Evidence from a national grant aid scheme for residential energy efficiency retrofits: application abandonment, retrofit depth and free-riding

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Keywords
retrofit, grants, abandonment

Abstract
In order to facilitate energy efficiency, retrofit works in the home, the Sustainable Energy Authority of Ireland administers the Better Energy Homes scheme as a means of contributing to a 20 % reduction in Ireland's energy use by 2020. At present, grant aid is available for up to four energy efficiency retrofit measures. This paper brings together findings on various aspects of the grant aid scheme, these being the abandonment of applications to the scheme, retrofit depth within the scheme and the extent to which free-riding has occurred in the scheme. We find that applications made through obligated energy suppliers, who are required to achieve reductions in residential energy consumption, are less likely to abandon an application but are more likely to be made for shallower retrofits. We find that applications for more complex retrofits and those made during winter months are more likely to be abandoned. The introduction of bonus payments for three- and four-measure retrofits did not have the desired effect in inducing these deeper retrofits, while free-riding in the scheme is found to be quite low for most measures examined.

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 EU, 2012). This paper brings together findings on various aspects of the grant aid scheme, these being the abandonment of applications to the scheme[1], retrofit depth within the scheme[2] and the extent to which free-riding has occurred in the scheme[3].

The Better Energy Homes scheme
The Better Energy Homes (BEH) scheme, originally known as the Home Energy Savings scheme, was developed by the Sustainable Energy Authority of Ireland (SEAI) and began in March 2009. It is a grant aid scheme for households to engage in energy efficiency improvements, with grants available for various measures. Grants aim to provide approx. 35 % of the costs of retrofitting. Grants are available for roof/attic insulation, wall insulation, heating system upgrades and solar thermal installation. This means that a household may adopt up to four measures as only one type of wall insulation (cavity, ex-

1. Findings on the abandonment of applications are taken from Collins, M. and Curtis, J. (2017) An examination of the abandonment of applications for energy efficiency retrofit grants in Ireland. *Energy Policy*, 100, 260–270.
2. Findings on retrofit depth are taken from Collins, M. and Curtis, J. (2016) An examination of energy efficiency retrofit depth in Ireland. *Energy and Buildings*, 127, 170–182.
3. Findings on free-riding are taken from Collins, M. and Curtis, J. (2016) Willingness-to-pay and free-riding in a national energy efficiency retrofit grant scheme: A revealed preference approach. *ESRI Working Paper* 551.

Table 1. Structure of the Better Energy Homes grant scheme over time.

Type	Sub-Category	Scheme: 1	2	3	4	5
		Mar-09	Jun-10	May-11	Dec-11	Mar-15
Roof	Roof Insulation	250	250	200	200	300
Wall	Cavity Wall Insulation	400	400	320	250	300
	Internal Dry-Lining	2,500	2,500	2,000	.	.
	Apartment or Mid-terrace House	.	.	.	900	1,200
	Semi-detached of End-of-terrace House	.	.	.	1,350	1,800
	Detached House	.	.	.	1,800	2,400
	External Wall Insulation	4,000	4,000	4,000	.	.
	Apartment or Mid-terrace House	.	.	.	1,800	2,250
	Semi-detached of End-of-terrace House	.	.	.	2,700	3,400
	Detached House	.	.	.	3,600	4,500
Heat Sys.	High Efficiency Boiler (oil or gas) with Heating Controls	700	700	560	560	700
	Heating Controls Upgrade only	500	500	400	400	600
Solar	Solar Heating	.	.	800	800	1,200
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

ternal or internal) or heating system upgrade (oil or gas boiler with heating controls or heating controls only) may be awarded aid. Grant aid can be awarded for each of these measures only once in a property's lifetime. The structure of the grant scheme has been altered over time, with changes to the absolute level of aid, the introduction of solar and the introduction of bonus payments for deeper retrofits. We refer to the periods in between these changes as scheme 1, scheme 2, etc., with details of these alterations provided in Table 1.

