures in England for 2007 is also compared (Figure 6). Cavity wall insulation had similar profiles but there were fewer installations reported in the EHS; HEED reports approximately 1.1 million or 41% more. The installation of condensing boilers according to the two sources was found to be very close; HEED reported 86 000 (4%) more installations. There were approximately 26% fewer loft insulation installations reported in HEED during the entire period; however, from 2003 onward there were only 7% fewer installations reported in HEED.

Household characteristics and uptake of efficiency measures

At the neighbourhood level, the rate of uptake of energy efficiency measures for the 2000–07 period (measured in quintiles) was significantly associated with income, tenure, the proportion of flats, climate and the proportion of the population with older adults and children (Table 3).

The rate of uptake is examined using a selection of data groups to reflect associations by programme. EEC 1 & 2, Installers, Fuel Poverty Schemes, and the Home Energy Check are shown separately; along with a Core Group (*i.e.* EEC, Installers, Fuel Poverty Schemes, and Home Energy Check combined) and all of HEED (*i.e.* the Core Group plus Local Authorities).

In the EEC group, neighbourhoods in the lowest income quintile (compared with the highest quintile) were more likely to be in the highest quintile for uptake (versus

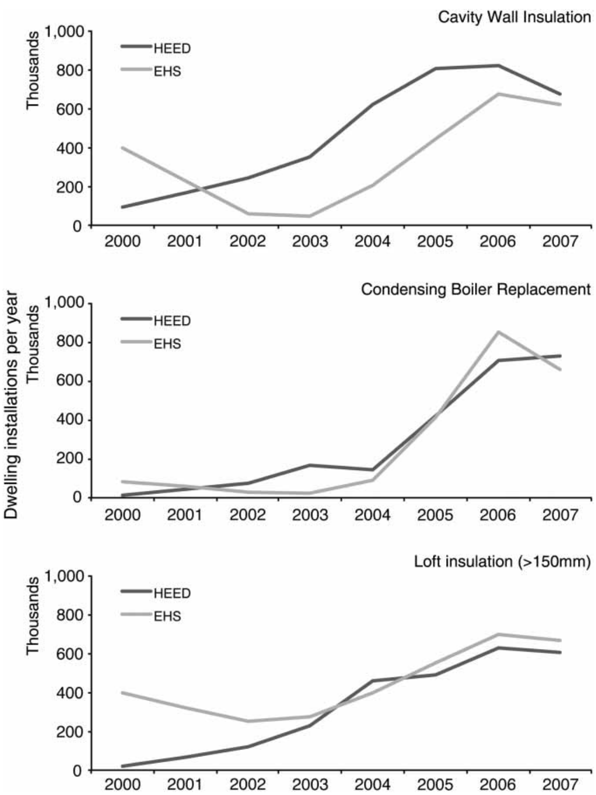

Figure 4 Uptake incidence of energy efficiency measures in HEED compared with EHS, 2000–07

lowest) of fabric efficiency measures (OR = 2.7) and heating efficiency measures (OR = 2.0). Efficiency measure uptake in the EEC group was higher for every additional 10% increase in the proportion of

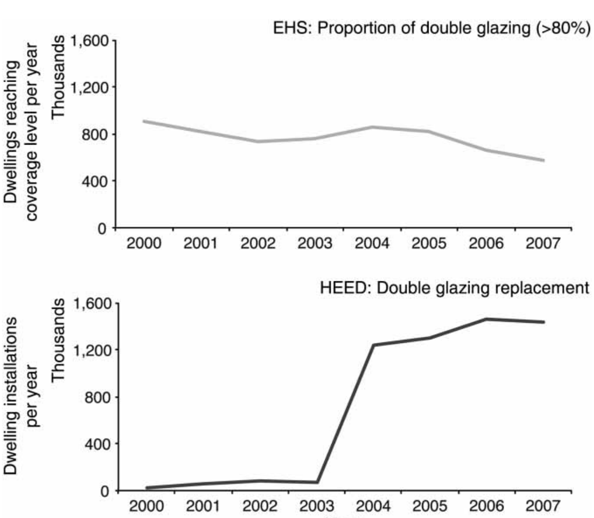

Figure 5 Number of installed (HEED) and proportion of double-glazing > 80% (EHS), 2000–07

owner-occupied dwellings (fabric OR = 1.27; heating OR = 1.11). For each additional 10% increase in owner-occupied dwellings the OR of being in the highest uptake group for fabric measures was lower at 0.84 and 0.91 for heat measures. The decrease in the OR means that as the proportion of owner-occupied dwellings increased, the odds of being in the highest uptake rate quintile were lower compared with the odds of being in the lowest uptake rate quintile.

