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Willingness-to-Pay and Free-Riding in a National Energy Efficiency Retrofit Grant Scheme: A Revealed Preference Approach

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Abstract: Understanding the drivers of energy efficient behaviour in the household can provide significant insights on how best to provide incentives for homes to engage in energy efficiency retrofits. This can have wide-reaching effects in reducing the demand for energy and in turn reducing carbon emissions. Many national grant aid schemes exist to support homes in engaging in retrofits, but these can also be availed of by free-riders, which are homes that would engage in a retrofit even in the absence of financial support. This paper explores retrofit choice, willingness-to-pay for retrofit works and free-riding in a grant aid scheme for residential energy efficiency retrofits. Household preferences are revealed through energy efficiency retrofits undertaken by Irish home owners, after having been presented with an array of retrofit measures and combinations thereof. We use a McFadden's choice model to estimate willingness-to-pay for energy efficiency renovation works using revealed preference data (McFadden, 1984). The results of this analysis are then used to estimate the extent to which free-riding has occurred in the scheme to date. We find that less efficient and larger homes are willing to pay more for energy efficiency improvements, and find that households which had previously engaged in a retrofit via the grant scheme were willing to pay over twice as much as those retrofitting for the first time. Free-riding varies by retrofit measure, with solar collector retrofits possessing close to zero free-riders, while free-riders comprised over 33% of heating controls retrofits.

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1. Introduction

With an estimated 67% of residential energy consumption used for space heating, and a further 14% used for water heating (European Commission, 2011), improved energy efficiency provides an opportunity for households to save money on energy bills, while improving the comfort of their homes. In order to facilitate energy efficiency retrofit works in the home, the Sustainable Energy Authority of Ireland (SEAI) administers the Better Energy Homes (BEH) scheme as a means of contributing to a 20% reduction in Ireland's energy use by 2020, as mandated by the European Union (European Parliament and the Council of the European Union, 2012). At present, grant aid is available for up to four energy efficiency retrofit measures. These are roof insulation upgrades, wall insulation upgrades, boiler and/or heating controls upgrades and solar collector installation.

The presence of grant aid provides an incentive for home owners to engage in energy efficient renovations. From the introduction of the BEH scheme in March 2009 through July 2016, over 179,000 homes have received financial support to engage in residential retrofit works. While this does not include retrofits conducted under other grant aid schemes, such as the Better Energy Warmer Homes scheme for homes subject to fuel poverty, or retrofits conducted without grant aid, this accounts for slightly over 10% of private dwellings in Ireland[1]. The scheme currently aims to provide ca. 35% of the costs of retrofit works but it is unknown what the optimal level of aid should be in order to induce more retrofits and in turn contribute to Ireland's energy efficiency targets. By gaining an understanding of how much home owners are willing to pay for energy efficiency improvements to their home, the level of grant aid provided can be optimised to reduce deadweight loss. This greater understanding can provide a measure of the extent to which a grant aid scheme has directly induced retrofitting works.

The possibility of improving the understanding of the willingness-to-pay of households raises two research questions. These are, firstly, how much households are willing to pay for residential energy efficiency improvements and, secondly, to what degree is free-riding a problem in the BEH scheme. We estimate the determinants of the choices made by BEH-participant households. From the results of this analysis we derive estimates of the average marginal willingness-to-pay for energy efficiency improvements. Fitting the willingness-to-pay of all households who completed a retrofit under the Better Energy homes scheme, we compare that willingness-to-pay to the actual cost of retrofits undertaken and assess the degree to which free-riding has occurred over the lifetime of the scheme. We find that upward of 7% of participants would have undertaken a retrofit even in the absence of grant aid, with approximately a further 8% applications which would have occurred with a lower level of grant aid than was available. This varies across retrofit measures, with heating controls retrofits possessing a much higher rate of free-riding. We find that house- holds who had previously completed a retrofit under the BEH scheme were willing to pay over three times more than those retrofitting for the first time.

The remainder of the paper is organised as follows. Section 2 provides a review of the literature and section 3 describes the data and methods of analysis used, while section 4 discusses the results of the research and section 5 concludes.

2. Literature review

The relevant literature can be divided into three areas. Firstly, literature on willingness-to-pay for energy efficiency is discussed in the international context. This is followed by the literature on free-riding in residential retrofitting and, finally, literature on energy efficiency retrofitting in the Irish context. Various studies have used discrete choice experiments to estimate willingness-to-pay for energy efficiency improvements. Banfi et al. (2008) presented participants in Switzerland with choices between remaining in their

[1] Based on Irish Census 2011, table CNA33

current home or to move to a home with varying energy efficient measures already having been undertaken. This paper used a fixed effects logistic regression to measure willingness-to-pay, finding a WTP of between 3% and 13% of the value of the home for different energy efficient measures. Kwak et al. (2010) used a similar design, employing a multinomial logit and a nested logit to analyse WTP in South Korea, finding a marginal WTP of $12.40 for a ventilation system and $1.20 for each additional millimetre of facade insulation. Farsi (2010) undertook a discrete choice experiment and used random effects regressions of various functional forms to analyse risk premia and willingness-to-pay for energy efficiency in rental apartments in Switzerland, finding a willingness-to-pay for various retrofit measures of between 0 and 11.3% of monthly rent. Achtnicht (2011) presented respondents in Germany with a choice between retrofitting options, including information on the costs, energy-saving potential, payback period and CO_2 savings. Using a fixed effects logit and a mixed effects logit, the marginal WTP for a percentage decrease in emissions was found to be €88 in West Germany, falling to €66.20 in East Germany.