The majority of applications are made privately, with a household first contacting a SEAI registered contractor and applying for the grant. If grant aid is approved, the contractor then installs the relevant measures, which is followed by a Building Energy Rating (BER) assessment and processing of the grant application. Other applications are made via 'obligated parties' and 'counterparties'. Obligated parties are energy distributors and retail energy sales companies. 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 EU, 2012). The State requires obligated parties to reach certain energy targets, 20 % of which must be achieved by reducing residential energy consumption (SEAI, 2014)[4]. There are 11 parties, of which six have engaged customers via the BEH scheme. Within our dataset, obligated parties possess unique, anonymous identifiers. Counterparties facilitate grant applications, interacting with the relevant obligated party, home owner, contractor and SEAI. These counterparties are generally related to obligated parties and are set up as a means of incorporating the grant application process into their own service offerings.

In the context of the BEH scheme, the relationship between these obligated parties and others involved in the grant process is described in Figure 1. As shown on the right of the figure, obligated parties make initial contact with households offering retrofit works. If a household is interested in retrofitting, the obligated party will then engage a counterparty to contact the household with regard to installation. The counterparty will then assign a contractor to complete the works and process the grant application on behalf of the SEAI, who will then award the relevant grant aid, provided the required standards are satisfied. Private applications, which are more common, are illustrated on the left of Figure 1. Households engage contractors to undertake the works and apply for a BEH grant once the installation is complete the grant application is processed.

Data

We use an administrative dataset of all applications to the BEH scheme, including household specific identifiers. The dataset comprises all applications made to the Better Energy Homes scheme from its inception in March 2009 to October 2015, i.e. the population of retrofits made via the BEH scheme. Over 160,000 homes or approximately 12 % of qualifying household stock (i.e. built prior to 2006) have made an application for a BEH grant. While there may be potential sample selection biases inherent in the BEH dataset, particularly related to low income households, the data represents the full population of retrofits undertaken under the BEH scheme and the analysis provides practical information on the households that engage with the scheme.

The BEH dataset includes information on the characteristics of the dwellings for which applications for grant aid are made. In addition to the intended retrofit measures, all applications, regardless of completion, include the date of application, a home-owner estimate of the year of construction, county-level location, type of dwelling (detached house,

4. The obligated parties are SSE Airtricity, Bord Gáis Energy, Bord na Móna, Calor Gas, Electric Ireland, Energia, Flogas, Gazprom, Lissan Coal Company, Enprova/REIL and Vayu. For further information see http://www.seai.ie/eeos/.

ground-floor apartment, etc.), whether the dwelling is located on an island (in which case it is entitled to 150 % of grant aid), whether an application is made via an obligated party and, if so, which obligated party. Additional information is provided for completed retrofits, including the total cost of works, the amount of grant aid awarded and the date of completion of each retrofit work. Prior to scheme 2, BER assessments were not mandatory and had low take-up. Retrofits in the data which included a Building Energy Rating Assessment provide further information, including the floor area of the dwelling, the assessed BER after completion of works and estimated pre-works BER.

Abandonment of applications

METHOD

We identify all first-time applications from March 2009 to March 2015, inclusive. Additional data available to October 2015 were excluded as abandonment of applications from April 2015 onward could not be identified. We consider abandoned applications to be those that have been cancelled or allowed to expire by the household, without any subsequent applications from that household occurring in the data.

Like Aravena et al. (2016) and Wilson and Dowlatabadi (2007), we consider retrofit investments to be a multi-stage process. This investment process begins with the household decision to engage in a retrofit, which includes the timing of retrofit adoption and the evaluation of the type of retrofit required. In the Irish context, this is followed by the grant application stage, whereby households apply to SEAI for grant aid under the terms of the BEH scheme. If grant aid is approved, the next stage is the installation of the chosen retrofit measures. While we may not be able to identify specific barriers to completion at this stage of the investment process, we aim to investigate abandonment behaviour as a function of applicant and application characteristics. Once a grant application has received initial approval, the household decides to complete the intended retrofit works based on the following constraint:

$$E[B_i] - (E[C_i] - G_i) > 0, \quad (1)$$

whereby the expected benefits, B, to household i of engaging in the chosen retrofit must exceed the costs, C_i, after the amount of grant aid applicable to the chosen retrofit, G_i is awarded. In this case, the benefits are comprised of outcomes such as energy cost savings, increased comfort, improved health outcomes, environmental benefits, etc., while costs include the direct monetary costs of retrofitting, search costs in deciding whether or not to continue with the chosen retrofit, finding a contractor, disruption while retrofit works are being installed, costs of financing, etc. Also included are opportunity costs, which could include the benefits available from using household income for other priorities. In the case that benefits to the household are equal to or less than the costs, and provided the benefits will not exceed costs if engaging in retrofit works at any point in the future, the retrofit will be abandoned. It follows that the probability of abandonment is expressed as follows:

