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Energy efficiency in the British housing stock: Energy demand and the Homes Energy Efficiency Database

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HIGHLIGHTS

- The energy efficiency level for 50% of the British housing stock is described.
- Energy demand is influenced by size and age and energy performance.
- Housing retrofits (e.g. cavity insulation, glazing and boiler replacements) save energy.
- Historic differences in energy performance show persistent long-term energy savings.

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ABSTRACT

The UK Government has unveiled an ambitious retrofit programme that seeks significant improvement to the energy efficiency of the housing stock. High quality data on the energy efficiency of buildings and their related energy demand is critical to supporting and targeting investment in energy efficiency. Using existing home improvement programmes over the past 15 years, the UK Government has brought together data on energy efficiency retrofits in approximately 13 million homes into the Homes Energy Efficiency Database (HEED), along with annual metered gas and electricity use for the period of 2004–2007.

This paper describes the HEED sample and assesses its representativeness in terms of dwelling characteristics, the energy demand of different energy performance levels using linked gas and electricity meter data, along with an analysis of the impact retrofit measures has on energy demand. Energy savings are shown to be associated with the installation of loft and cavity insulation, and glazing and boiler replacement. The analysis illustrates this source of 'in-action' data can be used to provide empirical estimates of impacts of energy efficiency retrofit on energy demand and provides a source of empirical data from which to support the development of national housing energy efficiency retrofit policies.

1. Introduction

The UK government has identified the residential building stock as being one of the most cost-effective and technology-ready sectors to substantially reduce the greenhouse gas (GHG) emissions over the next decade (DECC, 2012a). Proposals, for example, include cutting GHG emissions in existing homes by 29% by 2020 through a challenging 'whole house' retrofit programme, enabled under the 'Green Deal' (DECC, 2010a); plans also include all new homes to be 'zero carbon' by 2016 (CLG, 2007). These targets have set out a pathway that will see many billions of pounds invested in technologies to improve energy efficiency of demand (DECC, 2012a; European Commission, 2011; UNEP, 2011). Yet achieving these reductions in practice will depend on the ability to measure and track the energy demand of dwellings that have been the subject energy efficiency retrofits. The overall aim of this paper is to examine the effectiveness of one possible approach to measurement and tracking of energy demand through an analysis of the impact that historic energy efficiency interventions had on energy demand in UK dwellings between 2004 and 2007.

Developing energy efficiency intervention programmes for the UK housing stock that are capable of achieving significant and sustained reduction in energy demand requires nothing less than a step change in the available information on the state of the existing stock. The fact is, however, that such data has in the past been difficult to come by, for reasons of lack of interest, limited investment in high quality data, poor coordination and limited connexion between existing datasets and the ability of all stakeholders to learn and innovate (Dietz, 2010; Lowe and Oreszczyn, 2008; Oreszczyn and Lowe, 2010). The government, in acknowledging this need for data and its importance in meeting their GHG reduction commitments has developed a data-framework that draws together

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information on the UK's dwelling stock and its energy performance (DECC, 2011).

Since 1995 to 2012, the Homes Energy Efficiency Database (HEED) has collected data on energy efficiency measures installed in approximately 13 million dwellings in the UK, or half the housing stock, from a number of different sources including: energy suppliers, government funded schemes directed at vulnerable households (e.g. fuel poor, elderly, low income), energy efficiency surveys and retrofit installers (Energy Saving Trust, 2010). HEED offers a unique data source that provides information on both the features of the dwelling (e.g. age, size, type, location), its energy performance (e.g. loft insulation levels, wall construction, etc…), along with details on the installed efficiency measures (e.g. loft insulation, cavity filling, boiler replacement, etc…). In addition to this source of dwelling level energy details, the government has collected annual gas and electricity meter data from energy suppliers on energy demand for statistical reporting since 2004 (DECC, 2009b). In this study, these two sources of data were linked together by the government using the physical property address and made available for analysis.

The datasets in HEED represent 'in action' data, i.e. the product (and by-product) of a range of disparate activities that are centred on home energy efficiency. Its continual collection over the past 15 years has created a large population level database, detailing and tracking a large amount of retrofit activity in the housing stock. Linked to data on energy demand practices, these population level databases offer a rich resource from which to draw together evidence on energy performance, the uptake of energy efficiency measures along with changes in energy demand associated with such measures. In using this resource there are important issues that need to be explored to determine whether databases from a wide number of suppliers can be used to elucidate trends and relationships for dwelling energy demand and energy efficiency. It is also necessary to consider how a resource of this type will contribute to the on-going development of national housing energy efficiency retrofit policy.

The aims of this paper are to: (1) describe the HEED data, in particular to assess its overall representativeness as compared to other housing data for Great Britain (GB); (2) to describe the differences in energy demand (gas and electricity) of the HEED housing stock, segmented by built form characteristics and level of energy efficiency; (3) to determine the change in energy demand associated with the presence of energy efficiency interventions as they relate to changes in energy demand for a selected period (i.e. 2005–2007); and (4) to consider the policy implications of this 'in action' population level data source on developing housing energy efficiency retrofit policy.

1.1. Background

Although significant investments in energy efficient technologies and policies have seen a drop in per capita energy demand for key services (i.e. heating and hot water), total energy use in developed countries has grown steadily, particularly electricity use (IEA, 2008; Pérez-Lombard et al., 2008). Despite this growth, national GHG reduction plans and security of supply are dependent on considerable and rapid reductions in energy demand from buildings (European Commission, 2011; UK CCC, 2010). The UK Committee on Climate Change has acknowledged that an overall GHG emission reduction of greater than 80% by 2050 is required in the built environment (DECC, 2009a; UK CCC, 2010). Further, the Government has supported a target of 'zero carbon' for all new buildings by 2019 and near zero emissions from all existing buildings by 2030 (CLG, 2007; DECC and DCLG, 2010). Delivering this transformation will not only require a range of effective technology interventions but also a deeper level of understanding of the underlying relationships between people, energy use, buildings and environment. Without this insight the ability to develop evidence-based policies to tackle energy demand in buildings is severely compromised (Oreszczyn and Lowe, 2010).

1.2. Energy demand in UK houses

Between 1970 and 2008[1] estimates of per capita energy demand for lighting and appliances increased by 88%, meanwhile space heating is estimated to have peaked in the 1980s and has declined by approximately 8% per capita (DECC, 2012b). Total delivered energy demand in dwellings has grown by 30% during the same period, though peaking around 2004. Gas demand has fallen by 20% between 2005 and 2010; temperature, price and a general improvement in efficiency are cited as reasons for this decline (DECC, 2010b).

In 2010, domestic (i.e. residential) delivered energy accounted for approximately 33% (490 TWh) of total GB energy demand by final consumption, of which gas and electricity accounted for approximately 70% (344 TWh) and 23% (113 TWh) respectively (DECC, 2013). Fig. 1 shows an estimate of the total residential demand by service type and fuel[2] (DECC, 2010b). The majority of residential energy demand is for space and hot water heating (78%) with the remainder for appliances (16%) and cooking (3%).

1.3. Energy efficiency retrofit in UK houses

Since 1970, estimates of the average UK home energy efficiency, as defined by the Standard Assessment Procedure (SAP) 2005[3], have risen from 17.6 SAP points in 1970 to 54.7 SAP points in 2010 and the mean heat loss coefficient of dwellings is estimated to have fallen from 376 W/K to below 286 W/K (Palmer and Cooper, 2013). This increase in efficiency has largely been attributed to the increased uptake in whole house heating systems, more efficient boilers, improved glazing, and loft and cavity insulation and fuel switching to electricity.

Data on energy demand and energy efficiency of residential buildings in the UK takes various forms. There are several publicly available datasets on the UK housing stock, ranging from large cross-sectional surveys on the overall condition of homes and their theoretical energy performance, as found in the English Housing Survey[4] (EHS), to smaller most selective data sets from study surveys of home energy use (e.g. the CaRB Home Energy Survey (Shipworth et al., 2010)), or field trails that focus on particular dwelling or household features or technologies (e.g. the Milton Keynes Energy park (Summerfield et al., 2007)).

However, until recently, data that featured both energy demand and house characteristics at a population level among the UK housing stock was severely limited to historic surveys and small field studies. The most comprehensive and representative dataset that drew together information on energy demand and dwelling characteristics was the Energy and Fuel Use Survey (EFUS), a subset survey from the English House Condition Survey

[1] Following 2008, government statistics on national housing sector energy demand was revised using an update model (DECC, 2012b). As such, 2008 is selected to ensure accurate comparison against previous years.

[2] Residential energy demand by service type is estimated from DUKES data, national totals, and Domestic Energy Fact File data, service fractions. Renewable energy is not included. Services of Fuels $<1\%$ of total are not shown but are accounted for in the total.

[3] The standard assessment procedure (SAP) is a measure of the space and hot water heating cost normalised for floor area with an assumed standard heating profile (BRE & DECC, 2009). The SAP 2005 index is based on a logarithmic scale that runs from 1 to 100. The methodology has changed several times and makes precise interpretation of time series difficult.

[4] The English House Condition Survey (EHCS) was integrated with the Survey of English Housing (SEH) in April 2008; this created the English Housing Survey (EHS).

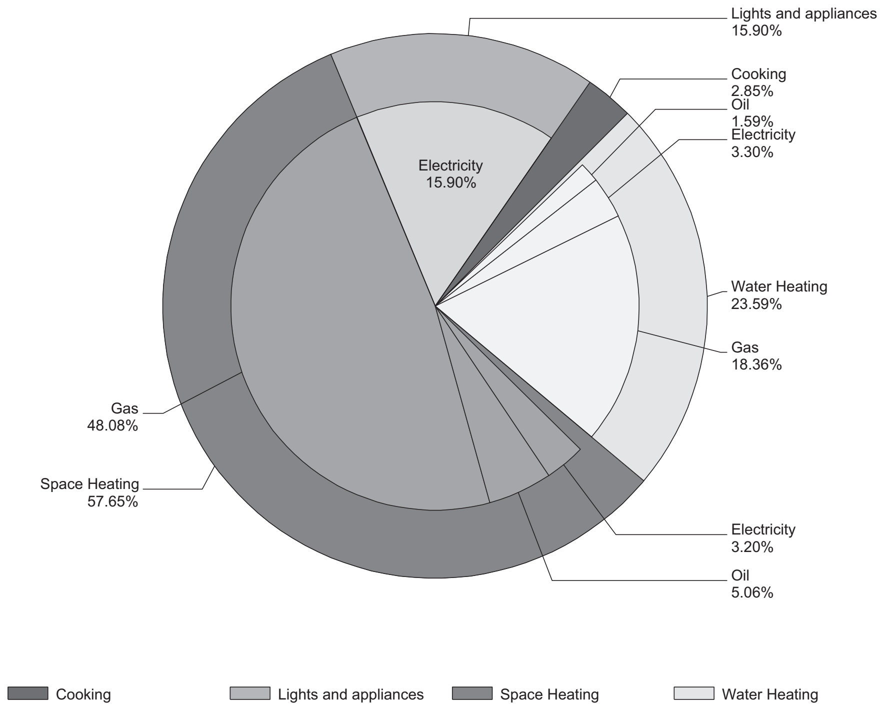

Fig. 1. UK residential fuel by service demand for 2010.

(EHCS) of 1996, which collected data on electricity and gas consumption of approximately 3000 households to measure energy efficiency of the housing stock and the potential for energy savings. This dataset is now over 14 years old, and does not necessarily represent how energy is currently used within dwellings, nor does it capture the effects of the last 10 years of energy efficiency programmes. A follow-up EFUS in 2001 was never released due to unsound weighting therefore making it unrepresentative (CLG, 2013). The recent EHS survey (i.e. 2011–2012) will include an Energy and Fuel User Survey, which will hopefully be of sufficient quality for analysis, but at the time of writing this dataset has not been released. Having repeat measure cross-sectional data on energy use with detailed dwellings characteristics is vital for providing context to small scale field trials and to track long term trends in energy performance levels and base lining energy use beyond the available window in this study.