The uptake of energy efficiency measures drawn from the Installers group follows a similar trend as for the EEC group, although the magnitude is different. Neighbourhoods in the lowest median income quintile were more likely to have a high uptake of fabric measures (OR = 5.3) and heating measures (OR = 4.1) than neighbourhoods in the highest income quintile. The likelihood of being in the highest fabric uptake group increased for every additional 10% increase in households on benefits[6] in a neighbourhood (OR = 1.05) but decreased for heating measures (OR = 0.99). In the Fuel Poverty Schemes group, neighbourhoods with low incomes were more likely to be in a high uptake group for fabric efficiency measures (OR = 10.7) and heating measures (OR = 6.5). The likelihood of a high uptake increased for every additional 10% increase in owner-occupied dwellings (fabric OR = 1.8; heating OR = 1.7). However, this group was less likely to be in the highest uptake as the proportion of flats increased (fabric OR = 0.76; heating OR = 0.88). As the proportion of benefits increased, the likelihood of a high uptake rate increased (fabric OR = 1.63; heating OR = 1.50). The likelihood of being in the highest uptake group in the Home Energy Check group, *i.e.* those who self-reported energy efficiency measures, is of a similar magnitude and trend to the EEC group.

For all sources of efficiency measures, income was highly significant for being in the highest uptake rate quintile of uptake (fabric OR = 12.2; heating OR = 7.0). The likelihood of being in the highest uptake rate quintile increased as the proportion of owner-occupied dwellings increased (fabric OR = 1.7; heating OR = 1.3). This was also found for each 10% increase in the percentage of homes with benefits (fabric OR = 1.3; heating OR = 1.1). Overall, the proportion of the neighbourhood population being older ($\geq$ 60 years) or having children increased the OR of being in the highest uptake quintile, but only slightly. Using the regional heating degree-days as an indicator of climate, compared with the warmest neighbourhood areas, those in the colder regions were more likely to be in the highest uptake quintile. However, this association is likely confounded (*i.e.* distorted) by the regional variation seen in the targeting of efficiency programmes. The ORs for the Core Programmes group are also reported for comparison with All Sources. It is found that the ORs are slightly higher in the Core group, but similar in trend.

The effect of only including incidence data from 2002 to 2007 is presented in Appendix D. Those results show that the uptake levels are very similar to the trends shown in the full analysis in Table 3.

Discussion

Energy efficiency uptake

Over the period of interest there has been a large number of reported energy efficiency measures in the English housing stock, as shown in HEED. Most measures have followed a varying but upward trajectory of installation rates since 2000, reflecting the course of activity undertaken by both government and non-government organizations. The database shows that the incidence of reported loft insulation and cavity wall insulation installations are steady post-2004, with a minor decline in cavity wall filling in 2007. The decline in HEED reported cavity measures is also reflected in the EHS estimates and therefore not necessarily an artefact of the reported data. Estimates from the UK CCC show that cavity wall insulation continues to decline in 2008 (0.52 million/year) before increasing again in 2009 (0.6 million/year) (UK CCC, 2012), which coincides with the introduction of the government-backed supplier obligation, the Carbon Emission Reduction Target (CERT). The cumulative number of reported condensing-boiler installations has grown more or less linearly since 2004, the rate of growth likely reflecting the natural replacement rate of boilers estimated at 1 million/year (UK CCC, 2012). The onset of this linear trend reflects the 2005 amendment to the building regulations that required all new and replacement boilers to have a minimum efficiency of 86% (*i.e.* to be condensing – in the UK, domestic boiler efficiencies are quoted on a gross calorific basis) from 2006 (CLG, 2010c).

Reported numbers of draughtproofing measures declined from 2004, which may reflect the increased emphasis in fabric and heating interventions. Reported double-glazing installations increased dramatically post-2002, which is most likely an artefact of the data source of the glazing data (FENSA). Those pre-2002 glazing installations that were reported have come from other data suppliers, notably from Fuel Poverty Schemes (*e.g.* Warm Front).

The higher uptake rates of fabric measures are concentrated in the midland and northern regions of England, around the major cities and metropolitan areas. While an association was shown with colder climates, this relationship may also be related to the activities of several government schemes in those areas. For example, EAGA, the Warm Front scheme provider was most active in the north (EAGA, 2004), which may reflect the generally higher occurrence of fuel poverty in northern regions (DECC, 2013). Higher heating measures uptake was also concentrated around major cities in England, but not specifically northern cities. Since 1998, the government has required that all landlords have their gas installations inspected yearly (HMSO, 1998). Therefore, the concentration of boiler upgrades may reflect the replacement of defective units and householders' decisions to upgrade, but also the number of rental properties for which regular inspections take place. This trend suggests that regulatory controls around heating system maintenance may be effective in driving replacement of old boilers, particularly in the landlord market.