$$P(Abandonment_i = 1) = P(E[B_i] - (E[C_i] - G_i) \leq 0)$$

$$= f(Z_i, M_i, R_i, C_i, O_i), \quad (2)$$

where Z_i is a vector of household characteristics. This includes technical characteristics such as the age of a dwelling, and the preferences of the household, which vary by household depending on opportunity costs, behavioural biases such as non-standard beliefs and preferences (Dellavigna, 2007) and the disruptive impact of retrofit installation. M_i represents the characteristics of the retrofit, including the types of measure and retrofit intensity for which grant aid was applied. We control for the most commonly applied for combinations of measures and group others based on the number of measures

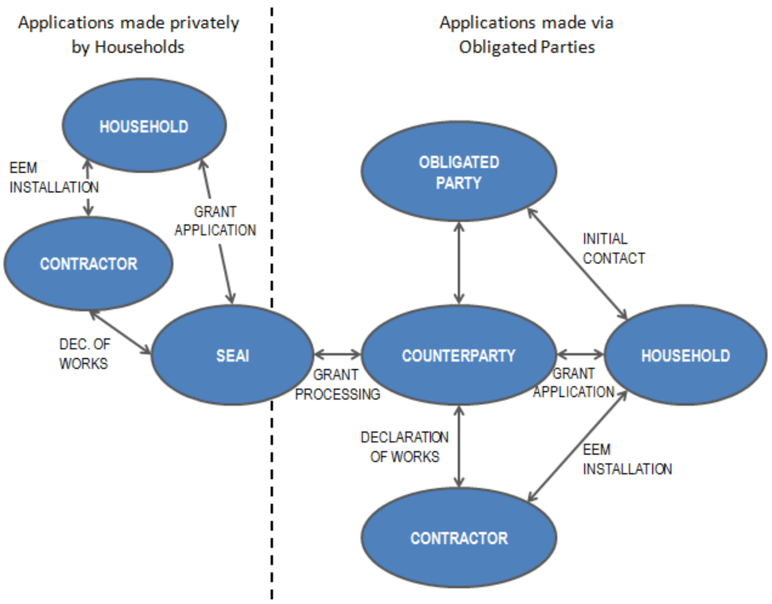

Figure 1. Obligated parties and their relationships.

included. R_i represents the regulatory conditions, such as the amount and structure of grant aid available and minimum retrofit standards required for grant application success. O_i is a vector of characteristics of the obligated party involved, where applicable. As the choice between whether to fully abandon an application or not is a binary choice, we utilise a standard logistic regression, modelling the probability of abandonment as follows:

$$P(Abandonment_i = 1) = \frac{e^{(\Sigma \beta_i X_i)}}{1 + e^{(\Sigma \beta_i X_i)}}, \qquad (3)$$

where X_i is a vector comprising factors affecting the application abandonment decision, such as Z_i, M_i, R_i, C_i and O_i. For the purpose of interpretation, estimated results are presented as odds ratios. Odds ratios represent the constant effect a predictor variable has on the likelihood of, in this case, a household choosing to abandon an application for grant aid. These are calculated as the ratio of the odds that an event will occur when a predictor variable takes a value one unit greater than its standard value, relative to the odds of that event occurring when that variable takes its standard value. The odds ratio of the n[th] coefficient is calculated as e^{β_n} with standard error $e^{\beta_n} \cdot s_n$, where s_n is the standard error of the estimated coefficient β_n (Cameron and Trivedi, 2005).