The Government has prioritised investment in energy efficiency through a number of public and supplier-led schemes and programmes since the mid-1990s including: the energy efficiency standards of performance (1994–2002), Warm Front (2000 onwards), the energy efficiency commitment (2002–2008) and the carbon emission reduction targets (2008–2012). Recently, the government has set out the Energy Company Obligation (2012–2015) that will tackle priority households and fuel poverty along with the Green Deal (2012 onwards). The Green Deal is a departure from past efficiency programmes in that it is a market-based initiative to support energy efficiency improvements by providing loans to households to cover the upfront cost of a retrofit measure that is paid back through energy savings via the bill under a 'golden rule' whereby the payments should not exceed the energy savings (DECC, 2012c).

The successful delivery and uptake of efficiency measures in order to achieve the goal of reducing greenhouse gas emissions and tackle priority issues such as fuel poverty requires that policies are developed from an empirical foundation built on high quality data. In particular, continuous collection of such data is essential for the evaluation of past programmes and the development of future evidence-based policies. The development of HEED has in part been the exercise of reporting for government programmes (such as those detailed above) but has also drawn together other sources related to energy efficiency retrofits, such as heating system inspections and double glazing installers. As a result, HEED contains many (if not most) of the energy efficiency measures carried out under government programmes or through certified installers and therefore presents an opportunity from which to develop an energy efficiency evidence base for policy development and evaluation.

1.4. Methodology

The two main sources of data used in the analysis were energy supplier annualised meter point gas and electricity data and the Homes Energy Efficiency Database (HEED). The gas and electricity meter point data was provided by the Department of Energy and Climate Change (DECC) and covered the period of 2004 through 2007. The gas and electricity meter point values were derived from individual meter readings, via data aggregators of the gas and electricity suppliers. Access to HEED was also provided by DECC through the Energy Saving Trust (EST). The next section contains a detailed description of the two data sources and a description of the analysis methods.

2. Data

2.1. Gas and electricity meter data

The government collects annualised final consumption gas and electricity data for individual meter points from energy suppliers for the purpose of various statistical outputs; in 2007 there were approximately 22.6 million gas meters (22.3 million residential and 0.3 million non-domestic) and 29.1 million electricity meters (26.7 million residential meters and 2.4 million non-domestic meters) (DECC, 2009b). UK gas and electricity meters are classified into two types: daily (gas) or half-hourly (electricity) metered, and non-daily (gas) or non-half hourly (electricity) metered. The non-half hourly and non-daily meter data was linked to HEED by Government for use in this project. Between 2004 and 2008, gas and electricity accounted for just over 90% of total fuel delivered to UK dwellings (DECC, 2012b).

Gas non-daily meters are divided into categories based on their total expected annual load demand; gas meters contain no user identification and 'residential' users are determined to be those whose demand was less than 73.2 MWh/yr and those above are commercial or industrial (DECC, 2009b). Meter readings are converted into annual consumption values by the suppliers using a common methodology with two meter readings at least 6 months apart (when no meter reading is available an estimate based on past demand is used in its place) and is corrected to a seasonal normal demand and an end-user climate sensitivity adjustment to derive a total annual demand (OFGEM, 2013). The purpose of the seasonal correction is to allow for inter-year comparisons that are independent of weather. In terms of what the weather correction might mean for assessing the impact of energy efficiency interventions through the detection of changes in energy demand between years, it may be that long-term trends are more significant than year-on-year changes, but this will depend on the frequency of meter readings for which no information is available. The gas data annual period is 1 October to 30 September and covers a heating season.

Electricity non-half hourly meters are defined into classes representing likely demand profiles and contains a user type identifier. Residential electricity meters are classed into two types based on the meter, i.e. unrestricted electricity or Economy 7. Economy 7 refers to meters that are on a time charge tariff offering cheaper electricity during off-peak hours, typically an 8 h period, and are either time or radio switched (DECC, 2009b); in dwellings, these meters are most often associated with electric heating, either space heating (e.g. storage heaters) or hot water, offering the customer the advantage of electricity bought at off-peak rates and stored as heat for daytime use; in this work Economy 7 m were kept as distinct. Unrestricted meters are all other types of meters; these meters may be used for heating but are not time or radio switched. Electricity meters are annualised using actual meter readings or, if no readings are available estimates based on past use and historic usage patterns and are smoothed across an annual profile to derive a total annual demand in kWh (Elexon, 2010). The annualised electricity values are not corrected for weather. The electricity data annual period is from 30 January to 29 January.

Both the gas and electricity data underwent a cleaning process to remove or identify potentially erroneous data points, such as negatives and dummy values (e.g. '1' values). In this paper, a dataset that removed erroneous data points was used in all energy analysis.

2.2. Home Energy Efficiency Database

The Homes Energy Efficiency Database (HEED) currently contains information on the characteristics and energy efficiency on over 13 million homes from England, Wales, Scotland and Northern Ireland[5]. In 2010, there were approximately 27.3 million dwellings in the UK[6] and HEED covers approximately 50% of the UK housing stock (Energy Saving Trust, 2010). HEED was drawn together from approximately 60 datasets and collected from approximately 20 organisations. The bulk of HEED data was classified using the Reduced Standard Assessment Procedure (rdSAP) format, which attempts to categorise dwellings into common bands relevant to modelling energy demand (BRE and DECC, 2009). Where other forms were used, additional variables were added or were allocated to the best available class within rdSAP. The Energy Saving Trust undertook this data cleaning prior to the data being made available for use in this study.

The extract of the database in February of 2009 used in this study contained approximately 11.5 million distinct home identifiers. The data provided in HEED draws from survey data, and data on specific measures installed under a variety of government backed schemes and energy supplier obligations. Table 1 provides a summary list of these data sources and Fig. 2 shows a breakdown of the sources for the analysed extract of HEED. Note that the variables collected under each source vary and many sources for measures include survey data. HEED comprises information at the individual dwelling level rather than by households or occupants. It contains no information on households or dwelling occupant, aside from household tenure, and thus socio-cultural and economic factors cannot be determined directly. The database primarily contains information on the physical features of the dwelling as they pertain to the energy efficiency of the structure (i.e. fabric) and the heating system; see Table 2 for a summary of the survey and measures data. Approximately 2.7 M homes appear in at least two programmes (i.e. source datasets) and 1 M in three programmes, while the majority (7.2 M) are present in only one programme, see Appendix A for more details on HEED.

2.3. HEED and energy demand

For this study, a dataset containing all matched HEED dwellings and related annualised gas and electricity values for the period 2004–2007 was used; Table 3 shows the number of records contained within the source data sets. Note the number of records in electricity and gas represent all meters in Great Britain, both domestic (i.e. residential) and non-domestic and that the number of records for electricity meters includes those on a time-tariff (i.e. these meters have two records each for on and off-peak time). The two time tariffs are subsequently summed together for a single annual value. Also, the 2007 gas demand is for homes in HEED only and not the whole UK—this data was not made available for use in this work. For those comparisons between HEED and non-HEED energy demand, 2006 data was used. Comparisons of energy use and for installed efficiency measures were based on 2007 data in order to capture a longer time period and more interventions.

2.4. Analysis methods

The first step in the analysis sought to determine how representative of the British (i.e. England, Wales, Scotland) housing stock the meter-matched HEED sample was for a selection of key variables, i.e. age, type, tenure size and location. This was done by comparing HEED with three other databases: the 2008 English Housing Survey (EHS), the 2007–2009 Scottish House Conditions Survey (SHCS), and the 2010 Valuation Office Agency (VOA) Council Tax Property Attributes database for England and Wales. Together these data sources provide more or less complete coverage of the housing stock of Great Britain. Chi-square tests for goodness-of-fit at a 95% confidence interval were used to determine statistical significance. For computational purposes, a 10% randomly selected sample of approximately 1.2 million dwelling records representative of HEED was used for the population comparison, rather than the full HEED database (i.e. 11.5 M), see Appendix B for a χ^2 test for the HEED sample and full HEED database.

[5] The Homes Energy Efficiency Database (HEED) is collected and maintained by the EST on behalf of DECC.

[6] In 2010 it is estimated there are 22.7 million dwellings in England, 1.3 million in Wales, 2.5 million in Scotland and 0.75 million in Northern Ireland (DSDNI, 2011; Scottish Government, 2011; Welsh Assembly Government, 2011).

Table 1
Homes Energy Efficiency Database (HEED) data suppliers and programmes.

Programme	*Provider (s)*	*Survey/ measures*
Government schemes[a]	Warm front and warm homes Scottish central heating programme The warm deal	Survey and measures
Surveys	Home energy check National registry of social housing Local authorities	Survey
Installers	Boiler installers Glazing installers Insulation installers Cavity wall installers Local authorities Renewable installers	Measures
Energy Suppliers	Customer energy efficiency improvement schemes[b]	Measures

[a] Government schemes are primarily targeting vulnerable groups, i.e. fuel poor or high indices of deprivation.
[b] Energy supplier schemes target customers and are in fulfilment of carbon reduction targets set by the UK government.

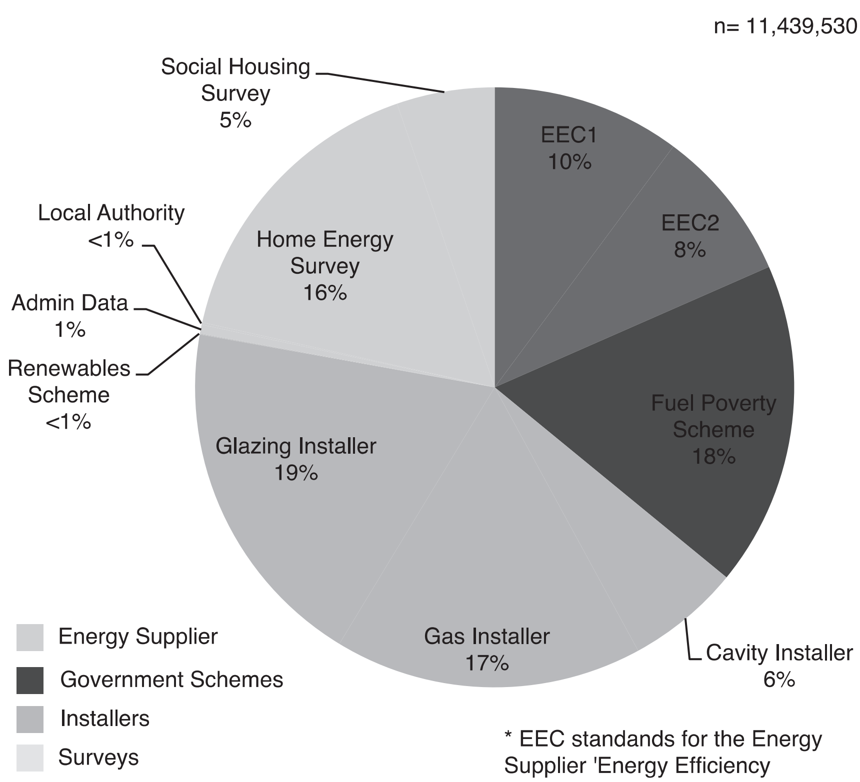

Fig. 2. HEED stock data sources for all years (1995–2010).

The 2008 EHS was used because the collection period aligned with the last year of HEED data, which is also the case for the 2007–2009 SCHS. The VOA holds data on both England and Wales and is revised every year therefore the latest extract was used. Both the EHS and SHCS provide a factor with which to weight variables in order to represent houses or households in England or Scotland, for the comparisons we used the houses weighting. No weighting was required for the VOA data. With respect to the potential changes in the stock since 2008, approximately 268,000 dwellings were built in 2009 and 2010 (approximately 0.1% of the total GB stock) (CLG, 2010a). Further details of the housing surveys are provided in Appendix C.

The EHS, SHCS, VOA and HEED were not collected using a common format (i.e. rdSAP)—they were all developed for different purposes. As a result only some variables can be compared and in some cases variable classes were banded together to create comparable data categories (e.g. dwelling type and number of bedrooms). Dwelling age is collected using a different age band for each survey and was too complex to band as dwelling completion rates fluctuate from year to year. Therefore, for the comparison of age, we did not perform a χ^2 goodness-of-fit test and instead present data for visual comparison.

The energy demand of meters for dwellings in HEED was compared to meters not present in HEED (or non-HEED) for the period covering 2004–2007 for gas and electricity. Using the detail date, it was possible to compare those groups of dwellings across the gas demand period based on when they entered HEED, and therefore were likely to have received an efficiency intervention, to

Table 2
Homes Energy Efficiency Database (HEED) example data.