The legislative and social focus that has characterized energy efficiency installations in England over the past ten years has driven the uptake of efficiency measures (Mallaburn & Eyre, 2014; Rosenow, 2012). The support of government initiatives to improve social and priority group housing directly (*e.g.* in the fuel poverty programmes) has also meant that information on energy efficiency is collected to report on target achievements. The analysis has shown (Table 2) that government-sponsored programmes and government legislation on energy suppliers to reduce the CO_2 emissions of their customers has had a considerable impact on reported numbers of efficiency improvements, accounting for 38% of all installations reported in HEED between 2000 and 2007. National regulatory requirements controlling the installation of glazing, cavity wall insulation and boiler inspections for landlords has meant that a great deal of data on energy efficiency were tracked and reported through these mechanisms, which accounted for approximately 42% of reported installations. There are measures that likely fall outside of these two reporting mechanisms, such as DIY or grey-market installations (*e.g.* installations which are paid for in cash, as a means to avoid value added tax), which may not be included in HEED, unless reported under a home survey. DIY is most likely to have an effect on the number of reported loft insulation and draughtproofing measures, as these are easy for the homeowner to carry out. DECC estimates that under the EEC Schemes (*i.e.* 2002–08) approximately 47 million m^2 of loft insulation were installed as DIY. Assuming an average loft space of 50 m^2 and a 10% wastage factor[7] this could mean that approximately 0.12 million/year installations were carried out during this period. Measures such as boilers, glazing, cavity filling, and hot water cylinder insulation require more specialized skill and would not likely be undertaken by dwelling owners but instead by builders and plumbers. Therefore, the reporting of these measures may be affected by grey market activities or those which are otherwise not certified. These potential sources of selection bias in the reporting will have differing effects on the results. If measures are consistently under-reported for certain house or household types and/or in certain geographic areas then the ratio of the odds would be affected, changing the relationship with those neighbourhood factors found to be

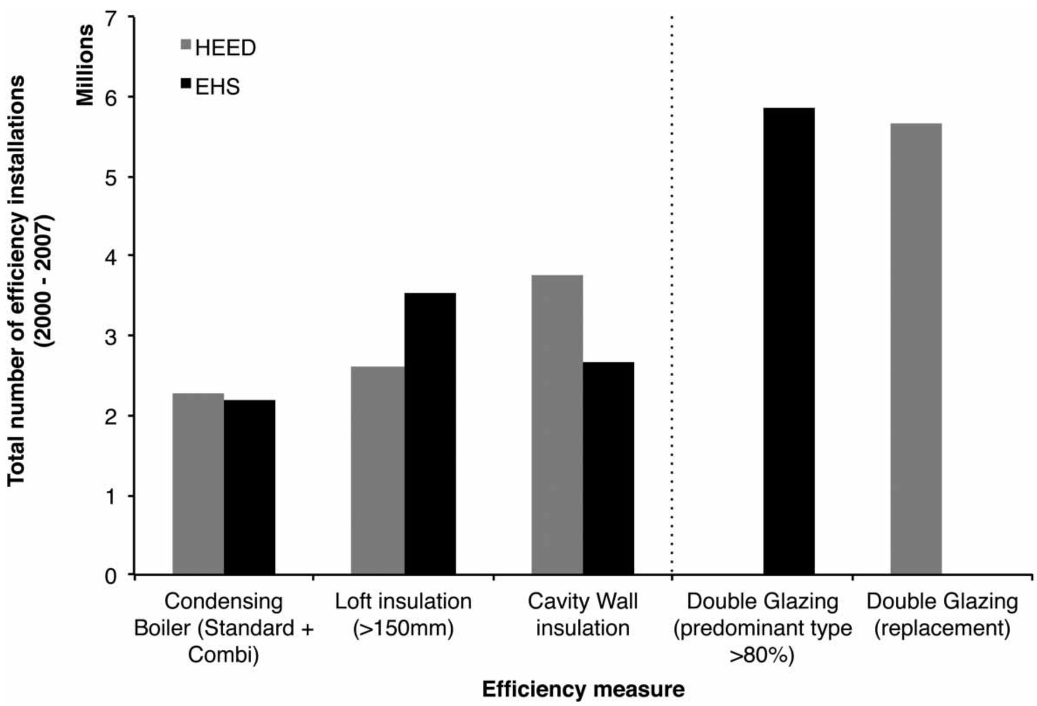

Figure 6 Comparison of the prevalence of energy efficiency measures in England between HEED and EHS, 2000–07

associated with the uptake of measures. However, given the size of the population examined, a large change in the reported measures would be needed to have an effect on the results. In this study these biases were treated as being randomly distributed throughout the housing stock.

Representativeness of national levels of energy efficiency uptake

As a data source, HEED has acted as a *de facto* repository for many of the energy efficiency installations that have taken place in England over the study period. The comparison between the uptake of a selection of energy efficiency installations in HEED and estimates in the EHS (*i.e.* an independent survey) over the period show some striking similarities and differences. The number of condensing boiler installations and loft insulations to $\geq$ 150 mm installations are very similar, especially post-2003. By comparison, however, there is a difference in the reported uptake of cavity wall insulation over the period. The cavity wall uptake trend is similar between the EHS and HEED (Figure 4), but HEED contains approximately 250 000/year more installations. The reported double-glazing installations in HEED shows a strong increase post-2002 following the introduction of accredited installation requirements. EHS, in comparison, shows a decline in the annual increase in the number of dwellings with $>$ 80% of all windows now (in 2013) double-glazed. However, the total number of dwellings with $>$ 80% double-glazing coverage increased from 50% in 2000 to 80% in 2007. Therefore, when compared with HEED it may be that the installations reported in HEED are being carried out in homes that already have a high proportion of double-glazing.