There exists a more narrow literature examining willingness-to-pay for energy efficiency improvements using revealed preference data. Cameron (1985) utilised a nested logit model to examine household behaviour and, specifically, whether they had engaged in a number of energy efficiency renovations, using the results to define a discrete choice model, the results of which were used to examine the appropriateness of financial incentives to retrofit. Grösche and Vance (2009) examined a survey of home owners in Germany which asked respondents if they had invested in a series of renovations. The results of this survey were used to impose a set of discrete choices on home owners, estimating the expected costs and energy efficiency gains associated with each measure. The results of that analysis were then used to calculate willingness-to-pay for energy efficiency improvements and hence free-riding. A conditional logit, random effects logit and error components logit model were used to find a mean willingness-to-pay of €3.28 per kilowatt hour energy efficiency improvement in East Germany, falling to €1.72 in West Germany.

Free-riding has been examined in some cases using data on the number of retrofits that have been completed before and after the introduction of a tax credit for retrofit works, where the probability of a home undertaking a retrofit is estimated, controlling for the availability of such a tax incentive. By controlling for this, the number of retrofits undertaken as a result of subsidisation can be estimated, leaving the share of free-riders. This method has been used by Nauleau (2014) in France, finding a free-ridership share of between 40% and 85% after the first two years of an income tax credit scheme, and Alberini et al. (2014) in Italy, who found the introduction of a tax credit increases window retrofits by up to 40% but that free-riding was rampant for other measures. Malm (1996) analysed the actions of clusters of home owners segregated by their energy use behaviours, estimating that 89% of consumers who purchased an energy efficient appliance would have done so in the absence of aid. Grösche and Vance (2009), as mentioned previously, estimated both willingness-to-pay and free-riding when analysing survey data on completed retrofits. By comparing the estimated willingness-to-pay of home owners to the expected costs associated with the chosen retrofit measure(s), it was estimated that 2,054 of the 2,128 households surveyed (96%) could be classed as free-riders.

In the Irish context, research has focussed on a number of aspects surrounding residential energy efficiency. For instance, Aravena et al. (2016) examined the propensity to apply for retrofit grant aid, while McCoy and Lyons (2016) examined the propensity to retrofit following the introduction of electricity smart meters. Collins and Curtis (2016) examined drivers of retrofit depth in Ireland, while both Aravena et al. (2016) and Collins and Curtis (2017) investigated the likelihood of homes abandoning an application for retrofit grant aid using stated and revealed preference data, respectively. In terms of the outcomes of retrofitting and the benefits of energy efficiency, Clinch and Healy (2000) examined monetary returns to investing in energy efficiency retrofits and environmental benefits of same, while Hyland et al. (2013) investigated the reflection of energy efficiency labelling in property prices. Carroll et al. (2016) used a stated preference survey to estimate the willingness-to-pay of renters for energy efficiency labels in rental apartments. To the authors' knowledge, however, there does not exist any literature with regard to the willingness-to-pay of home owners for energy efficiency improvements or free-riding in grant aid schemes in Ireland.

3. Data and empirical methods

3.1. The Better Energy Homes scheme

The Better Energy Homes scheme, originally known as the Home Energy Savings scheme, commenced in 2009 and is administered by the Sustainable Energy Authority of Ireland (SEAI). It is a grant aid scheme for households to engage in energy efficiency improvements, with grants available for various energy efficiency measures (EEMs). Grants are available for roof/attic insulation, one of three types of wall insulation (cavity insulation, external wall insulation or internal dry-lining), three types of boiler upgrade (oil boiler or gas boiler with heating controls upgrade or heating controls upgrade only) and solar collector (panel or tube) installation. This means that a household may adopt up to a maximum of four EEMs as only one type of wall insulation or boiler upgrade may be awarded grant aid. Upgrades must satisfy SEAI technical standards for grant applications to be successful. The level of grant aid available has changed over time, with information on the dates of these amendments and the changes made detailed in Table 1.

Table 1: Grant Structure

Measure	Category Sub-Category	Scheme 1 Mar-09 €	Scheme 2 Jun-10 €	Scheme 3 May-11 €	Scheme 4 Dec-11 €	Scheme 5 Mar-15 €
Roof	Attic Insulation	250	250	200	200	300
Wall	Cavity Wall Insulation	400	400	320	250	300
	Internal Dry-Lining	2500	2500	2000	.	.
	Apartment or Mid-terrace House	.	.	.	900	1200
	Semi-detached or End of Terrace	.	.	.	1350	1800
	Detached House	.	.	.	1800	2400
	External Wall Insulation	4000	4000	4000	.	.
	Apartment or Mid-terrace House	.	.	.	1800	2250
	Semi-detached or End of Terrace	.	.	.	2700	3400
	Detached House	.	.	.	3600	4500
Boiler	High efficiency boiler (oil or gas) upgrade with heating controls	700	700	560	560	700
	Heating Controls upgrade only	500	500	400	400	600
Solar	Solar Heating	.	.	800	800	1200
BER	Before & After Building Energy Rating	100	.	.	.	.
	Mandatory Before & After Building Energy Rating	.	100	80	50	50
Bonus	Bonus for 3rd measure	.	.	.	.	300
	Bonus for 4th measure	.	.	.	.	100

While the BEH scheme was introduced in March 2009, Building Energy Rating (BER) assessments did not become mandatory until June 2010. We possess a dataset of applications to the BEH scheme from the introduction of this mandatory BER assessment through July 2016. The Irish BER is an energy label pertaining to the the energy efficiency of a home. Homes are assigned to a 15-point alphanumeric scale ranging from A1 to G, with A1 being the most energy efficient. Grades are assigned based on the energy required for space heating, ventilation, water heating and lighting, less savings from energy generation technologies. For retrofits made under the BEH scheme, a pre-retrofit works is estimated as part of the final BER assessment. When assessing a property's post-works BER, the independent assessor will assess the property's building energy rating, which is registered for that property. The assessor then discounts the parameters of the characteristics relevant to the retrofit works to estimate the pre-works BER. Our dataset is comprised of all completed applications to the BEH scheme which included a BER assessment from the introduction of the scheme to August 2016.