Data type	*Data examples*	
Survey data	• Property type • Tenure • No of Bedrooms • Year of construction • Space heating fuel • Water heating fuel • Loft insulation thickness • External wall type	• Window type • Window frame type • Levels of draught-proofing • Main heating system • Secondary heating system • Hot water system • Heating controls (various types) • Energy rating (SAP/NHER) • Hot water tank insulation
Measures data	• New or additional loft insulation and depth • Cavity wall insulation • Solid wall insulation/flexible linings • Boiler replacements • Heating control upgrades	• Fuel switching • Compact florescent lamps • Renewable systems (e.g. solar thermal, solar PV, heat pumps)

Table 3
Count of records in data sources used in HEED and energy analysis.

Data	Records
HEED—Unique Homes in database	11,440,132
HEED—Homes matched with electricity[a]	11,685,235
HEED—Homes matched with gas	9,785,503
Electricity 2004	34,449,299
Electricity 2005	34,660,002
Electricity 2006	35,054,514
Electricity 2007	35,047,989
Gas 2004	21,243,433
Gas 2005	21,994,051
Gas 2006	22,265,312
Gas 2007[b]	9,785,500

[a] Note the number of matched electricity records exceed HEED records due to multiple meter matches.
[b] 2007 gas demand is present for those meters connected to HEED only.

the non-HEED dwellings. For example, a dwelling could enter HEED due to an intervention taking place in 2006 but would also have been connected to the preceding two years of demand (i.e. 2004 and 2005) and the subsequent gas year (i.e. 2007). Changes in gas and electricity demand within the two groups would be broadly effected by a number of exogenous and endogenous drivers, such as: fuel price and demand, energy efficiency, income and the ability to pay, behavior and others, but the effect of such impacts outside of energy efficiency were not investigated.

Gas and electricity demand was analysed for dwellings in HEED by their physical characteristics (i.e. age, size, type) and levels of intervention (i.e. loft insulation level, cavity insulation, glazing type) and provided for description. The 10% randomly selected sample representative of HEED was used for this analysis. Gas and electricity demand are normalised by number of bedrooms[7] as a proxy for dwelling size in an attempt to explore a size effect. Note that the fuel demand statistics are not directly comparable to DECC statistics due to the difference in years available for analysis (i.e. 2007 vs 2008) (DECC, 2011).

An impact analysis of the changes in demand over the period (i.e. 2004–2007) for dwellings with and without an energy efficiency intervention was performed using a crude 'retrospective case-control' method. Groups were selected based on whether they had experienced an intervention (case) or not (control). The cases were compared with the controls to determine the difference in energy demand in relation to known influencing factors, i.e. energy efficiency retrofits. The study was retrospective because the dwellings groups were selected after the interventions took place. While HEED contains a great deal of information on energy efficiency interventions, it also contains a number of dwellings (approximately 20%) that had only been surveyed. The control group consists of those dwellings that received no energy efficiency intervention logged in HEED and have only the basic level of energy efficiency and therefore would provide the greatest possible difference. A basic energy efficiency level for any home was defined as having walls insulated as built, single glazing, loft insulation <50mm, a non-condensing boiler and no draught stripping. As noted above, it was possible that those dwellings selected as part of the control group may have been subject to a occupant-led or non-HEED logged intervention, but there was no way to determine from the data if this was the case.

Four types of intervention were analysed, they are: loft insulation to >200 mm, cavity wall insulation filling, double glazing installation, and replacement of non-condensing with condensing boilers. The change in demand for the period 2005–2007 for those dwellings that were recorded as having an intervention in 2006 (determined using the detail intervention date) was compared to the change in demand for the control group for which no evidence of an intervention was recorded. A difference-of-differences test using the trend in the control group as a baseline was used to determine changes associated with the presence of an efficiency retrofit. The randomly selected 10% HEED sample was also used in this analysis.

3. Results

In the following section we present the results from the three analysis strands: (1) HEED dwelling characteristics, (2) HEED energy demand by dwelling and energy efficiency characteristics, and (3) the impact of energy efficiency retrofit on energy demand through a retrospective case-control study.

3.1. Comparison of HEED dwelling characteristics

The characteristics of dwellings in the selected 10% HEED sample are compared against representative samples for England, England and Wales, and Scotland. Tables 4 and 5 provide overview statistics for the selected compared variables. The results show

[7] For dwellings with 5+ bedrooms, an arbitrary value of 5.5 is used for normalisation.

Table 4
HEED (England) dwelling characteristics compared to EHS.

England[a]	HEED 10% (*n*)	HEED 10 (%)	EHS 2008 (%)
Dwelling type			
Flat-Maisonette	96,975	17.2	18.6
Bungalow	54,837	9.7	9.4
Terrace	141,109	25.1	28.6
Semi-detached	183,309	32.6	26.0
Detached	86,434	15.4	17.4
χ^2			12961.22
d.f.			4
p			<0.0001
Dwelling tenure			
Social rental	156,195	21.8	14.8
Private rental	67,499	9.4	17.7
Owner-occupied	493,481	68.8	67.5
χ^2			51585.46
d.f.			2
p			<0.0001
Dwelling size (bedrooms)			
1	71,315	12.6	9.1
2	142,619	25.3	27.1
3	267,307	47.4	44.2
4	58,600	10.4	15.5
5+	24,333	4.3	4.0
χ^2			19219.87
d.f.			4
p			<0.0001
Dwelling region			
North East	70,049	6.2	5.1
North West	159,820	14.2	13.6
Yorkshire and The Humber	120,624	10.7	10.6
East Midlands	91,541	8.1	8.8
West Midlands	116,000	10.3	10.5
East of England	109,080	9.7	10.9
London	132,433	11.8	14.2
South East	161,845	14.4	15.8
South West	107,767	9.6	10.3
χ^2			9810.57
			8
			<0.0001

[a] 10 HEED Sample, England only.

Table 5
HEED (England and Wales) dwelling characteristics compared to VOA.

England & Wales[a]	HEED 10% (*n*)	HEED 10 (%)	VOA, 2010 (%)
Dwelling type			
Flat-Maisonette	96,975	17.2	21.9
Bungalow	54,837	9.7	10.2
Terrace	141,109	25.1	27.3
Semi-detached	183,309	32.6	24.8
Detached	86,434	15.4	15.8
χ^2			20518.77
d.f.			4
p			<0.0001
Dwelling size (bedrooms)			
1	71,315	12.6	11.6
2	142,619	25.3	28.4
3	267,307	47.4	45.4
4	58,600	10.4	11.5
5+	24,333	4.3	3.0
χ^2			6798.72
d.f.			4
p			<0.0001
Dwelling region			
North East	70,049	6.2	4.8
North West	159,820	14.2	12.9
Yorkshire and The Humber	120,624	10.7	9.5
East Midlands	91,541	8.1	8.1
West Midlands	116,000	10.3	9.7
East of England	109,080	9.7	10.4
London	132,433	11.8	13.8
South East	161,845	14.4	15.1
South West	107,767	9.6	9.8
Wales	55,073	4.9	5.7
χ^2			14076.56
d.f.			9
p			<0.0001

[a] 10 HEED Sample, England and Wales only.

Table 6
HEED (Scotland) dwelling demographics comparison to SHCS.

Scotland	HEED 10 (n)	HEED 10 (%)	SHCS 2009 (%)
Dwelling type			
Flat-Maisonette	29,008	36.6	36.7
Bungalow	0	0.0	0.0
Terrace	20,334	25.6	25.5
Semi-detached	15,905	20.1	20.1
Detached	14,062	17.7	17.8
χ^2			1.2293
d.f.			3
p			0.746
Dwelling tenure			
Social rental	25,334	27.9	27.7
Private rental	9562	10.5	10.6
Owner-occupied	56,017	61.6	61.7
χ^2			1.5907
d.f.			2
p			0.4514
Dwelling size (bedrooms)			
1	11,274	19.3	19.2
2	22,321	38.1	38.1
3	19,314	33.0	33.1
4	3735	6.4	6.4
5+	1867	3.2	3.1
χ^2			1.9065
d.f.			4
p			0.753

Notes: a10 HEED Sample, Scotland only.

that the HEED data is not statistically representative of the English and Welsh stock for the selected variables. In all cases of comparison we reject the hypothesis that the compared variables of the HEED data set are the same as those of the English Housing Survey and VOA Council Tax (i.e. all *p*-values <0.0001 at a 95% confidence limit).

Table 6 shows a comparison of the Scottish dwellings in HEED and accepts the hypothesis that the HEED sample is statistically similar to the Scottish House Conditions Survey.

While the analysis of the populations represented in the HEED data does not support the hypothesis that the sample is the same as the other datasets that represent the housing stock of England, and England and Wales, it is not necessarily the case that HEED cannot be used to describe housing energy efficiency demand for those groups. Also, it is known that small divergences are shown to be significant for χ^2 goodness-of-fit tests for large sample and those comparisons are often made through visual inspection. A visual comparison of the data suggests that there are small differences for most categories, but many are within 1%. As such, a caution should be applied where findings from HEED are interpreted and generalised for the housing stock as a whole.

Overall, in the English and Welsh component of HEED, 'dwelling type' shows fewer flats and more semi-detached houses. There are fewer privately rented dwellings and more socially rented dwellings, likely reflecting the emphasis of the government and energy supplier programmes to target areas of high-deprivation and low-income groups. In terms of geographic coverage, there are fewer homes in the southern regions of England. Despite the targeting of the programmes, given the number of dwellings represented in HEED

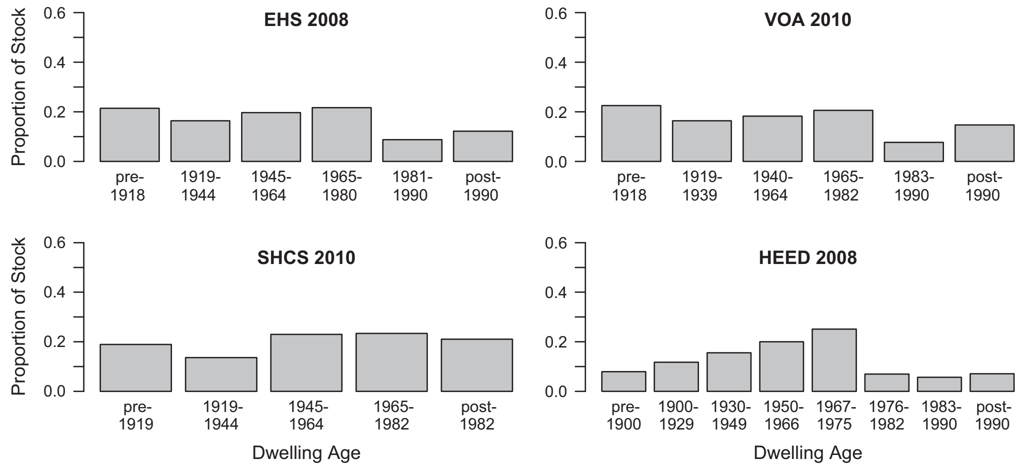

Fig. 3. Housing stock age band comparison.

(approximately 50% of all GB dwellings), HEED does compare *relatively* well to the representative housing stocks of Great Britain. The HEED data can be said to represent the Scottish housing stock, which likely reflects the collection process and inclusion of a proportion of building performance rating data (i.e. Energy Performance Certificates).

Age is compared graphically rather than statistically, due to the difference in category bands. Fig. 3 shows that there are more homes in the 1967–1982 period and fewer 1990+ homes then in the English and Welsh stocks.

3.2. HEED energy efficiency characteristics

Table 7 shows the distribution of a selection of energy efficiency features by dwelling characteristics, as compared to the HEED GB sample. This gives an indication as to the coverage for walls, lofts, glazing and heat systems within the selected population and whether there would be any significant population bias expected in any differences found. The differences in coverage by dwelling characteristic appear to be relatively small, although with less coverage of measures in 1967–1975 dwellings, and of heat systems in 3 bedroom dwellings.

3.3. Energy demand: HEED and non-HEED

In this section, we compare annualised gas and electricity meter data for the Great Britain (i.e. England, Wales and Scotland) HEED sample against the non-HEED meters. Following this, the gas and electricity use for the HEED stock is described.