There are several reasons for differences between the energy efficiency measures reported in the HEED database and national estimates of energy efficiency measures from surveys. First, it may be that the variables used to compare the EHS to HEED are not describing the same feature. This was the case for double-glazing. It could also be that the sampling strategy used to construct the EHS (*i.e.* randomly selected from postal addresses) somehow systematically excluded dwellings in areas with higher reported efficiency interventions, although it is not clear how this could occur. It may also be that the change in EHCS collection methodology for surveying lofts and cavities make the earlier years (1996 and 2003) more difficult to compare against. Further, HEED is not a continuous registry and so differences may also occur due to the periodic nature of the updating of the database. Nor is reporting in HEED mandatory outside of government-backed programmes, meaning that some installations are inevitably not captured. This will mean that the data used in this study are not complete and there may be measures not yet accounted for. An additional likely source of incompleteness is delays in getting data into HEED – an attempted was made to minimize this effect by not using data after 2007.

Table 3 Odds ratios (ORs) of the incidence rate of uptake of energy efficiency measures (incidence frequency over dwellings in 2005) from 2000 to 2007 at LSOA level and energy efficiency programme in England

Variable	Energy efficiency measures uptake incidence rate, 2000–07											
	Energy Efficiency Commitment		Installers		Fuel Poverty Schemes		Home Energy Survey		Core Programmes[c]		All sources	
	Fabric	Heat	Fabric	Heat	Fabric	Heat	Fabric	Heat	Fabric	Heat	Fabric	Heat
Quintile of median income in 2005												
Q1 vs Q5	2.71	2.05	5.29	4.11	10.74	6.56	2.59	1.67	12.99	7.38	12.23	6.98
Q2 vs Q5	1.51	1.26	2.77	2.15	6.04	3.85	1.88	1.43	5.18	3.32	5.02	3.24
Q3 vs Q5	1.36	1.07	2.01	1.43	4.07	2.66	1.69	1.25	3.24	1.91	3.18	1.87
Q4 vs Q5	1.11	0.95	1.38	1.06	2.45	1.91	1.33	1.12	1.81	1.31	1.8	1.3
Tenure (proportion of dwellings)												
Owner-occupied (units = 10%)[a]	1.27	1.11	1.43	1.18	1.88	1.69	1.28	1.08	1.81	1.33	1.73	1.3
Dwelling type (proportion of dwellings)												
Flats (units = 10%)[a]	0.84	0.91	0.78	0.87	0.76	0.88	0.83	0.92	0.71	0.81	0.7	0.8
Quintile of climate (heat degree-days in 2005)												
Q2 vs Q1	1.56	1.55	1.75	1.52	0.8	0.76	0.95	0.83	1.45	1.27	1.55	1.3
Q3 vs Q1	2.1	1.86	2.2	1.77	0.72	0.72	1.1	0.96	1.92	1.64	1.97	1.64
Q4 vs Q1	2.2	1.89	2.56	1.95	0.68	0.62	1.16	0.94	2.09	1.63	2.21	1.67
Q5 vs Q1	1.99	1.71	2	1.7	0.79	0.83	1.25	0.98	1.96	1.74	1.96	1.73
Council Tax Band (proportion of dwellings)												
Band A&B (units = 10%)[a]	1	0.98	0.98	0.98	1.16	1.13	1.01	0.99	1.03	1.01	1.02	1
Benefits (proportion of dwellings)[b]												
On benefits (units = 10%)[a]	1	0.96	1.05	0.99	1.63	1.5	1.12	1.04	1.32	1.13	1.33	1.13
Household age (proportion of dwelling occupants)												
Adults ≥60 years (units = −5%)[a]	1.03	1.02	1.02	1.01	1.03	1.01	0.99	0.99	1.04	1.01	1.03	1.01
Children ≥14 years (units = −5%)[a]	1.01	1.01	1	1.01	1.04	1.04	1.01	1.01	1.02	1.02	1.02	1.02

Notes: [a]ORs estimates correspond to each additional unit of change.
[b]Benefits include: disability, incapacity, income support, job seekers, pension.
[c]Core programmes include: EEC, Installers, Fuel Poverty and Home Energy Survey.
In this paper HEED is treated as a 'census'-level dataset (*i.e.* a survey of all households). As such, the reporting of inferential statistical tests such as *p*-values and confidence intervals is not correct in this context.