RESULTS AND DISCUSSION

The results of this research can be briefly summarised as follows:

- Applications comprising just one measure of either heating controls, attic, cavity or solid wall insulation and a combination of attic and cavity wall insulation were found to be the least likely to be abandoned.
- Applications for retrofits of three or four measures were all found to be more than three times more likely to be abandoned than an application for attic and cavity wall insulation. The organisational burden of these retrofits is likely much greater, in addition to greater disruption and monetary costs.
- Applications made via obligated parties are less likely to be abandoned than those made privately.
- Obligated parties possess a learning phase of six months, whereby a party's rate of abandonment falls steadily before stabilising at a rate almost half that of private applications. This adds to the idea that organisational burden is a cause of abandonment, as obligated parties generally organise for contractors to perform the works and handle administration work.

Table 2 presents the odds ratios of the estimated logit model. The reduced likelihood of abandonment when moving from 1- to 2-measure retrofits is likely due to the very low probability of abandonment of retrofits comprised of attic and cavity wall insulation, which made up 50 % of all applications. Only retrofits of attic insulation only, cavity insulation only and heating controls only were found to be less likely to be abandoned than attic and cavity insulation retrofits. Relative to attic and cavity retrofits, solid wall only or boiler with heating controls only retrofits were the next least likely to abandon, respectively, followed by solar and then attic and solid wall retrofits. Attic, cavity, boiler with heating controls and solar combined were found to be the most likely to be abandoned, while attic, solid wall, boiler with heating controls and solar combined were found to be less likely to be abandoned than both attic, wall and boiler with heating controls combinations. Again, this is likely due to the increased levels of disruption, organisational burden and capital costs to the household involved in engaging in more complex retrofits.

The extent to which applications made via obligated parties during their first six months are more likely to be abandoned than private applications falls slightly. There is no statistically significant evidence of variation in the likelihood of abandonment found for learning phases of 8 months or greater. We can therefore assume a learning phase of six months is the correct specification. We also find that applications for apartments are more likely to be abandoned than applications for houses and that a seasonal pattern exists with winter applications found to be more likely to be abandoned.

While we acknowledge the limitations of this research due to the lack of socio-demographic characteristics and lack of information of retrofits undertaken outside of the grant scheme, various policy implications may be taken from the findings of this research. Reducing abandonment rates is an important policy aim given the need to increase the energy efficiency of the housing stock. As applications made via obligated parties are less likely to be abandoned, lessons may be learned from this type of contracting relationship. Perhaps an independent third party could be formed to facilitate applications made privately. This third party could act as a intermediary for home owners, contractors and SEAI. This may be particularly useful for 3- and 4-measure retrofits, which are most likely to be abandoned. These often require more than one contractor to install the measures, which may be difficult to manage for a home owner. Administrators of the BEH scheme could also liaise with the owners of homes possessing higher abandonment risks to aid these applications. A third party may also be able to develop a network of contractors to perform works.

Retrofit depth

METHOD

We follow a similar approach to Gamtessa (2013) in defining the retrofit depth decision. In the context of the Better Energy Homes scheme, we consider a situation where household h may invest in up to four energy efficient measures to retrofit the home. These measures are available to households at a cost K_0, with benefits B_t accruing over time based on energy cost savings each year and increased comfort in the home. Weighing up the benefits and costs, the decision to adopt can be seen as dependent on a positive net present value (NPV) of adoption:

$$NPV = \sum_{t=0}^{n} (1 + r)^{-t} B_t - K_0 > 0, \qquad (4)$$

where r is the discount rate and n is the lifespan of the capital investment, i.e. the retrofit conducted. As households are unlikely to possess full information on the exact monetary and other benefits, a level of uncertainty is introduced. The benefits and costs of adoption also vary due to the number of agents involved. The benefits of adoption, B_{hmt} are a function of the characteristics of the household, Z_h, the obligated party, m, where applicable, and the time t at which an investment is made. The costs of adoption, K_{hj} are a function of the characteristics of the household, Z_h, the contractor, j, and the level of grant aid available to the household, R_h. Households therefore choose to make an investment when the expected net present value of investment is greater than zero:

$$E_0(NPV|Z_h) = E_0\sum_{t=0}^{n}(1+r)^{-t}[B_{hmt}|Z_h] - [K_{hj}|R_h] > 0 \qquad (5)$$

This profitability condition alone is not sufficient to define the retrofit intensity decision. Households will choose the number of measures which maximises the expected net present value of the retrofit investment, which may vary depending on opportunity costs, behavioural biases such as non-standard beliefs and preferences (Dellavigna, 2007) and non-monetary considerations such as the disruptive impact of installation. As we do not possess information on the characteristics of the decision makers of a household, such as income levels, environmental awareness, etc., we specify our model by assuming that the investment decision Y_i is a function of the vector of characteristics X_i. This vector which comprises factors similar to those entering the adoption decision such as, B_{hmt}, K_{hj} and r. We use all complete applications from our dataset, i.e. all applications where retrofit works were completed and grant aid awarded. Multiple applications from a household are treated as unique observations as, following the completion of one measure, the decision to make a further investment is affected by a different set of household characteristics to the previous investment decision.