3.4. Gas demand

Table 8 shows that the change in median gas demand in non-HEED meters between 2004 and 2006 is approximately −6.1%. For meters in HEED, the change in median gas demand between 2004 and 2006 is approximately −8.1%. Residential gas demand data is influenced by a long right tail, as can be seen in the <73.2 MWh/yr meters gas demand (Fig. 4). This is an inevitable consequence of the fact that energy demand data cannot be negative, but is subject to no well-defined upper limit (other than the very high 73.2 MWh artificial limit). Note also the upward flick in the distribution close to zero demand; dwellings that are unoccupied for part or all of a year may cause this.

Table 7
HEED Stock: Comparison of energy efficiency groups by dwelling characteristic.

Dwelling characteristic	HEED Stock	HEED stock energy efficiency groups			
	All (%)	*Wall type group (%)*	*Loft group (%)*	*Glazing group (%)*	*Heating system group (%)*
Dwelling type					
Bungalow	11	11	10	9	9
Detached house	19	20	19	20	22
Semi-detached house	39	38	37	37	37
Terrace house	31	31	33	33	31
Dwelling age					
pre-1900	8	9	9	9	10
1900–1929	12	12	13	13	12
1930–1949	16	16	17	17	17
1950–1966	20	20	19	19	20
1967–1975	25	23	22	22	19
1976–1982	7	7	7	7	7
1983–1990	6	6	6	6	6
post-1990	7	7	7	7	8
Number of bedrooms					
1	13	12	12	12	14
2	26	25	25	25	25
3	46	47	47	47	43
4	10	10	10	10	11
5+	4	5	5	5	7

3.5. Change in gas demand for HEED

HEED contains a time stamp for when a measure was introduced or a survey was carried out for each dwelling. Fig. 5 shows meters classified by the home details date, thus entering HEED. We see that energy demand for homes in HEED with a high likelihood of an intervention in 2005 begin to diverge (i.e. the slope) from the demands of their non-intervention counterparts in the following year. This is also true for dwellings with interventions in 2006. The change in demand is higher for those dwellings with an intervention within the gas period, with the exception of those entering in 2007, where it is unlikely the gas data would pick up in the change, depending on the reading frequency. Note that this is the bulk trend for all homes in HEED, regardless of the type of measure—more details are provided below on this.

Table 8
Residential gas demand for HEED and non-HEED meters.

Profile	Flag HEED	Year	Mean	Median	Std Dev (σ)
Gas[a] - Residential (< 73.2 MWh/yr)	*Non-HEED*	2004	19,734	18,214	11,137
	n=8,410,189	2005	19,433	17,877	11,008
		2006	18,625	17,107	10,836
		2007[b]	.	.	.
	HEED	2004	19,623	18,452	9725
	n=7,450,540	2005	19,141	17,926	9511
		2006	18,153	16,958	9252
		2007	17,468	16,226	9086

[a] Excludes erroneous data point.
[b] Non-HEED 2007—Gas meter values were only provided for those homes matched in HEED, therefore no statistics are available for this year from the processed data.

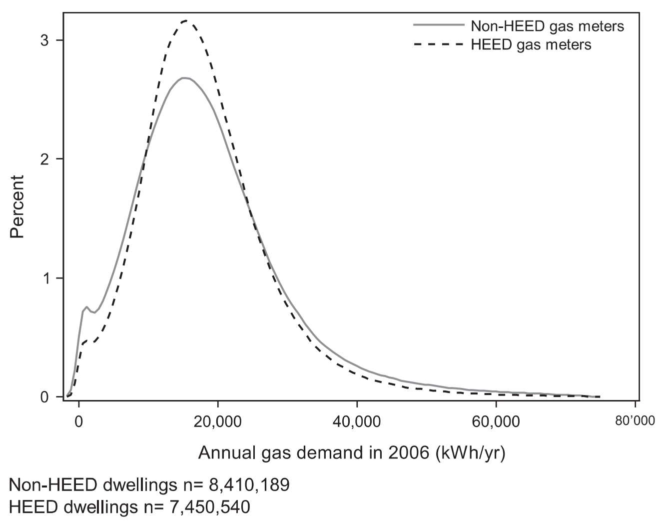

Fig. 4. Distribution of residential gas demand (< 73 MWh/yr) in 2006 for HEED and Non-HEED meters.

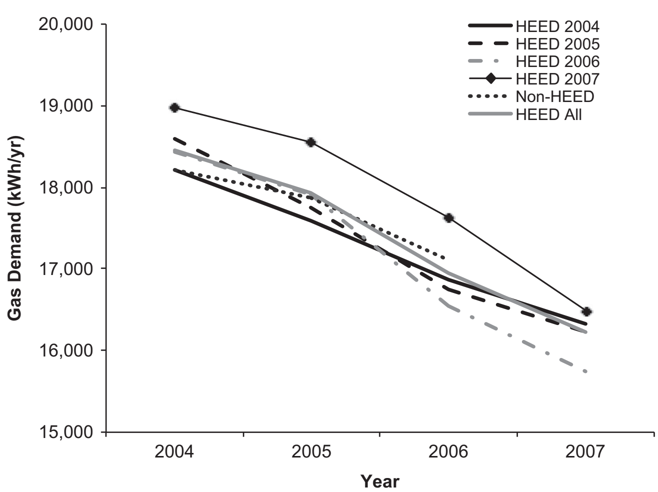

Fig. 5. Gas demand by HEED entry year.

Table 9
Residential electricity demand for HEED and non-HEED meters.

Profile	Flag HEED	Year	Mean	Median	Std Dev (σ)
Unrestricted[a]	Non-HEED	2004	4272	3548	3304
	n=9,212,105	2005	4311	3551	3359
		2006	4231	3519	3233
		2007	4163	3447	3230
	HEED	2004	4023	3410	2865
	n=7,362,544	2005	4027	3391	2894
		2006	3957	3359	2790
		2007	3888	3288	2770
Economy7[a]	Non-HEED	2004	6960	5587	5392
	n=2,685,662	2005	6750	5427	5225
		2006	6543	5275	5066
		2007	6675	5339	5237
	HEED	2004	6472	5069	4981
	n=1,735,592	2005	6199	4874	4769
		2006	6001	4756	4593
		2007	6067	4749	4728

[a] Erroneous data points are excluded.

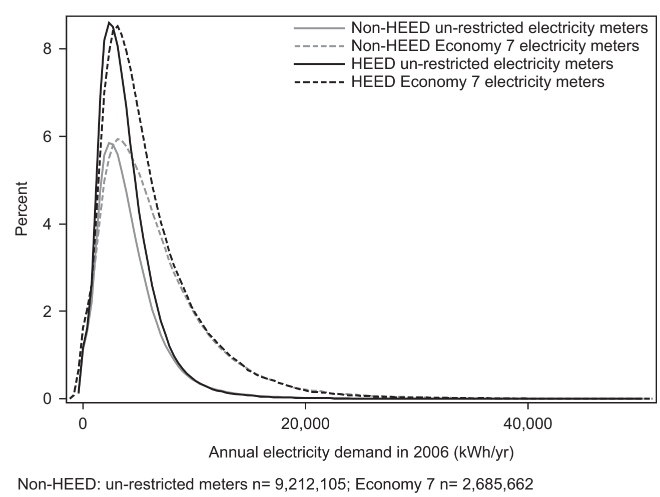

Fig. 6. Distribution of residential unrestricted (ordinary) and Economy 7 electricity demand.

3.6. Electricity demand

Table 9 shows that the change in the median unrestricted electricity demand in non-HEED meters between 2004 and 2006 is approximately −0.8%. The change between 2004 and 2007 for the same meters is 1.2%. For meters in HEED, the change in median unrestricted electricity demand between 2004 and 2006 is approximately −1.5% and the change between 2004 and 2007 is −0.9%. Non-HEED Economy 7 m saw a change in median of −5.6% between 2004 and 2006, compared to −6.2% for HEED Economy 7 m for the same period (change in medians for 2004–2007 is −3.5 and −5.6 for HEED and non-HEED meters respectively).

The electricity data (unrestricted and Economy7 meters) is influenced by a long right tail, as can be seen in the distribution of electricity demand (Fig. 6). Note that when considering this tail against the gas demand data, electricity meters are classed based

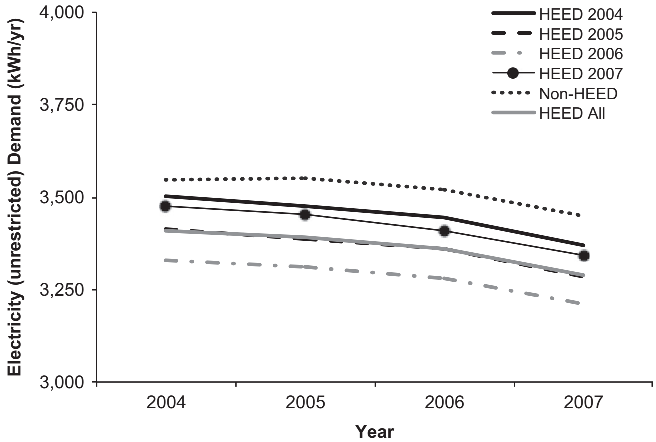

Fig. 7. Unrestricted electricity demand by HEED entry year.

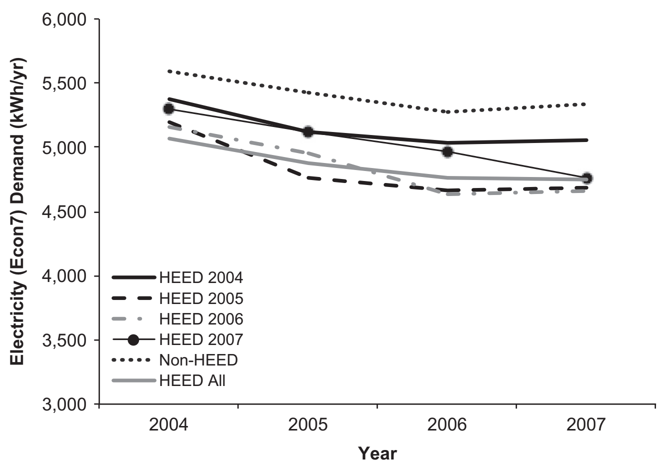

Fig. 8. Economy 7 electricity demand by HEED entry year.

on a user type and tariff, whereas the gas data is classified according to consumption. While the long right tail in gas may hold a number of non-domestic users, electricity demand is reflecting large users.

3.7. Change in electricity demand for HEED meters

Fig. 7 shows that the year-on-year change for all non-HEED and HEED groups is broadly similar, with non-HEED meters reducing by 0.8% from 2004 to 2007 and HEED meters reducing by 1.2%. Fig. 8 shows that change in Economy 7 m varies more across the period and groups. Note that the Economy 7 demand, which is associated with heating, is not weather corrected and therefore will be effected by changes in temperature. Note also that the trend change is similar across the groups. The group average change in unrestricted electricity for meters in HEED is a reduction of 3.5% as compared to a reduction of 2.5% for non-HEED meters. Economy 7 m in HEED broadly show a reduction of around 9.5% from 2004 to 2007 and non-HEED meters show a reduction of 4.1%. Again, note that the Economy 7 is not weather corrected and this change will reflect weather trends.

3.8. Gas and electricity statistics for HEED dwellings

The linked datasets provided an opportunity to tabulate gas and electricity demand by dwelling characteristics. Table 10 provides overview statistics for gas and electricity use in 2006 by a selection of dependent variables. The table shows that older dwellings typically demand more gas and Economy 7 electricity but that unrestricted electricity demand is very similar in old and new dwellings, with a slight increase in newer dwellings. Detached houses and bungalows record the highest gas demand, with a decline in demand by the level of detachment; this trend is also true in unrestricted electricity—although terraces seem to use more Economy 7 electricity than semi-detached dwellings. Median and mean gas and unrestricted electricity demand in private rental dwellings are very similar to demand in social rentals and owner occupied dwellings use a third more gas and ~25% more unrestricted electricity. However, median Economy 7 electricity demand in social rental properties is approximately 33% higher than private rentals. Median gas demand increases on average by 22% for every additional bedroom over 1 bedroom. The difference per bedroom is lowest when moving from 4 to 5+ bedrooms (14%) but this is likely due to the banding together of properties above 5 bedrooms as an arbitrary selection of 5. Median unrestricted electricity demand increases monotonically from 1 to 4 bedrooms. Again, the increase from 4 to 5+ bedrooms is 12% but is subject to the same caveat as for gas.

