Energy Policy 120 (2018) 183–196

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Heating system upgrades: The role of knowledge, socio-demographics, building attributes and energy infrastructure

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ARTICLE INFO

Keywords:
Residential heating
Space heating
Retrofit
Fuel switching

ABSTRACT

In the context of moving to a low-carbon economy there is wide interest among policymakers to improve knowledge of decisions surrounding residential heating systems. This research examines four aspects of decision-making with respect to heating system upgrades: home-owner decisions on whether to upgrade, decisions on fuel choice, fuel switching patterns, and an examination of the reasons why home-owners make these decisions. Among the key findings are that proximity to energy infrastructure, e.g. gas network, is an important determinant of residential heating systems upgrades, including fuel choice. With one exception no clear trend emerges on the likelihood of a broad range of socio-demographic variables, including age, income, and working status on home-owner decisions. A cohort of home-owners defined across a few socio-demographic characteristics, including mortgage holders, are predisposed to investing in a heating system upgrade compared to their peers but for reasons unknown do not invest. We also find that environmental concerns, across a number of dimensions, are not an important determining factor in either the decision to upgrade or the subsequent choice of heating system. Information on heating system alternatives is critical for good decision-making but we find that home-owners do not always rely on independent energy consultants for guidance.

1. Introduction

The increasing relevance of environmental problems and concerns for climate change have motivated countries to align their environmental and energy policies to reduce emissions. Through the Climate and Energy Policy Framework, the European Union (EU) has agreed to reduce greenhouse gas emissions for the year 2030 by 40% compared to 1990 levels. A significant amount of current emissions are produced as a consequence of the energy use in different sectors of the economy, especially at household level (European Commission, 2011). Two thirds of this energy consumption is used for space heating, especially in countries such as Ireland, Great Britain (Meier and Rehdanz, 2010), Germany (Braun, 2010; Michelsen and Madlener, 2012), France (Stolyarova et al., 2015) and Finland (Rouvinen and Matero, 2013).

At present the most used heating sources are coal, oil and gas. These sources produce significant negative environmental impacts by the generation of emissions, specifically carbon dioxide, nitrogen dioxide, and fine particulate matter (Greening et al., 2001; Kerkhof et al., 2009). Therefore, households' choices of domestic heating systems and their usage behaviour become a key element affecting overall environmental quality. Hence, understanding households' decision-making process regarding the adoption and replacement of heating systems as well as the factors that determine the choice of these systems are of relevance for climate mitigation policies. Understanding what drives households to make (or not make) such decisions will help policy-makers better design incentives to encourage movement to low carbon heating systems. This paper examines several elements of decisions around home heating systems. First, we consider whether households contemplate upgrading their heating systems. We specifically focus on home-owners, who have agency in this decision and avoid consideration of split incentives associated with rental tenants. The period of consideration for such decisions is 10 years, during which there has been considerable public discussion on the policy response to climate change and specifically in Ireland, where our dataset is located, a State agency has been encouraging households to upgrade their heating systems and improve the energy efficiency of their homes by means of media campaigns and financial incentives. Within that context all home-owners will have some level of awareness of the private (and public) benefits of upgrading their heating system, as well as a grant scheme to encourage action by home-owners. The second area we consider is the heating

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https://doi.org/10.1016/j.enpol.2018.05.036
Received 29 November 2017; Received in revised form 11 May 2018; Accepted 14 May 2018

system choice of home-owners that upgrade their heating systems to investigate whether there are systematic differences across home-owners that have upgraded their heating system associated with the type of heating system upgrade. Third, we examine the reasons behind the decisions either not to upgrade, or if upgrading what influenced their decisions. The latter analysis builds on work by Michelsen and Madlener (2013) and Sopha and Klöckner (2011), for example, whereas the earlier analyses follows in the vein of Braun (2010), Laureti and Secondi (2012),Couture et al. (2012), Michelsen and Madlener (2012)

Investments in energy efficiency measures such as improved heating systems are driven not only by financial and economic reasons, but also by behavioural and psychological factors such as attitudes, motivations, expectations and trust (Aravena et al., 2016; Pelenur and Cruickshank, 2014; Stern, 1992), the choice of indoor temperature levels or ventilation rates (Haas et al., 1998), environmental concerns (Lindenberg and Steg, 2007; Oikonomou et al., 2009) and other non-economic elements such as comfort and convenience (e.g. Jakob, 2006; Zundel and Stieß, 2011). There is also extensive literature examining the barriers to energy efficiency in the residential sector. Among the commonly cited barriers are financial or budget constraints, information, inconvenience or disruption, as well as such investments being considered superfluous (Jaffe and Stavins, 1994; Sorrell et al., 2004; Henryson et al., 2000; Clinch and Healy, 2000; Caird et al., 2008; Mills and Schleich, 2012; Achtnicht and Madlener, 2014). These are real considerations for home-owners but not central to this research. Financial or budget constraints, for example, may underpin the choices or outcomes of our analysis pertaining to whether home-owners contemplate heating system upgrades. However, with the exception of information our survey does not contain data on potential barriers facing home-owners and consequently the analysis is intended to identify whether there are systematic observable differences between home-owners that contemplate retrofitting their heating system and those that do not. In the context of the analysis considering choice of heating system upgrade among home-owners that did upgrade we assume barriers to investment as having already been wholly or partially overcome, as home-owners have made an investment.

As noted above, information/knowledge, or lack thereof, is a well recognised barrier to energy-efficiency investments. Specifically related to investment in heating systems, Michelsen and Madlener (2016) argue that knowledge of energy efficiency is a key driver in the decisions of home-owners to switch from fossil fuel based heating systems to low carbon alternatives. But few papers have examined the behaviour of pro-environmental home-owners, as distinct from home-owners that possess pertinent information with respect to energy efficiency investments. Relevant knowledge is accumulated over time by the provision of information and education, including information that is not necessarily specific to heating system technologies. Pro-environmental home-owners reveal themselves in terms of environmental behaviours such as recycling activities or installation of energy efficiency measures. Ramos et al. (2016) examine whether pro-environmental households are more likely to invest in energy efficiency with two divergent findings. First, environmental concerns are generally less important for high-cost investments with less frequent replacement, where economic considerations predominate. Stated environmental attitudes do not show any effect on energy efficiency investments. Second, home-owners engaging in pro-environmental practices, such as recycling or participating in environmental policy activism, are more likely than others to invest energy efficiency. The authors attribute the divergence to ‘compliance bias’ and conclude that environmental attitudes are not necessarily translated into real actions. These findings are mirrored elsewhere in the context of space heating energy use, as opposed to capital investment (Lange et al., 2014; Brounen et al., 2013). This paper expands the empirical analysis on this issue considering home-owners’ pro-environmental behaviours, as well as, knowledge of energy and environmental matters. We hypothesize that such home-owners may be more likely to invest in upgraded heating systems that others with lower knowledge levels or fewer pro-environmental behaviours

The evidence in relation to the determinants of choice of energy systems and fuel switching patterns in the literature is both wide ranging and mixed. Local availability and proximity of fuels is found to be a significant variable (Braun, 2010; Laureti and Secondi, 2012; Fu et al., 2014; McCoy and Curtis, 2018) with access to natural gas networks playing an important role in fuel choice decisions in the US, France and Ireland (Mansur et al., 2008; Couture et al., 2012; Fu et al., 2014). Socio-demographic characteristics are also important drivers but the findings are often case or country specific. High emission fuels such as oil and coal are often associated with lower income home-owners (e.g. Fu et al., 2014; Laureti and Secondi, 2012; Özcan and Gülay et al., 2013) though other studies find only negligible income effects or none (e.g. Braun, 2010; Lillemo et al., 2013; Couture et al., 2012). The effects of higher education and economic status on fuel choice are generally similar to those associated with income. In the case of occupant age, Özcan and Gülay et al. (2013) find that household heads aged 50 and above are more likely to choose gas, oil and electricity compared to coal and other solid fuels for reasons of ease of use and for health concerns, whereas Decker and Menrad (2015) find that neither age, education nor income are important variables in explaining choice of residential heating systems. Property age is an important influencing factor in some situations (Laureti and Secondi, 2012; Michelsen and Madlener, 2012) whereas property size and type are more relevant in others (Michelsen and Madlener, 2016).