Applications to the grant scheme are generally made privately, with a household first contacting an SEAI registered contractor, before applying for the grant. The contractor then installs the relevant retrofit measures, which is followed by a BER assessment and processing of the grant application. Some applications are made via ‘obligated parties’ and ‘counterparties’. Obligated parties are energy distributors and retail energy sales companies, while counterparties are parties authorised by SEAI to submit applications to the BEH scheme, undertake administrative tasks relating to grant processing and receive grant monies on a homeowners behalf. The Energy Efficiency Obligation Scheme, pursuant to the EU Energy Efficiency Directive, imposes a legal obligation on member states to reduce annual energy sales to final consumers by 1.5% by 31 December 2020 (European Parliament and the Council of the European Union, 2012). Obligated parties are required by the Irish State to reach certain energy targets, 20% of which must be achieved by reducing residential energy consumption.[2] We do not include in our analysis retrofits made via obligated parties and/or counterparties as we do not possess information on other incentives offered by these parties to home owners, which may include further up-front payments, reductions in energy bills, etc.

While we possess data on the choice of attic and wall insulation retrofits, we choose not to include these in our analysis. This is because of the direct non-monetary benefits associated with insulation retrofits, specifically improved warmth and comfort in the home following the installation of insulation. Heating system and solar heating upgrades, on the other hand, are predominantly energy saving measures and do not provide the same degree of noticeable non-monetary gains. As we are unable to accurately measure the extent of these benefits, which are likely to be significant drivers of retrofit choice, we focus instead on those measures whose benefits can be more accurately measured. We are therefore interested only in homes which did not pursue insulation retrofits, i.e. homes who undertook retrofits comprised of one or more of a boiler upgrade with heating controls, heating controls only and solar collector installation. For the purposes of this research, we refer to these measures as supply-management retrofits, as these measures affect the supply of energy required for space and/or water heating by improving the efficiency of supply and/or the source of supply. We refer to insulation retrofits, on the other hand, as demand-management retrofits, as these reduce the demand for energy required for space heating.

As all participating homes had the option to engage in a retrofit including one or more of these three supply-management retrofit measures, we identify those who engaged in demand-management retrofits as choosing not to engage in a supply-management retrofit. As pre- and post-works BER values are based on the property as a whole, the energy efficiency improvements cannot be separated based on the measures undertaken and, as a result, retrofits comprised of both a demand- and a supply-management retrofit measure are discarded. This leaves six possible options for each participant household within our truncated dataset that undertook a retrofit. These are the choice of not engaging in a supply-management retrofit, the choice of each of the three measures individually, or the choice of engaging in one of a boiler upgrade with heating controls or heating controls only, combined with a solar collector installation. As solar collectors were not introduced to the BEH scheme until May 2011, retrofits prior to this time are seen as having only three choices, i.e. no retrofit, boiler with heating controls or heating controls only. All retrofit measures, including those excluded, are detailed in table 2.

The Better Energy Homes dataset also provides information on the characteristics of each dwelling, including the floor area (in m^2), the type of dwelling, divided by types of houses (detached, semi-detached, end-of- or mid-terrace) and apartments (ground-, mid-, top-floor or maisonette) although these are pooled in the analysis due to distinctions between dwelling types for the purposes of the grant scheme (see fig. 1. The data contains unique dwelling identification numbers, which allows us to identify homes which have undertaken multiple retrofits as part of the BEH scheme. Details of the retrofits undertaken include the costs of each individual measure undertaken and the BER of a home before and after all retrofit works undertaken as part of an application to the scheme. Table 3 provides some descriptive statistics of the number of retrofits undertaken by households in our dataset. Table 3 also summaries the mean costs involved and mean energy

[2]The obligated parties are SSE Airtricity, Bord Gáis Energy, Bord na Móna, Calor Gas, Electric Ireland, Energia, Flogas, Gazprom, Lissan, Vayu, and Enprova/REIL. Retrofit Energy Ireland Limited (REIL) is an obligated party representing the Irish oil industry for which Enprova is a designated counterparty. For further information see http://www.seai.ie/eeos/

Table 2: Supply- and Demand-Management Retrofit Measures

Demand-Management Retrofits	Supply-Management Retrofits
Attic Insulation	*One of:*
	Oil Boiler with Heating Controls
One of:	Gas Boiler with Heating Controls
Cavity Wall Insulation	Heating Controls only
External Wall Insulation	
Internal Dry-Lining	Solar Collector

Table 3: Mean observed energy efficiency improvements and costs for household supply-management retrofits

	Number of Households	BER Improvement ($kWh/m^2/yr$)	Energy Use Improvement (kWh/yr)	Total Cost of Retrofit (€)	Total Cost per unit Energy Use Improvement (€$/kWh/yr$)	Household Cost of Retrofit (€)	Household Cost per unit Energy Use Improvement (€$/kWh/yr$)
No Supply-Management Retrofit	70,345	.	.	.	.	.	.
Boiler with Heating Controls	21,535	96.01	11,855.71	3,456.45	0.40	2,812.47	0.32
Heating Controls only	2,346	55.29	7,846.01	1,500.02	0.29	1,022.17	0.19
Solar Collector	3,800	34.14	4,928.54	5,897.46	1.84	5,054.51	1.57
Boiler w/ Heating Con., Solar	376	98.65	15,298.85	8,451.97	0.74	6,971.39	0.61
Heating Controls, Solar	397	56.28	9,619.34	7,065.87	1.07	5,735.20	0.88

efficiency improvement accrued by households. While the dataset is comprised of observations spread over slightly more than six years. This period was characterised by economic recovery in Ireland and inflation remained very low during this time. As such, we treat our data as a cross-section and choose not to account for inflation. Energy efficiency improvements are measured as both the improvement achieved in a home's overall Building Energy Rating and that same improvement, accounting for the total floor area of the home. The total cost of retrofitting represents the cost paid by the household before grant aid is awarded, while the household cost of retrofitting represents the net cost to the household after grant is awarded.