Efficiency uptake and neighbourhood characteristics

The work on drivers of energy efficiency in England by Tovar (2012) and earlier by Brechling & Smith (1994) have identified a number of household characteristics (*e.g.* income, age and type of households, and tenure) associated with uptake. The results shown in this study are broadly in agreement, whereby across all sources of data in HEED there is a strong relationship between having a high uptake rate of energy efficiency retrofits and neighbourhood income levels (Table 3). This effect is particularly evident in areas with low median incomes, which see a high likelihood of being in the highest quintile for the incidence rate of uptake of energy efficiency measures under Fuel Poverty related schemes. The results also show that as the proportion of dwellings that are owner-occupied has increased, so too does the likelihood of having a high uptake rate. This suggests that homeowners, who have more control over the maintenance and operation of the dwelling, are either seeking or accepting more energy efficiency measures. Areas with a higher proportion of dwellings with household occupants on benefits increases the likelihood of being in a high uptake group: this also reflects the targeting of programmes towards low income or vulnerable individuals. There was a small positive effect on uptake related to the number of older persons ($\geq$ 60) under the energy efficiency commitment and a small positive effect related to the number of children ($\leq$ 14) under the fuel poverty schemes. These relationships support the notion that over the eight-year period from 2000 to 2007, many energy efficiency measures have been focused on households that cannot necessarily afford the measure but who do have the autonomy to decide on its installation. This study also supports the hypothesis that institutional functions and policy priorities are drivers of energy efficiency uptake. For example, the uptake rate under fuel poverty schemes appropriately reflected the target group, *i.e.* increased likelihood of higher rates of uptake in low-income neighbourhoods compared with higher income areas. Also, it was interesting to note that under the supplier obligation installations (*i.e.* EEC) the likelihood of a neighbourhood having a high uptake rate and being in the lowest income quintile was smaller than for other programmes or data sources.

The results of this study have shown that the uptake rates for energy efficiency measures are lower in neighbourhoods with middle and high incomes and also in the rental market. While it may be that the higher-income neighbourhoods are possibly more able to afford investment in energy efficiency measures, to date the evidence suggests that their participation is lower than low-income neighbourhoods who have had direct government support. The Green Deal policy is focusing on these households by providing a mechanism to avoid having to raise the upfront investment required for the retrofit by allowing capital costs of measures to be paid off through energy bills. It is intended to encourage those middle- and higher-income households that may have interest and autonomy to improve the energy efficiency of their home but who may not want (or may not be able) to raise the capital to make the requisite investments. In terms of the rental market, the Green Deal's focus on the household paying the energy bill being responsible for the long-term cost of the measure could prove to be attractive to landlords who may otherwise wish to avoid investing in measures that have no direct benefit to their rental income. The findings of this work support the need to target this group, but it is unclear whether a market-based mechanism (versus direct government targeting) will increase the uptake rate.

Implications of research

Understanding the historical rate of energy efficiency uptake and those social and physical characteristics associated with this uptake is important both for policymakers evaluating and developing future retrofit delivery programmes, and researchers investigating the distributional impact of these measures on households or undertaking research on drivers affecting energy demand. For policymakers, knowledge of the historical rate of uptake and distributional targeting for different efficiency measures could help in their assessment of whether core efficiency programme targets are being met, who is benefiting, and which types of household future policies need to focus on. For researchers, knowledge of these uptake rates could help to shape technology diffusion and help to focus future interventions, for example, with respect to income levels. More studies on past programmes are needed to understand household responses to particular policies and initiatives for the uptake of energy efficiency measures. Doing so will help ensure that resources and investment are appropriately targeted through well-developed and evidence-based policies.

The study design used here has implications more generally for approaches to examining trends and drivers of energy and energy efficiency in the built environment. The concepts of incidence and prevalence, common currency in health research, are used here to examine the uptake of energy efficiency. This work begins to apply an approach to studying population-level energy efficiency using the methods used in epidemiology, and is thus a move towards more evidence-based policies (Sorrell, 2007). Energy epidemiology reinterprets the research approach of health sciences and seeks to explore the causes and effects of key factors on energy outcomes at a population (and sub-population) level. The approach is described in detail elsewhere (Hamilton, Summerfield, et al., 2013). For the uptake of energy efficiency this approach requires that key determinants of energy use, such as the occurrence of energy efficiency retrofits, are presented in a manner that provides a baseline for further studies.

Conclusions

Domestic energy efficiency measures targeting fabric and heating systems in England have, generally speaking, been delivered through a combination of government programmes, household elected installations and regulatory control mechanisms. Over the 2000–07 period there is evidence that those government programmes targeting vulnerable households or those living on benefits have succeeded, as areas with lower incomes show higher rates of uptake. In addition, the uptake rate is higher in areas with higher proportions of owner-occupied dwellings, suggesting that decision-making autonomy is an important factor in the seeking or acceptance of efficiency retrofits.

A further issue supported by this research is the misalignment of landlord and tenant benefits related to energy efficiency measures, with higher rates of uptake observed for heating measures in areas with flats. This likely reflects the requirement for landlords to have their gas heating system checked annually, which does not apply to owner-occupiers. While market-based policies such as Green Deal now attempt to address these split incentives, it does appear, from the data on condensing gas boiler installations, that regulatory mechanisms can be very effective. The higher rates of uptake of heating measures in areas with flats likely reflect the requirement of annual checks of gas heating systems. It would be difficult to roll such a mechanism out into the owner-occupied dwellings unless the ownership structure of boiler units changes over time. For example, a structure based on service contracts, whereby owner-occupiers rented boilers or hot water heaters, would likely contain some form of maintenance standard over the life of the contract.