We specify two models of estimation in order to exploit differences in how the data may be interpreted. Firstly, an ordered logistic regression is used to estimate the probability of a household choosing each available level of retrofit intensity. These models fail to take into account time-variance in certain characteristics, as it is possible that a household may choose not to invest ($Y_i = 0$) at a time t in order to generate a greater net present value at a later date. Karshenas and Stoneman (1993) provide a detailed review of modelling technology diffusion over time.

The number of measures adopted by a household is both categorical and ordered, in that more measures generally lead to greater improvements in energy efficiency. An ordered logit is used to measure the probability that the number of measures applied for, Y_i, is equal to a certain outcome. This is estimated as the probability that a linear function of the independent variables is within the range of the cutpoints estimated for the outcome:

$$P(Y_i = n) = P(k_{n-1} < \sum \beta_i X_i + u_i \leq k_n) \qquad (6)$$

Secondly, we examine the likelihood that an application will be made for a more comprehensive retrofit, i.e. any retrofit comprised of two or more measures, excluding attic and cavity insulation retrofits. We exclude attic and cavity retrofits from the more comprehensive category as this is by far the most common retrofit and is a relatively easy combination to implement. Viewing this as a binary choice between a less or a more comprehensive retrofit, a logistic regression is used to model the probability of an application being for a deeper retrofit. This probability is estimated as follows:

$$P(More\ Comprehensive) = Y_i = \frac{e^{(\sum \beta_i X_i)}}{1 + e^{(\sum \beta_i X_i)}} \qquad (7)$$

Where Y_i represents the probability of an application being made for a more comprehensive retrofit, X_i is a vector of characteristics and β_i is a vector of estimated coefficients.

Table 2. Effects on likelihood of abandonment.

	Odds ratio	s.e.
Measures (ref = attic + cavity)		
Boiler only	1.514***	(0.0276)
Solid Wall only	1.148***	(0.0329)
Solar only	1.680***	(0.0579)
Attic + Solid Wall	1.884***	(0.0496)
Attic + Cavity + Boiler	4.758***	(0.122)
Attic + Solid Wall + Boiler	4.216***	(0.126)
Attic + Cavity + Boiler + Solar	5.762***	(0.490)
Attic + Solid Wall + Boiler + Solar	3.380***	(0.252)
Other (1 measures)	0.875***	(0.0338)
Other (2 measures)	2.411***	(0.0588)
Other (3 measures)	5.253***	(0.155)
Other (4 measures)	3.710***	(0.455)
Scheme (ref = sch. 1)		
2	1.017	(0.0173)
3	1.097***	(0.0225)
4	1.340***	(0.0278)
5	1.482***	(0.131)
Year of Construction (ref = pre-1900)		
1901–1920	0.884**	(0.0390)
1921–1940	0.746***	(0.0275)
1941–1960	0.710***	(0.0238)
1961–1980	0.638***	(0.0197)
1981–2000	0.611***	(0.0189)
2001 -	0.753***	(0.0250)
Region (ref=Greater Dublin Area)		
County with City	0.848***	(0.0142)
South East (ex. GDA,L,C,W)	0.920***	(0.0172)
Border Midlands West (ex. G)	1.243***	(0.0216)
Apartment (ref =House)	1.318***	(0.0472)
Island (ref = Mainland)	1.115	(0.171)
GDP (z, continuous)	1.022*	(0.00896)
Obligated Party (ref=private application)		
New Obligated Party	0.868*	(0.0502)
Exp. Obligated Party	0.532***	(0.0179)
Season (ref=Spring)		
Summer	0.898***	(0.0167)
Autumn	0.951**	(0.0174)
Winter	1.212***	(0.0202)
Observations	229,246	

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

RESULTS AND DISCUSSION

The results of this research can be briefly summarised as follows:

- The introduction of bonus payments for three- and four-measure retrofits has not coincided with any increase in the number of measures undertaken or more comprehensive retrofits.
- We estimate a period of early adoption lasting for the first twelve months of the BEH scheme where deeper retrofits were most likely.
- Retrofits undertaken via obligated parties generally comprise fewer retrofit measures. Some obligated parties focus primarily on attic and cavity retrofits, while others focus on boiler with heating controls upgrades.