The literature on determinants of heating systems using microdata includes a large number of empirical studies that are focused on the determinants of households’ expenditure on space heating in different countries, such as Germany Schuler et al. (2000); Rehdanz (2007), Great Britain (Meier and Rehdanz, 2010), Norway (Vaage, 2000), Austria (Haas et al., 1998; Hecher et al., 2017), the US (Mansur et al., 2008) among others. A methodology used in several of these papers is the discrete-continuous method originally developed by Dubin and McFadden (1984) where the decision about demand for space heating is divided into two stages. In the first stage the household chooses the technology or heating system and in the second stage, given the available technology, the household decides how much energy it consumes. Therefore, there is a clear differentiation between the demand for heating systems and the demand for energy itself caused by the use of the system. An alternative methodology is the conditional demand approach, which focuses on the demand for energy as a function of a given technology, (e.g. Leth-Petersen and Togeby, 2001; Rehdanz, 2007; Meier and Rehdanz, 2010). There is a small but growing literature using choice experiments to study the attributes that explain the choice of different heating systems by households (e.g. Rouvinen and Matero, 2013). A more recent approach focuses on the use of multinomial logit models in which the choice of heating systems is the dependent variable and is explained by a number of covariates such as building and household's characteristics (Braun, 2010; Couture et al., 2012; Laureti and Secondi, 2012; Michelsen and Madlener, 2012). It is within this latter literature that this paper is positioned, adding some new dimensions. We closely follow the approach of Braun (2010) considering first the broader decision process contemplating an investment in a heating system upgrade, and subsequently the more focused decision of heating system choice among home-owners that actually upgrade. We find that home-owners’ knowledge or actions on energy or the environment are not significant determinants of decisions either regarding heating system upgrades or choice of heating system/fuel type. Even among home-owners who are actively making decisions about home heating, knowledge, past environmental behaviours, socio-economic and dwelling characteristics have little explanatory power in determining heating system and fuel choice. Proximity to a networked fuel, specifically natural gas, is a key determinant of home-owners home heating choices.

The rest of the paper is organized as follows. In Section 2 we describe the methodology. Section 3 presents into detail the survey design and implementation. Section 4 describes the data used in the estimations and presents some descriptive statistics. Section 5 shows the results followed by the discussion and analysis in Section 6. Finally, Section 7 concludes the paper.

2. Methodology

In the context of better understanding heating systems upgrades we examine the issue from a number of perspectives. First, we attempt to identify whether there are systematic differences between home-owners that contemplate retrofitting their heating system and those that do not. We next examine whether there are systematic differences across home-owners that have upgraded their heating system associated with the type of heating system upgrade. Households have a demand for space heating, which is an energy service demand potentially delivered by a large combination of technologies and fuels. We consider three types of heating system upgrades based on primary fuel type: 'Non-networked', 'Gas+', and 'Electricity+'. 'Non-networked' comprises heating systems using off grid fuels, i.e. neither electricity nor natural gas. Fuels within this category include home heating oils, such as kerosene, liquefied petroleum gas (LPG) and solid fuels such as peat, coal and wood. The 'Gas+' category centres around a natural gas fuelled heating system but may also include secondary heating sources such as an open fire (e.g. solid fuels) or a portable electric heater. The 'Electricity+' category is analogous to 'Gas+' except that electricity is the primary heating source. If natural gas is used for heating it falls within the to 'Gas+' category. Finally, we consider the extent to which fuel switching occurs when heating systems are upgraded.

We use a multinomial logit (MNL) model framework to examine whether home-owners consider heating system upgrades and also to examine the choice of heating system if they decide to upgrade (McFadden, 1973). We proceed by describing the methodology in the context of home-owners evaluating heating systems upgrade options but same methods are applicable to considering systematic differences between home-owners in the following three categories: home-owners that do not consider heating system upgrades, those that considered but ultimately did not upgrade their heating system and those that upgraded their heatings system.

Formally, when evaluating upgrading their heating systems home-owners maximise utility subject to prices and their budget constraint. Assuming space heating preferences are weakly separable from other goods, the indirect utility function for home-owner i, $i = 1...N$, is

$$U_{ij} = V_{ij}(P_{i1}...P_{ij}...P_{iJ}, Y_i) + \varepsilon_{ij} \tag{1}$$

where j is the index for heating system with $j = 1...J$, P_{ij} refer to heating system prices, and Y_i is home-owner income. The error term ε_{ij}, while known to the home-owner, is unobserved by the researcher. Household i will replace their heating system with alternative j if and only if $V_{ij} > V_{ik}\ \forall\ k \neq j$. Applying Roy's identity to equation (1), home-owners' Marshallian demands for heating systems can be recovered (Dubin and McFadden, 1984). But for our purposes we are interested in the choice of heating system replacement rather than the level of demand. Because of ε_{ij}, home-owner i's choice is random from the researcher's point of view. Typically in discrete choice modelling the error terms ε_{ij} are assumed independently and identically Type I extreme value (Gumbel) distributed, which is the multinomial logit (MNL) model (McFadden, 1973). The probability of home-owner i choosing heating system j is then written as:

$$P(heatingsystem_j) = P_{ij} = \frac{exp(V_{ij})}{\sum_{k=0}^{J} exp(V_{ik})} \tag{2}$$

We specify V_{ij} as a linear function and assume that preference weights are invariant across home-owners, $V_{ij} = \alpha_j + \beta_j x_{ij}$, with x_{ij} representing explanatory variables (e.g. property attributes or home-owner characteristics). The MNL's estimated parameters are not easily amenable to direct interpretation so we follow two approaches to understand the model's results. We present either relative risk ratios (RRRs) or marginal effects. RRRs are the relative probability of an outcome compared to the base outcome corresponding to a unit change in the predictor, holding all else constant, and are calculated as the exponent of the parameter estimate, e^{β_j}. Marginal effects show the absolute change in probability of a home-owner choosing option j in response to a change in some observed factor $z \in x_{ij}$ (Train, 2009):

$$\frac{\partial P_{ij}}{\partial z} = \beta_z P_{ij}(1 - P_{ij}) \tag{3}$$

The marginal effects depend not only on the factor's coefficient estimate, β_z, but also on the remaining coefficient estimates and variables through P_{ij}. While RRRs will help identify differences in choices relative to a base case, marginal effects show the absolute change in probability and hence provide a means to easily evaluate whether the effects are sufficiently large to have policy relevance.

In the MNL model the ratio of two probabilities (P_{ij}/P_{ik}) does not depend on any alternatives other than j and k, irrespective of the other alternatives available. With this assumption the MNL model exhibits what is termed independence from irrelevant alternatives (IIA). While the IIA property is realistic in some choice situations, Hausman-McFadden and Small-Hsiao tests are often used to examine the validity of the IIA assumption (Hausman and McFadden, 1984; Small and Hsiao, 1985). A number of simulation studies have shown that these tests perform rather poorly, even in large samples (Fry and Harris, 1996, 1998; Cheng and Long, 2007). Specifically, Cheng and Long (2007) conclude that "tests of the IIA assumption that are based on the estimation of a restricted choice set are unsatisfactory for applied work", while Long and Freese (2014) note that different IIA tests often provide conflicting results and advise against their use. McFadden's early advice on empirical applications is relevant in this regard, which was that MNL models "should be limited to situations where the alternatives can plausibly be assumed to be distinct and weighed independently in the eyes of each decision maker" (McFadden, 1973). For our empirical applications it is not unreasonable to assume that home-owners perceive a clear distinction between choice outcomes. In the first model there is a clear distinction between the three outcomes: upgrades not considered; upgrades considered but not implemented; and upgrades considered and implemented. In the model examining the choice of upgraded heating systems there are also three distinct categories based on fuel types: not networked; and either gas or electricity as the primary fuel. The specification of our MNL models based on fuel-type combinations follows several previous applications in Germany and France (Braun, 2010; Couture et al., 2012; Laureti and Secondi, 2012; Michelsen and Madlener, 2012).

2.1. Determinants of switching

Following the MNL analysis of heating system choice we then delve more deeply into the determinants of home-owner switching behaviour. To examine this we firstly create binary variables indicating if home-owners have replaced their system have also changed fuel type. Formally this is estimated as a logit model where $Prob(Y = 1|x) = p(x)$ and $log\frac{p(x)}{1-p(x)} = \beta_0 + \beta_1 X_i \epsilon_i$. X_i is a matrix of observed home-owner characteristics.

We then examine switching patterns by creating a transition matrix of current and previous fuels used. To further understand motivations for both upgrading and keeping an existing system we then present a statistical analysis of the responses to survey questions posed to home-owners regarding their reasons for switching, information sources used in making the decision and reasons for keeping their existing system.