It is worth noting that our dataset represents only applicants to the Better Energy Homes scheme, which aims to provide aprox. 35% of the costs of retrofitting. Applicants to this scheme are home owners who are likely to come from more socio-economically advantaged cohorts of the population. This is because certain lower cohorts are served by other schemes, such as the *Better Energy Warmer Homes* scheme, which provides the full cost of retrofitting to home owners in receipt of certain benefits[3]. As all households in the dataset have engaged in some form of retrofit, their willingness-to-pay for energy efficiency improvements is likely greater than would be found in a nationally representative sample.

3.2. Average marginal willingness-to-pay estimation

We follow the example of Grösche and Vance (2009), who utilise a McFadden's random utility model framework (McFadden, 1984) to estimate the utility function of a household presented with discrete retrofit choices using revealed preference data. Home owners are presented with a choice of one of six retrofit options. These include the option not to retrofit, and each of the five alternative retrofit combinations outlined in section 3.1. Each household i is faced with a choice j of one of these options. The utility associated with each option, U_{ij}, is measured as a function of X_{ij}, which comprises household and alternative specific characteristics, and an option-specific constant, α_i:

$$U_{ij} = \alpha_j + \beta_{ij} X_{ij} + \varepsilon_{ij} \quad (1)$$

We specify the utility function with two main drivers of utility, being the cost of retrofit j for household i, C_{ij} and the energy efficiency improvement of that retrofit, I_{ij}. Estimation of the costs and benefits of each

[3]These are Fuel Allowance under the National Fuel Scheme, Family Income Supplement, One Parent Family Payment or Job Seekers Allowance for over six months if the recipient has children under 7 years of age

retrofit option for each household is discussed in section 3.3 and these vary based on the characteristics of the household, which are represented by the vector Z_i. When presented with each retrofit option, we model the probability that a household will choose each available alternative, based on the characteristics of each alternative that are relevant to the utility of the household, as defined in the following utility function:

$$U_{ij} = \alpha_j + (\beta_1 + \sum_{l=1}^{n} \beta_l Z_{il})\hat{C}_{ij} + (\beta_2 + \sum_{m=1}^{n} \beta_m Z_{im})\hat{I}_{ij} + \epsilon_{ij} \quad (2)$$

The average marginal willingness-to-pay, $M\bar{W}TP$ is represented by the marginal rate of substitution of energy efficiency improvements for money, i.e. the amount of money a household is willing to exchange for energy efficiency improvements. As shown below, this is calculated as the ratio of the marginal utility gained from improving the energy efficiency of the home to the marginal utility lost by a home as the cost of retrofitting rises:

$$M\bar{W}TP_i = MRS_{IC} = \frac{\delta C}{\delta I} = -\frac{\frac{\delta U}{\delta I}}{\frac{\delta U}{\delta C}} = -\frac{\beta_2 + \sum_{m=1}^{n} \beta_m Z_{im}}{\beta_1 + \sum_{l=1}^{n} \beta_l Z_{il}} \quad (3)$$

The average marginal willingness-to-pay is calculated for each household that completed a retrofit and multiplied by the observed energy efficiency improvement (measured in kWh/yr) of that retrofit to provide the overall willingness-to-pay of each household:

$$WTP_i = I_{ij} * M\bar{W}TP \quad (4)$$

This willingness-to-pay is compared to the observed total cost of retrofitting and the observed cost to the household to estimate free-riding in the scheme. We use three estimation approaches to modelling retrofit choice and thus willingness-to-pay. We first use an alternative-specific conditional logit specification to estimate the likelihood of each household choosing each alternative. This is the baseline equation specified by equation 2, including alternative-specific constants for each individual measure and fixed cost and energy efficiency improvement effects. Secondly, an error components logit captures the latent effects of the organisational burden of retrofitting, as is found by (Collins and Curtis, 2017) to have a significant impact on the decision to undertake retrofit works. This error component groups applications which resulted in a retrofit comprised of more than one measure, as these often require greater organisation in choosing contractors and arranging for more than one installation.

Thirdly, a mixed effects logistic regression adds random effects associated with the value placed on energy efficiency improvements and the expected cost at application level in order to account for taste heterogeneity among households. Application level random effects were chosen as opposed to household level effects as, even though some households engaged in more than one retrofit, each application was made from a different baseline level of energy efficiency of the home and, as such, tastes may have changed within households over time. Not all of the required data is available, however. The expected costs and expected energy efficiency improvements associated with each alternative must be estimated based on retrofits observed in the data. The estimation of these variables is discussed in detail in section 3.3.

3.3. Expected costs and energy efficiency improvements

To provide each household in our sample with a choice of either not to retrofit or one of five potential retrofit combinations, we estimate the expected cost and benefit of retrofitting from a household point of view. Taking all completed supply-management retrofits, we estimate the expected BER improvement and total cost of retrofitting, i.e. the gross cost before grant aid is awarded, as a function of the characteristics of the household, i, and retrofit option presented, j. The energy efficiency improvement gained by a home, ΔBER_i is modelled as a function of that home's pre-works energy rating, BER_i, the type of dwelling, D_i, and the retrofit measures presented, M_j. The expected energy use improvement, ΔE_i, is therefore calculated as the product of the home's BER improvement and floor area, measured in square metres, F_i. The BER improvement is thus presented as a function of X_i, which is a vector of independent variables:

$$E[\Delta E_{ij}] = \Delta BER_{ij} * F_i \quad (5)$$

$$\Delta BER_{ij} = \gamma_0 + \gamma_{ij} X_{ij} + \upsilon_{ij} \quad (6)$$

$$X_{ij} = X(BER, D, M) \quad (7)$$

The expected cost to the household is similarly estimated by first modelling the expected total cost of household, i, undertaking the retrofit option presented, j. This total cost, TC_{ij} is modelled as a function of that home's pre-works energy rating, BER_i, the type of dwelling, D_i, floor area, F_i and the retrofit measures presented, M_j. The total cost is thus presented as a function of Z_i, which is a vector of independent variables, as discussed. The expected cost to the household, HC_{ij} is then calculated as the net cost, after subtracting the level of grant aid appropriate to the retrofit option presented, G_j at the time of investment.

$$E[HC_{ij}] = TC_{ij} - G_j \quad (8)$$

$$TC_{ij} = \theta_0 + \theta_{ji} Z_{ij} + \omega_{ij} \quad (9)$$

$$Z_{ij} = Z(BER, D, F, M) \quad (10)$$

These outcomes are estimated using OLS regressions, the results of which are discussed in section 4.1. We consider OLS suitable to provide unbiased estimates for this analysis due to the large sample size, use of continuous, real dependent variables, a small number of non-correlated independent variables.