Results from both the ordered logit and standard logit are presented in table 3. Variation exists across obligated parties, relative to private installations. The estimation results show that, relative to private installations, certain obligated parties are either more or less successful in engaging households in multiple-measure retrofits. Obligated parties (OPs) 1, 2 and 3 are more likely to provide one-measure retrofits, while OPs 4, 5 and 6 are more likely to provide households with higher numbers of measures. OP4 possesses the greatest upward deviation in terms of the number of measures provided from private applications in terms of the number of measures provided. For every energy saving measure implemented by an obligated party, a credit is awarded toward this target. Some obligated parties may focus on providing retrofits that earn the most credits, whereas others may choose to focus on attic and cavity retrofits as these provide less disruption and may be easier to implement. The outcome is that some obligated parties may provide more multiple-measure retrofits and more retrofits in total although this may perhaps lead to lesser energy efficiency improvements. For example, attic and cavity insulation in a house provides a credit of 4,550 kWh, whereas the highest grade of boiler with heating controls upgrade provides a credit

Table 3. Effects on retrofit depth.

	No. Of Measures Ordered Logit		More Comp. Standard Logit	
	Coef.	s.e.	Coef.	s.e.
Scheme (ref = Sch. 1)				
2	0.0159	(0.0156)	0.134***	(0.0325)
3	-0.266***	(0.0186)	-0.00747	(0.0362)
4	-0.693***	(0.0165)	-0.0591	(0.0367)
5	-1.343***	(0.0408)	-0.435***	(0.0803)
Year of Build (ref = pre-1950)				
1951–1970	0.627***	(0.0206)	-0.714***	(0.0240)
1971–1980	0.901***	(0.0196)	-0.959***	(0.0237)
1981–1990	1.084***	(0.0209)	-1.223***	(0.0275)
1991–200	1.032***	(0.0194)	-1.316***	(0.0253)
2001–	1.148***	(0.0213)	-1.381***	(0.0298)
Region (ref = Greater Dublin Area)				
County w/ City	0.958***	(0.0186)	-0.378***	(0.0203)
Border Midlands West	0.983***	(0.0258)	-0.387***	(0.0231)
South & East (ex. GDA)	0.738***	(0.0288)	-0.180***	(0.0225)
Apartment (ref = House)	-0.666***	(0.0386)	0.406***	(0.0484)
County Income (z, continuous)	-0.304***	(0.0111)	0.120***	(0.0121)
Island (ref = Mainland)	-1.745***	(0.177)	-0.104	(0.240)
Season (ref = Spring)				
Summer	-0.158***	(0.0165)	0.0390	(0.0228)
Autumn	-0.115***	(0.0159)	-0.262***	(0.0244)
Winter	0.0587***	(0.0154)	-0.374***	(0.0238)
Obligated Party (ref = Private application)				
ID 1	-0.220***	(0.0574)	-1.575***	(0.173)
ID 2	-0.776***	(0.114)	-2.186***	(0.307)
ID 3	-0.0984***	(0.0249)	-0.485***	(0.0416)
ID 4	0.967***	(0.0550)	-1.380***	(0.145)
ID 5	0.850***	(0.129)	-1.158***	(0.310)
First 12 months (ref = Rest of scheme)			0.229***	(0.0326)
Observations	165,447		165,447	

Standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1) of 8,070 kWh. Strategically, obligated parties may be making a choice between quality and quantity. This focus on certain types of retrofit measures over others may indicate mismatches between the credits awarded and the cost to the obligated parties of performing these measures, as obligated parties often offer discounts on energy bills to households who undertake retrofit measures.