The development of a longitudinal and area-based energy efficiency data framework, albeit in an *ad hoc* fashion, is an important tool in examining and evaluating the rate and targeting of uptake over time. Although nationally reported statistics provide an overview of the number of energy efficiency measures installed, they are unable to support a more detailed examination of what local factors may be associated with trends over time. The use of more area-based data such as DECC's national energy efficiency data framework will offer another tool to examine household level effects that can more clearly support policy. It will be important to review and further study how household characteristics affect the level of uptake, in order to ensure that future government greenhouse gas abatement targets from energy efficiency in the housing sector are met.

Finally, the approach used to examine the uptake of energy efficiency supports the application of epidemiological methods to problems of energy efficiency. Epidemiology provides a set of methods and analysis tools for the study of populations. Here an ecological study design was used to examine trends and generate hypotheses related to the uptake of energy efficiency in England. Concepts of incidence and prevalence were developed and provided a means of considering the distribution of efficiency measures and its change in the population over time. As more data becomes available to government and researchers, it is vital that the approaches make most use of the spatial, temporal and other characteristics of this data to aid in establishing a robust evidence base. These approaches are essential to develop and evaluate policies and inform action that supports the UK meeting its greenhouse gas emissions reduction targets.

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Endnotes

[1]FENSA was established in adherence to the 2002 Building Regulations of April 2002 to regulate the replacement of windows and doors.

[2]For the purpose of this study, the lower layer super output area (LSOA) is referred to as a 'neighbourhood'. The terms are used interchangeably when referring to the level of analysis. Whilst it is acknowledged that this is not necessarily a true description of a neighbourhood, it is a useful reference and aligns with the ONS description of available spatial statistics.

[3]The significance of pre- and post-2002 double-glazing refers to a requirement introduced in the British Building Regulations of 2002 requiring that all windows (and replacement windows) conform to lower *U*-values.

[4]In 2008 the English Housing Survey replaced the former EHCS and Survey of English Housing.

[5]Council Tax has been the technical term for local, property-based taxation in England since 1993.

[6]Benefit recipient is shorthand for those in receipt of one or more categories of state support.

[7]This methodology described follows that of DECC, set out in Table 3.21 in the Energy Consumption UK Statistics 2012 update.

Appendix A: Details of the Homes Energy Efficiency Database (HEED)

HEED consists primarily of information on the physical characteristics of the dwelling, including: dwelling type, age, number of bedrooms, wall type and insulation level, loft insulation, glazing type, heating system, and fuel type. The bulk of HEED data have been classified using the Reduced Standard Assessment Procedure (rdSAP) format, which attempts to categorize dwellings into common bands relevant to modelling energy demand (BRE & DECC, 2009).

HEED comprises information at the individual dwelling level rather than by households or occupants. It contains no information on households or dwelling occupants, aside from the tenure; so socio-economic factors cannot be determined directly. HEED contains details on a range of energy efficiency interventions, including: loft insulation, cavity wall insulation, double-glazing installation, condensing boiler installation, draughtproofing, heating controls (*e.g.* thermostats), and hot water cylinder upgrades. A home enters HEED as a result of being part of a survey (self-completed by the occupants or collected by others) or having an efficiency intervention. Approximately 70% of all dwellings in HEED had at least one efficiency intervention between 2000 and 2007. Table A1 shows the number of installations per year in England for a selection of energy efficiency retrofits in HEED.

HEED has several limitations with respect to the interpretation of the data. In particular, the variety of sources from which the data are drawn can mean that the quality is not standardized with respect to collector bias or sample control. Also, there is a large amount of data missing on a number of physical characteristics of the home, which is due to the some data providers only collecting information required by their accreditation body or programme policies. The interpretation of results should bear these issues in mind. Table A2 shows the coverage of HEED energy efficiency variables for all dwellings in the period of study, 2000–07.

Appendix B: Lower super output area (LSOA)-level variables

Table B1 shows the datasets and variables (with geographic levels) used in the energy efficiency uptake analysis in England, 2000–07.

Appendix C: Interpolation of English Housing Survey (EHS) data

Table C1 shows the results from the linear interpolation between EHS years (*i.e.* 1996, 2001, 2003, 2005, 2007 and 2009). The results of these interpolations for a selection of energy efficiency levels are used for comparison against reported efficiency installations in the HEED.

Appendix D: Analyses of energy efficiency uptake using HEED. 2002–07

Table D1 shows the results of the ecological analysis for the total uptake of energy efficiency measures by programme 2002–07 and the association with LSOA-level dwelling and household characteristics.

Table A1 Total number of energy efficiency installations per year in England, 2000–07

Efficiency installations in England (thousands)[a]	Year								Total
	2000	2001	2002	2003	2004	2005	2006	2007	
Loft insulation	28	96	190	334	591	612	682	644	3177
Condensing boiler install	18	59	110	240	264	600	969	1071	3331
Heating system install[b]	25	89	174	315	401	927	1395	1474	4801
Double-glazing install	33	95	157	148	1810	2733	2617	2707	10 300
Cavity insulation	92	168	251	362	652	853	917	764	4060
Hot water cylinder install	0	1	2	2	12	46	57	66	186
Draughtproofing	13	70	77	224	388	175	158	52	1158
Solar hot water install	0	0	1	2	14	15	38	41	110
Total[c]	192	519	851	1388	3867	5361	5863	5749	23 790

Notes: [a]Figures are for the total number of installations; dwelling may have more than one measure.
[b]Heating system includes condensing boiler replacement.
[c]Total does not include condensing boiler install, as this is included in heating system.