Figs. 9–11 compare HEED dwelling characteristics (i.e. age, type and tenure) and gas and unrestricted electricity demand per bedroom; the figures give the *mean* gas or electricity use[8], rather than the preferred median. The figures show there is a size effect for electricity (i.e. size and electricity are positively related) but no relationship with dwelling type, age or tenure. Gas demand variation across different dwelling types (excluding bungalows and flats) shows that dwellings with more exposed surface area (i.e. detached houses and bungalows) use slightly more per bedroom. Gas demand by age also shows that older dwellings use more gas, which may be related to their overall level of energy efficiency and/or also reflect large bedrooms. There appears to be only a slight difference between tenure types, with owner-occupied properties consuming more gas per bedroom.

3.9. Energy efficiency characteristics of HEED dwellings

The following section shows the difference in energy demand for varying levels of energy efficiency characteristics (i.e. lofts, wall type, glazing, boiler type) within the HEED data set. Table 11 shows median gas demand by age and dwelling type for loft insulation levels (<50 mm, 50–200 mm, >200 mm) and cavity wall insulation (filled vs unfilled). The average difference across all age bands for dwellings with >200 mm of loft insulation is 1.6% less than those with <100 mm. Across dwelling types, the average difference between >200 mm loft insulation is 6.7% less than for <100 mm. The average difference for cavity fillings by age group is 7.9% less than those with cavity unfilled and for dwelling type is 9.4% less than cavity unfilled.

Table 12 shows median gas demand by age and dwelling type for glazing type (pre-2002 vs post-2002 double) and boiler type (condensing vs non-condensing). The average difference across all age bands for dwellings with post-2002 double glazing is 3% less than those with pre-2002 double glazing. Across dwelling types, the difference between post-2002 double glazing is 4.5% less than pre-2002 glazing[9]. The average difference for condensing boiler upgrades by age group is 8.8% less than those for non-condensing boilers and for dwelling type is 9.2% less.

[8] In order to control the effect that large energy using meters may have on the results, Tukey's method of determining outliers is used. This method treats any value as an outlier that is greater than the 75th percentile plus 1.5 times the inter-quartile distance, or less than the 25th percentile minus 1.5 times the inter-quartile distance. No data with missing classes is used in these figures.

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

Table 10
HEED Stock—Residential gas and electricity demand in 2006 by dependent variables.

	Gas[a] (kWh/yr)				Unrestricted[b] (kWh/yr)				Economy 7[b] (kWh/yr)			
	N	Mean	σ	Median	*N*	Mean	σ	Median	*N*	Mean	σ	Median
Dwelling age												
Missing	575,785	17,333	9,606	16,087	512,664	3796	3303	3223	135,471	5825	5679	4502
Pre-1900	30,360	18,950	12,121	17,063	31,399	3881	3881	3111	9703	7298	6870	5561
1900–1929	57,969	18,723	10,763	17,267	53,366	3687	3654	3098	10,507	6340	6377	4689
1930–1949	77,944	17,930	9169	16,918	71,396	3706	3084	3178	14,980	6186	5731	4732
1950–1966	90,841	16,703	8567	15,780	83,885	3484	2999	2978	24,317	6338	6352	4906
1967–1975	117,502	16,939	8661	15,982	109,336	3569	3017	3086	31,198	6226	5710	4849
1976–1982	29,510	15,534	8408	14,536	28,982	3393	2804	2890	8340	6159	5109	4929
1983–1990	21,334	15,678	8754	14,452	19,455	3474	2892	2930	10,128	6182	4875	5082
post-1990	28,156	16,234	8677	15,005	27,808	3740	3250	3235	7448	6207	5479	4995
Dwelling type												
Missing	525,816	17,557	9700	16,300	469,962	3863	3354	3284	125,464	5924	5664	4605
Flat[b]	70,660	11,557	8341	10,242	80,964	2440	3000	1967	31,701	5313	5857	4309
Bungalow	45,614	17,379	8,527	16,129	41,898	3318	2798	2784	11,949	6539	5913	4828
Terrace	140,100	16,004	8,487	14,983	123,555	3494	3033	3038	29,913	6364	5702	4845
Semi-det.	175,690	17,533	8,276	16,571	156,505	3788	2911	3310	32,973	6341	5832	4765
Detached	71,521	22,823	10,592	20,992	65,407	4663	3683	4023	20,092	6898	6258	5135
Dwelling Tenure												
Missing	379,225	17,538	9533	16,357	344,089	3801	3267	3239	102,485	6221	5789	4819
Social[c]	120,802	13,637	7784	12,964	126,730	3019	3136	2506	35,136	5960	6252	4791
Private[d]	64,594	13,863	8485	12,796	56,245	3207	3576	2651	14,906	4900	5779	3569
Owner	464,780	18,507	9633	17,186	411,227	3917	3186	3347	99,565	6105	5601	4658
Number of Bedrooms												
Missing	535,083	17,461	9714	16,217	476,968	3806	3336	3231	130,776	5906	5696	4558
1	50,004	12,457	8541	11,137	54,634	2459	2884	1934	20,850	5658	5903	4685
2	127,067	14,397	7737	13,541	120,175	2988	2791	2554	35,701	6102	5910	4662
3	248,788	17,526	8261	16,590	223,153	3807	2905	3357	48,354	6217	5667	4637
4	50,471	23,129	10,503	21,560	45,824	4912	3848	4358	11,471	6866	5778	5390
5+	17,988	26,292	12,726	24,246	17,537	5589	4540	4890	4940	8148	7315	6171

[a] Excluded gas meters = 8,069 due to erroneous values; [b]Excluded electricity meters = 18.190 due to erroneous values; HEED Sample size is 1,286,372, approximately 20% had no matched gas meter and 7% no matched electricity meter.
[b] Flats include purpose built, maisonette and converted.
[c] Social includes registered social landlords (RSL) and local authority.
[d] Private rental.

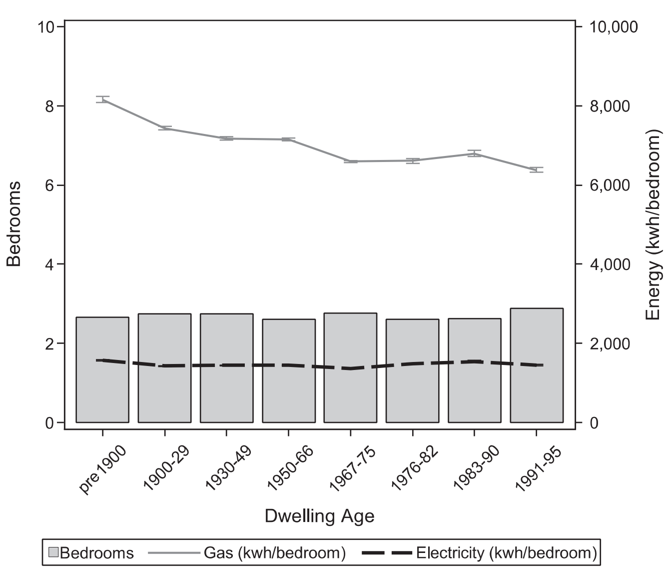

Fig. 9. Mean gas and electricity demand per bedroom by dwelling age.

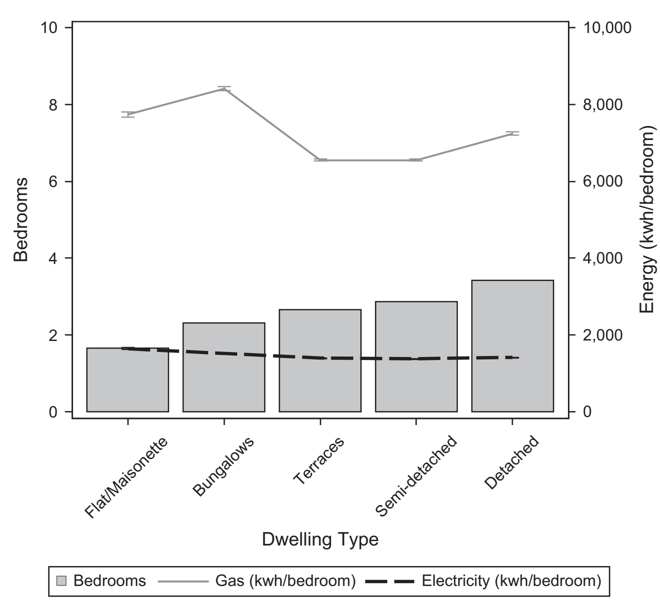

Fig. 10. Mean gas and electricity demand per bedroom by dwelling type.

3.10. Energy efficiency interventions: a case-control study

Using the date of the intervention in the HEED data, the change in energy demand between 2005 and 2007 associated with the presence of an energy efficiency measure in 2006 is compared against a control group with no such measures recorded. The comparison is made for dwellings with loft insulation top-ups to greater than 200 mm, cavity filling, post-2002 double glazing replacement and replacement of non-condensing with condensing boilers.

3.11. Case and control groups

Fig. 12 shows a comparison of the control group against the HEED population and the intervention group (i.e. having an efficiency retrofit). The control group has fewer bungalows and semi-detached and detached dwellings than the HEED population or the intervention group, and more flats and terraced houses. This is likely the result of fewer measures being applied to flats than any other dwelling form. In terms of tenure, the control group offers a similar distribution but with slightly more owner occupied dwellings than the HEED population. There are more pre-1929 and 1950–1966 dwellings than the HEED population, which would be expected given that the definition relies on basic levels of efficiency. The control also has more 1 bedroom dwellings than the HEED population and fewer 3 bedroom dwellings, which may be related to the control having more flats/maisonettes. Appendix D provides more details on the Case and Control groups (Fig. 13).

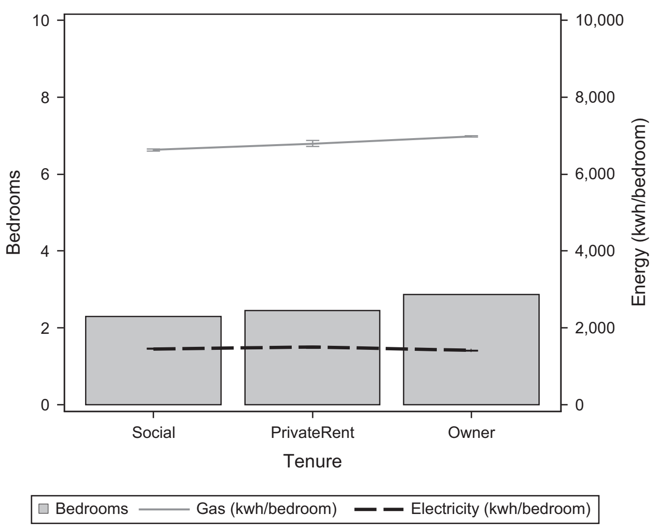

Fig. 11. Mean gas and electricity demand per bedroom by tenure.

3.12. HEED: impact of energy efficiency measures

Table 13 shows the change in demand for the period 2005–2007 for dwellings with an energy efficiency retrofit. The mean change in gas demand in the control group over the period is approximately −6.6%, which is used to define the exogenous trends seen within dwellings with the effect of energy efficiency measures. When compared against the mean change in demand for those dwellings with an efficiency measure that occurred in 2006, it appears that the presence of cavity filling and condensing boiler upgrades are associated with the biggest drop in gas demand over the control trend, i.e. −9.2% and −8% points respectively. Dwellings with lofts and double glazing replacement show only a slight reduction over the control of −1.3% and −1.6% points respectively.