3.4. Free-riders

We use three categories to define the level of free-riding that an application may or may not possess. These are based on a comparison of the total cost of the completed retrofit, the cost to the household of the retrofit following the award of grant aid, and the total willingness-to-pay of each household for that retrofit. This is calculated as the product of the average marginal willingness-to-pay associated with the application and the observed total yearly energy efficiency improvement gained as a result of engaging in the chosen retrofit. Free-riders are those applications for which a household was willing to pay more than the total cost of the retrofit, i.e. they would have completed the relevant works even in the absence of grant aid. 'Partial free-riders' are those applications for which a household was willing to pay more than the final cost, after grant aid, but less than the total cost. In this case the retrofits would not have been completed without grant aid but would have been completed with a lower level of aid than was received. 'Dependants' are those whose willingness-to-pay was equal to, or less than the cost to the household and thus would not have completed the retrofit without the full amount of grant aid.

4. Results and Discussion

4.1. Expected costs and energy efficiency improvements of each retrofit option

Table 4 presents the results of the OLS regression used to estimate the expected costs and improvements of each retrofit option. Table 5 then provides a comparison of the observed costs to the household and energy efficiency improvements and the fitted, or expected costs and improvements for those who did undertake a retrofit. Looking first at energy efficiency improvements, the fitted expected energy efficiency improvements possess similar mean values to those of the observed improvements, albeit with slightly lower standard deviations, implying greater clustering around the mean. These lower standard deviations are likely due to the distributions having shorter tails, as the observed distributions possess some extreme values on the positive side, which are not predicted by the OLS model. Overall, the fitted expected improvements appear to fit the data quite well. Looking at expected costs, the fitted values possess very similar mean values for all retrofit combinations, although the standard deviations of the fitted distributions are much smaller.

Table 4: Estimated effects of household and retrofit characteristics on expected benefits and costs of retrofitting

	(1) BER Improvement	(2) Total Cost of Retrofit
Pre-Works BER	0.369***	3.006***
	(0.00323)	(0.177)
Floor Area		2.722***
		(0.253)
Archetype (ref = Detached House)		
Semi-Detached/End-of-Terrace House	-21.78***	-588.9***
	(1.381)	(111.6)
Mid-Terrace House/Apartment	-28.98***	-321.1**
	(1.905)	(134.2)
*Pre-Works BER*Archetype (ref = Detached House)*		
Semi-Detached/End-of-Terrace House	0.0807***	0.247
	(0.00459)	(0.242)
Mid-Terrace House/Apartment	0.118***	-0.391
	(0.00602)	(0.309)
*Floor Area*Archetype (ref = Detached House)*		
Semi-Detached/End-of-Terrace House		3.795***
		(0.494)
Mid-Terrace House/Apartment		2.862***
		(0.671)
Retrofit Combination (ref = Boilerw/ Heat. Con.)		
Heating Controls only	-20.12***	-1,897***
	(0.711)	(35.05)
Solar Collector	-42.27***	2,455***
	(0.590)	(29.09)
Boiler w/ Heat. Con., Solar	20.25***	4,964***
	(1.680)	(82.84)
Heating Controls, Solar	-15.52***	3,587***
	(1.641)	(80.97)
Constant	-17.19***	2,261***
	(0.951)	(79.10)
Observations	28,454	28,454
R-squared	0.661	0.394

Standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1)

Table 5: Comparison of observed and fitted costs and energy efficiency improvements

	Mean Energy Efficiency Improvement (kWh/yr)		Mean Cost to Household (€)	
	Observed	Fitted	Observed	Fitted
Boiler with Heating Controls	11,855.71	11,971.22	2,812.47	2,813.15
	(6,744.27)	(4,991.07)	(1,499.34)	(311.46)
Heating Controls only	7,846.01	8,154.98	1,022.17	1,004.63
	(5,689.67)	(4,010.48)	(1,319.59)	(295.20)
Solar Collector	4,928.54	5,138.65	5,054.51	5,049.37
	(4,303.99)	(3,777.87)	(1,955.44)	(288.68)
Boiler w/ Heating Con., Solar	15,298.85	15,962.14	6,971.39	6,983.67
	(7,674.45)	(5,396.05)	(2,545.45)	(339.49)
Heating Controls, Solar	9,619.34	9,967.97	5,735.20	5,789.05
	(5,362.57)	(4,369.51)	(3,565.55)	(307.03)

Standard deviation in parentheses

4.2. Household willingness-to-pay

Results of the conditional, error components and mixed effects logit models, excluding alternative-specific constants and random effects parameters, are presented in table 6, with full results included in Appendix A. Model 3 details the baseline conditional logit specification. In model 4, the error components model, a constant specific to multiple measure retrofits is specified as a normally distributed random error allowing for taste heterogeneity with regard to search and organisational costs for home owners. There is no logically predefined sign for this coefficient as some owners may place extra value on improved status effects or environmental conscience, while others may lose utility from the additional administrative burden. As the specification used includes this normally distributed error component and normally distributed residual, the model reduces to a multinomial probit (McFadden and Train, 2000).