Scheme rule changes have had mixed impacts. Scheme 5 possesses the lowest level of retrofit intensity despite this scheme specifically including an incremental bonus for installing three or four measures. This suggests that the number of measures retrofitted is not responsive to changes in financial incentives. It is possible that the behaviour of early adopters to the scheme was influenced more so by the level of grant aid available and, as these early adopters have left the scheme. The model regarding more comprehensive retrofits examines the presence of such an early adopter effect, whereby those households who are more likely to engage in more comprehensive retrofits are also more likely to retrofit earlier than others. We estimate our model using a dummy for the first 12 months of the BEH scheme. The model shows that an early adopter effect does appear to exist, with applications during the first twelve months of the scheme more likely to be made for deeper retrofits.

Free-riding

METHOD

To estimate the extent of free-riding, we first estimate how much households are willing to pay, in Euro, for improved energy efficiency. By comparing this willingness-to-pay to what each household actually paid, we can estimate whether a household would have been willing to pay for their chosen retrofit even in the absence of grant aid. We use McFadden's random utility model framework (McFadden, 1984), which allows for the estimation of predictors of households' choices. This allows for the estimation of the magnitude of the positive impact of greater expected energy efficiency improvements on the likelihood of a household choosing a specific alternative and the negative impact of increased cost on such choice. The measured trade-off between these magnitudes provides an estimate of how much extra cost a household is willing to trade for improved energy efficiency and hence, the willingness-to-pay of households for energy efficiency. This is an established methodology and represents an important tool for economists as it provides for the valuation of non-monetary goods.

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.

As all participating homes had the option to engage in a retrofit including one or more of these three retrofit measures, we identify those who engaged in insulation 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 insulation and one or more of the three measures of interest are discarded. This leaves six possible options for each participant household within our 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.

We estimate the utility function of a household 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 above. 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 follows:

$$U_{ij} = \alpha_j + \left(\beta_1 + \sum\nolimits_{l=1}^{n} \beta_l Z_{il}\right) \hat{C}_{ij} + \left(\beta_2 + \sum\nolimits_{m=1}^{n} \beta_m Z_{im}\right) \hat{I}_{ij} + \epsilon_{ij} \qquad (8)$$

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}. These vary based on the characteristics of the household, which are represented by the vector Z_i. α_j is an alternative-specific constant. 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.

The average marginal willingness-to-pay is calculated as the marginal rate of substitution of energy efficiency for money. This is the average Euro amount a household is willing to pay per kWh/m²/yr improvement in their Building Energy Rating. This is the ratio of the marginal utility from improving the home to the marginal utility lost as the cost of retrofitting rises:

$$\overline{MWTP_\iota} = MRS_{IC} = \frac{\delta C}{\delta I} = -\frac{\frac{\delta U}{\delta I}}{\frac{\delta U}{\delta C}} = -\frac{\beta_2 + \sum_{m=1}^{n} \beta_m Z_{im}}{\beta_1 + \sum_{l=1}^{n} \beta_l Z_{il}} \qquad (9)$$

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:

$$WTP_i = I_{ij}.\overline{MWTP_i} \quad (10)$$

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 above, including alternative-specific constants for each individual measure and fixed cost and energy efficiency improvement effects. Secondly, as a test for robustness, an error components logit and mixed effects logit are estimated. The 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.

The mixed effects logit then 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. The estimate coefficients of these models do not differ in sign or magnitude, the results of the conditional logit are used to calculate willingness-to-pay. For each of the three choice models, expected costs and expected energy efficiency improvements associated with each alternative are estimated by OLS regression based on retrofits observed in the data.

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. 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.

Table 4. Mean marginal willingness-to-pay by sub-group of the sample.

	Homes	Mean (€)	Std. Dev.
All	26,707	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 (m²):			
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)

RESULTS AND DISCUSSION

The results of this research can be briefly summarised as follows:

- The average willingness to pay across the population of retrofits is found to be €0.127/kWh.
- Those who had previously undertaken a BEH retrofit are found to be willing to pay over twice as much as those who had not. This likely reflects a greater understanding of the benefits of energy efficiency retrofits
- Among all completed retrofits, 8 % are classed as free-riders, i.e. these would have been completed even in the absence of grant aid, while a further 7 % would have occurred with less aid than was awarded but would not have occurred without aid.