Table A2 Per cent coverage of selected variables in HEED, 2000–07

Dwelling characteristic	Percentage coverage
Dwelling type	
Missing	33
Flat/maisonette	8
Bungalow	8
Mid-terrace	12
End of terrace	5
Semi-detached	23
Detached	12
Number of bedrooms	
Missing	39
1	6
2	15
3	30
4	7
5+	2
Dwelling age	
Missing	54
Pre-1900	3
1900–1929	5
1930–1949	8
1950–1966	9
1967–1975	11
1976–1982	3
1983–1990	3
1991–1995	2
1996–2002	1
post-2002	0
Household tenure	
Missing	41
Owner-occupier	44
Privately rented	4
Rented from a local authority	5
Rented from a housing association	5
Region	
North East	7
North West	16
Yorkshire and The Humber	12
East Midlands	8
West Midlands	11
East of England	10

(*Table continued*)

Table A2 Continued

Dwelling characteristic	Percentage coverage
London	11
South East	15
South West	10
Energy efficiency installation	
Loft insulation to 250 mm	
Missing	81.81
0–250 mm	5.45
25–250 mm	2.16
50–250 mm	4.57
75–250 mm	1.02
100–250 mm	4.64
150–250 mm	0.33
Cavity insulation	
Missing	75
Cavity wall insulation (pre-1976)	15
Cavity wall insulation (post-1976)	3
Cavity wall insulation (unknown age)	7
Glazing replacement	
Missing	66
Double-glazing replacement	34
Heating system replacement	
Missing	81
Other	3
Condensing boiler	13
Non-condensing boiler	2

Table B1 Datasets and variables (with geographic levels) used in the energy efficiency uptake analysis in England, 2000–07

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	ONS (2010)
Dwelling Type	Valuation Office Agency	LSOA	2011	‘Bungalow’ ‘Flat/Maisonette’, ‘Terrace’, ‘Semi-Detached’, ‘Detached’, ‘Other’, ‘Unknown’	Count of domestic properties	Dataset of the number of domestic properties in dwelling type bands from the Valuation Office Agency property attribute tables for council tax	ONS (2012)
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 the Department of Work and Pensions covering benefit claims during August 2005	ONS (2012)
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 multistage modelling approach	Experian (2009)
Household Tenure	Office for National Statistics	LSOA	2001	‘Owned’, ‘Rented from council’, Other social rented’, ‘Private rented’, ‘Living rent free’	Count of households in domestic properties	Dataset from the 2001 Census describing the household tenure related to the accommodation in question	ONS (2012)
Heating Degree-Days	Met Office	LSOA	2005	‘Heat degrees’	Estimate of the annual average degrees below 15.5 in °C	Dataset of the annual sum of heating degrees below 15.5°C over a 5×5 km^2 grid of England. Data are converted to LSOA by an overlay and averaging of the grid points	UK Met Office (2012)
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	ONS (2012)

Table C1 Results from THE interpolation of English Housing Survey (EHS) data, 1996–2007, for selected dwelling energy efficiency levels