3. Survey design

An online survey questionnaire was developed to elicit information on household's heating systems, and decisions on the upgrade or

Table 1
Variable descriptions and summary statistics.

Variable	Description	All Households		All Homeowners		Home-owners that upgraded heating system	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Dependent Variable for model results reported in Table 4:							
'Not considered'	Heating system upgrade not considered	0.772	0.420	0.657	0.475	-	-
'Considered, not upgraded'	Heating system upgrade considered but did not subsequently upgrade	0.076	0.266	0.116	0.320	-	-
'Upgraded'	Heating system upgrade considered and subsequently upgraded	0.152	0.359	0.227	0.419	1.000	0.000
Dependent Variable for model results reported in Table 5							
'Not-networked'	Incl. oil, liquefied petroleum gas (LPG), peat, coal and firewood	0.505	0.500	0.566	0.496	0.472	0.500
'Gas+'	Grid supplied natural gas & other secondary fuels	0.351	0.477	0.338	0.473	0.419	0.495
'Electricity+'	Electricity & other secondary fuels	0.144	0.351	0.096	0.295	0.109	0.313
Dwelling Attributes							
$Built-pre1971$	Built pre 1971	0.305	0.460	0.263	0.441	0.323	0.469
$Built1971-1990$	Built 1971–1990	0.233	0.423	0.280	0.449	0.310	0.464
$Built1991-$	Built 1991 or later	0.462	0.499	0.457	0.498	0.367	0.483
No. Rooms	Number rooms in property, incl. kitchens but excl. bathrooms	5.699	1.826	6.262	1.711	6.310	1.773
House	If property is detached/semi-detached	0.722	0.448	0.815	0.388	0.860	0.347
$TownSize<5k$	Rural locations, villages and small towns	0.337	0.473	0.406	0.491	0.371	0.484
$TownSize5-50k$	Mid sized towns	0.364	0.481	0.343	0.475	0.310	0.464
$TownSize50k+$	Cities	0.299	0.458	0.251	0.434	0.319	0.467
$GasInArea-k$	If respondent aware possible to connect to gas network	0.517	0.500	0.468	0.499	0.515	0.501
Household characteristics							
$No.\leq 18$	Number of occupants 18 years or younger (min = 0, max = 5)	0.772	1.085	0.773	1.097	0.812	1.172
$No.\geq 65$	Number of occupants 65 years or older (min = 0, max = 4)	0.281	0.712	0.372	0.810	0.441	0.854
Mortgage	Own with a mortgage	0.345	0.476	0.525	0.500	0.498	0.501
Nomortgage	Own without a mortgage	0.313	0.464	0.475	0.500	0.502	0.501
$Age1534$	Aged between 15 and 34 years	0.284	0.451	0.190	0.392	0.223	0.417
$Age3559$	Aged between 35 and 59 years	0.513	0.500	0.544	0.498	0.498	0.501
$Age60plus$	Aged 60 and above	0.203	0.402	0.266	0.442	0.279	0.450
$Rent-public$	Rent from a local authority	0.090	0.286	-	-	-	-
$Rent-private$	Rent from a private landlord	0.252	0.434	-	-	-	-
$Status-working$	At work	0.520	0.500	0.520	0.500	0.528	0.500
$Status-home$	Looking after home/family or retired	0.280	0.449	0.330	0.470	0.310	0.464
$Status-student$	Student or 'other'	0.092	0.289	0.070	0.255	0.074	0.263
$Status-notworking$	Unemployed or unable to work due to sickness or disability	0.108	0.311	0.081	0.273	0.087	0.283
UniversityEd	University education	0.454	0.498	0.444	0.497	0.410	0.493
Income	Income, €'000	38.146	24.901	42.461	25.607	42.789	26.265
N	Number of observations	1506		991		229	

replacement of their heating system, and a range of other related factors. The survey was tested in four iterations. For the first iteration the research team developed an initial draft. This was followed by two pretesting iterations in which the survey was circulated amongst colleagues, which was followed by a pilot survey. At each stage the questionnaire was refined to improve the text, question ordering, questionnaire structure and layout.

The final survey was launched using the panel from an international online consumer panel company with approximately 54,000 panellists across Ireland. This panel is demographically representative of gender, age, region and principal-economic status in Ireland. Two screening questions were also included in the middle and at the end of the survey to ensure accuracy (Sills and Song, 2002; Podsakoff et al., 2003; Bertsch et al., 2017). Block randomisation was not possible due to the skip logic between sections, however where possible questions were randomised to mitigate bias.

3.1. Comparison with national population

The sample of households was targeted to be representative of the national population according to the age of the head of household, their principal economic status and gender. Based on a comparison with the Central Statistics Office Quarterly National Household Survey (QNHS) Q4 2016 this was largely achieved. Some differences do exist, the largest of which are as follows: our sample under-represents 15–19 year olds by 7% and those aged over 65 by 4%; with regard to principal employment status our sample contains 5% more retired head of households than the national average; the largest regional discrepancy is a 5% under-representation of households in the Mid-West region.

We also compare our sample to a special QNHS Module on Household Environmental Behaviours conducted in Q2 2014, as this contains the most recently available information on the dwelling stock and installed heating systems. Again our sample is broadly representative in terms of dwelling type, construction period, type of tenure and primary heating source. The largest differences in each category are as follows: detached houses are under-represented by 8% in our sample; households using electricity as their primary means of central heating are over-represented by 7%; older dwellings are under-represented, with 7% less dwellings constructed before 1960 in our sample; owner-occupiers are over-represented by 8% relative to the national average. Appendix A provides further details.

4. Data

All data used in the analysis come from the online survey described above. In total 2430 respondents were interviewed from which 1506 usable responses were collected. This discrepancy is because 436 respondents failed the data quality screening questions, 315 were dropped as the quotas on certain characteristics were already filled, 120 were not the decision makers, and 53 did not complete the survey. Only sub-samples are used in the analysis, specifically home-owners as opposed to rental tenants. This sub-sample is discussed in the next section followed by summary of the variable types that are included in regressions relating dwelling attributes, occupants' characteristics, and knowledge of energy and environmental issues.

4.1. Sub-sample for model estimation

While the survey data is demographically representative of gender, age, region and principal-economic status, the research focus is home-owners and subsequently home-owners that upgraded their residential heating system. There are 991 home-owners in the survey data, of which 229 upgraded their heating system in the last 10 years. Descriptive statistics for these sub-samples are reported in Table 1. For comparison Table 1 also includes descriptive statistics for the entire sample, as well as all home-owners. There are only minor differences between the sample of all home-owners and those that replaced their heating system. There are proportionally fewer newer properties (i.e. built 1991 or later) that considered replacing their heating system compared to all home-owner properties, 36.7% versus 45.7%. This is not unexpected as heating systems within many newer properties would still be within the anticipated lifetime of the original heating system. There is also a slight difference between the two samples based on location or town size. There are proportionately more properties located in larger cities that have considered replacing their heating system compared to the sample of all home-owners, 31.9% versus 25.1%. While incomes are often higher in larger cities, there is no substantial difference between stated incomes in the two sub-samples. Otherwise there are no obvious differences between the sample of all home-owners and those that upgraded their heating system.

Secondary heating systems are an important consideration in Ireland, as 62% of households continue to use a stove, range or open fire as a secondary heating source (CSO, 2016). Data on both primary and secondary heating systems were collected and with this information households are categorised as using 'Non-networked', 'Gas + ', or 'Electricity + ' heating systems. Table 1 shows the proportion of respondents in each category, with over half of all homes fuelling their heating systems with only non-networked energy sources (e.g. oil, LPG, or solid fuels). For the sample of 229 home-owners that considered replacing their heating system, Table 1 also shows their final choice. Just over 47% chose a heating system with 'Non-networked' fuels, 42% a 'Gas + ' system, and 9% an 'Electricity + ' system.

4.2. Dwelling attributes

A number of dwelling attributes are included in our analysis of domestic heating system upgrades. Specifically we consider year of construction, dwelling type and geographical location. The year of construction is included as older houses tend to have solid fuel systems installed and due to the rapid expansion of the gas grid between 1990 and 2008 (Rogan et al., 2012) whether a dwelling has gas central heating is largely a function of time and geography.