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 4 details the calculated average marginal willingness-to-pay and delta-method standard errors 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. 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 kWh energy saving each year than a household engaging in a retrofit for the first time. 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

Table 5. Distribution of free-riders by retrofit measure.

		Dependents	Partial Free-riders	Free-riders	Total
All Retrofits	Homes	22,671	2,102	1,933	26,706
	Prop.	0.85	0.08	0.07	
Boiler w/ Heating Controls	Homes	17,892	1,493	1,196	20,581
	Prop.	0.87	0.07	0.06	
Heating Controls only	Homes	848	579	699	2,126
	Prop.	0.4	0.27	0.33	
Solar	Homes	3,250	22	34	3,306
	Prop.	0.98	0.01	0.01	
Boiler w/ Heating Controls, Solar	Homes	339	3	3	345
	Prop.	0.98	0.01	0.01	
Heating Controls only, Solar	Homes	342	5	1	348
	Prop.	0.98	0.01	0	

possess a larger MWTP than smaller homes, which may stem from the characteristics of those who live in very large homes.

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 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.

The highest 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, relative to €1,022 for heating controls only retrofits.

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. 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. Further unobserved costs include the cost of the default option for households who are replacing their boiler due to a breakdown or wear-and-tear as their default option is not to do nothing. As this is unobservable in the data, the estimated negative effect of cost on the probability of choice is likely biased upward, in turn downwardly biasing willingness-to-pay and hence free-riding estimates for these households.

Conclusion and general discussion

This paper brings together evidence from various pieces of research on the Better Energy Homes scheme, a national grant aid scheme to support home owners in undertaking residential energy efficiency retrofits. Specifically, we discuss the grant scheme under three headings, these being abandonment of applications, retrofit depth and free-riding. In order to gain greater efficiencies in funding residential retrofits, lessons can be learned from examining the scheme to date, particularly with regard to households experiences, the introduction of obligated parties and efficiencies in the financial structure of the scheme.

One noticeable trend from households is the type of retrofits applied for. As the scheme has progressed, the average number of measures applied for has fallen. Early adopters in the scheme were more likely to engage in deeper retrofits and following the first twelve months of the scheme, applicants appear less interested in deep retrofits. For the first three years of the scheme, applications were dominated by two-measure retrofits, mostly comprised of attic and cavity wall insulation retrofits, which are quite cheap and easy to undertake, relative to other measures.

As the number of homes in the building stock requiring such a retrofit fell, the number of applications for such naturally fell. Since then, boiler with heating controls retrofits have dominated the pool of applications. Moving forward, in order to achieve decarbonisation of the residential sector, deeper retrofits may be seen as an opportunity for policy. However, applications for deeper retrofits are more likely to be abandoned by households. It may be worthwhile, in that case, for the establishment of a third-party support to help organise retrofits on behalf of home owners, similar to the roles played by obligated and counterparties at present.

Helping to understand how to gain greater efficiency in the financing structure, we examined the impact of the introduction of bonus payments for three- and four-measure retrofits. We did not find any evidence, however, that the introduction of such payments had a positive impact on the propensity of homes to engage in deeper retrofits. This is in contrast to other international studies, which found greater numbers of deeper retrofits under schemes with progressive funding arrangements (Neuhoff et al., 2012).

Applications made by obligated parties are less likely to be abandoned, adding further credence to the idea that organisational burden is the main barrier to retrofit completion. By incentivising energy retailers and suppliers to engage in residential retrofitting, the number of homes in engaging in retrofits has likely risen. On the other hand, the incentive structure for obligated parties has encouraged quantity over quality in conducting retrofits. Parties are awarded credits based on the installed retrofit measures attributed to them. This has led to a focus by obligated parties on engaging in as many retrofits of the same measures as possible. This incentive structure may require some tweaking to incentivise deeper retrofits into the future, although this might come at a cost of fewer total retrofits.

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Acknowledgements

We acknowledge the Sustainable Energy Authority of Ireland for data access and thank contributors at SEAI, participants to the ESRI-UCD Energy Research Conference, the Irish Economic Association annual conference and others for helpful comments and suggestions. This research has been financially supported by the Sustainable Energy Authority of Ireland and the ESRI's Energy Policy Research Centre.