Model 6 then details the mixed effects logit specification, with normally distributed random effects parameters provided in Appendix A. The signs of the estimated coefficients are the same in all three models and the magnitudes of the estimated coefficients are broadly similar. Importantly, all of the estimated fixed effects are found to be statistically significant across all models, with costs and improvements both possessing the expected effects on choice. Cost coefficients are broadly negative, reducing choice probabilities, while energy efficiency improvement coefficients are broadly positive, increasing the likelihood of retrofit choice. As these coefficents are broadly similar, we follow Revelt and Train (1999) in calculating willingness-to-pay using fixed effects coefficients, in this case, those estimated by the conditional logit specification.

An interesting variation in tastes is found across household characteristics. While higher costs reduce the likelihood of a retrofit option being chosen, households which have previously undertaken a retrofit are much more likely to choose a costlier retrofit than homes pursuing an energy efficiency retrofit for the first time. This perhaps indicates that those who are more aware of the benefits of retrofitting see the reward of energy savings and comfort improvements as worth additional costs, or could suggest that homes retrofitting for the first time underestimate the improvement in quality of life that can be achieved. The negative affect of cost on retrofit choice is much stronger in less energy efficient homes, relative to more energy efficient homes. Homes with a larger floor area are more likely to choose a more expensive retrofit than smaller homes. Perhaps this is due to the socio-economic status of those who live in larger homes, with wealthier families more likely to live in a larger home and are thus less likely to see costs as an inhibiting factor with regard to retrofitting. We do not, however possess any information on the socio-economic status of participants to the BEH scheme. In terms of the expected energy efficiency improvement, greater expected

Table 6: Effects of costs, benefits and household characteristics on the likelihood of retrofit choice

$x10^{-2}$		(3) Conditional Logit	(4) Error Components Logit	(5) Mixed Effects Logit
Expected	Cost	-0.825***	-0.774***	-0.791***
		(0.0666)	(0.0626)	(0.0636)
Interaction with Expected Cost:				
	Pre-Works BER	-0.000794***	-0.000807***	-0.0008065***
		(6.00e-05)	(5.88e-05)	(5.99e-05)
	Floor Area	0.00161***	0.00147***	0.00145***
		(7.74e-05)	(7.64e-05)	(7.88e-05)
	Previous Retrofit	0.0922***	0.0554***	0.0541***
		(0.0146)	(0.0141)	(0.0146)
Expected Improvement		0.111***	0.106***	0.1072***
		(0.0103)	(0.00968)	(0.0098)
Interactions with Expected Improvement				
	Pre-Works BER	0.000133***	0.000132***	0.000132***
		(1.43e-05)	(1.36e-05)	(1.4e-05)
	Floor Area	-0.000379***	-0.000378***	-0.000376***
		(2.47e-05)	(2.39e-05)	(2.44e-05)
	Previous Retrofit	0.0843***	0.0664***	0.0664***
		(0.00483)	(0.00452)	(0.00462)

Standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1)
Full results, including alternative specific constants and random effects parameters are presented in appendix Appendix A

improvements increase the likelihood of a retrofit option being chosen. This effect increases in less energy efficient homes but reduces in homes with a larger floor area. Significant differences are also found among homes who have previously engaged in a retrofit relative to first-time retrofits.

Taste heterogeneity is found to be close to zero for both expected costs and expected energy efficiency improvements. As the estimated coefficients of the mixed effects and error components logit are broadly similar, possessing the same signs and magnitudes as the alternative-specific conditional logit, willingness- to-pay calculations are based on the conditional logit specification. Table 7 details the calculated average marginal willingness-to-pay and delta-method standard error of the sample as a whole and of various sub-groups. An average marginal willingness-to-pay (MWTP) of €$0.127/kWh/yr$ is found across all homes in our dataset who participated in a supply-management retrofit. All MWTP figures are found to be statistically different to zero at the 99% level using delta-method standard errors. Looking first at whether a household had previously engaged in a retrofit, those who had are found to be willing to pay an average of over twice as much for each additional kilowatt hour energy saving each year than a household engaging in a retrofit for the first time. This is consistent with the estimated cost coefficients described above. This indicates that home owners extract a much larger surplus than they expect, as evidenced by this much larger willingness-to-pay for future retrofits. This may in turn indicate that quite a large degree of information asymmetry exists with regard to the benefits of retrofitting for those retrofitting for the first time and that closing this information gap may lead to more and deeper retrofits.

Looking at the energy efficiency of a home prior to retrofit works, the calculated MWTP rises moving from more efficient properties to less efficient properties. This MWTP figure falls from €0.136 to €0.125 when moving from a C-rated home to a G. This is quite an intuitive result, as less energy efficient homes are more likely to be in need of retrofitting works and possess greater potential for improvements in quality of life. The differences here are quite small, however, with C- and G-rated categories found to be the only categories which possess statistically significant differences to each other. Larger homes are also found to possess a smaller MWTP than larger homes.

4.3. Free-riders

As discussed in section 3.4, we use three categories to define the level of free-riding an application may or may not possess. These are 'Free-riders', 'Partial free-riders' and 'Dependants'. For applications where the willingness-to-pay was found to be lower than the amount paid, we consider this excess amount paid to

Table 7: Average marginal willingness-to-pay by sub-group

	Households	Mean	Std. Error
All	26,706	0.127***	(0.008)
No Previous Retrofit	24,438	0.116***	(0.007)
Previous Retrofit	2,268	0.249***	(0.019)
Pre-Works BER:			
C	6,300	0.125***	(0.01)
D	10,081	0.126***	(0.008)
E	5,934	0.128***	(0.007)
F	2,774	0.132***	(0.006)
G	1,617	0.136***	(0.005)
Floor Area:			
0 - 50	317	0.146***	(0.007)
51 - 100	6,996	0.138***	(0.007)
101 -150	11,125	0.13***	(0.008)
151 - 200	5,298	0.122***	(0.008)
200 +	2,970	0.099***	(0.009)

represent how much the household was willing to pay for hidden benefits such as comfort gains, improved environmental conscience, status effects, etc., which we discuss below. The number of households in each of these categories is detailed by retrofit combination in table 8.