Dwelling type is decomposed into detached houses and other. Braun (2010) find that row dwellings are more likely to have gas connections in Germany and as this is driven by the economics of density in network roll-out we would expect similar findings in Ireland. Dwelling size is included by using a variable which identifies the number of rooms in each dwelling.

Given that most gas and electric central heating systems are installed in urban locations we also include a variable capturing the town size in which the dwelling is located. For the purposes of the analysis this is categorised as: population less than 5000 inhabitants; between 5000 and 50,000 inhabitants; and greater than 50,000 inhabitants.

The fuel efficiency of the various systems and fuels included in our sample varies widely. Therefore, information on dwelling efficiency is important to consider, particularly if the occupants of inefficient dwellings are also using inefficient systems. Building energy performance certificates (EPC) are routine in property transactions but only 28% of respondents were aware of their property's EPC rating so we are unable to use this information within the estimated models. Instead, we use several variables indicating a home-owner's awareness and engagement with a number of energy and environmental issues, which are discussed separately below.

4.3. Occupant's characteristics

A range of previous studies have found that the socioeconomic characteristics of occupants are correlated with the type of heating system installed, and the usage of secondary heating systems (Braun, 2010; Couture et al., 2012; Laureti and Secondi, 2012). Based on this literature we include home-owner income, education, property tenure, employment status of head of household, and the composition of the household.

4.4. Knowledge of fuel cost, emissions and energy efficiency

The choice of heating system replacement or persistence in keeping an existing heating system may be a function of knowledge of the relative costs and benefits of different types of fuels and heating systems. Knowledge or concern for environmental damage associated with emissions may also be a factor. Preferences can differ significantly from behaviour and information deficiencies can be prevalent in this domain (Gillingham et al., 2009). To account for this in modelling choice of heating system replacement we ask respondents a range of questions relating to both their knowledge and behaviours with regard to energy and other domains (waste and recycling) which might be correlated with their energy saving behaviours. Table 2 provides an overview of these variables and some descriptive statistics, while Appendix A provides information on the source questions from which the variables are derived.[1] These variables comprise both continuous and count measures.

For the knowledge questions each correct answer is summed and standardised between zero and one. The resulting distributions, displayed in Fig. 1, suggest a broad spectrum of knowledge relating to these factors within the population and have a typical bell-shaped distribution. Knowledge is concentrated across domains within certain individuals, as indicated by the low correlations in Table 3. This would suggest different consumer groups with varying awareness and perhaps preferences relating to fuel cost, efficiency of different systems and carbon emissions associated with generating electricity with different fuels. The highest correlations observed are those relating to the generated count variables relating to household waste disposal and energy efficiency installation behaviour. This suggests that those with an awareness of energy efficiency labels engage in a variety of ways to recycle and dispose of household waste in environmentally friendly ways, and consequently may be more likely to have installed a range of energy efficiency measures in their homes. The correlations observed for these variables while positive and statistically significant are still relatively low, allowing several of them to be included as explanatory variables in regressions.

5. Results

5.1. Contemplated heating system upgrade

A MNL model is estimated with 3 outcomes related to whether home-owners considered a heating system upgrade: heating system

[1] The questions relating to energy efficiency measures installed and waste and recycling are adapted from a previous survey conducted by the Irish Central Statistics Office (CSO). Details available at http://www.cso.ie/en/releasesandpublications/er/q-env/qnhsenvironmentmoduleq22014/.

Table 2
Description of energy knowledge and energy/environmental behaviour variables.

Variable	Type of information	Description	All Households		All Homeowners		Households that considered replacing heating system	
			Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
fuel_cost_knowledge	Knowledge	Summation and standardisation of correct answers from 14 questions testing respondent's knowledge of both the unit cost in kWh and actual cost in commonly bought quantities of various fuels	0.299	0.127	0.293	0.126	0.295	0.128
emission_knowledge	Knowledge	Summation and standardisation of correct answers from 10 questions testing respondent's knowledge on the carbon emissions associated with burning various fuels and electricity	0.413	0.168	0.416	0.160	0.409	0.173
count_label	Knowledge	Count of correct answers from 2 questions testing respondent's knowledge of commonly used energy efficiency labels	1.411	0.740	1.460	0.726	1.461	0.725
count_disposal	Behaviour	Count of 3 of environmentally friendly waste disposal methods respondents use (household, medical, and electrical)	2.539	0.647	2.627	0.577	2.650	0.570
reduce_waste	Behaviour	Count of 6 of measures households take to reduce domestic waste	0.367	0.259	0.376	0.260	0.395	0.263
count_install	Behaviour	Count of 8 of energy efficiency measures respondents have installed in their homes	1.916	1.578	2.299	1.589	2.701	1.613

upgrade not considered (i.e. 'Not considered'), heating system upgrade considered but did not subsequently upgrade (i.e. 'Considered, not upgraded'), heating system upgrade considered and subsequently upgraded (i.e. 'Upgraded'). As indicated earlier the estimated MNL model parameters are not amenable to direct interpretation and instead RRRs are reported in Table 4. We present RRR estimates with respect to a baseline or reference category of 'Considered, not upgraded' and discuss the estimates in turn with respect to the three categories of explanatory variables within the model: dwelling attributes, home-owner characteristics, and home-owner energy and environmental knowledge. The models were estimated using `mlogit` command in Stata™.

5.1.1. Dwelling attributes

There are five dwelling attribute variables included as explanatory variables: the dwelling type (i.e. detached/semi-detached house or otherwise), dwelling age, number of rooms in the property, town size, and whether the respondent was aware that it is possible to connect to the gas network. Compared to the base case of 'Considered, not upgraded' only three variables have RRR estimates statistically different than 1, with the asterisks in Table 4 indicating statistical significance different than 1. Detached/semi-detached houses, as well as properties in mid-sized towns or cities are approximately half as likely to have considered a heating system upgrade compared to other property types and locations, approximately half as likely. If the respondent is aware that a gas network connection is possible (i.e. *GasInArea*) they are nearly two times more likely to have 'Upgraded' their heating system. In general, while there are some differences in RRRs associated with dwelling attributes, there are no strong distinguishing dwelling attributes associated with home-owners that do not even contemplate an upgrade of their heating system. Of home-owners that do consider upgrading their heating system, the availability of network gas is strongly associated with home-owners that do subsequently upgrade. This result does not imply that these home-owners necessarily switched to gas, as this group may also incorporate gas customers that upgraded their existing gas boilers.

5.1.2. Home-owner characteristics

A number of home-owner characteristics variables have RRR estimates statistically different than 1. These include the age variables, respondents with university education, mortgage holders, and those not in employment, which indicates that such home-owners compared to the respective baselines have differing likelihoods of considering a heating system upgrade and its subsequent installation. The RRR estimates related to the number of occupants aged 18 and less or aged 60 and above, as well as income are not statistically different than 1 suggesting no systematic difference in outcomes across these home-owner characteristics. Curiously, compared to the reference category of 'Considered, not upgraded' home-owners with university education, mortgage holders, or not in employment, and those older than age 35 are both less likely to have not considered a heating system upgrade, or less likely to have subsequently upgraded their heating system. So these are cohorts that are predisposed to investing in a heating system upgrade (i.e. they have considered as opposed to not considered an upgrade) but for some reason do not follow through to installation.

5.1.3. Household energy and environmental knowledge

With two exceptions none of the variables associated with knowledge and behaviours of energy or environmental matters have RRRs significantly different than one. Home-owners with higher numbers of energy efficiency measures installed (i.e. *countinstall*) are more likely to have an 'Upgraded' outcome. Installation of energy efficiency measures (e.g. insulation, high efficiency glazing, energy efficiency lighting, etc.) often occur as part of a large energy efficiency retrofit of which a heating system upgrade could be one element. However, knowledge of commonly used energy efficiency labels (i.e. *countlabel*) is associated with a lower likelihood of an 'Upgraded' outcome. Overall, there is not