Figs. 13 and 14 show the mean gas demand over the period 2004–2007 for the control and dwellings that received a cavity and boiler measure in 2004, 2005, 2006 and 2007—these measures are looked at in more detail due to the magnitude of change. The purpose of the comparison is to determine if the presence of an efficiency measure shows a change in demand in subsequent years. Fig. 14 shows that the change in mean gas demand associated with the presence of cavity wall filling is very apparent in the following year. A cavity filling in 2005 shows a drop in demand for that year while dwellings with an installation in 2006 appear to have the same change as the control group but then a large drop in 2006, this is also true for 2007. In Fig. 14, a boiler installation also shows a large drop in demand in the year of the intervention along the lines described for cavity wall filling. Overall, the presence of an energy efficiency intervention does show a reduction in gas demand in subsequent years as compared to a control group.

4. Discussion and conclusions

4.1. The representativeness of HEED

HEED contains information on approximately 50% of dwellings in the UK. The results of the housing stock population comparisons for the English and Welsh sample of HEED and England and Wales

Table 11
Gas demand by dwelling age and type by loft insulation level and cavity filling.

HEED: Median Gas Use 2007	Stock[a]		Lofts				Cavity walls[b]		
	N	Median	Missing Median	< 50mm Median	50-200 mm Median	> 200 mm Median	Missing Median	Cavity filled Median	Cavity as built Median
Dwelling Age									
Missing	575,785	16,235	16,097	15,712	16,060	16,008	–	–	–
pre-1900	30,360	17,430	16,034	17,311	18,824	18,085	–	–	–
1900–1929	57,969	17,593	16,502	17,742	18,256	17,388	–	–	–
1930–1949	77,944	17,010	16,153	17,392	17,409	16,960	16,134	18,134	16,185
1950–1966	90,841	15,904	14,910	16,473	16,492	15,874	14,387	17,344	15,754
1967–1975	117,502	16,011	15,555	16,761	16,881	15,936	15,081	17,228	16,048
1976–1982	29,510	14,484	13,324	15,214	15,967	14,516	12,902	15,877	14,723
1983–1990	21,334	14,486	13,336	15,137	15,933	14,375	13,000	15,782	14,683
post-1990	28,156	14,950	13,732	15,058	16,024	15,612	13,137	16,060	15,343
Stock	1,029,401	16,201	15,890	16,700	16,887	16,095	16,125	17,227	15,537
Dwelling type									
Missing	525,816	16,423	16,316	16,523	16,533	14,396	16,631	16,601	14,635
Flat	70,660	10,318	10,072	10,925	10,992	10,402	9960	10,750	10,006
Bungalow	45,614	15,955	15,858	17,958	17,234	15,608	14,602	18,115	16,268
Terraces	140,100	15,033	14,858	15,362	15,027	14,948	14,964	14,983	14,339
Semi-det.	175,690	16,557	16,163	17,316	16,726	16,517	16,212	17,709	15,904
Detached	71,521	21,012	20,627	21,719	21,132	20,600	21,912	22,531	19,709
Stock	1,029,401	16,201	15,890	16,700	16,887	16,095	16,125	17,227	15,537
		N=	700,875	41,031	140,300	147,195	565,101	136,878	205,318

[a] Sample excludes dwellings with no gas meters and erroneous values (256,971).
[b] Other wall types have been removed from this sample for the purposes of comparison (solid =116,811 and timber =5293) and pre-1930s.

Table 12
Gas demand by dwelling age and type by glazing and boiler type.

HEED: Median Gas Use 2007	Stock[a]		Glazing			Boilers		
			Missing	Double pre-2002	Double post-2002	Missing	Non-condensing	Condensing
Dwelling Age								
Missing	575,785	16,235	15,697	15,896	16,646	16,542	16,010	15,323
pre-1900	30,360	17,430	16,781	17,609	16,818	14,522	18,580	17,633
1900–1929	57,969	17,593	16,598	18,008	17,332	16,435	18,790	17,103
1930–1949	77,944	17,010	16,158	17,503	16,957	16,231	18,014	16,049
1950–1966	90,841	15,904	14,985	16,471	15,853	15,252	16,946	15,039
1967–1975	117,502	16,011	15,752	16,541	15,860	16,006	16,836	14,922
1976–1982	29,510	14,484	13,510	15,597	14,393	13,514	15,451	13,861
1983–1990	21,334	14,486	13,144	15,370	14,765	13,224	15,583	13,970
post-1990	28,156	14,950	13,534	15,544	15,145	14,569	15,367	14,446
Stock	1,029,401	16,201	15,606	16,681	16,482	16,241	17,017	15,330
Dwelling type								
Missing	525,816	16,423	15,982	16,047	16,738	16,556	16,344	15,521
Flat	70,660	10,318	9,952	10,993	9,594	9,822	11,242	9,800
Bungalow	45,614	15,955	15,656	17,007	15,830	15,933	17,132	15,121
Terraces	140,100	15,033	14,906	15,212	14,519	14,841	15,675	14,429
Semi-det.	175,690	16,557	16,102	17,140	16,293	16,191	17,478	15,767
Detached	71,521	21,012	20,457	21,473	20,345	20,509	21,649	20,226
Stock	1,029,401	16,201	15,606	16,681	16,482	16,150	16,890	15,162
		N=	462,775	201,258	315,221	576,299	232,362	200,593

[a] Sample excludes dwellings with no gas meters and type1 flags (256,971).

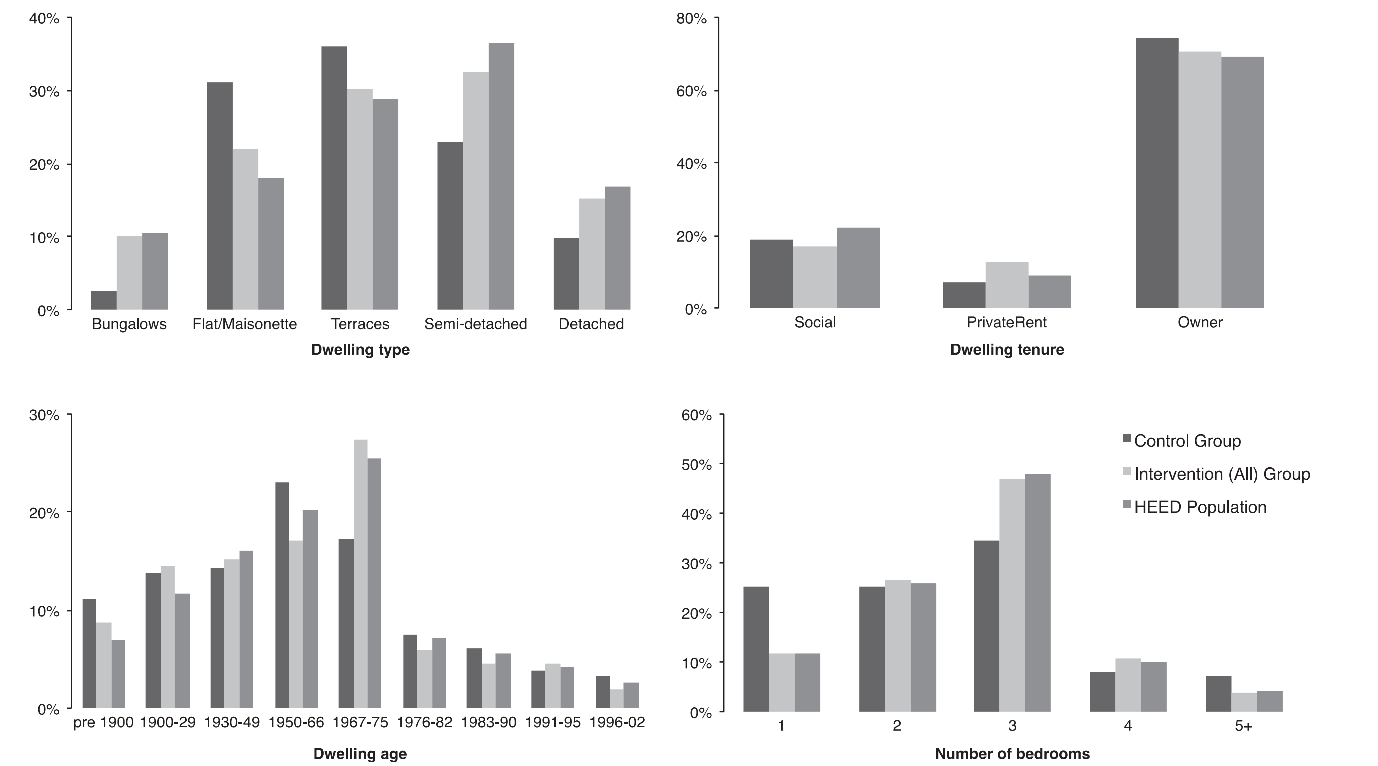

Fig. 12. Population comparison of control group, intervention group (2006 measure only) and HEED.

housing stock datasets suggest that the dwellings in HEED are not strictly statistically representative, but note that this is unlikely given the large sample size. The English and Welsh sample of HEED has fewer flats and more semi-detached houses, more 1 and 3 bedroom dwellings, more socially rented dwellings, and less coverage in the Southern English regions. However, many of the key variables in HEED do seem to be similarly distributed (i.e. within 1% point) and can offer a degree of representative descriptiveness. The Scottish sample of HEED has been shown to be representative the Scottish housing stock datasets. HEED has been expanding by roughly 8% per year in recent years. Therefore, the discrepancies between HEED and the dwelling stock as a whole may reduce in the future, but this is unclear and dependent on future government programmes (i.e. Green Deal and ECO).

In terms of the representative nature of the *dwellings* in HEED as compared to the rest of the housing stock it is clear that there are some features that are not well represented. In the first instance the majority (~80%) of HEED homes will have had some sort of energy efficiency measure. Also, it is not possible to be exact on the number of homes outside of HEED that have had some level of retrofit. Further, several of the programmes in HEED will have been developed to target certain household types (e.g.

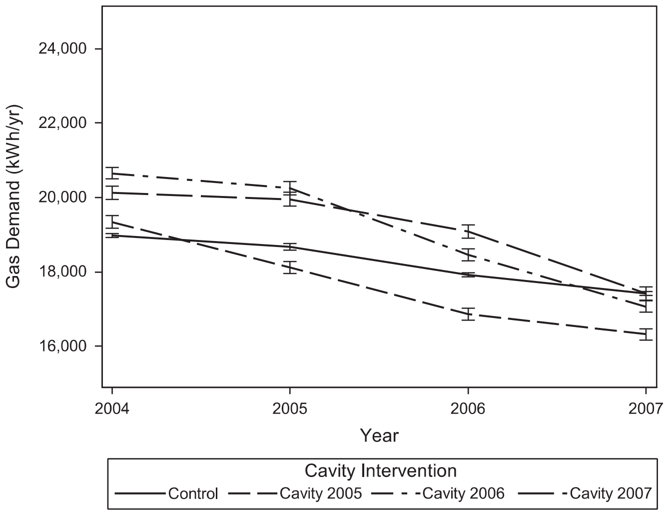

Fig. 13. HEED case control: cavity intervention gas demand 2005–2007.

fuel poor[10]) who may live in dwellings with certain characteristics that may tend to bias the representativeness of the data. These issues will be further explored in subsequent analysis.

There will also be limitations to the HEED and energy dataset that have to do with collection methods (i.e. different surveys using different forms), issues of self-selection for surveys and misclassification or assessor bias. Also, a dwelling will enter HEED as a 'snap shot', which means that the energy efficiency characteristics recorded for the dwelling will be more or less correct at a particular date. However, these features may not persist over time and changes would only be picked up if dwellings were revisited at a later date. This may occur in the long run through Energy Performance Certificates (currently covers 4.5 million properties in Great Britain), which rate the energy performance of the dwelling and collect characteristics at the time of sale or rental (at some point, nearly every home in Britain will be rented or sold and thus subject to an EPC).

For policy development that seeks to target certain areas and housing types, the dwellings that HEED represents is of intense interest as it speaks equally to those dwellings that have not had efficiency measures through programmes captured under HEED, which have been the bulk of efficiency measures delivered in the UK. Those dwellings not in HEED must be the targets of the upcoming Green Deal and ECO. From our analysis, these programmes will need to draw in more households living in semi-detached houses and flats, larger properties (i.e. >3 bedrooms), social and private rental tenures and a focus on the Southern regions.