Efficiency measure (10 000s)	Survey year											
	1996	1997*	1998*	1999*	2000*	2001	2002*	2003	2004*	2005	2006*	2007
Loft insulation thickness												
None	69.0	62.2	56.5	53.0	52.9	57.4	66.6	76.8	84.1	85.7	80.7	73.6
$<$ 100 mm	926.4	803.0	690.5	599.8	541.8	527.3	556.6	587.5	580.2	547.5	512.1	483.3
100–150 mm	584.8	650.5	710.9	760.8	795.0	808.2	798.1	773.9	747.3	729.5	726.1	719.6
150 mm+	214.5	265.4	314.4	359.6	399.1	431.1	456.0	483.0	522.5	577.8	647.4	714.2
No loft	233.8	267.4	295.7	313.5	315.6	296.6	257.9	227.2	227.5	237.5	233.3	228.2
Type of wall and insulation												
Cavity with insulation	284.3	348.5	408.5	460.3	499.7	522.6	528.7	533.4	553.5	597.4	664.6	726.8
Cavity uninsulated	1033.7	1014.7	996.3	979.3	964.2	951.8	942.5	935.7	928.6	909.3	869.6	826.0
Other	710.5	685.2	663.1	647.2	640.5	646.3	664.0	679.3	679.5	671.4	665.4	666.1
Extent of double-glazing												
No double-glazing	821.9	760.9	700.1	639.8	580.2	521.5	464.2	409.4	358.7	315.4	281.7	253.2
Less than half	288.3	268.6	249.9	233.4	220.0	211.0	205.8	198.1	183.0	168.1	160.8	154.8
More than half	302.2	295.1	290.1	289.5	295.2	309.5	331.6	349.5	352.3	346.0	338.3	326.4
Entire house	616.1	723.9	827.9	924.2	1009.1	1078.7	1133.5	1191.5	1267.7	1348.6	1418.8	1484.5
Extent of double-glazing												
Less than 80% double-glazed	1267.9	1184.1	1102.0	1023.6	950.6	884.9	825.8	763.3	690.9	625.0	580.6	542.7
80% or more double-glazed	760.5	864.3	965.9	1063.2	1153.8	1235.8	1309.4	1385.1	1470.7	1553.1	1619.0	1676.2
Boilers												
Standard boiler	1042.1	1057.0	1068.0	1070.9	1061.9	1037.0	997.3	964.2	954.1	942.5	907.6	878.2
Back boiler	276.6	278.9	280.7	281.3	280.2	276.8	270.1	258.0	239.1	218.1	201.2	194.4
Combination boiler	280.3	305.8	333.1	364.1	400.6	444.5	496.0	549.2	595.9	625.4	631.5	628.7
Condensing boiler	0.0	4.4	8.5	12.0	14.4	15.5	15.4	15.4	18.2	30.0	52.8	69.8
Condensing (combi) boiler	0.0	7.6	15.0	21.7	27.4	31.9	35.0	37.3	43.4	72.7	134.7	183.7
No boiler	429.4	394.6	362.7	336.9	319.9	315.0	321.4	324.4	311.0	289.4	271.8	264.2
Total	2028.5	2048.4	2068.0	2086.8	2104.5	2120.7	2135.1	2148.4	2161.6	2178.1	2199.6	2218.9

Table D1 Odds ratios (ORs) of the incidence rate of uptake of energy efficiency measures from 2002 to 2007 at LSOA level and energy efficiency programme in England

	Energy efficiency measures uptake incidence rate, 2002–07											
	Energy Efficiency Commitment		Installers		Fuel Poverty Schemes		Home Energy Survey		Core Programmes[c]		All sources	
Variable	**Fabric**	**Heat**	**Fabric**	**Heat**	**Fabric**	**Heat**	**Fabric**	**Heat**	**Fabric**	**Heat**	**Fabric**	**Heat**
Quintile of median income in 2005												
Q1 vs Q5	2.71	2.04	5.07	4.04	9.31	6.03	2.30	1.57	11.86	6.98	11.03	6.68
Q2 vs Q5	1.51	1.26	2.68	2.12	5.49	3.70	1.78	1.42	4.86	3.23	4.73	3.16
Q3 vs Q5	1.36	1.07	1.95	1.42	3.76	2.57	1.61	1.24	3.11	1.86	3.05	1.85
Q4 vs Q5	1.11	0.95	1.36	1.06	2.38	1.89	1.31	1.11	1.79	1.29	1.78	1.29
Tenure (proportion of dwellings)												
Owner-occupied (units = 10%)[a]	1.27	1.11	1.44	1.18	1.88	1.7	1.27	1.07	1.82	1.33	1.74	1.30
Dwelling type (proportion of dwellings)												
Flats (units = 10%)[a]	0.84	0.91	0.79	0.87	0.79	0.89	0.84	0.92	0.72	0.81	0.71	0.81
Quintile of climate (heat degree-days in 2005)												
Q2 vs Q1	1.56	1.55	1.77	1.51	0.74	0.73	0.98	0.85	1.47	1.28	1.54	1.30
Q3 vs Q1	2.11	1.86	2.25	1.76	0.66	0.66	1.14	0.97	1.92	1.63	1.96	1.65
Q4 vs Q1	2.20	1.89	2.61	1.94	0.6	0.57	1.15	0.95	2.04	1.63	2.14	1.67
Q5 vs Q1	1.99	1.71	2.03	1.69	0.75	0.8	1.32	1.01	1.96	1.79	1.96	1.79
Council Tax Band (proportion of dwellings)												
Band A & B (units = 10%)[a]	1	0.98	0.98	0.98	1.14	1.11	1	0.98	1.03	1	1.02	1
Benefits (proportion of dwellings)[b]												
On benefits (units = 10%)[a]	1	0.96	1.04	0.99	1.62	1.52	1.11	1.03	1.31	1.13	1.32	1.13
Household age (proportion of dwelling occupants)												
Adults ≥ 60 years (units = −5%)[a]	1.03	1.02	1.02	1.01	1.04	1.02	1	0.99	1.04	1.01	1.04	1.01
Children ≥ 14 years (units = −5%)[a]	1.01	1.01	1	1.01	1.04	1.04	1.01	1.02	1.02	1.03	1.02	1.03

Notes: [a]ORs estimates correspond to each additional unit of change.
[b]Benefits include disability, incapacity, income support, job seekers and pension.
[c]Core programmes include EEC, Installers, Fuel Poverty and Home Energy Survey.
In this paper HEED is treated as a 'census'-level dataset (*i.e.* a survey of all households). As such, *p*-values are not reported.