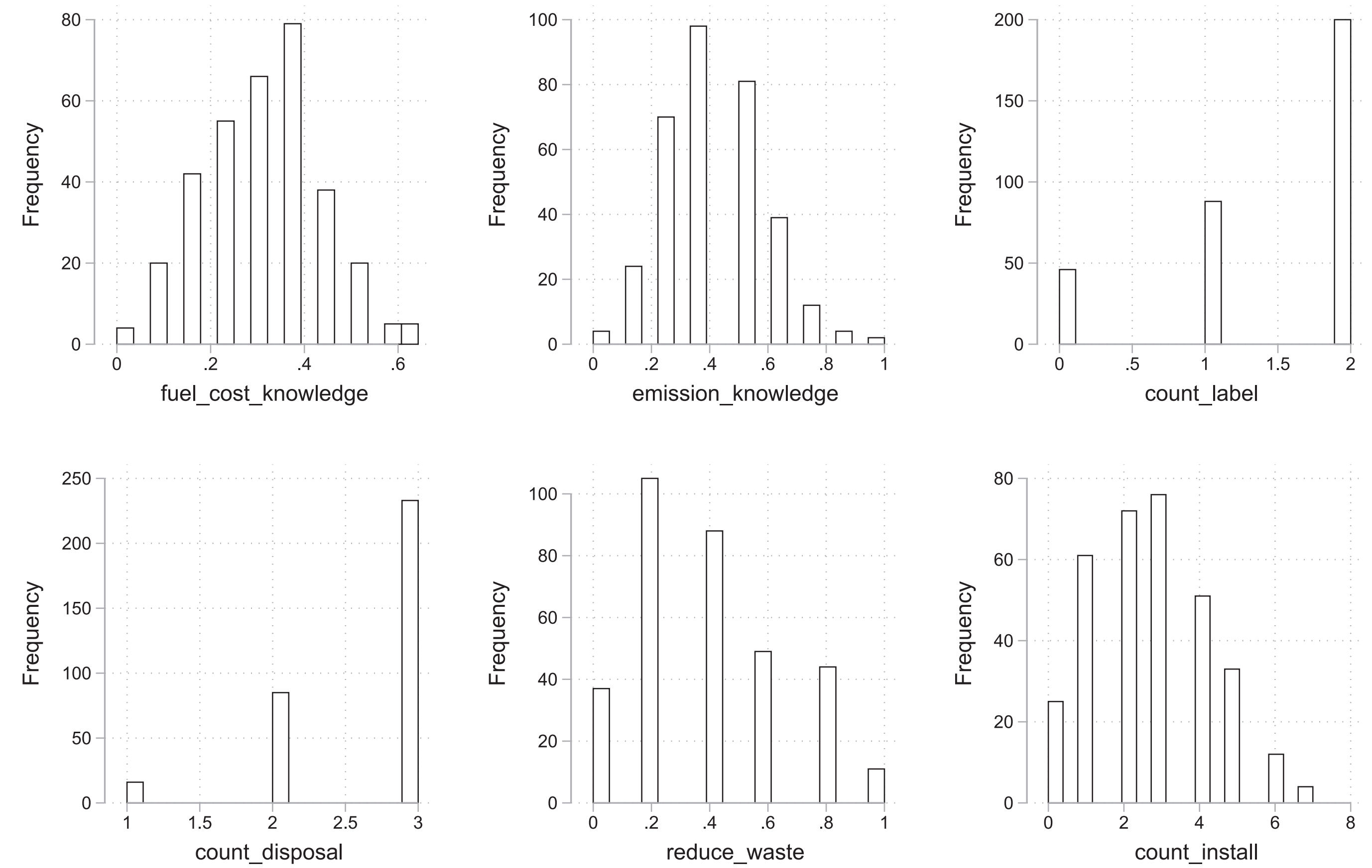


Fig. 1. Distributions of energy knowledge and energy/environmental behaviour variables.

Table 3
Correlation matrix of energy knowledge and energy/environmental behaviour variables.

	fuel_cost_knowledge	emission_knowledge	count_label	count_disposal	reduce_waste	count_install
fuel_cost_knowledge	1.000					
emission_knowledge	-0.012	1.000				
count_label	-0.046	0.057	1.000			
count_disposal	-0.036	-0.020	0.043	1.000		
reduce_waste	-0.064	-0.059	0.136*	0.188*	1.000	
count_install	0.113*	-0.021	0.133*	0.196*	0.360*	1.000

Note: N = 334.*denotes significance at 5% level.

no clear distinguishing trend among outcomes related to the consideration of investing in heating system upgrades associated with home-owners' knowledge or behaviours associated with energy or environmental matters.

5.2. Heating System Upgrade Choice

In this section we present model estimates examining the choice of heating system upgrade with three potential outcomes: 'Non-networked', 'Gas + ', and 'Electricity + '. As described earlier 'Non-networked' comprise heating systems using off grid fuels, the 'Gas + ' category centres around a natural gas fuelled heating system and the 'Electricity + ' category is analogous to 'Gas + ' except that electricity is the primary heating source. If natural gas is used for heating it falls within the to 'Gas + ' category. In this case we report the MNL estimates in Table 5 as marginal effects, calculated by Eq. (3). The marginal effects give the change in probability for each outcome associated with a change the explanatory variables in the model. For an increase in the probability that one of the heating replacement outcomes is selected there is a commensurate reduction in the sum of the probabilities of the other choices. Marginal effects were calculated with the `margins` command in Stata™. Where the marginal effect relates to a categorical variable the discrete first difference from the base category is reported.

5.2.1. Dwelling attributes

Of the dwelling attribute variables only two have statistically significant marginal effects estimates; those relating to availability of network gas and the size of town in which the property is located. Marginal effects associated with building type and age, as well as size in terms of number of rooms were largely statistically insignificant. The likelihood of properties in cities (> 50,000 population) is 27% points higher than properties in other areas of upgrading to a 'Gas + ' heating system. In medium sized towns (5–50,000 population) the comparable figure is 17% points. The likelihood of a 'Not-networked' heating system upgrade is substantially lower for properties in medium sized towns and cities ranging from 16% to 34% points compared to other areas. The higher marginal effects for cities potentially reflects the availability of networked gas in all large cities in contrast to medium

Table 4
Relative Risk Ratios versus 'Considered, not upgraded' option.

	'Not considered'	'Upgraded'
Reference category 'Considered, not upgraded'		
Dwelling attributes		
*Built*1971 − 1990	1.182	1.042
	(0.350)	(0.343)
*Built*1991−	1.463	0.875
	(0.415)	(0.280)
No. Rooms	0.968	0.913
	(0.063)	(0.071)
House	0.532***	1.059
	(0.181)	(0.409)
*TownSize*5 − 50*k*	0.629**	0.755
	(0.163)	(0.225)
*TownSize*50*k*+	0.665*	1.047
	(0.201)	(0.347)
GasInArea	1.415	1.984*
	(0.322)	(0.517)
Home-owner characteristics		
No. ≤18	0.935	1.091
	(0.094)	(0.125)
No. ≥65	1.208	1.283
	(0.242)	(0.283)
Mortgage	0.610**	0.629**
	(0.163)	(0.188)
*Age*3559	0.967	0.623*
	(0.302)	(0.217)
*Age*60*plus*	0.549**	0.430***
	(0.226)	(0.200)
Status − home	1.610	1.020
	(0.487)	(0.355)
Status − student	1.665	1.093
	(0.953)	(0.657)
Status − notworking	0.442***	0.466***
	(0.162)	(0.198)
UniversityEd	0.670**	0.593***
	(0.151)	(0.152)
Income	1.003	1.002
	(0.004)	(0.005)
Household energy and environmental knowledge and behaviour		
fuelcostknowledge	0.601	0.622
	(0.538)	(0.630)
emissionknowledge	0.767	0.462
	(0.557)	(0.387)
countlabel	0.816	0.658***
	(0.127)	(0.116)
countdisposal	1.078	1.343
	(0.192)	(0.295)
countinstall	0.945	1.323***
	(0.071)	(0.108)
reducewaste	0.954	1.033
	(0.414)	(0.507)
Constant	26.857	4.037
	(24.774)	(4.285)
N	968	
Log likelihood	-779.364	
Pseudo R^2	0.069	

Robust standard errors in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ and relate to tests of difference from 1. Relative risk ratios are calculated as the exponents of the estimated coefficients of the MNL model.

sized towns where it is not available in all instances. The availability of a network gas connection has a strong impact on heating system upgrade choice. Where a respondent is aware that a gas network connection is possible (i.e. *GasInArea*) they are 59% points more likely to choose a 'Gas + ' heating system upgrade compared to respondents not aware of the availability of network gas. As noted previously, not all home-owners choosing a 'Gas + ' heating system upgrade have switched to gas as a heating fuel. As will be discussed later, many heating system upgrades do not encompass fuel switching. However, the high marginal effect associated with the variable *GasInArea* indicates strong home-owner satisfaction with gas-based heating systems.

Table 5
Model Marginal effects.