4.2. Energy demand, energy efficiency and building characteristics

The HEED data, when linked to individual annualised gas and electricity meter values allowed for the description of energy demand between dwelling characteristics, such as age, size, type and tenure and different levels of energy efficiency. From our analysis, we see that gas demand is influenced by the level of detachment of a property (i.e. detached and bungalows), whereby dwelling forms with a greater exposed surface area have higher gas demand compared to those that are smaller and have less surface area. There is a strong size effect, with large dwellings using both more gas and electricity. It would be expected that electricity and heating demand would be influenced by size and also by occupancy.

The difference in gas demand between similar dwellings with different levels of energy efficiency is very clear. Those dwellings with improved levels of efficiency (i.e. loft insulation, cavity filling, double glazing and boiler replacement)—regardless of form or age—use less than their non-improved counterparts. This comparison suggests that there is long term savings associated with efficiency measures. This is particularly important for the justification of continued roll out of energy efficiency retrofits, i.e. that higher efficiency levels can indeed maintain a lower demand, and improve financial payback estimates. While the energy savings for any given dwelling will be influenced by the household, the change in gas demand associated with the presence of an energy efficiency measure suggests that real savings can occur following an intervention (i.e. a drop in the subsequent years). Energy savings were associated with loft insulation, cavity filling, double glazing and boiler replacements. The savings are clearly shown by a change in gas demand in the following years, where demand beforehand follows the control trend. These outcomes are particularly important for the government's flagship energy efficiency policies, in particular the Green Deal that will rely on consumers retrofitting their property voluntarily and paying back the deferred upfront cost of the measure through savings from the energy bill.

From a physical point of view, cavity wall filling reduces the heat loss through the largest exposed area of a house (i.e. the external walls) and is thus associated with a larger change in demand. By comparison, lofts and windows are a much small proportion of this exposed area and a smaller change in demand. Also, in the UK many lofts will already have had some level of insulation and the change between 100 mm and 200 mm will be smaller as a result. In theory, a boiler upgraded from a non-condensing to a condensing boiler should save gas by the change in efficiency alone; the average efficiency of a non-condensing gas boiler is approximately 70% (Palmer and Cooper, 2013) and industry rating schemes suggest approximately 86% for condensing. A boiler upgrade may also reflect other changes to the heat system, such as thermostatic valves or thermostats, which could also have an effect. These possibilities are not explored in this paper.

These savings suggest that government energy efficiency retrofit policy under the Green Deal and ECO should continue to focus on 'substantial' measures, i.e. cavity wall insulation, double glazing and boiler replacements, and solid wall insulation (not analysed here). Loft insulation shows relatively small savings in energy demand and, given its low installation cost, it is perhaps a 'low-hanging' fruit measure that could be targeted through education of households, a proposal that is supported by the estimates of do-it-yourself (DIY) installations (DECC, 2012b).

4.3. HEED: an example of data collection 'in action'

The Homes Energy Efficiency Database is an example of what can be characterised as 'in action' data. HEED is not the product of a large omnibus survey or a concerted monitoring and reporting exercise; instead HEED is the product (and by-product) of a range of disparate activities that are centred on home energy efficiency. HEED offers a repository and framework for these sources, one that is clearly flexible to a range of data types and quality.

It is unlikely that HEED will offer the same insight as a well structured research design on the impact of energy efficiency or an omnibus survey in terms of representativeness, but what is clear is that is has an extraordinary usefulness as a framework within which to collect and link data sources together. Due to the nature and range of its coverage (i.e. containing information on approximately 50% of UK dwellings) it can reasonably be used as a source

[10] Fuel poverty in the UK is the condition whereby a household spends more than 10% of their income on fuel to maintain an adequate level of warmth (DECC, 2010c).

Table 13
HEED case control: Energy efficiency intervention and change in energy demand 2005 to 2007.

HEED: Intervention 2005	Stock	Median gas use (kWh/yr)				% Change 2005–2007	Adj % Change 2005–2007
	N	2004	2005	2006	2007		
Control	166,670	18,919	18,572	17,861	17,353	−6.6%	
Lofts—2006	18,113	20,486	20,099	19,268	18,520	−7.9%	−1.3%
Cavity—2006	13,964	20,623	20,178	18,393	17,006	−15.7%	−9.2%
Glazing —2006	38,688	20,112	19,612	18,693	18,017	−8.1%	−1.6%
Boiler—2006	27,938	19,430	18,833	17,232	16,091	−14.6%	−8.0%

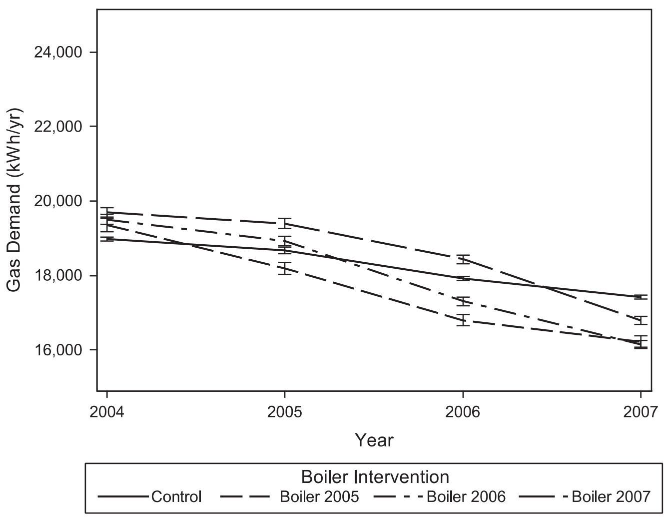

Fig. 14. HEED case control: cavity intervention gas demand 2005–2007.

to describe the broad energy performance characteristics of the UK housing stock. When linked to energy, HEED is capable of offering insight into the differences in demand due to dwellings characteristics and levels of energy efficiency and the change in demand associated with an energy efficiency retrofit.

4.4. Supporting evidence-based policy and research

Creating a data framework that is based on well-structured and consistent data of a high quality begins to lay the foundations for a stronger connexion between evidence and policy. While HEED is not a ‘gold standard’, it does offer a useful resource from which to build such a data foundation, which is reflected in the intention of the government to continue to develop the National Energy Efficiency Data-framework (DECC, 2011). However, the move towards quantifying the impact of energy efficiency investment in the UK's housing stock requires greater attention to how data is collected and also an acknowledgement of the type of questions that it can attempt to answer. It has been suggested that the major limitations to undertaking evidence-based policy and practice (EBPP) assessment for energy policy is that the evidence base consists of disparate techniques, methodologies and studies, and is influenced by complex and contested theoretical issues (Sorrell, 2007). Drawing together energy and building data for the residential stock within such a framework provides the opportunity for more systematic reviews, of the sort employed in health studies and education, which have the potential to encourage the development of a stronger and more robust foundation for studying people, energy and building.

The recently announced Research Council UK Centre for Energy Epidemiology is proposing to focus on developing this evidence base using population level datasets (EPSRC, 2013). Its focus will be on using this data to better understand the energy demand of individuals at a population level through the use of an interdisciplinary research approach based on the methods used in health sciences, in particular energy epidemiology.

Table 14
HEED variable coverage.

HEED variable	% Coverage
Dwelling characteristics	
Type	49.2%
Age	44.8%
Number of bedrooms	48.5%
Tenure	62.4%
Primary fuel type	65.8%
Energy efficiency characteristics	
Wall type	44.9%
Loft insulation level	38.2%
Glazing type	55.4%
Heating system type	41.5%
Draught proofing	2.9%
Lighting coverage	14.1%

Acknowledgements

The data used in this study was kindly made accessible by the Department of Energy and Climate Change and the Energy Saving Trust as part of the EPSRC-funded Buildings and Energy Data Framework's project (EP/H021957/1). The authors would also like to remember Harry Bruhns (1951–2011) who was a driving force behind the development of these linked data sources, and will be greatly missed.

Appendix A. Homes Energy Efficiency Database details

The extract of the Homes Energy Efficiency Database (HEED) provided for use in this study contained approximately 11.5 million distinct dwellings. The data provided in HEED draws from survey data and data on specific measures installed under a variety of government backed schemes and energy supplier obligations. Many dwellings in HEED have multiple variables for which details of the dwellings are known, approximately 50% of dwelling present in HEED have between 4 and 10 variables with information. The coverage of any given variable depends on the scheme or survey under which information was collected. For example, dwellings from the gas system installers will have a high coverage of boiler related variables but may not have other variables such as loft insulation levels. Table 14 gives the percentage covered (i.e. n_{variable}/N) for a selection of dwelling characteristics and energy efficiency measures. Table 15 shows the total number of installations of energy efficiency measures occurring in all UK dwellings during the collection period 2005–2008.

Table 15
HEED total number of installations in the UK stock 1995–2008.

Efficiency installations[a] in UK	Programme					Total
	Local government	EEC & CERT	Installers	Fuel poverty scheme	Home energy check	
Loft insulation	81,987	486,143	1,173,153	997,406	663,839	3,424,997
Condensing boilers	59,497	371,749	1,648,549	743,312	672,946	3,523,742
Heat systems[b] l	82,944	526,046	2,358,831	1,105,376	951,487	5,065,500
Double glazing	237,691	1,506,535	5,097,291	2,308,147	1,811,902	11,091,843
Cavity insulation	187,826	549,770	1,550,303	1,259,432	770,620	4,340,999
Hot water cylinder	6765	22,558	87,345	27,402	43,048	189,039
Draught proofing	20,009	112,259	181,816	672,373	215,443	1,209,403
Solar hot water	2773	9317	30,544	12,038	52,733	115,068
Total	679,492	3,584,377	12,127,832	7,125,486	5,182,018	28,960,591

[a] Figures are for total number of installations, a dwelling may have numerous installations.
[b] Heat system measures include condensing boilers.

Table 16
HEED stock data sources for energy data period.

HEED data source	Period				
	All	2004	2005	2006	2007
Energy suppliers	18.5%	19.3%	25.9%	15.9%	16.4%
Government schemes	17.5%	27.7%	17.9%	2.8%	2.8%
Installers	42.0%	36.9%	43.0%	51.6%	61.2%
Survey	22.1%	16.1%	16.1%	29.7%	19.6%
N	11,439,530	2,204,915	3,178,845	3,543,226	3,121,310

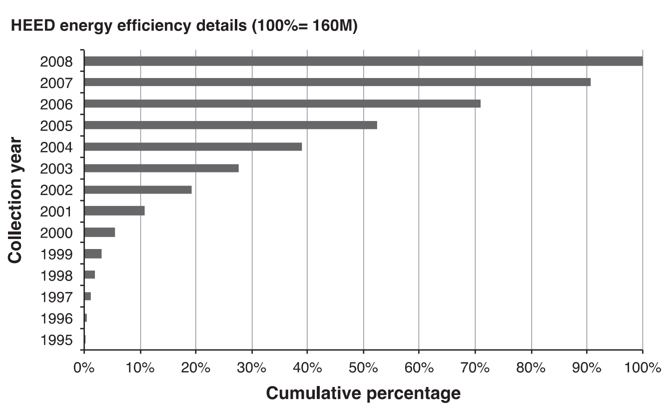

Fig. 15. HEED data observations collection period.

Date of energy efficiency installation

For each record in HEED there is a date for when a detail of the dwelling was recorded or when an intervention occurred; in the extract used for this study the dates range from 1995 to 2008. This detail date is often for when a measure was installed or a survey undertaken; however this is not necessarily the date of the intervention since the stamp could have been applied after a period of time for any number of reasons. Therefore the detail year and month are used to broadly determine the 'state' of a dwelling's energy efficiency levels for a given energy year. The majority of HEED data was collected after 2004, see Fig. 15 below.

The gas and electricity supplier data covered the period 2004–2007, which coincided with the majority of HEED data collection; approximately 60% of all the dwellings information in HEED was collected over that period (see Table 16). Note that the annualisation process of the energy meter data means that a change in energy demand will depend on the frequency of meter readings within a year. This means that measures installed in later gas years may not be fully reflected for those meters that have not had

Table 17
HEED Full Sample and HEED 10% Sample Comparison.