Of all completed retrofits, without considering hidden benefits, 82% of households are found to be dependent on grant aid, with a further 9% partially dependent on grant aid, leaving a free-riding rate of 9%. This is quite a low level of free-riding relative to other studies discussed in section 2, which saw levels of free-riding from upwards of 40% (Nauleau, 2014) to as much as 96% (Grösche and Vance, 2009). This varies across retrofit combinations. Boiler with heating controls retrofits, by far the most common retrofit in our sample, possess very similar figures to the sample as a whole. A much higher level of free-riding is found for heating controls only upgrades, with 37% of retrofits being classed as free-riders and a further 26% classed as partial free-riders. This is a much less expensive retrofit option than the others and led to a relatively large energy efficiency improvement. If no grant aid were awarded for this option, heating controls only upgrades would have had the lowest cost per unit energy efficiency improvement relative to all other options after grant aid. Given the high level of free-riding, it may be worth considering a reduction in the level of grant aid for this retrofit, as a large proportion of retrofits would still have occurred. Solar collectors, on the other hand, possess very low levels of free-riding, as 98% of retrofits were found to be either wholly or partially dependent on grant aid. This is likely due to costs, as solar collectors were by far the most expensive of the one-measure retrofits under consideration, with an average cost of €5,054.

In addition to energy savings, households who engage in retrofits receive other, non-measurable benefits. These can include increased comfort due to more responsive heating systems, improved environmental conscience, status effects from being known to have made such an investment, health benefits from living in a warmer home, improved sale value of the home, etc. For this reason we attempt to account for these non-measurable benefits by incrementally increasing the willingness-to-pay of all homes as a proportion of measured willingness-to-pay. It is difficult, however, to identify a most appropriate level of non-measurable benefits as this can change from household to household and from retrofit to retrofit. For example, a boiler and heating controls upgrade may provide a greater comfort gain than a solar upgrade, while a solar upgrade may provide a greater status effect as it is observable to others. Retrofitting also includes non-measurable costs, such as search costs for households for information on retrofitting, finding the right contractor, etc, along with the organisational burden and disruption involved with works being undertaken. We believe the non-measurable benefits, however, to be greater and, as such, non-measurable benefits can be considered as

Table 8: Distribution of free-riders by retrofit combination

		Number of Households	Proportion
All Retrofits	Dependents	22,671	0.85
	Partial Free-Riders	2,102	0.08
	Free Riders	1,933	0.07
		26,706	
Boiler w/ Heating Controls	Dependents	17,892	0.87
	Partial Free-Riders	1,493	0.07
	Free Riders	1,196	0.06
		20,581	
Heating Controls only	Dependents	848	0.40
	Partial Free-Riders	579	0.27
	Free Riders	699	0.33
		2,126	
Solar	Dependents	3,250	0.98
	Partial Free-Riders	22	0.01
	Free Riders	34	0.01
		3,306	
Boiler w/ Heating Controls, Solar	Dependents	339	0.98
	Partial Free-Riders	3	0.01
	Free Riders	3	0.01
		345	
Heating Controls, Solar	Dependents	342	0.98
	Partial Free-Riders	5	0.01
	Free Riders	1	0.00
		348	

the net non-measurable benefits in this context.

Table 9 details the change in the level of free-riding for varying levels of non-measurable benefits. Increasing the willingness-to-pay for retrofit works leads to incremental increases in the share of both whole and partial free-riders, reducing the number of homes which are seen as dependent on grant aid. For example, non-measurable benefits to the value of 50% of a home's willingness-to-pay leads to a fall in the share of dependants to 70% and an increase in the share of free-riders to 18%. These deviate further to 55% and 34% for dependants and free-riders, respectively, when non-measurable costs are raised to 100%. Using a 100% level of hidden costs raises the share of free-riders to levels closer to those found in similar studies, although estimates remain lower than those discussed in section 2.

Following the earlier discussion of households who had engaged in a previous retrofit, 40% of those who had previously engaged in a retrofit were found to be free-riders, with a further 12% found to be partial free-riders. Adding non-measurable benefits to the value of 50% of a households willingness-to-pay leads to a free-riding rate of 59.8%, with a further 9.7% classed as partial free-riders. This indicates that the majority of those in possession of higher levels of information about retrofits and their benefits would proceed with retrofitting works in the absence of grant aid or with lower levels of grant aid than were received. Grant aid can therefore be seen as a reasonably effective means of bridging the information gap and inducing retrofits when households undervalue the benefits of engaging in such energy efficiency retrofits. Given this finding, a more appropriate means of inducing energy efficiency retrofits could be to provide more information on the benefits, monetary or otherwise, to households considering an energy efficiency investment.

Table 9: Level of free-ridership by retrofit combination at varying levels of non-measurable benefits

	Non-Measurable Benefits:	10% Households	20% Households	50% Households	100% Households
All Retrofits	Dependents	21,949	21,138	18,595	14,615
		(0.82)	(0.79)	(0.7)	(0.55)
	Partial Free-Riders	2,362	2,605	3,242	3,768
		(0.09)	(0.1)	(0.12)	(0.14)
	Free Riders	2,395	2,963	4,869	8,323
		(0.09)	(0.11)	(0.18)	(0.31)
Boiler w/ Heating Controls	Dependents	17,241	16,505	14,146	10,408
		(0.84)	(0.8)	(0.69)	(0.51)
	Partial Free-Riders	1,770	2,029	2,738	3,384
		(0.09)	(0.1)	(0.13)	(0.16)
	Free Riders	1,570	2,047	3,697	6,789
		(0.08)	(0.1)	(0.18)	(0.33)
Heating Controls only	Dependents	783	724	587	428
		(0.37)	(0.34)	(0.28)	(0.2)
	Partial Free-Riders	560	533	445	308
		(0.26)	(0.25)	(0.21)	(0.14)
	Free Riders	783	869	1,094	1,390
		(0.37)	(0.41)	(0.51)	(0.65)
Solar	Dependents	3,245	3,234	3,203	3,150
		(0.98)	(0.98)	(0.97)	(0.95)
	Partial Free-Riders	23	29	37	44
		(0.01)	(0.01)	(0.01)	(0.01)
	Free Riders	38	43	66	112
		(0.01)	(0.01)	(0.02)	(0.03)
Boiler w/ Heating Controls, Solar	Dependents	338	335	323	306
		(0.98)	(0.97)	(0.94)	(0.89)
	Partial Free-Riders	4	7	14	18
		(0.01)	(0.02)	(0.04)	(0.05)
	Free Riders	3	3	8	21
		(0.01)	(0.01)	(0.02)	(0.06)
Heating Controls Solar	Dependents	342	340	336	323
		(0.98)	(0.98)	(0.97)	(0.93)
	Partial Free-Riders	5	7	8	14
		(0.01)	(0.02)	(0.02)	(0.04)
	Free Riders	1	1	4	11
		(0)	(0)	(0.01)	(0.03)