	'Not-networked'	'Gas + '	'Electricity + '
Dwelling attributes			
*Built*1971 − 1990	0.035	0.030	-0.065
	(0.054)	(0.047)	(0.041)
*Built*1991−	-0.013	0.057	-0.045
	(0.060)	(0.054)	(0.054)
No. Rooms	0.016	0.007	-0.023*
	(0.014)	(0.012)	(0.014)
House	0.099	-0.008	-0.090
	(0.083)	(0.069)	(0.074)
*TownSize*5 − 50*k*	-0.156**	0.170**	-0.014
	(0.074)	(0.069)	(0.063)
*TownSize*50*k*+	-0.335***	0.274***	0.061
	(0.080)	(0.085)	(0.072)
GasInArea	-0.503***	0.590***	-0.087*
	(0.069)	(0.069)	(0.049)
Home-owner characteristics			
No. ≤18	0.006	-0.015	0.009
	(0.017)	(0.020)	(0.024)
No. ≥65	-0.010	-0.021	0.031
	(0.029)	(0.027)	(0.029)
Mortgage	-0.099*	0.105**	-0.007
	(0.053)	(0.051)	(0.046)
*Age*3559	0.045	0.031	-0.077
	(0.070)	(0.063)	(0.074)
*Age*60*plus*	-0.014	0.034	-0.020
	(0.088)	(0.087)	(0.085)
Status − home	-0.073	0.097*	-0.025
	(0.054)	(0.054)	(0.047)
Status − student	-0.081	-0.185	0.266*
	(0.134)	(0.122)	(0.143)
Status − notworking	-0.067	-0.121*	0.188*
	(0.106)	(0.066)	(0.112)
UniversityEd	-0.016	0.019	-0.003
	(0.052)	(0.052)	(0.056)
Income	-0.002**	0.001	0.001
	(0.001)	(0.001)	(0.001)
Household energy and environmental knowledge and behaviour			
fuelcostknowledge	0.106	0.081	-0.188
	(0.221)	(0.162)	(0.160)
emissionknowledge	0.097	-0.233*	0.136
	(0.121)	(0.124)	(0.109)
countlabel	0.013	-0.019	0.006
	(0.026)	(0.023)	(0.023)
countdisposal	0.010	0.019	-0.029
	(0.036)	(0.032)	(0.037)
countinstall	0.029*	0.002	-0.032*
	(0.017)	(0.011)	(0.017)
reducewaste	-0.107	-0.179**	0.287***
	(0.090)	(0.084)	(0.074)

Robust standard errors in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

5.2.2. Home-owner characteristics

Estimated marginal effects associated with the respondent's age or education and the number of number of occupants aged 18 and less or aged 60 and above are all statistically insignificant. The marginal effect for income is statistically significant in one instance but the magnitude of the effect is practically negligible. The largest estimated marginal effects are associated with property tenure and some employment status categories. Home-owners with mortgaged properties are over 10% points more likely to have chosen a 'Gas + ' heating system upgrade and are 10% points less likely to have chosen a 'Not-networked' heating system upgrade compared to home-owners that own their properties without a mortgage. Where the home-owner is described as being unemployed, not working due to illness or disability, or a student there is a substantially higher likelihood that the heating system upgrade was an 'Electricity+' system between 19% and 27% points compared to other home-owners.

5.2.3. Household energy and environmental knowledge

Across the variables associated with knowledge and behaviours of energy or environmental matters one might anticipate positive marginal effects associated with either 'Gas+' or 'Electricity+' heating system upgrades due to such upgrades generally being more efficient from a financial or emissions perspective. In general, the estimated marginal effects are not consistent with such a narrative. For example, the marginal effect for the *emissionknowledge* variable, which relates to knowledge about emissions from various fuels and electricity, is statistically significant only in the case of 'Gas+' but negative at -0.233. Compared to other fuels, especially 'Not-networked' fuels such as peat and coal, one would have anticipated a significant and negative marginal effect for 'Not-networked' fuels but instead it is positive though not statistically significant. In the case of the *reducewaste* variable one might have anticipated a negative marginal effect for 'Not-networked' upgrades but possibly positive marginal effects associated with 'Gas+' and 'Electricity+' upgrades, as home-owners that undertake measures to reduce waste may also make decisions to reduce emissions. While some of the marginal effects estimates are consistent with a narrative that environmentally aware home-owners are more likely to choose less rather than more emissions intensive heating system upgrades, overall there is not an overwhelming trend across the 6 associated variables in the model.

5.3. Examination of switching

The following sections examine the factors which contribute to home-owners changing both their heating system and fuel type. We present a series of regression models examining the determinants of switching, and some descriptive statistics on switching patterns and the primary reasons home-owners cite for their decision to upgrade or keep their current system.

Table 6 presents the determinants of changing fuel type for those who have also changed heating system. Results are presented as odds ratios, a coefficient greater than (less than) one indicates higher (lower) propensity to change system. Households living in dwellings built between 1971 and 1990 are more likely to have changed fuel type relative to the other categories. Households in larger towns are less likely to change fuel type when upgrading their system relative to other categories. This result is explored in more detail in the next sections but is related to the technological lock-in that seems to occur once home-owners switch to a networked fuel. Households who's reference person is in the $35-59$ age are less likely to have changed fuel type than other categories.

Previous installation of energy efficiency measures is associated with a higher probability of changing fuel type. Included in all estimations in the minimum average temperature in December, January and February for the past 30 years in each county. The aim of including this variable is to assess if local temperature is a contributing factor in home-owner decisions. If cold temperatures are associated with a greater propensity to switch we would expect an odds ratio less than one. Neither the sign nor the significance of this variable indicate that this is the case.

5.3.1. Switching patterns

While the regression results do not indicate a very clear pattern in fuel switching behaviour, the survey data we have collected allows us to delve more deeply into this question. Table 7 presents a transition matrix which describes home-owner switching patterns. Given the low numbers in some cases, this is presented as counts rather than percentages. The rows indicate the previous fuel a home-owner used and the columns the current fuel. For example, the results in row 1 indicate that of the 28 home-owners who previously used coal, five still use coal, one has switched to electric heating, seven to gas, twelve to oil, one to peat and two to wood.

A few clear trends emerge. The first is that the vast majority of home-owners either switch to natural gas or oil, or keep using their current fuel. Very few switch to other fuels and only two adopt heat pumps. Once home-owners select natural gas as their primary means of central heating very few change from this, although some do switch to electric heating.

Table 6
Determinants of switching system and fuel type.

	Changed fuel type
Dwelling attributes	
*Built*1971 − 1990	2.046*
	(0.876)
*Built*1991−	1.399
	(0.685)
No. Rooms	1.166
	(0.117)
House	0.471
	(0.248)
Newbuild	0.603
	(0.235)
*TownSize*5 − 50*k*	1.101
	(0.413)
*TownSize*50*k*+	0.337**
	(0.148)
GasInArea − *k*	1.118
	(0.544)
30*yeartemp*	1.111
	(0.096)
Home-owner characteristics	
No. ≤18	1.206
	(0.201)
No. ≥65	0.951
	(0.218)
Mortgage	1.800
	(0.783)
*Age*3559	0.464*
	(0.214)
Age60plus	0.435
	(0.293)
Status − *home*	0.430*
	(0.192)
Status − *student*	0.209**
	(0.142)
Status − *notworking*	1.078
	(0.591)
UniversityEd	1.105
	(0.389)
Income	1.001
	(0.007)
Household energy and environmental knowledge and behaviour	
fuelcostknowledge	0.307
	(0.364)
emissionknowledge	0.685
	(0.674)
countlabel	0.777
	(0.163)
countdisposal	1.374
	(0.435)
countinstall	1.229*
	(0.149)
reducewaste	0.568
	(0.359)
Observations	220
chi2	31.767

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 7
Fuel switching patterns.

Previous fuel	Coal	Elec.	H. Pump	LPG	Gas	Oil	Peat	Wood	Total
Coal	5	1	0	0	7	12	1	2	**28**
Elec.	0	8	1	0	1	4	0	1	**15**
Heat pump	0	0	0	0	0	0	0	0	**0**
LPG	0	0	0	0	0	3	0	0	**3**
Natural Gas	0	5	0	0	58	0	0	2	**65**
Oil	4	3	1	4	27	46	6	6	**97**
Peat	0	1	0	0	0	2	6	0	**9**
Wood	0	0	0	0	0	1	1	0	**2**
Total	**9**	**18**	**2**	**4**	**93**	**68**	**14**	**11**	**219**

Table 8
Reasons for replacing system.