Great Britain	HEED[a] (*n*)	HEED (%)	HEED[a] 10% (%)
Dwelling age			
Pre-1900	462,141	7.9	7.9%
1900–1929	684,956	11.7	11.7%
1930–1949	906,658	15.6	15.5%
1950–1966	1,167,139	20.0	20.0%
1967–1975	1,463,750	25.1	25.2%
1976–1982	405,962	7.0	6.9%
1983–1990	328,952	5.6	5.6%
post-1990	410,421	7.0	7.0%
χ^2			11.9843
d.f.			7
p			0.1011
Dwelling type			
Flat-Maisonette	1,256,778	19.6	19.6%
Bungalow	588,662	9.2	9.2%
Terrace	1,619,047	25.2	25.1%
Semi-detached	1,993,108	31.1	31.0%
Detached	960,679	15.0	15.0%
χ^2			2.1417
d.f.			4
p			0.7097
Dwelling tenure			
Social rental	1,811,016	22.4	22.5%
Private rental	772,352	9.6	9.5%
Owner-occupied	5,494,295	68.0	68.0%
χ^2			4.9031
d.f.			2
p			0.0862
Dwelling size (bedrooms)			
1	822,167	13.2	13.3%
2	1,647,076	26.5	26.5%
3	2,866,957	46.1	46.0%
4	621,709	10.0	10.0%
5+	261,396	4.2	4.2%
χ^2			2.7461
d.f.			4
p			0.6012
Dwelling region			
North East	702,766	5.7	5.6%
North West	1,599,855	12.9	12.9%
Yorkshire and The Humber	1,199,671	9.7	9.7%
East Midlands	914,464	7.4	7.4%
West Midlands	1,161,697	9.4	9.3%
East of England	1,088,751	8.8	8.8%
London	1,323,260	10.7	10.7%
South East	1,617,462	13.0	13.0%
South West	1,076,835	8.7	8.7%
Wales	1,168,235	9.4	9.4%
Scotland	553,061	4.5	4.4%
χ^2			27.9954
d.f.			10
p			0.0018

[a] HEED and HEED 10% Sample are of England and Wales only.

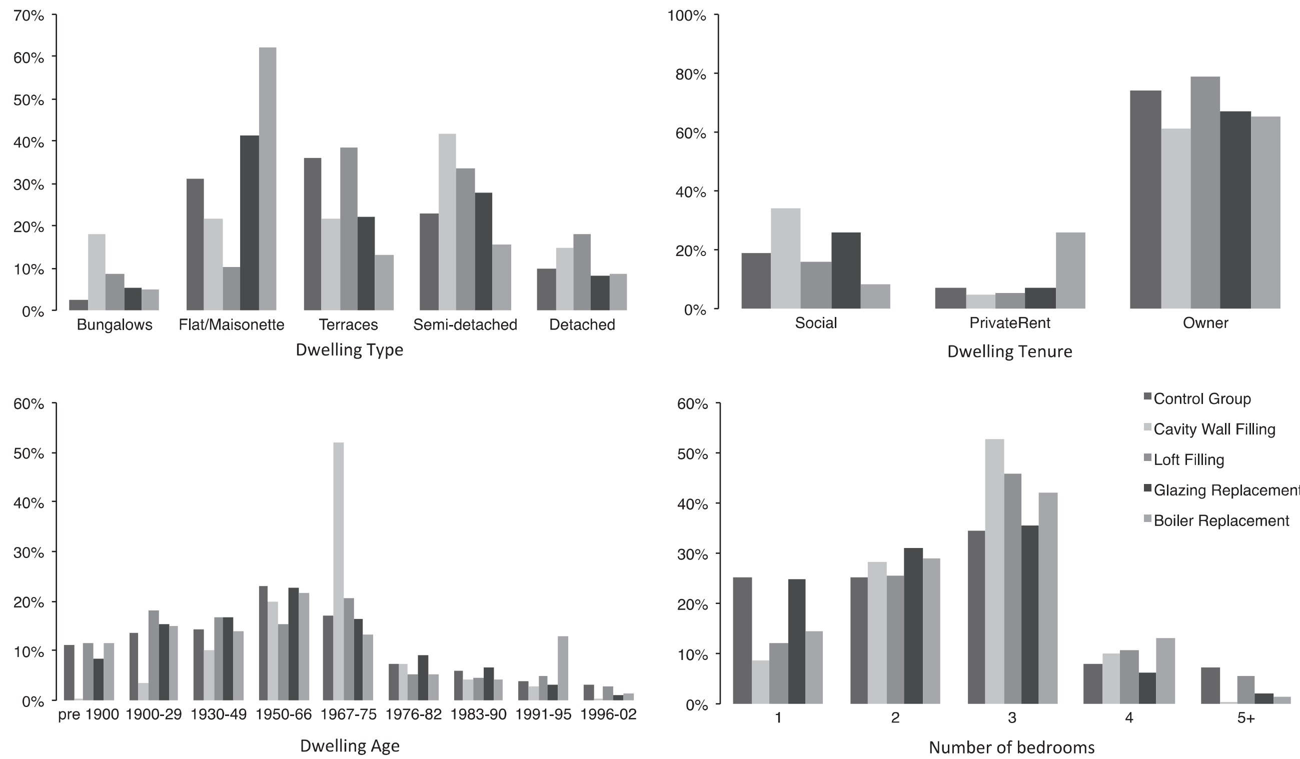

Fig. 16. Population comparison of control group, intervention group (by intervention type and for 2006 measure only) and HEED.

twice-yearly readings or where the measure occurs after a reading for the given gas year. Therefore in this study we looked at the change in demand between 2005 and 2007 for those dwellings that have received a measure in 2006 or before (Table 16).

Appendix B. HEED and HEED Sample Comparison

See Table 17.

Appendix C. Great Britain Stock Data

The English Housing Survey reports on the overall condition of English dwellings and the households living in them (CLG, 2010b). The survey provides data on housing stock characteristics (including age, type and size) based on survey work undertaken between 2007 and 2009. The surveyed sample of properties where physical inspections were carried out contains 16,150 occupied or vacant dwellings, or 0.7% of the housing stock of 22.7 million dwellings in England. The EHS provides a statistically random sample of the English stock against which HEED can be compared. The EHS provide a factor with which to weight variables in order to represent houses or households in England, for the comparisons we use the houses weighting.

The Scottish House Conditions Survey reports on the households and physical condition of the Scottish stock (Scottish Government, 2009). The survey includes an interview and physical survey of approximately 3000–4000 dwellings, undertaken in a continuous format with the aim of achieving a 15,000 sample over 5 years. The survey collects physical characteristics of the dwellings (e.g. age, type, size, energy efficiency, etc.) and household features (e.g. tenure, income, etc.) The survey sample is stratified by area and randomly selected and attempts to be representative of the 2.4 million dwellings in Scotland, the dwelling weighting factor is also used for the comparison.

The VOA's Council Tax Property Attributes tables are collected as part of the VOA's responsibility to group properties into the appropriate council tax band (VOA, 2010). As part of the banding process, the VOA collects information on the characteristics of the property that may affect its value (including, age, type, area, and number of bedrooms). The VOA data is considered a ‘global’ listing, as it will contain information on all dwellings within an area (i.e. local council) and thus should have all dwellings in the stock. Note that the VOA only collects information for England and Wales. The VOA in maintaining a current valuation list revises the data annually; the data used in the comparison comes from an extract made in September 2010. The VOA dataset provides information at the Local Authority level for approximately 24.7 million residential properties.

Appendix D. HEED Case and Control Groups

Fig. 16 shows the case and control groups by dwelling characteristics and energy efficiency retrofit. The loft insulation intervention group has fewer flats/maisonettes than the control, slightly fewer social tenure dwellings, more 1900–1929 and 1967–1975 dwellings and more dwellings with 3 bedrooms. The lack of lofts in flats would explain why this dwelling form is less represented (note that flats in converted houses can have lofts). The reduced number of flats may also explain the lower 1950–1966 aged dwellings as this was a dominant housing form during that post-war expansion period. The cavity intervention group has more bungalows and semi-detached dwellings, more social tenure, more 3 bedroom dwellings, and a much higher 1967 to 1975 age group. In terms of both age group and dwelling type, the date cavity walls were introduced and the predominant dwelling forms that characterise that period may explain this. Cavity walls were the dominant wall

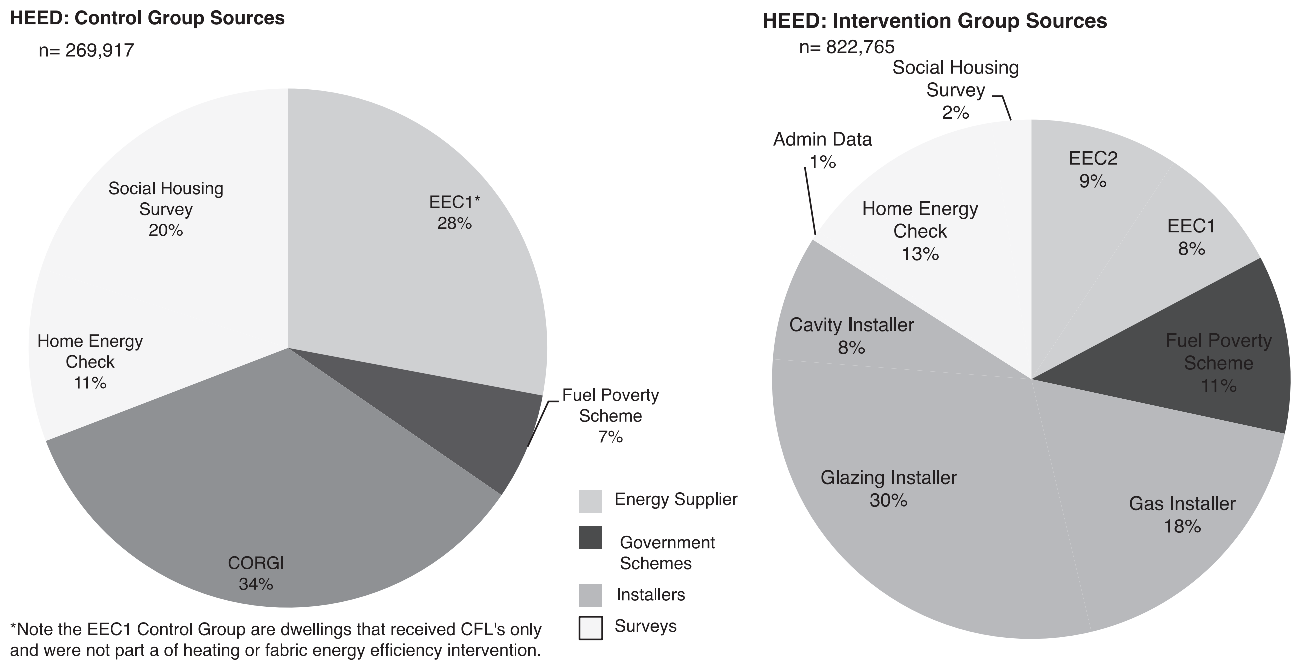

Fig. 17. HEED: control group and intervention group data sources.

type in dwellings built in the inter-war and post-war period, with post-1975 cavity walls more likely to be constructed with insulation partly or completely filling the cavity. The glazing insulation group have more flats and semi-detached dwellings than the control group, along with more social tenured dwellings and fewer pre-1900 and post-1996 homes. The age grouping could be explained by the possible heritage controls surrounding pre-1900 homes and for post-1996 homes to already have more efficient windows (although not necessarily as efficient as post-2002 double glazing). The condensing boiler intervention group have more flats and fewer terraces than the control group, along with more privately rented dwellings and fewer 1 bedroom dwellings and a high proportion of dwellings in the 1991–1995 age band. The increased number of flats and privately rented dwellings may also be explained by the source of most of the boiler data, i.e. gas installers. Many privately rented dwellings (largely flats) are required to have their boilers certified yearly and problems being identify more quickly and thus boilers being replaced, leading to these tenures being more heavily represented in the data and thus the sample. The increased number of dwellings in the 1991–1995 age group could reflect the replacement cycle of a boiler (e.g. ~15 years).

Fig. 17 shows the HEED data sources for the control group and intervention group. The control group is primarily comprised of survey data and data coming from sources where there were non-heating or fabric interventions. For example, gas installer data will include boiler checks and other home features but the homes did not necessarily have the boiler replaced. The intervention group data sources include a range of government schemes, supplier-led programmes, and other industry schemes.

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