Proportion of retrofits in parenthesis

5. Conclusion

The Better Energy Homes scheme was introduced in Ireland to help meet Ireland's obligated reduction in energy consumption by improving the energy efficiency of the residential building stock. Designing the scheme in a more efficient manner could lead to an increase in the total number of residential energy efficiency retrofits and make more money available for other projects and schemes for the grant provider to reduce energy use in Ireland. We examine, using revealed preference data on retrofits completed under the scheme, how much Irish households are willing to pay for energy efficiency improvements. The results of this analysis are then used to estimate the proportion of completed retrofits that could be classed as free-riders, i.e. that would have occurred in the absence of grant aid.

We find larger homes are less willing to pay for energy efficiency smaller homes. Households who had previously completed a retrofit were found to be willing to pay over twice as much as homes retrofitting for the first time. Without accounting for hidden benefits, we estimate that 9% of retrofits would have occurred without grant aid, which is quite a low rate in an international context, with studies discussed in section 2 finding rates of free-riding ranging from 40% to 96%, although large variation exists across retrofit combinations. Solar collectors were found to have a free-riding rate of only 1%, while heating controls retrofits were found to have a free-riding rate of 33%. These rates increase incrementally as hidden benefits are included in the estimations.

The findings of this research complement the literature on willingness-to-pay for energy efficiency upgrades, providing analysis using revealed preference data. In the Irish context, this adds to the literature, providing evidence of an aspect of energy efficiency retrofitting which has not been previously explored. The policy implications of this research are quite clear. As such a high level of free-riding is found to exist in heating controls retrofits, it may be prudent to consider reducing the level of grant aid awarded for this measure. This may allow for greater funding for other measures, the inclusion of further measures, additional retrofits under other grant aid schemes, etc. The most notable implication, however, stems as a result of the willingness-to-pay analysis, where a much greater willingness-to-pay figure was estimated for those households who have previously undertaken an energy efficiency retrofit. This implies that those who have a greater understanding of the benefits of retrofitting are willing to pay more, in turn providing evidence that those retrofitting for the first time do not possess full information on the benefits of engaging in retrofit works. It may be worth considering offering lower levels of grant aid to second- or third-time retrofits, or an overall reduction in grant aid, supplemented by a bonus for first-time retrofits. It should be considered imperative to examine improvements in the information available to households contemplating an investment in an energy efficiency upgrade. This could come in many forms, such as the provision of technical advisory reports to homes considering engaging in a retrofit, which would provide a trustworthy source of information. Alternatively, this could also come in the form of marketing materials focussed on explaining the benefits or the provision of estimates of energy cost savings associated with certain retrofits for certain home types, among other forms of information.

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Appendix A. Full results of logistic regression models

Table A.10: Full logistic regression results

		(3)	(4)	(5)
		Conditional Logit	Error Components Logit	Mixed Effects Logit
Expected Cost		-0.825***	-0.774***	-0.791***
		(0.0666)	(0.0626)	(0.0636)
Interaction with Expected Cost:				
	Pre-Works BER	-0.000794***	-0.000807***	-0.0008065***
		(6.00e-05)	(5.88e-05)	(5.99e-05)
	Floor Area	0.00161***	0.00147***	0.00145***
		(7.74e-05)	(7.64e-05)	(7.88e-05)
	Previous Retrofit	0.0922***	0.0554***	0.0541***
		(0.0146)	(0.0141)	(0.0146)
Expected Improvement		0.111***	0.106***	0.1072***
		(0.0103)	(0.00968)	(0.0098)
Interactions with Expected Improvement				
	Pre-Works BER	0.000133***	0.000132***	0.000132***
		(1.43e-05)	(1.36e-05)	(1.4e-05)
	Floor Area	-0.000379***	-0.000378***	-0.000376***
		(2.47e-05)	(2.39e-05)	(2.44e-05)
	Previous Retrofit	0.0843***	0.0664***	0.0664***
		(0.00483)	(0.00452)	(0.00462)
Retrofit Option (ref=No Supply-management Retrofit)				
Boiler w/ Heat. Con.		0.0517	-0.0504	-0.0215
		(0.131)	(0.122)	(0.1237)
Heating Controls Only		-3.466***	-3.775***	-3.765***
		(0.0543)	(0.0515)	(0.052)
Solar Collector		1.034***	0.617***	0.669**
		(0.258)	(0.239)	(0.2423)
Boiler w/ Heat. Con, Solar		-0.530	-1.025***	-0.952**
		(0.346)	(0.321)	(0.3255)
Heating Controls, Solar		-1.031***	-1.507***	-1.448***
		(0.290)	(0.270)	(0.2733)
Mean Random Effects				
	Chose difficult retrofit		0	
			(0)	
	Expected Cost			0.000058
				(0.0138)
	Expected Improvement			-0.000017
				(0.00126)

Standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1)

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