Reason for changing	Agree	Disagree
System broke	33%	56%
Not working well	59%	30%
Carbon emissions	45%	29%
Fuel Costs	69%	17%
Received government grant	19%	71%

5.3.2. Reasons for replacing system

In Table 8 we present results of survey questions which asked home-owners who changed system to nominate the main reasons for changing their heating system (N = 231). Various options were presented and home-owners were asked to select choices based on a five point Likert scale ranging from "Agree Strongly" to "Disagree Strongly". Answers were then aggregated into two categories, "Agree" or "Disagree". The primary reasons for replacing heating systems were related to fuel costs (69% agree), and systems not working well (59% agree). We can observe some evidence of environmental concern among respondents as 45% of them agree that carbon emission is a factor to consider when replacing heating systems. Interesting, policy push factors were not widely cited with 71% of home-owners disagreeing that this was an important consideration for them.

In the survey home-owners who switched heating systems were also asked regarding the source of information they used when making their decision. Results are presented in Table 9. We can see that the main source is the research home-owners do themselves on the available systems followed, by a recommendation from a plumber or tradeperson. This shows that people rely more on trade-persons working in plumbing/heating than their own neighbours. It is interesting that the recommendations of energy consultants and companies are not of high relevance or consideration to those who have decided to switch. This may be explained by a perception that such companies or consultants may only advise certain types of technologies or fuel types aligned with their business. However, we cannot confirm this as we did not ask further questions explaining these decisions.

5.3.3. Reasons for keeping system

In addition to presenting the reasons for replacing heating systems, we were also interested in why home-owners keep their existing heating system. Of those who have not replaced their current system in the past 10 years (N = 766), a wide variety of reasons exist for keeping the status quo. Survey responses are presented in Table 10, where we can see that respondents are basically happy with their existing system and have the perception that the replacement will not be any better for them. Financial constraints are cited by nearly 25%. Non-financial costs, such as disruption are cited by very few home-owners

Table 9
Information source for home-owners who switched.

Information source for heating replacement	Percent
My own research	37%
Recommendation of plumber/trades person	33%
Recommendation of friend/neighbour/relative	15%
Recommendation of energy consultant	7%
Recommendation of energy company (obligated party)	6%
Other (please specify)	1%

Table 10
Reasons for keeping system.

Reason for keeping current system	Percent
I don't think a replacement will be any better	44%
I would like to but it is too expensive	24%
I'm planning on replacing it in the future	10%
It doesn't need to be changed	8%
It's not something I think about very often	8%
Other	4%
Replacement is too disruptive	3%

6. Discussion

A few key features emerge from our results. In terms of characteristics of the property's occupants no clear trend emerges with respect to choices for replacement heating systems. There is no substantial difference in likelihood of choosing a particular heating system associated with factors such as income, education, working status, or families with higher numbers of children or elderly occupants. This is interesting given that we have focused on a subsection of homeowners who have agency in this decision. This means that decisions for heating systems are processes that entails more complex elements than only socio-economic variables.

In addition to the socioeconomic and dwelling characteristics we collected detailed information on occupants' knowledge of energy costs, energy efficiency, and fuel emissions as well as data on some of their actual environmental behaviours. We use this information to identify if home-owners' knowledge or actions on energy or the environment are important in their choice of heating systems. The use of these types of variables goes beyond previous similar analyses that have used the usual socio-demographic and dwelling characteristic variables (Braun, 2010; Couture et al., 2012) or stated preferences on environmental issues (Michelsen and Madlener, 2012). The a priori expectation was that occupants who engage in environmentally sustainable behaviours or that have a good understanding of emissions, energy efficiency or fuel costs are more likely to opt for either electricity or gas fuelled heating systems, as these are usually the least emissions intensive (per delivered energy) and cost economical heating systems. Though some parameter estimates are statistically significant, no clear trend emerges. Knowledge of energy or environmental issues or engagement in environmentally sustainable behaviours do not seem to explain choice of heating system. This is interesting because if knowledge is correlated with information, then it is important to analyse the channels of how information can effectively affect adoption. However, this specific analysis is beyond the objective of our paper and would be an interesting topic for future research.

The key determinant of home-heating choice is proximity to a networked fuel. The convenience of networked gas and electricity seems to override any socioeconomic factors or any environmental preferences. This confirms previous research which indicates that a key determinant of choice of fuel heating system is proximity to source and availability of alternatives (Mansur et al., 2008; Arabatzis and Malesios, 2011; Fu et al., 2014; Wu et al., 2017; McCoy and Curtis, 2018). These results are reinforced by the analysis of fuel switching patterns. Of those home-owners who switched, the vast majority changed to gas or oil. This reflects the prevalence of these fuels in Ireland, and perhaps the lack of financial incentives encouraging home-owners to move to renewable or electric central heating. Given the convenience of networked gas it is not surprising that once adopted, home-owners do not switch from this fuel. In so far as home-owners are switching from solid fuel or oil to gas, this move can be welcomed. However, if this reluctance to switch from gas suggests technological lock-in there is cause for concern. Should distributed renewable heating technology, such as heat-pumps, improve and costs reduce, this may not provide sufficient incentive for home-owners to adopt these measures and policy may need to address this.

European and Irish policy frameworks seek to reduce greenhouse gas emissions (European Commission, 2011; DCCAE, 2017). With one third of energy used for space heating (Meier and Rehdanz, 2010; Braun, 2010), heating systems within the residential sector is an important policy focus. If residential heating systems are to be de-carbonised, strong policy signals and incentives will be necessary. Relying on home-owners to do the 'right' thing is unlikely to succeed. Residential heating systems installed today have a potential lifetime of up to 20 years so it is important that home-owners face the right incentives as soon as possible.[2] Ireland has long prohibited the sale and burning of bituminous coal in certain areas, which was initially undertaken for health reasons. This prohibition will be extended nationwide by Autumn 2018 but consideration should be given to extending the ban to other fuels, or at least increasing the carbon tax on fuels to reflect environmental externalities. Previously, subsidies were available to support adoption of condensing oil and gas boilers. In the short term, subsidies in the residential sector should be redirected towards the electrification of heating, consistent with the low carbon roadmap for Ireland (Deane et al., 2013). In addition, home-owners did not seem well-informed about available subsidies to replace their existing systems. This should be considered and the importance of plumbers and other tradespeople as an information source should be noted.

Determining the split between electrification and gasification of heating merits further research, however, gasification of residential heating at any scale is only a viable option in areas where the gas network exists. While this network currently provides methane to home-owners, this was not always the case. Historically, the proportion of hydrogen within this mix would have been considerably higher. In the long term decarbonisation will likely require re-purposing the natural gas network for biogas and/or hydrogen. This topic is garnering increasing interest and was considered in an influential report by the Committee on Climate Change in the UK (CCC, 2016). In addition, the UK government has recently invested £25 million of funding for an innovative programme considering using hydrogen gas for heating in homes across the UK, with an initial focus on the city of Leeds (Northern Gas Networks, 2018). Our results indicate that proximity to gas is a key determinant of both the decision to upgrade heating systems and the choice of heating system. In addition, the low numbers of home-owners switching away from gas illustrates the strong position of natural gas as a fuel source within many residential properties. The low carbon roadmap for Ireland (Deane et al., 2013) envisages strong use of natural gas in the residential sector, equivalent to 2010 levels in some of its low carbon 2050 scenarios. With many home-owners having a strong affinity to natural gas as a domestic fuel, the de-carbonisation of the natural gas grid may practically be an easier route to deliver the de-carbonisation of the residential sector.

7. Conclusion

Environmental concerns, particularly climate change, have motivated countries to align their environmental and energy policies to reduce greenhouse gas emissions. With the residential sector accounting for a substantial share of emissions a major transformation in energy use within the sector is required. This work examines the drivers of decisions related to space-heating in the home. While the dataset used in this study was collected to be representative of all Irish households, the analysis focuses specifically on home-owners who have agency in home heating system decisions.

Our results both confirm existing research and adds new insights. For instance, we find that a key determinant of choice of heating system fuel is proximity to source and availability of alternatives. Previous research finds that several socio-demographic variables, including income, education, and age of home-owner, are important determinants of heating system choice though the income effects are all noted as being minor (Laureti and Secondi, 2012; Couture et al., 2012; Michelsen and Madlener, 2012; Braun, 2010). We find that not to be in the case in the Irish situation but there are also similarities between the studies, for example, the presence of children or older adults in the home has no discernible impact on heating system decisions.

This study finds two additional important insights. First, we find that home-owners' knowledge or actions on energy or the environment are not significant determinants of decisions regarding system upgrades choice of heating systems. Even among home-owners that are environmentally conscious strong policy incentives will be necessary to encourage de-carbonisation of home heating systems. Second, we find that a key determinant of home-heating choice is proximity to a networked fuel, specifically natural gas, which echoes a comparable finding from France (Couture et al., 2012). The availability of a gas network connection leads to a strong positive marginal effect on the likelihood of a gas fuelled heating system with a reduction in the likelihood of heating systems with other fuel types. With the potential for the gas network to transition to biogas (Czyrnek-Delêtre et al., 2016), the gas network is potentially critically important infrastructure for de-carbonising the residential sector. A biogas network would obviate the need to convince multitudes of individual home-owners to transition to low-carbon alternatives.

Our analysis also provides important insights to policy-makers and practitioners trying to encourage the transition to low carbon options. Home-owners, both those that have upgraded their heating systems and those that have not, are potentially making decisions with incomplete information. For example, almost half of those that do not upgrade believe a new system will not be any better than their existing heating system; whereas those that do upgrade rely to a much greater extent on either on their own research or recommendation of a trades-person rather than advice from an independent energy consultant.

Taken as a whole, this study suggests that even among home-owners who are actively making decisions about home heating, knowledge, past environmental behaviours, socioeconomic and dwelling characteristics have little explanatory power in determining heating system and fuel choice. Path dependance and technological lock-in are powerful forces to contend with when a transition of this magnitude is required. The provision of district heating, and other networked heating sources will be key to a low-carbon transition.

Acknowledgements

This research is supported by Science Foundation Ireland under Grant No. 12/RC/2302. The research was part funded by Gas Networks Ireland through the Gas Innovation Group Grant No. 2015-SR-002 and by Science Foundation Ireland (SFI) through MaREI — Marine Renewable Energy Ireland Research cluster. Funding from the ESRI's Energy Policy Research Centre is also gratefully acknowledged. This research has also been supported by the Grantham Institute for Climate Change and the Environment and the ESRC Centre for Climate Change Economics and Policy under grant number ES/K006576/1. This paper also benefited greatly from comments by the editor of this journal and two anonymous reviewers.

[2] The Chartered Institution of Building Services Engineers estimates a 15 year expected lifetime for a domestic gas or oil boiler http://www.cibse.org/Knowledge/knowledge-items/detail?id=a0q20000008I7oZAAS.

Appendix A. Survey questions on knowledge of fuel cost, efficiency and emissions

Figs. 2–7

* 3. This question relates to the average price per unit of different fuels. We indicate below the units we refer to. These are the units that fuel is commonly bought in, and reflect the price you might pay in a shop of from a supplier. For example a 40kg bag of coal or bale of briquettes.

Please indicate below how much you think each fuel costs:

	A: less than 1 euro	B: about 2-6 euro	C: about 15-20 euro	D: more than 25 euro
Bale of peat briquettes	○	○	○	○
40kg bag of standard coal	○	○	○	○
Litre of gas oil (kerosene)	○	○	○	○
Natural Gas per kWh	○	○	○	○
Typical electricity day rate per kWh	○	○	○	○
Wood pellets per kilo (bulk delivery)	○	○	○	○
Liquid Petroleum Gas (LPG) (11.35kg cylinder of butane)	○	○	○	○

Fig. 2. Questions on fuel cost per commonly purchased unit.

* 4. This question is about the price of fuel per unit of energy delivered. The prices here are all in the same units, the kilowatt hour. They reflect the price in cent per kilowatt hour of energy delivered.

Please indicate how much you think each fuel might cost:

	A: about 3-10 cent	B: about 10-20 cent	C: about 20-30 cent
Coal	○	○	○
Electricity	○	○	○
Liquid Petroleum Gas (LPG)	○	○	○
Natural Gas	○	○	○
Oil	○	○	○
Peat	○	○	○
Wood	○	○	○

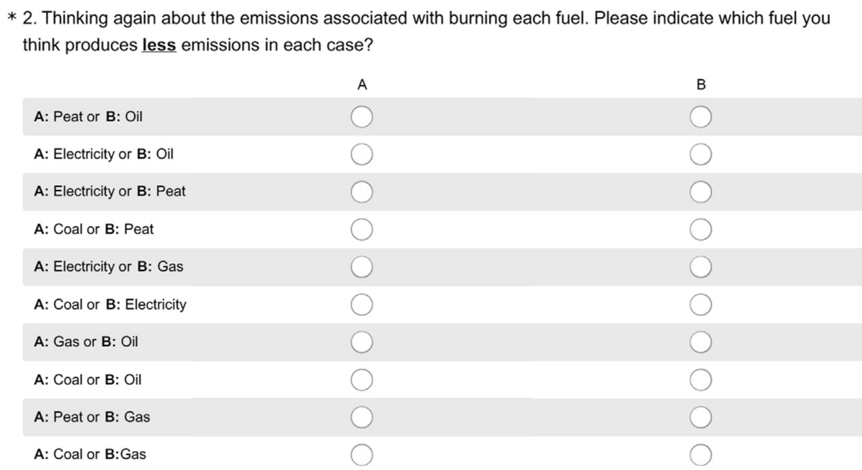
Fig. 3. Questions on fuel cost per kWh.

* 1. I'm going to give you three options which reflect the typical efficiency of different heating systems. This reflects the amount of heat your system gives out relative to the amount of energy (in fuel) that goes in.

Please indicate how efficient you think each system is:

	A: about 20-40 percent efficient	B: about 50-85 percent efficient	C: above 85 percent efficient
Stove without Back Boiler	○	○	○
Stove with Back Boiler	○	○	○
Open Fire	○	○	○
Oil fired boiler (Kerosene)	○	○	○
Gas fired boiler	○	○	○
Wood products or biomass boiler	○	○	○
Condensing boiler	○	○	○

Fig. 4. Questions on efficiency of commonly used heating systems.


* 2. Thinking again about the emissions associated with burning each fuel. Please indicate which fuel you think produces **less** emissions in each case?

	A	B
A: Peat or **B:** Oil	○	○
A: Electricity or **B:** Oil	○	○
A: Electricity or **B:** Peat	○	○
A: Coal or **B:** Peat	○	○
A: Electricity or **B:** Gas	○	○
A: Coal or **B:** Electricity	○	○
A: Gas or **B:** Oil	○	○
A: Coal or **B:** Oil	○	○
A: Peat or **B:** Gas	○	○
A: Coal or **B:**Gas	○	○

Fig. 5. Questions on carbon emissions associated with producing electricity from various fuel sources.

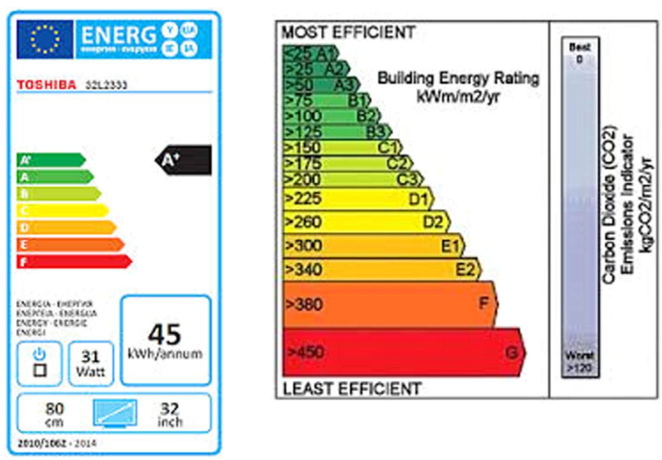
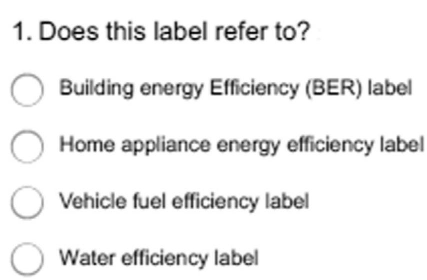


Fig. 6. Energy labels presented to respondents.


1. Does this label refer to?

○ Building energy Efficiency (BER) label

○ Home appliance energy efficiency label

○ Vehicle fuel efficiency label

○ Water efficiency label

Fig. 7. Questions on energy labels presented to respondents.

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